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REVERSIVE AND NON-REVERSIVE MAGNETIC CP STARS. I. CATALOG.

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ABSTRACT

An analysis of the distribution of signs of the longitudinal magnetic field component B_z is presented for a sample of 307 chemically peculiar (CP) stars with reliably measured magnetic fields. For each star, the root-mean-square field B_{rms} and the extreme values of B_z are used to classify the field configuration as either reversionary or non-reversionary. Among the 173 non-reversionary stars, 100 exhibit a predominantly negative B_z sign, while only 73 display a positive sign, corresponding to an excess of negative polarities by a factor of about 1.37. A subsample of stars with at least five independent measurements (254 objects) yields a similar ratio of 1.38, confirming the robustness of the asymmetry. The observed predominance of negative B_z values among non-reversionary CP stars in the solar neighbourhood is statistically significant. Possible origins of this asymmetry remain unclear and will be addressed in future studies.

Key words: stars: magnetic field — stars: chemically peculiar

1 INTRODUCTION

Magnetic fields are found in approximately 10% of OBA-type stars on the main sequence. In terms of effective temperature, mass, and luminosity, these objects do not differ from normal stars, but exhibit significant anomalies in the chemical composition of their atmospheres: the abundances of some elements, in particular rare-earth elements, exceeds the solar value by up to three orders of magnitude (see, e.g., [Ghazaryan et al. 2018](#)). In addition, the rotation velocities of magnetic stars are approximately in 3–4 times lower than those of normal stars ([Netopil et al. 2017](#)).

The first magnetic field in a star (78 Vir) was discovered by [Babcock \(1947\)](#). The technique he introduced allowed the measurement of only the longitudinal component B_z , under the assumption of a global, coherent field structure covering the entire stellar surface. To a first approximation, this configuration is dipolar. Although more complex geometries are possible, the dipole component remains dominant. The measured strengths of the large-scale magnetic fields in CP stars range from about 100 G ([Aurière et al. 2007](#)) up to 35 kG ([Babcock 1960](#)).

The longitudinal component reaches its maximum value at the magnetic poles, and at the magnetic equator it becomes zero. As the star rotates, the observer views different regions of the surface with varying B_z orientations, resulting in periodic changes of the measured field strength and polarity.

This behaviour is naturally explained by the oblique rotator model ([Stibbs 1950](#)). The choice of sign (+ or –) is a matter of convention. Currently, researchers follow the system introduced by [Babcock \(1947\)](#). If during the rotation period the B_z curve changes sign, the field is called reversionary, and if the sign remains constant, then it is called non-reversionary.

Since the rotation period is unknown for most of the stars studied and, therefore, it is impossible to carry out detailed modeling of the magnetic field, to estimate it we use the value of the root-mean-square magnetic field B_{rms} and its error:

$$B_{\text{rms}} = \sqrt{\frac{1}{n} \sum_{i=1}^n B_{zi}^2}; \quad \sigma_{\text{rms}} = \sqrt{\frac{1}{n} \sum_{i=1}^n \sigma_i^2}. \quad (1)$$

The purpose of this study is to search for a possible correlation between the strength and configuration of the magnetic field of individual stars and the parameters of the large-scale Galactic magnetic field in the solar neighbourhood.

The first attempt at such an analysis was made by [Romanyuk \(1994\)](#). Based on 64 non-reversionary CP stars, it was found that in 36 objects the negative sign of the longitudinal field predominates, and in 28 it is positive. However, due to the small sample size, it was premature to conclude that a genuine asymmetry exists in the distribution of magnetic stars. A substantial increase in the number of studied objects was clearly required.

Over the next 30 years, our group conducted an active search for new magnetic stars in the northern hemisphere. In total, about 200 objects were discovered. In parallel with these efforts, large international collaborations have carried out a number of survey

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Table 1. Catalog of reversive and non-reversive magnetic CP stars. The stars are arranged in ascending order of their HD and BD catalog numbers. The table columns contain: star name, distance r , root-mean-square magnetic field and its error $B_{\text{rms}} \pm \sigma$, minimum and maximum extremal values of the longitudinal field B_z , number of measurements n , and reversibility signature.

Star	r , pc	$B_{\text{rms}} \pm \sigma$, G	B_z (min)/(max), G	n	Revers. type	Star	r , pc	$B_{\text{rms}} \pm \sigma$, G	B_z (min)/(max), G	n	Revers. type
HD 315	219	1520 ± 680	−1600 / +2000	5	+/-	HD 34736	373	4000 ± 500	−6000 / +5000	100	+/-
HD 965	237	400 ± 50	−400 / +600	78	+/-	HD 34889	353	642 ± 134	−1000 / +600	6	+/-
HD 1048	139	136 ± 55	−70 / +240	4	+/-	HD 349321	460	2700 ± 300	−4400 / +1900	20	−
HD 2453	174	588 ± 202	−1030 / −520	28	−	HD 35177	347	940 ± 274	−400 / +700	4	+/-
HD 2887	331	436 ± 249	−700 / +500	6	+/-	HD 35298	358	2323 ± 330	−2810 / +2920	13	+/-
HD 2957	316	520 ± 120	−930 / +670	7	+/-	HD 35456	346	440 ± 80	+200 / +500	6	+
HD 3980	68	1200 ± 200	−1600 / +2000	11	+/-	HD 35502	363	1490 ± 140	−2250 / −100	25	−
HD 4478	575	990 ± 850	−1000 / +1300	3	+/-	HD 36313	386	1020 ± 450	−1500 / +1100	12	+/-
HD 4778	104	1026 ± 454	−1100 / +1400	30	+/-	HD 36429	338	425 ± 170	−840 / +160	5	−
HD 5441	385	409 ± 40	−440 / 0	6	−	HD 36485	382	3220 ± 318	−3700 / −1900	10	−
HD 5601	277	1190 ± 100	−2000 / −300	8	−	HD 36526	448	2130 ± 200	−980 / +3480	9	+
HD 5737	216	324 ± 142	−400 / +500	23	+/-	HD 36644	338	1992 ± 125	−2500 / +2300	9	+/-
HD 5797	565	669 ± 46	−100 / +1000	10	+	HD 36668	393	1875 ± 447	−2100 / +2000	10	+/-
HD 6757 A	298	2730 ± 160	+2300 / +2900	30	+	HD 36916	260	500 ± 125	−1000 / −200	8	−
HD 8855	485	354 ± 145	−600 / +270	6	+/-	HD 36955	448	843 ± 219	−1300 / 0	6	−
HD 9147	787	400 ± 150	−370 / +600	5	+/-	HD 36997	424	762 ± 73	−1600 / +1100	6	+/-
HD 9996	140	833 ± 174	−1700 / +600	20	−	HD 37017	360	1490 ± 338	−2600 / +300	44	−
HD 10783	169	1269 ± 260	−1200 / +1800	17	+/-	HD 37058	382	1090 ± 412	−1200 / +900	11	+/-
HD 11187	389	616 ± 239	−500 / +400	11	+/-	HD 37140	420	450 ± 210	−900 / +500	8	+/-
HD 11503	51	545 ± 344	−1100 / +500	18	−	HD 37333	335	869 ± 246	−1290 / +560	6	−
HD 11948	180	468 ± 39	−750 / +330	8	−	HD 37479	435	1980 ± 155	−1600 / +3500	15	+
HD 12288	251	1643 ± 150	−3100 / −200	42	−	HD 37633	417	520 ± 122	+200 / +800	6	+
HD 12447	50	365 ± 266	−510 / +570	22	+/-	HD 37642	369	2100 ± 180	−3000 / +3000	12	+/-
HD 12767	106	242 ± 94	−230 / +290	8	+/-	HD 37687	446	613 ± 195	+500 / +700	5	+
HD 13404	217	3680 ± 380	−4800 / −2100	20	−	HD 37776	394	1260 ± 385	−2000 / +2000	150	+/-
HD 14437	234	1829 ± 260	−2600 / −800	26	−	HD 37808	185	950 ± 172	+300 / +1200	5	+
HD 15089	41	303 ± 47	−300 / +400	16	+/-	HD 38129	178	438 ± 173	−600 / −200	3	−
HD 15144	79	802 ± 216	−1150 / −530	20	−	HD 38823	110	1510 ± 110	−2500 / +1500	12	+/-
HD 16145	249	725 ± 66	−820 / +500	3	+/-	HD 39082	166	1290 ± 330	−1100 / +1600	6	+/-
HD 16605	621	1627 ± 119	−2400 / −800	7	−	HD 39658	371	930 ± 190	−970 / +1350	7	+/-
HD 16705	487	524 ± 155	−400 / +720	4	+/-	HD 40142	308	700 ± 50	−780 / +780	4	+/-
HD 17330	427	415 ± 38	−500 / −300	30	−	HD 40146	474	595 ± 105	−650 / +650	3	+/-
HD 18078	388	800 ± 100	−850 / +1200	25	+/-	HD 40312	51	340 ± 60	−240 / +360	20	+/-
HD 18296	107	440 ± 216	−1000 / +1350	8	+/-	HD 40652	377	781 ± 61	−1200 / −270	6	−
HD 19712	166	2211 ± 232	−3800 / +2000	13	+/-	HD 40711	487	500 ± 180	−650 / +320	6	−
HD 21699	178	973 ± 247	−800 / +1600	8	+/-	HD 40759	411	1990 ± 240	+600 / +2400	30	+
HD 22316	137	1250 ± 348	−2200 / +600	19	−	HD 41403	283	330 ± 150	−500 / +450	12	+/-
HD 22470	117	733 ± 408	−1100 / +1200	12	+/-	HD 42605	283	270 ± 47	−480 / +100	9	−
HD 22920	191	307 ± 159	+200 / +400	4	+	HD 42616	231	620 ± 238	−840 / −440	4	−
HD 24155	161	803 ± 170	−440 / +1660	8	+	HD 43819	246	560 ± 100	−20 / +740	4	+
HD 24712	48	802 ± 171	+300 / +1300	30	+	HD 45107	492	300 ± 150	−140 / +570	8	+
HD 25267	100	241 ± 91	−345 / −15	7	−	HD 45530	273	590 ± 270	−650 / +750	5	+/-
HD 25823	124	668 ± 470	−100 / +1200	18	+	HD 45583	314	2880 ± 600	−2500 / +3800	30	+/-
HD 25999	158	1155 ± 233	−900 / +1400	6	+/-	HD 47103	360	3526 ± 365	−4000 / −2700	8	−
HD 27309	88	1755 ± 602	−4000 / −200	25	−	HD 47152	121	856 ± 207	−600 / +1500	4	+
HD 27404	165	1326 ± 174	−3100 / +1400	15	−	HD 47756	277	420 ± 120	−650 / +150	7	−
HD 279021	257	954 ± 151	−960 / +1300	5	+/-	HD 49223	714	390 ± 210	−120 / +590	6	+
HD 29009	239	480 ± 217	−600 / +900	10	+/-	HD 49333	216	618 ± 300	−800 / +800	8	+/-
HD 290665	392	2024 ± 53	−2900 / +4000	10	+/-	HD 49713	212	2560 ± 460	−2880 / +2200	9	+/-
HD 294046	355	495 ± 163	−900 / +330	4	−	HD 49976	102	1490 ± 360	−2000 / +2200	18	+/-
HD 29762	392	409 ± 50	+150 / +560	4	+	HD 50169	507	1220 ± 220	−1500 / +2000	30	+/-
HD 29925	365	1064 ± 170	−1400 / −200	10	−	HD 50403	305	663 ± 82	−330 / +1100	5	+
HD 30466	195	1464 ± 293	+1000 / +2200	14	+	HD 50461	257	1500 ± 700	−2800 / +2200	9	+/-
HD 32145	287	2000 ± 293	−2100 / +2400	7	+/-	HD 51418	178	401 ± 200	−460 / +750	15	+/-
HD 32633	217	2760 ± 263	−4100 / +1700	50	−	HD 51684	222	1410 ± 65	−1800 / −1100	5	−
HD 335238	385	1738 ± 247	−3040 / +2260	12	+/-	HD 52628	220	2000 ± 80	−2050 / +2100	10	+/-
HD 341037	333	1100 ± 48	−1400 / −840	6	−	HD 53081	770	450 ± 100	−600 / +600	5	+/-
HD 34162	363	440 ± 100	−750 / +190	6	−	HD 54118	96	1030 ± 256	−1600 / +1600	7	+/-
HD 343872	526	2930 ± 320	−700 / +4500	40	+	HD 54824	282	589 ± 153	−860 / +480	8	+/-
HD 34452	142	743 ± 434	−300 / +1000	13	+	HD 55522	278	505 ± 100	+38 / +873	3	+
HD 34719	160	930 ± 220	−1300 / +1300	9	+/-	HD 55755	555	2670 ± 150	−3280 / +2180	5	+/-

Table 1. (Contd.)

Star	r , pc	$B_{\text{rms}} \pm \sigma$, G	B_z (min)/(max), G	n	Revers. type	Star	r , pc	$B_{\text{rms}} \pm \sigma$, G	B_z (min)/(max), G	n	Revers. type
HD 58260	629	2290 ± 300	$+2000 / +2600$	10	+	HD 130559	73	1375 ± 100	$-1300 / -200$	12	—
HD 59435	518	800 ± 50	$-1200 / +900$	35	+/-	HD 133029	157	2420 ± 319	$+1300 / +3300$	16	+
HD 61045	488	680 ± 532	$-160 / +470$	5	+/-	HD 133652	122	1110 ± 200	$-2100 / +700$	9	—
HD 61468	515	1900 ± 51	$-2500 / -1000$	5	—	HD 134214	93	458 ± 150	$-900 / -200$	20	—
HD 62140	95	1336 ± 306	$-2200 / +3200$	30	+/-	HD 134793	180	770 ± 250	$-800 / +900$	6	+/-
HD 63347	175	831 ± 139	$-1100 / +1100$	11	+/-	HD 135679	265	1025 ± 43	$+200 / +1300$	6	+
HD 63401	185	400 ± 80	$-650 / +340$	4	+/-	HD 137193	264	680 ± 220	$+230 / +970$	4	+
HD 64486	104	855 ± 513	$-1300 / +600$	6	—	HD 137509	196	1020 ± 416	$-1200 / +2200$	8	+/-
HD 64740	245	565 ± 114	$-870 / +530$	15	+/-	HD 137909	35	750 ± 100	$-900 / +1000$	50	+/-
HD 65339	97	3200 ± 440	$-5400 / +4200$	100	+/-	HD 137949	79	1500 ± 120	$+980 / +1920$	20	+
HD 66350	472	480 ± 100	$-660 / +520$	5	+/-	HD 138633	302	277 ± 25	$-300 / +300$	5	+/-
HD 70331	467	2800 ± 184	$-3000 / -2000$	14	—	HD 138777	355	1870 ± 57	$+1700 / +2200$	9	+
HD 71866	130	1680 ± 236	$-1600 / +2000$	10	+/-	HD 140160	68	860 ± 712	$-1840 / +760$	4	+/-
HD 72295	370	200 ± 130	$-360 / +110$	8	—	HD 142070	180	400 ± 60	$-700 / +600$	20	+/-
HD 72968	104	480 ± 288	$-700 / +500$	20	+/-	HD 142301	144	2100 ± 420	$-4100 / +1600$	4	—
HD 73340	149	1644 ± 218	$-2300 / -900$	5	—	HD 142502	431	547 ± 36	$-500 / +660$	6	+/-
HD 74521	154	812 ± 141	$-200 / +1400$	10	+	HD 142554	448	1310 ± 290	$-2250 / +1740$	5	+/-
HD 78316	188	208 ± 205	$-640 / +460$	25	+/-	HD 142990	142	1304 ± 255	$-2500 / +600$	20	—
HD 79158	190	672 ± 226	$-1500 / +1000$	20	+/-	HD 143473	162	4292 ± 362	$+4200 / +5100$	6	+
HD 80316	135	410 ± 120	$-590 / +649$	5	+/-	HD 144334	136	783 ± 257	$-1400 / +500$	20	—
HD 81009	145	1430 ± 236	$-100 / +2500$	10	+	HD 147010	130	4032 ± 402	$-5500 / -2500$	20	—
HD 83368	71	576 ± 264	$-800 / +800$	12	+/-	HD 148199	167	900 ± 247	$-900 / +1700$	12	+/-
HD 86170	273	257 ± 88	$-340 / -150$	4	—	HD 149764	175	700 ± 65	$-1213 / +30$	3	—
HD 86592	153	1908 ± 115	$-260 / +2670$	10	+	HD 149822	146	450 ± 180	$-690 / +510$	7	+/-
HD 89069	314	434 ± 29	$-700 / +600$	13	+/-	HD 149911	119	580 ± 32	$-700 / +300$	5	—
HD 90044	106	740 ± 373	$-800 / +700$	6	+/-	HD 151199	103	280 ± 100	$-400 / +150$	5	—
HD 92499	269	1000 ± 140	$-1255 / -964$	3	—	HD 151965	175	2602 ± 282	$-3700 / -550$	8	—
HD 92664	153	803 ± 40	$-1300 / -100$	18	—	HD 152107	55	1487 ± 250	$+500 / +2000$	50	+
HD 93507	327	2164 ± 278	$+1600 / +2600$	12	+	HD 153882	161	1750 ± 462	$-1800 / +3100$	15	+
HD 93700	335	836 ± 50	$-1170 / -490$	9	—	HD 154708	148	6000 ± 50	$+5764 / +7530$	3	+
HD 94603	450	518 ± 69	$-145 / +900$	5	+	HD 158450	159	1570 ± 180	$-4400 / +800$	10	—
HD 94660	166	2352 ± 265	$-3300 / -1800$	6	—	HD 159545	408	613 ± 125	$-360 / +1100$	4	+
HD 96237	350	750 ± 83	$-1000 / -700$	4	—	HD 161321	140	573 ± 118	$-600 / +900$	6	+/-
HD 96446	465	1105 ± 248	$-2100 / -1100$	11	—	HD 164258	116	800 ± 300	$-500 / +1200$	6	+/-
HD 98088	127	802 ± 284	$-1200 / +1000$	10	+/-	HD 164827	324	1567 ± 615	$-2300 / +1600$	5	+/-
HD 99563	255	600 ± 80	$-680 / +670$	6	+/-	HD 165474	171	470 ± 100	$-300 / +600$	20	+/-
HD 101065	109	2241 ± 450	$-2300 / -1040$	3	—	HD 166473	140	2150 ± 220	$-2200 / -600$	3	—
HD 103192	95	204 ± 104	$-250 / -100$	4	—	HD 168733	198	815 ± 276	$-800 / -400$	4	—
HD 107000	277	200 ± 60	$-240 / +390$	15	+/-	HD 168796	215	610 ± 100	$-900 / +500$	7	+/-
HD 107612	176	320 ± 140	$-440 / +430$	7	+/-	HD 168856	204	657 ± 221	$-1100 / +360$	4	—
HD 108651	72	380 ± 240	$-200 / +560$	5	+	HD 169842	403	370 ± 180	$-660 / +380$	8	+/-
HD 108662	77	620 ± 200	$-1150 / +550$	50	—	HD 169887	376	680 ± 250	$-2300 / +2020$	9	+/-
HD 108945	82	537 ± 313	$-347 / +440$	15	+/-	HD 170000	93	350 ± 150	$-180 / +640$	15	+
HD 109026	116	342 ± 95	$+140 / +470$	5	+	HD 170397	113	615 ± 252	$-650 / +870$	10	+/-
HD 110066	137	204 ± 50	$-370 / +300$	15	+/-	HD 170565	235	1760 ± 170	$+40 / +1960$	6	+
HD 111133	192	806 ± 143	$-1500 / -500$	10	—	HD 170836	666	490 ± 140	$-700 / +300$	3	—
HD 112381	124	3400 ± 245	$-3700 / -3100$	5	—	HD 170973	251	530 ± 100	$-600 / +800$	8	+/-
HD 112413	30	1350 ± 200	$-1400 / +1600$	100	+/-	HD 173650	247	326 ± 275	$-500 / +700$	15	+/-
HD 112528	226	900 ± 100	$-1000 / +970$	8	+/-	HD 175362	146	3570 ± 448	$-6500 / +4000$	20	+/-
HD 113894	192	791 ± 40	$-1200 / +1000$	11	+/-	HD 178892	249	5410 ± 470	$+2100 / +8000$	32	+
HD 115605	181	620 ± 120	$-750 / +680$	7	+/-	HD 179761	210	480 ± 238	$-590 / +170$	4	—
HD 115708	128	927 ± 405	$-1860 / +1600$	11	+/-	HD 180058	641	277 ± 74	$-390 / +310$	4	+/-
HD 116114	138	1923 ± 113	$-2200 / -1800$	13	—	HD 182532	316	461 ± 108	$-40 / +620$	5	+
HD 116458	125	1925 ± 273	$-2300 / -1500$	10	—	HD 183339	322	1296 ± 465	$-1600 / +1800$	6	+/-
HD 118022	60	808 ± 225	$-2800 / -200$	80	—	HD 184471	460	350 ± 100	$-20 / +800$	15	+
HD 118054	148	575 ± 304	$-1000 / +200$	6	—	HD 184927	599	1465 ± 430	$-1200 / +3000$	15	+
HD 119213	91	1220 ± 440	$-500 / +1600$	13	+	HD 187128	336	400 ± 66	$+373 / +437$	3	+
HD 119419	134	1770 ± 455	$-4200 / +1800$	20	—	HD 187474	97	1488 ± 143	$-1800 / +1800$	10	+/-
HD 122532	153	665 ± 268	$-900 / +900$	9	+/-	HD 188041	85	1100 ± 200	$-200 / +1500$	10	+
HD 124224	75	570 ± 323	$-437 / +811$	14	+/-	HD 188501	462	1172 ± 72	$-2200 / +50$	11	—
HD 125248	87	1505 ± 295	$-2500 / +2800$	15	+/-	HD 189160	332	995 ± 197	$-200 / +1500$	4	+
HD 125823	120	470 ± 253	$-440 / +370$	9	+/-	HD 189775	248	1375 ± 540	$-540 / +2240$	3	+
HD 126515	131	1720 ± 373	$-2000 / +2000$	15	+/-	HD 189963	621	410 ± 130	$-700 / +300$	6	—

Table 1. (Contd.)

Star	r , pc	$B_{\text{rms}} \pm \sigma$, G	B_z (min)/(max), G	n	Revers. type	Star	r , pc	$B_{\text{rms}} \pm \sigma$, G	B_z (min)/(max), G	n	Revers. type
HD 191742	329	578 ± 43	$-900 / -200$	4	—	HD 225114	277	970 ± 220	$-1450 / +750$	20	+/-
HD 192224	440	480 ± 130	$-680 / +680$	8	+/-	HD 225627	393	204 ± 59	$-50 / +300$	5	+
HD 192678	220	1410 ± 160	$+1000 / +1800$	30	+	HD 231054	321	1650 ± 240	$+380 / +2500$	5	+
HD 192913	242	483 ± 221	$-670 / +380$	5	+/-	HD 258686	629	6000 ± 320	$+5100 / +7900$	17	+
HD 196178	168	973 ± 238	$-1500 / -700$	9	—	HD 260858	790	536 ± 76	$+300 / +700$	4	+
HD 196502	116	490 ± 200	$-700 / -200$	15	—	HD 279021	257	954 ± 151	$-960 / +1300$	5	+/-
HD 196606	251	1005 ± 192	$-1565 / +1040$	5	+/-	HD 290665	392	2024 ± 53	$-2900 / +4000$	10	+/-
HD 196655	323	400 ± 100	$-530 / +450$	4	+/-	HD 294046	355	495 ± 163	$-900 / +330$	4	—
HD 196691	371	1650 ± 250	$-800 / +2290$	5	+	HD 335238	385	1738 ± 247	$-3040 / +2260$	12	+/-
HD 199180	385	278 ± 45	$-350 / -5$	7	—	HD 338226	550	1080 ± 200	$+440 / +1490$	7	+
HD 199728	213	400 ± 200	$-470 / +1120$	6	+	HD 341037	333	1100 ± 48	$-1400 / -840$	6	—
HD 200177	156	1124 ± 433	$-1900 / +300$	4	—	HD 343872	526	2930 ± 320	$-700 / +4500$	40	+
HD 200311	330	1490 ± 427	$-2600 / +2600$	22	+/-	HD 349321	460	2700 ± 300	$-4400 / +1900$	20	—
HD 200405	370	194 ± 24	$-265 / -50$	4	—	HDE 293764	385	3760 ± 220	$+2700 / +4700$	16	+
HD 201174	305	1311 ± 75	$+500 / +2100$	40	+	BD +00 1659	862	288 ± 99	$+160 / +365$	6	+
HD 201601	35	600 ± 100	$-1100 / +600$	100	+/-	BD +00 4535	526	2157 ± 180	$-2900 / +2400$	6	+/-
HD 204815	512	390 ± 145	$+60 / +600$	5	+	BD +17 3622	315	1390 ± 180	$+900 / +1600$	4	+
HD 205198	304	1714 ± 557	$-3700 / -222$	5	—	BD +32 2827	568	524 ± 156	$-770 / +60$	3	—
HD 207188	293	1220 ± 310	$-1510 / +1000$	4	+/-	BD +35 3616	417	520 ± 160	$-500 / +540$	6	+/-
HD 208217	122	970 ± 45	$-1800 / +800$	6	—	BD +40 175A	300	2650 ± 178	$-3400 / -2000$	8	—
HD 209051	336	2225 ± 520	$-3300 / -1040$	7	—	BD +40 175B	300	1426 ± 148	$+780 / +2660$	6	+
HD 210432	232	1230 ± 190	$-1810 / +530$	4	—	BD +41 43	850	290 ± 150	$-450 / +100$	11	—
HD 213258	111	950 ± 49	$-1200 / -400$	26	—	BD +42 659	427	913 ± 68	$-1000 / +1300$	4	+/-
HD 215441	460	17500 ± 500	$+10000 / +20000$	50	+	BD +44 4130	540	2728 ± 132	$-3094 / -2398$	4	—
HD 216018	143	1200 ± 120	$+1000 / +1400$	12	+	BD +46 570	474	450 ± 68	$+260 / +570$	4	+
HD 217833	204	3000 ± 500	$-6200 / -1500$	12	—	BD +51 3356	507	3209 ± 598	$-218 / +4786$	3	+
HD 221006	119	600 ± 150	$+410 / +990$	3	+	BD +53 1183	595	703 ± 111	$-810 / +1030$	7	+/-
HD 221934	312	1100 ± 400	$-1490 / -1130$	4	—	BD +64 352	505	4240 ± 390	$-5500 / -2700$	17	—
HD 221936	444	2200 ± 300	$-2500 / +2900$	27	+/-	V1356 Ori	917	2282 ± 800	$-3200 / -800$	6	—
HD 223640	100	653 ± 218	$-20 / +820$	4	+			$\pm$	$/$		

projects, leading to the discovery of hundreds of new magnetic CP stars. Notable among these are the BinaMiCS (Binarity and Magnetic Interactions in various classes of Stars; [Neiner et al. 2015](#)), MiMeS (Magnetism in Massive Stars; [Wade et al. 2016](#)), and BOB (B-fields in OB stars; [Schöller et al. 2017](#)) projects. Thus, it became possible to perform analysis at a new level, using much more extensive observational material.

2 CATALOG AND SAMPLE ANALYSIS

Currently, magnetic fields have been detected in a significant number of CP stars. However, for many objects only a few measurements have been made, which does not allow constructing a phase magnetic curve and confidently classifying the field as reversible or non-reversible. For this reason, a list of stars was compiled for which there are at least three measurements of the longitudinal component of the magnetic field.

The primary data sources were the catalogs [Romanyuk & Kudryavtsev \(2008\)](#), [Bychkov et al. \(2009\)](#), together with the later compilation by [Bychkov et al. \(2021\)](#). Additionally, the database of our group was used. The final catalog includes only those objects for which the root-mean-square value B_{rms} confirms the presence of a magnetic field with high confidence.

The resulting sample of reversible and non-reversible magnetic CP stars is presented in Table 1. In addition to the magnetic field parameters, it contains distances to objects that were obtained from the parallaxes of the Gaia DR3 mission ([Gaia Collaboration 2020](#)). Almost all magnetic stars from catalog are nearby objects ($r \leq 1$ kpc). In a few cases where the Gaia parallaxes for binary systems are unreliable, distances determined from spectroscopic

data. A star is classified as non-reversible if one of the extreme values of the longitudinal field exceeds the other by at least a factor of two or more times. For reversible fields in the table, (+/-) is indicated in the corresponding column.

In total, the catalogue contains 307 magnetic CP stars. A reversible field is observed in 134 objects (44%), while the remaining 173 stars (56%) exhibit a non-reversible configuration. Among the latter, 73 objects have a positive field sign (+) and 100 have a negative sign (-). Thus, in the non-reversible subsample the ratio of negative to positive polarities is approximately 1.37. In the earlier study of [Romanyuk \(1994\)](#), based on a smaller sample, this ratio was about 1.28.

To classify a star as reversible or non-reversible, it is necessary to have a sufficient number of measurements of the longitudinal field. Obviously, three observations are not enough to confidently construct the B_z curve and determine the alternation of signs. In order to check the stability of the obtained conclusions, stars were selected from the catalog for which at least five magnetic field measurements were made. For the majority of these objects, even in the absence of a known rotation period, five measurements provide a reliable characterisation of the field behaviour, and the probability of misclassification is greatly reduced.

A separate issue concerns super-slowly rotating stars, for which all measurements can occur at the same rotation phase. However, statistical estimates indicate that such objects constitute only a few percent of the total CP star population (see, e.g., [Mathys 2020](#)), and therefore they cannot significantly affect the overall conclusions.

After applying the selection criterion ($n \geq 5$), a total of 254 magnetic CP stars remain. Among these, 77 are non-reversible stars with a negative sign (-), 56 have a positive sign (+), and 121 dis-

play reversible fields (+/−). The ratio of negative to positive polarities in this restricted subsample is 1.38, in excellent agreement with the value obtained from the full catalogue. Thus, in all the cases considered, the advantage of stars with a negative sign of the longitudinal field remains.

All stars are located within 1 kpc from the Sun, with the absolute majority (90%) located at a distance of less than 500 pc. The nearest object is HD 112413 at 30 pc, while the most distant is V1356 Ori at 917 pc. The mean distance of the sample is $\langle r \rangle = 275$ pc.

The root-mean-square magnetic field B_{rms} varies in a wide range, from 200 G (HD 72295 and HD 107000) to 17 500 G (HD 215441), with a mean value of $\langle B_{\text{rms}} \rangle = 1290 \pm 220$ G. The B_{rms} distribution shows that the field strengths of most stars do not exceed a few kilogauss: only 15 objects (6%) have $B_{\text{rms}} \geq 3$ kG.

3 CONCLUSIONS

This paper presents a catalogue of magnetic CP stars containing 307 objects with reliably measured values of the longitudinal magnetic field B_z . All stars lie relatively close to the Sun, with distances not exceeding 1 kpc. For each object, the catalogue lists the root-mean-square magnetic field B_{rms} , the extreme values of B_z , the number of observations, and the classification of the field as reversible or non-reversible.

An analysis of the full sample of 307 stars reveals that among non-reversible objects, those with a negative longitudinal field sign are approximately 37% more common than those with a positive sign. This excess is larger than the value reported in the earlier study of [Romanyuk \(1994\)](#). A subsample restricted to 254 stars with five or more observations yields a similar predominance of the negative sign, confirming the robustness of the detected asymmetry.

On the basis of this statistically significant sample, it is concluded that non-reversible magnetic CP stars in the solar neighbourhood possess a predominantly negative longitudinal magnetic field. The physical origin of this asymmetry remains unclear. Possible explanations include a connection with the orientation of the large-scale Galactic magnetic field in the local region or evolutionary peculiarities of magnetic stars. A more detailed analysis, involving magnetic field modelling that incorporates rotation periods and comparisons with 3D-models of the Galaxy, will be the subject of future investigations.

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QUANTUM-MECHANICAL DESCRIPTION OF MATTER IN COMPACT STARS

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ABSTRACT

An analytical study presents the physical phenomena occurring in superdense stars, with particular attention to the structure and properties of the crystalline crust. Numerical estimates of the density and lattice parameters of matter in the crust are provided. It is shown that under extreme conditions of density, as realized in compact stellar objects, the matter forms a degenerate electron gas whose properties are governed by quantum-mechanical principles.

Key words: compact objects – neutron stars – dense matter – degenerate matter

1 INTRODUCTION

Compact stars are astronomical objects formed as end products of stellar evolution, characterized by extremely high densities and small radii. They are the remnants of massive stars that have exhausted their hydrogen fuel and undergone subsequent nuclear burning stages, including helium fusion, leading to the explosive event of a supernova. The explosion leaves behind a dense central remnant surrounded by an extended nebula. The class of compact objects includes neutron stars, white dwarfs, and black holes (Shapiro & Teukolsky 1983; Yakovlev 2016).

The principal distinction between compact and normal stars lies in their density and size. Compact stars have dimensions much smaller than those of main-sequence stars of comparable mass. Neutron stars are of scientific interest because they serve as natural laboratories for studying matter under extreme physical conditions. They allow testing of theoretical models of superdense matter by comparing observational data with the predictions of particle interaction theories (Yakovlev 2016).

Although neutron stars have been studied for decades, their internal structure remains incompletely understood. Some models describe a relatively simple composition with a thin outer crust over a layer of neutron fluid, while others propose a more complex stratification. In such models, the outer crust comprises several layers differing in density and nuclear composition, with a crystalline layer of iron on the surface, beneath which lies degenerate matter. The core may consist of exotic phases such as quark–gluon plasma or pion condensate (Haensel et al. 2007; Yakovlev 2016).

2 OBSERVATION AND RESULTS

At extreme densities ranging from 10^4 – 10^7 g cm^{−3} in white dwarfs to above 10^9 g cm^{−3} in neutron star crusts, matter ceases to obey classical thermodynamic behavior. Instead, its properties are dominated by the Pauli exclusion principle, a cornerstone of quantum mechanics (Lattimer & Prakash 2004; Takibayev & Boshkayev 2017).

This principle forbids identical fermions (electrons) from occupying the same quantum state, resulting in the formation of a degenerate electron gas—a state in which pressure arises solely from the filling of energy levels up to the Fermi energy. Such degeneracy pressure is the fundamental component of the equation of state of compact stars.

Degeneracy occurs when the average interparticle distance becomes comparable to the electron de Broglie wavelength, necessitating a full quantum-statistical treatment via the Fermi–Dirac distribution (Landau & Lifshitz 1976; Takibayev & Boshkayev 2017).

The Fermi–Dirac distribution for fermions at temperature T is given by:

$$f(E) = \frac{1}{e^{\frac{E-\mu}{kT}} + 1} \quad (1)$$

where μ is the chemical potential.

In the limit $T \rightarrow 0$, $f(E) = 1$ for $E < E_F$, and $f(E) = 0$ for $E > E_F$, meaning all states below the Fermi level are occupied.

Considering a system of noninteracting electrons in volume V , each quantum state is characterized by momentum p . The number of states per phase-space element is limited to

$$\frac{2}{h^3} d^3p d^3r,$$

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where the coefficient 2 reflects the two spin states of the electron.

Let the number of electrons within a volume V be N , and the electron number density be:

$$n_e = \frac{N}{V}. \quad (2)$$

At $T = 0$, the electrons occupy all quantum states from $p = 0$ up to the maximum momentum, the Fermi momentum p_F , which is determined by the condition:

$$N = \frac{2V}{h^3} \int_0^{p_F} 4\pi p^2 dp. \quad (3)$$

Performing the integration, we obtain:

$$n_e = \frac{8\pi}{3h^3} p_F^3. \quad (4)$$

Hence, the Fermi momentum is given by:

$$p_F = h(3\pi^2 n_e)^{1/3}. \quad (5)$$

This fundamental quantity determines all the physical properties of the degenerate gas. The energy of an electron with momentum p in the non-relativistic regime takes the form:

$$E = \frac{p^2}{2m_e}, \quad (6)$$

while in the relativistic regime it is given by

$$E = \sqrt{p^2 c^2 + m_e^2 c^4} - m_e c^2. \quad (7)$$

Fermi energy:

$$E_F = E(p_F). \quad (8)$$

For typical white-dwarf densities, the Fermi energy is $E_F \sim 0.1$ – 2 MeV, which often exceeds the thermal energy kT , thereby leading to degeneracy.

Degeneracy occurs when

$$kT \ll E_F. \quad (9)$$

For white dwarfs, the typical temperature is $T \sim 10^7$ K, while the Fermi temperature is $T_F \sim 10^{10}$ K; hence, $T/T_F \sim 10^{-3}$ – 10^{-4} .

Temperature corrections are therefore negligible, and the pressure is determined almost entirely by quantum effects rather than by thermal motion.

The theoretical foundation of neutron-star models is based on the quantum theory of matter and on the concept of a degenerate Fermi gas of spin- $\frac{1}{2}$ particles. However, many aspects concerning the internal structure of neutron stars, as well as the nuclear reactions and microscopic processes occurring within them, remain insufficiently understood. Therefore, the further development of neutron-star physics is closely associated with the formulation of new theoretical approaches and models, as well as the discovery of novel astrophysical phenomena.

Let us consider the state of matter in the outer layers of neutron stars and note the main characteristics of these regions. They represent superdense crystalline structures whose density increases rapidly with depth, i.e., with increasing gravitational pressure. The outer crust constitutes an extremely dense crystal that, with depth, transforms into a Coulomb lattice immersed in a sea of degenerate electrons. Under the action of intense pressure, atoms lose their bound electron shells and remain as “bare” nuclei fixed at the lattice sites, embedded in the degenerate Fermi liquid of electrons (Takibayev & Boshkayev 2017; Takibayev et al. 2013). Beginning at densities $\rho > 1.2 \times 10^7$ g cm $^{-3}$, inverse beta-decay reactions become energetically possible:

$$e^- + p \rightarrow n + \nu_e.$$

The inner crust is defined as the region where the process of neutronization of atomic nuclei begins, that is, nuclei become increasingly neutron-rich. The matter in this region consists of an ultrarelativistic Fermi gas of degenerate electrons, a lattice of “bare” nuclei, and a population of free neutrons.

However, in this region the neutrons still form a non-relativistic Fermi gas. At greater depths, beginning from densities of the crystalline lattice exceeding $\rho > 3 \times 10^{13}$ g cm $^{-3}$, the contribution of the neutron Fermi gas to the total pressure starts to dominate over that of the electron component.

Let us introduce several quantities and definitions essential for the subsequent discussion. The de Broglie wavelength of a neutron is given by

$$\lambda = \frac{h}{\sqrt{2m_n E_n}}, \quad (10)$$

or equivalently,

$$\lambda_n = \frac{2\pi\hbar}{\sqrt{2m_n E_n}}. \quad (11)$$

If $E_n \approx 0.1$ MeV, then $\lambda \approx 90$ fm; for $E_n \approx 0.4$ MeV, $\lambda \approx 45$ fm; and for $E_n \approx 0.8$ MeV, we obtain $\lambda \approx 31.8$ fm.

The number density of neutrons can be related to the Fermi momentum if the neutrons are densely packed and form a degenerate Fermi gas:

$$n_n = \frac{2}{h^3} \int_0^{p_F} 4\pi p^2 dp = \frac{8\pi}{3h^3} p_F^3, \quad (12)$$

since $p_F = \hbar k_F$. Hence, for $E_F = E_n \approx 0.1$ MeV, one obtains $k_F \approx 0.0695$ fm $^{-1}$, which corresponds to a number density of the degenerate neutron Fermi gas of

$$n_n = \frac{8\pi}{3} (6.95 \times 10^{11})^3 \text{ cm}^{-3} = 2.8 \times 10^{36} \text{ cm}^{-3}, \quad (13)$$

and an average inter-neutron spacing of $r_n \approx 7.2$ fm.

Let us now return to the region of interest within the neutron star, namely the outer and inner crusts, where the densities lie in the range 1.2×10^7 g cm $^{-3} < \rho < 1.4 \times 10^{14}$ g cm $^{-3}$. In this region, the most characteristic feature is the presence of crystalline structures, which represent the energetically most favorable configuration of matter in this density range (Takibayev & Boshkayev 2017).

3 CONCLUSIONS

In the crustal layers of neutron stars, the dominant forces are gravitational and Coulomb, which act in opposition to one another. Gravitational pressure tends to compress the matter, while the degeneracy pressure of the electron Fermi gas counteracts this compression, since the electrons in the lattice are densely packed.

The electron component of the matter is directly related to the mass density, because the number of electrons must exactly compensate the positive charge of the “bare” nuclei in the lattice.

Thus, in each layer of the crust—and even within every unit cell of the crystalline lattice—charge neutrality must be maintained in equilibrium. This condition allows the thermodynamic characteristics of the matter to be expressed as functions of the density.

The mass density of matter can be related to the interionic spacing in the lattice by the relation

$$\rho = nm_i, \quad (14)$$

where m_i is the mass of nuclei of species i .

From Eq. (10), one can express the nuclear concentration in the crust of a neutron star for different density values as

$$n_A = \frac{\rho}{m_A}, \quad (15)$$

and the distance between neighboring nuclei occupying the lattice sites is determined by

$$d = \frac{1}{n_A}. \quad (16)$$

Let us illustrate these parameters using examples of specific nuclei—phosphorus and sulfur. Assuming that the lattice is composed of phosphorus nuclei at a density of $\rho = 10^6 \text{ g cm}^{-3}$, we obtain a concentration of $n = 0.19 \times 10^{29} \text{ cm}^{-3}$. In this case, the corresponding interionic distance between phosphorus nuclei is $d = 3.7 \times 10^3 \text{ fm}$.

For sulfur nuclei occupying the lattice sites of the neutron-star crust, the concentration is found to be $n = 0.18 \times 10^{29} \text{ cm}^{-3}$, and the distance between neighboring nuclei is $d = 3.8 \times 10^3 \text{ fm}$.

The same parameters were also calculated for densities of $\rho = 10^7 \text{ g cm}^{-3}$, $\rho = 10^9 \text{ g cm}^{-3}$, $\rho = 10^{11} \text{ g cm}^{-3}$, and $\rho = 10^{13} \text{ g cm}^{-3}$.

Based on the obtained data, a simple graph illustrating the dependence of density on the inter-nuclear distance was constructed. It should be noted that the nuclei considered here, ^{31}P and ^{32}S , differ only slightly in mass.

In Figure 1, the black line shows the dependence $\rho \propto d^{-3}$, demonstrating the smooth increase in density with decreasing inter-nuclear distance. In modeling the crystalline structure of matter in the neutron-star crust, density values corresponding to different depths were used. The analysis revealed that the matter density increases monotonically with depth, accompanied by a decrease in the lattice parameter. This be-

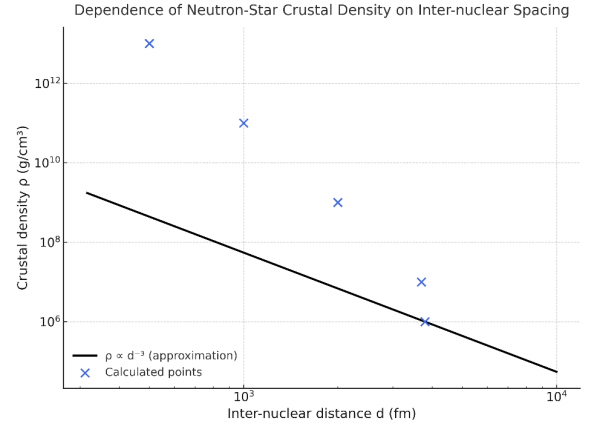


Figure 1. Dependence of the crustal density of a neutron star on the inter-nuclear spacing in the superdense lattice

havior is consistent with the increasing degree of degeneracy and the progressive compression of the crystal lattice.

An important consequence of variations in the parameters of the crystal lattice in the crust of a neutron star is their impact on the transport properties of matter, such as thermal conductivity, electrical conductivity, and viscosity. In contrast to the simple geometric relation $\sim d^{-3}$, these characteristics are governed by microscopic particle scattering processes and depend on the quantum properties of a degenerate Fermi gas.

Under the conditions prevailing in the crust of a neutron star, degenerate electrons are the primary carriers of heat and electric current. The transport coefficients of a degenerate electron gas in the neutron star crust can be described within the framework of kinetic theory (Landau & Lifshitz 1976), where the Fermi momentum p_F , the Fermi velocity v_F , and the collision frequency ν play a key role.

The thermal conductivity of a degenerate electron gas may be approximated as:

$$k \sim \frac{1}{3} C_v v_F^2 \tau, \quad (17)$$

where C_v is the electron heat capacity, v_F is the Fermi velocity, and

$$\tau = \frac{1}{\nu}$$

is the characteristic time between collisions. For a degenerate gas, the heat capacity is proportional to the temperature and the density of states:

$$C_v \propto n_e \frac{kT}{\varepsilon_F}, \quad (18)$$

As the matter density increases, the Fermi momentum grows according to:

$$p_F \sim (3\pi^2 n_e)^{1/3} \propto \rho^{1/3},$$

which leads to an increase in the Fermi velocity and, consequently, to an enhancement of thermal conductivity. However, this increase is not monotonic, since a decrease in the

Table 1. Estimate of transport properties of neutron star matter

Regime	$\rho, g/cm^3$	n_e, cm^{-3}	$\frac{p_F}{m_e c}$	σ, s^{-1}	k
Relativistic	10^9	3×10^{32}	~ 8	10^{22}	10^{20}
Ultrarelativistic	10^{13}	3×10^{36}	~ 80	10^{26}	10^{24}

lattice spacing strengthens electron scattering by lattice ions, as well as by impurities and structural defects.

The electrical conductivity of matter in the crust of a neutron star is given by:

$$\sigma \sim \frac{n_e e^2}{m_e^* \nu} \quad (19)$$

where m_e^* is the effective electron mass. Similarly to thermal conductivity, an increase in density leads to a higher concentration of charge carriers; however, the concurrent rise in collision frequency at high densities limits the growth of conductivity.

Of particular interest is the transition from the non-relativistic to the relativistic regime of the electron gas.

At the high densities characteristic of the deeper layers of the crust, the condition

$$p_F \gg m_e c,$$

and the electron energy is given by

$$E \approx p_F c.$$

In this regime, the dependence of pressure on density, as well as the transport coefficients, is modified, which may lead to deviations from the simple power-law relations obtained in the non-relativistic approximation.

Let us present several numerical estimates for layers with densities $\rho = 10^9 g/cm^3$ and $\rho = 10^{13} g/cm^3$, adopting the following initial assumptions: the electron fraction $Y_e \approx 0.5$ (order of magnitude), the nucleon mass $m_{\text{nuc}} = 1.66 \cdot 10^{-24} g$, the electron number density $n_e = \frac{Y_e \rho}{m_{\text{nuc}}}$, and $\nu = 10^{17} c^{-1}$, $T = 10^8 K$. The estimates of the transport coefficients demonstrate a significant increase in both electrical and thermal conductivity with increasing density. However, this increase is not strictly proportional to the growth in electron concentration, since compression of the crystal lattice leads to an enhanced scattering frequency.

Thus, the reduction of the inter-nuclear spacing within the crystal lattice with depth reflects not only the geometric compression of matter but also significantly affects the microphysical transport processes. This may lead to modifications in the thermal and electrical properties of the neutron star crust, which, in turn, can manifest in observable characteristics such as thermal evolution and X-ray emission.

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LUMINESCENT RECOIL OF THE COSMIC DUST GRAINS

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ABSTRACT

Cosmic dust particles of micrometer and nanometer sizes can luminesce in the optical range of the spectrum under the influence of electromagnetic radiation and electron and proton fluxes. We have suggested that the luminescence of cosmic dust particles may have impact on the spatial position of these small particles. We have shown that the time-constant process of absorption of UV photons by a cosmic crystalline dust particles followed by the re-emission of luminescent photons, will cause the movement of such particles of dust in the opposite direction - luminescent thrust. In the spatial system the star – small particle – ground-based observer, where star, small particle and observer are located on one and the same straight line, the luminescent recoil can lead to its distancing from the star. For the case of diamond nano-dust particles of various sizes, we calculated the velocities of their movement taking into account the contribution of the luminescent recoil. The results of calculations are provided. For variously dispersed crystalline dust particles of different chemical and mineralogical composition, we have considered also various aspects and patterns of their interaction with external factors and forces in the context of the phenomenon of luminescent recoil. In fact, we have shown that in addition to light pressure, the movement of cosmic dust particles can also be caused by the phenomenon of luminescent recoil.

Key words: radiation mechanisms: non - Thermal - (ISM:) solar system – dust - extinction

1 INTRODUCTION

Here we will define the solid cosmic matter segment and the conditions that will be considered. Thus, in this work, we will consider: 1) dust particles of micrometer and nanometer sizes; 2) micro- and nanometer dust located far from strong gravitational fields (stars and planets); 3) the rectilinear motion of micro- and nanometer dust particles; 4) cold crystalline micro- and nanometer dust whose temperature is an order of magnitude lower than that of millimeter dust particles orbiting in the gravitational fields of stars and planets; 5) only the short-wavelength spectrum will be taken into account as the exciting electromagnetic radiation $\Delta\lambda \leq 390$ nm.

Only the case where the re-emitted light is non-equilibrium, non-thermal radiation will be considered. We will need to keep in mind that photoluminescent radiation from solids is non-equilibrium, incoherent radiation, and does not represent any type of scattering.

The space environment is the interplanetary and interstellar medium characterized by the presence of variously dispersed dust matter. This dust matter forms cloud structures, compact or extended complexes of dust particles with a characteristic chemical and mineralogical composition. The range of sizes of individual dust particles covers significant intervals of their

diameters (cross sections), from millimeter to nanometer dust particles.

Micrometer and nanometer dust particles irregularly fill interplanetary and interstellar spaces, being influenced by external forces (gravity, electromagnetic and corpuscular radiation) and processes, including collisions of dust particles with each other. Cosmic dust has a diverse chemical and mineralogical composition; however, it can be divided into three main classes: silicate, organic, and metallic dust. The composition of the substance of individual dust particles determines, to no small extent, the evolutionary path of these nano-, micro- and macro- formations. Ground-based registration, detection of cosmic dust matter can be carried out using spatial features of the distribution of this dust matter. The phenomena occurring in the system: the light source (star) – dust – Ground-based observer, provide us with information about the physicochemical properties of dust particles. Under these phenomena we mean: absorption, emission, scattering, and polarization of light by the dust matter. Individual dust grains can be characterized by different internal structure and shape, including homogeneous spheroids; the core - mantle spheroids; asymmetric grains and, etc. Cosmic dust plays a significant role in the evolution of the planetary systems and nebulae. In addition, it is the arrays and cloud formations of micrometer and nanometer dusts that are the main element of the space ‘laboratory’, which is a spatial system: Star – Dust

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– Ground based observer. That is why the cosmic dust is an object of a close attention within the interests of astrophysics, space physics and astrochemistry. It seems to us that one more phenomenon can carry significant information about the nature of cosmic dust. This is the phenomenon of luminescence of cosmic dust particles excited by electromagnetic and corpuscular radiation of stars. Cosmic dust particles of micro and nano-sizes can luminesce in the optical range of the spectrum, under the influence of hard electromagnetic radiation and fast electron and proton fluxes from the sun and stars. We put forward the supposition that the luminescence of cosmic dust particles can have a significant effect on the spatial position of these small particles and on some of their dynamic properties. The present work is devoted to the consideration of our supposition.

2 LUMINESCENCE OF SMALL COSMIC DUST PARTICLES

Cosmic dust particles are constantly exposed to hard electromagnetic radiation and fluxes of fast charged particles, namely the effects of X-ray and ultraviolet radiation, as well as fluxes of high-energy electrons and protons of the solar (stellar) wind.

In clouds of particles, if the sizes of these particles are comparable to the wavelength of incoming hard electromagnetic radiation, scattering and diffraction phenomena can occur on small particles of this short-wavelength radiation. In the case of particles significantly larger than the wavelength, the phenomenon of absorption of incoming hard electromagnetic radiation may occur.

We believe that, in addition to the optical consequences of such absorption processes, there may also be dynamic consequences leading to changes in the spatial positions of the particles. The short-wavelength electromagnetic radiation absorbed by the substance of a particle can cause photoluminescence of that particle with different afterglow periods ($\Delta t = 0$ for fluorescence; $\Delta t > 0$ for phosphorescence).

At the same time, photoluminescent emissions of particles will have a longer wavelength than that of the exciting radiation, which may belong to the ultraviolet range of the spectrum. The characteristics of photoluminescent emissions of a specific particle depend on its chemical and mineralogical composition, temperature, and the state of the substance (crystalline or amorphous).

For the majority of particles of silicate or organic composition, at temperatures $T < 273\text{ K}$ and in the crystalline state of the substance, it is possible to expect the appearance in the optical range of the spectrum of two or more photoluminescent bands with maxima in the vicinity of $\lambda \approx 440$ and $\lambda_1 \approx 730\text{ nm}$.

In fact, X-ray or ultraviolet radiation of the interstellar medium can cause blue and red photoluminescent glow of dust particles.

The physical features of photoluminescence of micrometer and nanometer mineral dust particles were studied under laboratory conditions, demonstrating characteristic blue and red emissions in the luminescence spectra. In particular, grains of meteoritic forsterite and diamond were considered (Gucsik et al. 2012, 2013; Gaft et al. 2005; Gorobetz & Rogozhin 2001). Figure 1 shows the photoluminescence spectrum of diamond.

Bombardment of dust particles by fluxes of fast electrons and protons causes the phenomenon of cathodoluminescence of the substance of these dust particles. In this case, the characteristics of cathodoluminescent emissions of a specific particle

will depend on its chemical and mineralogical composition, temperature, and the state of the substance.

In general, the processes of photoluminescence and cathodoluminescence of solid crystalline substances are similar, differing mainly only in the method of supplying the exciting energy. In our case, photoluminescence of particles can be caused by solar (stellar) hard electromagnetic radiation, while cathodoluminescence of particles can be caused by fluxes of high-energy electrons and protons of the solar (stellar) wind.

In both cases, the dust particle will re-emit the absorbed energy in the optical range of the spectrum in the form of one or more luminescent emissions. The phenomena of cathodoluminescence of dust particles, taking into account the corresponding interstellar conditions, will also be characterized by a certain period of afterglow.

The physical peculiarities and characteristics of cathodoluminescence of micrometer and nanometer mineral particles were studied under laboratory conditions, which demonstrated characteristic blue and red emissions in the luminescence spectra.

In particular, grains of meteoritic forsterite and diamond were considered (Gorobetz & Rogozhin 2001; Gucsik et al. 2012, 2013). Figure 2 shows the cathodoluminescence spectrum of forsterite. In this case also, two bands are observed in the cathodoluminescence spectrum of the Forsterite grains exhibit luminescent features with maxima near $\lambda \approx 490$ and $\lambda_1 \approx 730\text{ nm}$. This indicates that fluxes of fast electrons of the solar (stellar) wind can induce blue and red cathodoluminescent glow in small particles.

A change in the temperature of the substance of a small particle, or its enrichment with impurities in the form of various ions, can lead to variations in the spectral positions and emission profiles associated with photoluminescence and cathodoluminescence spectra of this particle. The prolonged presence of silicate and diamond particles in the field of action of the solar wind can lead to their chemical enrichment with various ions. At the same time, there may be an adsorption process with the formation of a dust particle mantle, or a process of volumetric absorption of ions by substance of a particle with subsequent localization of ions in the vacancies of the crystal lattice – ion implantation. Ground-based registration of the luminescent glow of interstellar dust particles (variously dispersed cosmic dust) is a specific instrumental task that is not considered here.

3 MOVEMENT OF SMALL DUST PARTICLES CAUSED BY LUMINESCENT PHOTONS

In the space environment, dust particles are exposed to gravitational fields as well as electromagnetic and corpuscular radiation. A dust particle is subjected to the full spectrum of electromagnetic radiation and charged particles with a wide range of energies originating from the illuminating star.

We are interested in the dynamic consequences of the interaction between radiation and a dust particle, specifically the absorption of energy by the particle's substance, followed by the re-emission of part of the absorbed energy. It should be noted that theoretical models describing the motion of small cosmic dust particles in strong gravitational and electromagnetic fields often treat these particles as spherically symmetric, homogeneous bodies with properties similar to those of a black body (Poynting 1903, 1904; Robertson 1937; Mann, Meyer-Vernet & Czechowski 2014; Meyer-Vernet et al. 2015; Czechowski & Mann 2018; Stamm et al. 2019).

Crystalline cosmic dust particles of micrometer and nanome-

ter sizes possess well-defined physical properties; however, they often exhibit irregular shapes and complex chemical and mineralogical compositions. Metallic, silicate, and organic small particles are characterized by specific mechanical, optical, and electrical properties.

These characteristics determine the nature of the interaction between incoming radiation and the particle material. Dust particles reflect part of the incoming energy (e.g. photons in the optical range) while absorbing another part (ultraviolet photons), depending on the spectral position of the absorption bands of the crystalline substance.

The widths and profiles of the absorption bands, as well as their spectral positions, depend, among other factors, on the chemical and mineralogical composition of the particle and its temperature. A cosmic dust particle can be considered as a microparticle or nanoparticle, the substance of which may be in either crystalline or amorphous states. In this study, we consider only small crystalline particles.

Considering the above, and taking into account the optical anisotropy of the material of a small particle, it can be expected that the re-emitted energy (luminescent radiation) will be emitted in specific directions, depending on the location of the corresponding conduction bands in the crystal and the spatial orientation of luminescence centers.

Taking into account the size range of a small particle, we can expect the presence of only a few luminescence centers localized within the particle. In fact, a real cosmic dust particle can simultaneously reflect optical photons in the direction of the illuminating star, absorb ultraviolet photons, and re-emit the absorbed energy in the form of luminescence photons in the opposite or other directions (depending on the optical anisotropy of the crystalline substance of the particle).

Let us consider spherically symmetric crystalline particles. A silicate or diamond particle will have a characteristic absorption spectrum. If a small particle does not absorb radiation in the optical range of the spectrum ($\Delta\lambda = 400\text{--}800\text{ nm}$) but has an absorption band in the ultraviolet range ($< 390\text{ nm}$), then optical photons incident on the particle will be reflected, scattered (elastic collision), whereas ultraviolet photons will be absorbed, followed by subsequent processing of the absorbed energy.

Excluding non-radiative processes, it can be expected that a small particle will release the acquired excess energy in the form of optical radiation, i.e. it will emit a luminescent photon into the environment. This luminescent radiation will be characterized by a longer wavelength relative to the absorbed radiation.

Taking into account all macroscopic aspects of this phenomenon, as well as the relative constancy in time of the external radiation source (stars), it can be expected that a particle will simultaneously and continuously reflect optical photons, absorb UV photons and luminesce, emitting excess energy into the environment. We believe that not only ordinary light pressure, but also the absorption of short-wave UV or X-ray radiation by a small particle, followed by the emission of luminescent photons, will lead to dynamic consequences. Momentum of the emitted luminescent photon will cause the recoil of this small particle in the direction opposite to the direction of emission of the luminescent photon.

The time-constant process of absorption of the UV photons by a small particle, followed by the re-emission of luminescent photons, will cause the movement of a small particle in the opposite direction - luminescent thrust. In the spatial system star-small particle, where both star and small particle are located on one and the same straight line, the luminescent recoil can lead both to the approaching the small particle to

the star or to its distancing from the star. Considering the crystal state of the substance of a particle proposed by us, accompanied by the anisotropy of its optical properties, it can be expected that the diameter of a small particle will be an important factor determining the direction of movement of this small particle - to or from the star. A particle of nanometer size, consisting of hundreds of thousands of atoms (molecules) can emit a luminescent photon in the direction from the star. In other words, the radiation from the illuminating star can, as it were, 'permeate' into the particle, being first absorbed and then re-emitted in the direction from the star. A crystalline particle of micrometer or millimeter size consisting of millions of atoms (molecules) can emit a luminescent photon in the direction of the illuminating star. In other words, the radiation from the illuminating star can first be absorbed by this particle, and then re-emitted in the direction of the star. The emission of luminescent photons by a crystalline particle in the forward or inverse directions will lead to a change in the spatial coordinates of the small particle, its approach or distance from the illuminating star in a real space environment, under conditions of gravity and ordinary light pressure, the processes described above will be more complex. So, in the case of small nanometer-sized particles, the luminescent thrust can lead to their deceleration, whereas for small micrometer or millimeter-sized particles - to their acceleration, at which the action of the luminescent thrust will be added to the action of ordinary light pressure. As the crystalline particle approaches the circumstellar space of illuminating star, its behavior will begin to change. By the phenomenon of luminescent thrust will lose its physical significance, and the crystalline particle will obey to the Poynting-Robertson effect. Below we will consider a specific case when a crystalline particle is located at a considerable distance from the illuminating star and the effect of gravitational forces is minimal. In fact, this is the case when the change in the spatial position of a small particle will be determined by the radiation from the illuminating star (or stars). We will consider only the case when a small particle is in a crystalline state, characterized by the optical anisotropy of its substance.

According to Wichmann (1967), the general momentum conservation equation for the case of interaction of a photon with a material surface will have the form

$$P + mv = -P' + mv' \quad (1)$$

Here $P = h/\lambda$ is the momentum of a photon, and mv is the momentum of a material body of finite mass m . It is evident that the right-hand side of Eq. (1) describes the elastic interaction (reflection) of a photon with the surface of a material body.

Equation (1) is also applicable to our case: a photon characterized by momentum h/λ is absorbed by the substance of a small particle (inelastic interaction), which initially possesses momentum mv , and is subsequently re-emitted within a time interval of 10^{-8} to 10^{-4} s in a direction opposite to the motion of the particle. The emitted photon carries momentum h/λ' , thereby imparting an additional acceleration (recoil) to the small particle in the direction of its motion.

At the same time, $h/\lambda' < h/\lambda$ indicates optical luminescence of a small particle excited by ultraviolet photons, and mv' represents the momentum of the particle after emission of the luminescent photon.

Depending on the shape and size of the particle, as well as the optical anisotropy of its crystalline substance, luminescence centers may have different spatial orientations, being located either on the irradiated side ("hemisphere") or on the non-irradiated side of the small particle.

For example, the optical anisotropy of diamond is associated with residual mechanical stress or irregular distribution of impurities (Varshavsky 1968). These physical features can lead to luminescent recoil either in the direction of motion of the particle (when luminescence centers are located on the irradiated hemisphere) or in the opposite direction (when they are located on the non-irradiated hemisphere). Of course, there may be other locations of luminescence centers. However, if they are located on the non-radiated side of the surface, the luminescent recoil can cause slowing down the movement of such a small particle.

Let us consider a specific case of a small diamond particle (the crystalline state of the substance) characterized by a spherical shape, density $\rho = 3.5 \text{ g cm}^{-3}$, diameter $d = 100 - 100000 \text{ nm}$, standard luminescence centers, exciting ultraviolet radiation $\lambda = 266 \text{ nm}$, and luminescence radiation $\lambda = 731 \text{ nm}$. We transformed Eq. (1) to calculate v' assuming a rectilinear movement of a small diamond particle with an initial speed $v = 4 \times 10^4 \text{ cm sec}^{-1}$, for the case of emission of luminescent photons in the direction opposite to the direction of movement of this diamond particle. Assuming that each 1 nm^2 of the surface of the irradiated 'hemisphere' of this small particle can absorb 1 UV photon and also re-emit 1 luminescent photon of the optical range, we have $n_{\text{abs}} = n_{\text{rad}}$ where n_{rad} is a number of photons emitted by the surface of the irradiated 'hemisphere' with an area of $S_{1/2} = 2\pi R^2$. Therefore, in fact, we can write: $(P+P')n_{\text{rad}}$. The inclusion of the n_{rad} coefficient into the transformed Eq. (1) made it possible to pass from the generalized case for a single photon (absorbed/emitted) to the specific case for the flux of luminescent photons emitted by the 'hemisphere' of a diamond particle of finite mass – m , of nanometer or micrometer dimensions. When this diamond particle is distancing from the illuminating star, the number of UV photons absorbed by it will decrease over time. The condition $n_{\text{abs}} = n_{\text{rad}}$ that we have accepted, will be expressed for the quantum yield of luminescence as $K = n_{\text{rad}}/n_{\text{abs}} = 1$, and for the energy yield of luminescence as $\mu = E_{\text{rad}}/E_{\text{abs}} < 1$. At the same time, the difference in the energies of the absorbed and emitted photons will be spent on the excitation of atomic systems of the diamond dust substance.

The results of our calculations are presented in Table 1. In the first column – the radius of the particle (r), in the second – its mass (m), and in the third – the speed (v') (taking into account the contribution of the luminescent recoil). Here we did not take into account any additional circumstances or effects. As can be seen from the table, such a diamond particle with a radius of 50 nm and an initial speed v is characterized by the largest increment of speed due to the luminescent recoil. At the same time, a diamond particle with a radius of $5 \times 10^4 \text{ nm}$ and with the same initial speed v , is characterized by a virtually zero speed increment. It is obvious that for the case when the luminescence centers will be located on the unilluminated 'hemisphere' of the diamond dust particle and, consequently, luminescent photons will be emitted in the direction of the diamond particle movement with an initial speed $-v$, this will lead to a relative deceleration of the movement of this diamond dust particle.

Under the conditions considered for a diamond dust particle with a diameter of 100 nm and an initial velocity $V = 0$, the change in spatial coordinates due to luminescent thrust will be insignificant on the scale of cosmic distances. This kind of diamond dust particle, moving only due to luminescent recoil, will approximately overcome 9,000,000–10,000,000 km per 10^6 year. However, despite of insignificance of such distances, this physical phenomenon will be accompanied by appropriate consequences, including a gradual change in the size and

shape of dust clouds, complexes consisting of such diamond dust grains. It should also be taken into account that the spatial orientation of the luminescence centers for each selected individual diamond dust grain can be arbitrary.

Luminescent recoil can cause the acceleration of the diamond particle in arbitrary directions, including transversal. Not all of the diamond dust particles moving due to luminescent thrust in the presence of external factors and forces can make rectilinear movements. Some of them can move along curved trajectories. This means that for real dust clouds, the movement of, for example, diamond dust particles due to the luminescent recoil will be changed not so much in the size of the cloud, but predominantly in its shape – spatial geometry. This process will be the more intense the greater the influence of the gravitational forces and ordinary light pressure from the illuminating star on the dust particles. Of course, we take into account the shape peculiarities of nanometer-sized cosmic dust particles, including non-standard deviations of their surface area to their volume S/V . Therefore, in fact, the concept of hemisphere of a small cosmic dust particle used by us has a conditional character defining the boundaries of the illuminated fraction of the surface from the unlit one. For small cosmic particles of the corresponding chemical-mineralogical composition, the phenomenon of luminescent recoil can be characterized by features determined by the luminescence time of mineral phases at low temperatures. The luminescence time of a small cosmic particle, for example, a diamond particle, can be defined (Simonia 2007a) as

$$t = t' + \tau \quad (2)$$

Where t' is the period of exposure to a small particle of the short wavelength electromagnetic radiation absorbed by it (for example, UV radiation), and τ is the period of afterglow of the cosmic particle after the termination of absorption of short wavelength radiation (after termination of luminescence excitation).

It is known that photoluminescence of a solid substance can be divided into two types: fluorescence $\tau = 0$, when the luminescence of a substance stops immediately after the termination of its excitation, and phosphorescence $\tau > 0$, when the luminescence of a substance continues after the termination of its excitation. At low temperatures, solid substances can phosphoresce for a relatively long time, with a characteristic afterglow period τ from a few seconds to several tens of minutes. At the same time, phosphorescence will be characterized by a gradual weakening of its intensity, obeying a specific pattern of attenuation associated with the value of the temperature of the solid substance and its chemical-mineralogical composition.

In our case, a diamond dust particle will move under the influence of the luminescent recoil for several minutes and even after the excitation of this luminescence ceases. In fact, the phosphorescent diamond dust particle will still move forward but irregularly (after the termination of the short wavelength exciting radiation), experiencing a gradual slowdown correlating with the law of glow attenuation.

The termination of the action of exciting radiation on a dust particle can be conditioned by only two factors: (1) an extreme unsteady process in the illuminating star or circumstellar space; and (2) a significant distance of a small cosmic particle from the illuminating star, at which the flux of exciting electromagnetic radiation (X-ray, UV) will become extremely weak, insufficient to excite the luminescence of a cosmic dust particle.

In principle, there are circumstances of chemical nature when ions of interstellar gas adsorbed or implanted into the

substance of a dust particle can change the chemical composition of a nano-dust, thereby changing the luminescent properties of its substance. However, this kind of change in luminescent properties will require significant periods of time.

Taking into account the peculiarities of the shapes of small cosmic particles, the optical anisotropy of their crystalline substance and, taking into account the expression proposed by [Simonia \(2007a\)](#) for the luminescence intensity of cometary dust particles, we express the luminescence intensity of a small cosmic particle (for example, a diamond dust particle) as follows:

$$I_L = \frac{S'}{2} \int_{E_1}^{E_2} F dF \quad (3)$$

Where $S'/2$ is the area of the luminescent ‘hemisphere’ of a small cosmic particle, F is the energy of photoluminescent photons (of the corresponding wavelength) emitted by 1 nm^2 of the luminescent surface of the particle under the condition $E_2 > F > E_1$. Obviously, for the case $S' = 4\pi r^2$, when the luminescence centers are homogeneously distributed over the surface of a small cosmic particle, its luminescence intensity I_L will be maximal, but such a small particle will be stationary without making any movements, including forward movement.

As an exciting radiation of a small particle luminescence, we assumed UV radiation in the range of 200–390 nm. At the same time, the phenomena discussed above can be characterized by similar properties under other conditions as well, when the wavelength of the exciting radiation will be $100 < \lambda < 200 \text{ nm}$, and the wavelength of the luminescent radiation of a small particle will be $390 > \lambda' > 200 \text{ nm}$, i.e., the case of ultraviolet luminescence of a small cosmic particle. There may be other manifestations too, for example, X-ray luminescence of the small cosmic particles, including metal particles. It is clear that in real conditions, a small cosmic particle will be influenced by a number of external factors and forces, including gravity, light pressure, and collision phenomena (dust–dust, gas–dust), etc. The primary characteristics of a moving small cosmic particle will also be important, including its mass, size, initial velocity, and temperature of its substance.

Taking a small cosmic particle in the first approximation as a spherical dust particle of a nanometer size, of a certain chemical-mineralogical composition, the substance of which would be characterized by a crystalline state and assuming the absence of external factors and forces, we showed that such a dust particle could move, accelerate or slow down under the action of luminescent photons (causing luminescent recoil) emitted in the appropriate direction. One of the determining factors of this kind of movement caused by the luminescent thrust is the optical anisotropy of the dust particle substance, in which the luminescence centers should be spread out only on a fragment (‘hemisphere’, a limited volume) of the dust particle substance. The forced emission of an amorphous dust particle would be characterized by an isotropic distribution of luminescence centers over the surface of the dust particle and naturally would not lead to the appearance of a preferred direction (the only direction) of the luminescent recoil. Such a particle under the action of luminescent photons would remain stationary; its spatial position would not change for a certain period of time. It should also be added here that solid crystalline substances are characterized by a high luminescence yield, whereas substances in the amorphous state luminesce weakly or do not luminesce at all.

So, the minimum conditions for the occurrence of luminescent thrust in a small cosmic particle are: (1) nanometer or micrometer sizes of a particle; (2) a preferred location (one of the ‘hemispheres’) of luminescence centers in the substance of

a particle; crystalline state of this substance; (3) a significant luminescence yield of the particle substance $E_{\text{rad}}/E_{\text{abs}} \geq 50\%$; (4) presence of noticeable absorption bands in the X-ray or UV ranges of a particle substance spectrum; (5) absence of impurities (ions) quenching luminescence in the particle substance; (6) reemission by a substance of a particle of the absorbed energy in the form of UV or optical photons (absence of non-radiative transitions).

As a matter of fact, these are the minimum and sufficient conditions for the occurrence of a luminescent recoil force applied to a small cosmic particle as a result of absorption by a small particle of the short wavelength electromagnetic radiation and return of excess energy by such particle in the form of luminescent photons emitted in any one preferred direction.

These conditions narrow the list of cosmic dust particles that can be characterized by the phenomenon of luminescent thrust. Not all representatives of the cosmic dust particles can have the appropriate size, chemical and mineralogical composition, and crystalline state of substance, low albedo, and high absorption coefficient in the short wavelength range of the spectrum and high luminescence yield. However, a number of substances can satisfy the proposed conditions, namely, carbon in the crystalline state and some silicates. This means that nano- and micro-dispersed diamond, forsterite, enstatite and other cosmic dust can be characterized by luminescent thrust during the luminescence of their substances.

Predetermining condition for the occurrence of luminescent recoil, during the luminescence of a small cosmic particle is the emission of luminescent photons by a particle in only one concrete direction. For the occurrence of such a natural selectivity, it is necessary that the substance of the cosmic dust particle be in a crystalline state, which in turn would determine the optical anisotropy of this substance. Ideally, in the laboratory conditions (vacuum, temperature $T < 77 \text{ K}$) under the influence of the exciting ultraviolet monochromatic radiation, for example with a wavelength of 220 nm and, provided that a small particle with radius r will have a spectral ‘window’ of absorption in the range of 219–221 nm and a reflection coefficient less than 0.001 in the UV and optical ranges ($\lambda' > 221 \text{ nm}$), we can expect a rectilinear and conditionally uniform movement of this small particle with a speed v under the influence of luminescent photons. Ultraviolet radiation ($\lambda = 220 \text{ nm}$) of the laser can cause the movement of a small particle due to the luminescent recoil for a certain period of time. This movement can be conditionally uniform if the luminescent photons are emitted in the direction opposite to the direction of movement of the particle. When a small particle is moving away from the UV radiation source, while absorbing fewer and fewer UV photons, the particle will experience a gradual slowdown. The ideal laboratory conditions considered by us, including exposure of a small particle to monochromatic UV radiation and an extremely small reflection coefficient of the substance of such a particle, determine the specific nature of its movement.

In the space environment (but away from powerful gravitational fields), there are two factors that can determine the movement of a small dust particle: light pressure and luminescent recoil. The first factor, the light pressure, is realized when the incoming radiation is reflected. The second factor, the luminescent recoil, is realized when excess energy is re-emitted into the environment in the form of luminescent photons. A dusty particle can simultaneously reflect incoming radiation and re-emit part of the absorbed energy in the optical range, i.e., to luminesce.

In other words, two processes can take place in the space

environment: reflection and luminescence. Based on the above, we can conclude that these two processes are concomitant and complementary. If the emission of luminescent photons occurs only in one direction, then these two concomitant processes (reflection and luminescence) will cause the movement of a small particle in the radiation field. Both of these physical processes manifest themselves in the interaction of radiation with a substance in the form of the receipt or recoil of energy and momentum by a small particle. This is a kind of unifying principle of the processes of reflection and luminescence.

At the same time, there are fundamental differences due to the actual difference in the nature of these phenomena. According to [Wiedemann \(1888\)](#), luminescence is the emission of photons, which is excessive over thermal radiation, and continues after excitation ceases for a time many orders of magnitude greater than the period of light oscillations.

This definition of [Wiedemann \(1888\)](#) separates luminescence from scattering, the reflection of light, which stops almost instantly, during 10^{-15} seconds after the termination of external irradiation of the object with light. With the luminescence of the type of fluorescence, the duration of the excited state of atoms and molecules of the substance is 10^{-8} seconds, and the luminescence of the phosphorescence type is 10^{-4} seconds. Scattering, reflection of light by substances is a ‘fast’ phenomenon, whereas luminescence of the same substance is a ‘slow’ phenomenon.

For our case, this means that the light pressure on a small cosmic particle will almost instantly cause its movement, whereas the luminescent thrust occurs with some delay. The movement of the cosmic nano-particle may be preconditioned due to the ‘fast’ light pressure and the time-lagging luminescent recoil. These various physical phenomena will be characterized by their own time scales.

In the space environment and in other real conditions of motion of a small particle under the influence of light pressure and luminescent recoil, these are two complementary, concomitant physical phenomena within the same physical system but at different time intervals. However, in our opinion, there may be an ideal case when a small particle will be irradiated with monochromatic radiation, have a narrow spectral ‘window’ of absorption and re-emit luminescent photons of the same wavelength – resonant fluorescence. In this case, all the absorbed energy will be re-emitted in the form of luminescent photons into the environment in a certain direction. In the case of resonant fluorescence, all the energy absorbed by the small particle will be re-emitted and the movement of this small particle will be caused only by the luminescent recoil in the actual absence of light pressure. This case is, of course, ideal, but in principle possible. We have shown that in the interstellar medium, far from powerful gravitational fields, hard electromagnetic radiation from stars absorbed by crystalline dust particles can be re-emitted by these particles into the environment in the form of optical (luminescent) photons, which cause a change in the speed of dust particles and, in some cases, in the direction of their movement.

These are the dynamic consequences of luminescence of interstellar crystalline dust particles. Luminescent crystalline dust particles of the interstellar medium will change their spatial position over long periods of time.

4 DISCUSSION

Luminescent photons emitted by a crystalline cosmic particle in any selected direction will cause a luminescent recoil, which in turn, in terms of the constant process of luminescence of

this particle, will lead to its movement in the direction from the source of excitation (star), or towards it. At the same time, luminescent thrust in most cases can be a concomitant process to the process of light pressure on a small particle, contributing to the acceleration (movement) of such a small particle.

Our reasoning concerned only the dust particles being in a crystalline state. There is no doubt that the light pressure and the luminescent recoil are two different phenomena, occurring at different rapidities (10^{-15} sec for reflection/scattering and 10^{-8} – 10^{-4} sec for luminescence). In the case of luminescence of the phosphorescence type, the process of relaxation of the atomic–molecular systems of a substance of a dust particle will occur for a conditionally long time from the triplet state.

We showed also that for the case of the resonant fluorescence of a small particle, all the absorbed energy will be re-emitted into the environment at the same wavelength, which will cause the movement of a small particle only under the action of luminescent photons. In principle, this can be considered as the actual absence of light pressure, or as a kind of transformation of the ‘fast’ reflection process into the ‘slow’ luminescence process of the particle. In this case, the resonant fluorescence is not enough; therefore, an extremely low albedo of the particle and the presence of characteristic absorption bands in the spectrum of the substance of this particle will also be necessary.

These circumstances lead us to the conclusion that the motion of a cosmic dust particle under the action of resonantly emitted luminescent photons is an ideal case that can take place only in very specific conditions, for example, in conditions of extremely low temperatures. It would be interesting to conduct laboratory experiments on the acceleration of nanometer particles by resonant luminescent photons in the beam of an ultraviolet laser.

We found it necessary to verify our results (Table 1) for the case of a small diamond dust particle with an absorption band in the shorter wavelength range of the UV spectrum and, respectively, with luminescent emissions in the shorter wavelength range of the optical spectrum. According to [Tarashchan \(1978\)](#), the maximum of the excitation spectrum of the blue luminescence of diamond (427.5 nm) has a wavelength of 230 nm. Based on our transformed Eq. (1) for the case of a diamond dust particle with a diameter $d = 1000$ nm and an initial speed $v = 4 \times 10^4$ cm sec $^{-1}$, we calculated the value of $v' = 40000.0161$ cm sec $^{-1}$.

The obtained value represents the luminescent contribution to the acceleration of a diamond dust particle. This result fully confirms the validity of our conclusions. In the astrophysical projection of the problem, an interesting aspect is revealed. It is known that near the wavelength $\lambda \approx 217.5$ nm there is a fundamental interstellar absorption observed in different directions in the spectra of various galactic objects. The origin of this absorption is still debated. A number of studies have considered the possible role of fine-dispersed graphite dust, which can effectively absorb ultraviolet radiation of the mentioned wavelength ([Ehrenfreund et al. 2006](#); [Herrero et al. 2022](#)).

We assume that if a crystalline carbon–diamond nano-dust can absorb UV radiation near 220 nm, then it will re-emit luminescent photons in the range $\Delta\lambda = 330$ –430 nm. This means that interstellar dust clouds consisting of nanometer-sized diamond dust particles can contribute to the formation of this fundamental absorption, with slow but constant motion under the action of luminescent photons emitted in the near ultraviolet or in the short-wavelength region of the optical spectrum. The blue glow of circumstellar dust may be a manifestation

of this kind of phenomenon. If, however, these dust clouds and complexes of nanometer-sized diamond dust re-emit an excess of energy in the range $\lambda < 300$ nm, their presence may be generally undetectable by ground-based instruments at all.

We believe that the fundamental absorption band near 217.5 nm can be caused by the absorption of nanometer diamond dust moving under the action of luminescent photons, slowly changing the symmetry forms of cloud formations.

Small cosmic particles in the form of micrometer and nanometer dust particles of various chemical and mineralogical composition can also luminesce under the action of charged particle fluxes (the phenomenon of cathodoluminescence).

Bombardment of nano-dust particles by fast electron fluxes can lead to cathodoluminescence of these nano-dust particles with the subsequent occurrence of the phenomenon of luminescent recoil. However, the cathodoluminescence of mineral substances is characterized by a flash nature and a lower quantum yield; therefore, in fact, the movement of cosmic dust particles under the action of cathodoluminescent photons can be slower and irregular.

It is necessary to keep in mind other possible phenomena, namely X-ray luminescence, infrared fluorescence and thermoluminescence of fine-dispersed cosmic dust (Simonia 2004, 2007a, 2016, 2007; Simonia & Gucsik 2019). The phenomena considered will also depend on the shape of a small particle and, in the case of nano-dust, on the non-standard ratio of its surface area to volume. The depth of penetration of electrons into the substance of the nano-dust particle will be different, varying depending on the energy of the electrons, the physicochemical characteristics of the substance of the dust particle and other factors. If a small cosmic particle is characterized by the presence of unstable isotopes, this may contribute to the direction of the luminescent recoil. This may be especially true for particles of micrometer sizes.

The main differences of the phenomenon of luminescent thrust of cosmic crystalline dust particles from the Poynting–Robertson effect are: (a) the phenomenon of luminescent thrust can cause the movement of a dust particle only far from powerful gravitational fields; (b) the phenomenon of luminescent thrust can only cause rectilinear movement of a dust particle; (c) the phenomenon of luminescent thrust of a cosmic dust particle can lead to an increase in the distance between the radiation source (star) and the dust particle (in most cases). In other words, if a cosmic dust particle is subject to the Poynting–Robertson effect, it slows down and gradually falls onto the star in a spiral trajectory, while a dust particle subject to the luminescent thrust phenomenon accelerates, gradually moving away from the star in a rectilinear trajectory.

Luminescent recoil of cosmic dust is a localized physical phenomenon, relevant only for a specific class of dust particles far from powerful gravitational fields. In contrast, ordinary radiation pressure and the movement of cosmic dust due to the Poynting–Robertson effect are global phenomena.

We have considered here the phenomenon of luminescent recoil for small cosmic particles of micrometer and nanometer sizes for the case of a crystalline state of substance of small particles. We focused our attention mainly on the individual process of emission of luminescent photons by a crystalline substance of a small particle. We have shown that, under the action of short-wavelength electromagnetic radiation, a small cosmic dust particle can emit a flux of luminescent photons, which conditions the luminescent thrust of a small dust particle. It should be emphasized that we considered the case when a small cosmic dust particle is located far from powerful gravitational fields and emits luminescent radiation only by a fragment, area or ‘hemisphere’ of its surface.

Table 1. Luminescent recoil for the cosmic dust particle.

Radius r (nm)	Mass m (g)	V' (cm sec $^{-1}$)
50	1.785×10^{-15}	40000.00298
500	1.785×10^{-12}	40000.00003
5000	1.785×10^{-9}	40000.00003
50000	1.785×10^{-6}	40000.

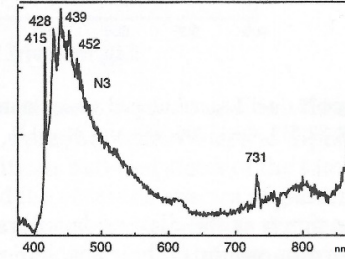


Figure 1. Photoluminescence spectrum of diamond (N3 centers) (Gaft et al. 2005).

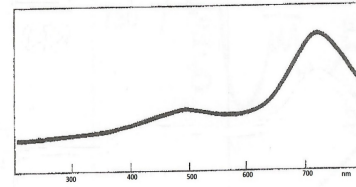


Figure 2. Cathodoluminescence spectrum of forsterite from the Murchison meteorite (Gorobetz & Rogozhin 2000)

5 CONCLUSION

Interplanetary and interstellar dust is exposed to external factors and forces. In particular, micrometer and nanometer dust particles of various chemical and mineralogical composition, sizes and shapes are constantly exposed to hard electromagnetic radiation and fluxes of fast charged particles. Individual dust particles and cloud dust formations evolve by changing their composition, shape and position. We have shown that in addition to light pressure, the movement of small dust particles can also be caused by the phenomenon of luminescent recoil. At the same time, the radiations that cause this phenomenon can be both hard electromagnetic radiation and fluxes of fast electrons and protons. We have also shown that the luminescent thrust of a small particle will cause a change in its spatial position over a long period of time. The luminescent recoil will have its contribution in the process of acceleration of cosmic dust.

It seems advisable to conduct laboratory experiments at low temperatures for nanometer and micrometer crystalline mineral grains with a small albedo, when the luminescence of these grains is excited by monochromatic ultraviolet radiation. Such experiments can expand and concretize the understanding of the peculiarities of the phenomenon described by us.

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A METHOD FOR EXTRACTING THE EMISSION COMPONENT IN STELLAR SPECTRAL LINES

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ABSTRACT

This article describes a method for separating the contribution of emission components belonging to the stellar envelope from the contribution of stellar photosphere lines in high-resolution spectrograms obtained at the Tusi-Shamakhy Astrophysical Observatory (ShAO). A polynomial approximation method is proposed to account for the instrumental function. Application of this method allows one to separate the emission component belonging to envelope radiation for different variable stars.

Key words: Stars: atmospheres – Stars: circumstellar matter – Techniques: spectroscopic – Line: profiles.

1 INTRODUCTION

It is well known that in many stars the presence of additional radiation-producing matter in the surrounding environment — such as stellar envelopes and gas–dust discs — is revealed in optical spectra through additional emission components in spectral lines. Since hydrogen constitutes the main fraction of stellar matter (~ 75 – 80 per cent), these emission components are most prominently manifested in the strong photospheric profiles of hydrogen lines.

The study of variability in spectral-line profiles in non-stationary stars is of great importance for understanding the physical processes occurring in their atmospheres. Examples of such objects include young stars of the T Tauri and Herbig Ae/Be types, Be stars, supergiants, flare stars, and symbiotic stars. These objects generally exhibit spectral variability in various forms within their line profiles. In most cases, such variability is attributed to the interaction between the central star and its surrounding environment, particularly gas–dust discs.

As a result, hydrogen lines observed in the spectra of these stars often display, in addition to the normal absorption profile, various types of emission components superimposed on the photospheric profile. In astrophysics, such profiles are commonly classified as P Cygni, inverse P Cygni, double-peaked, or single-peaked profiles (e.g. Sobolev 1985; Huseynov 2010).

A correct estimation of the contribution of the emission component in hydrogen lines is essential for understanding

the physical state of the circumstellar matter and the active processes occurring within it. The separation of the emission spectrum from the photospheric radiation, and its subsequent analysis, is based on the theory of stellar atmospheres and radiative transfer — one of the fundamental areas of astrophysics (see e.g. Mihalas 1978; Unsöld 1969). Various approaches to this problem exist, depending on the quality of the observational material and available resources. The simplest method involves obtaining, in addition to the target star spectrum, the spectrum of a standard star with identical fundamental parameters, chemical composition, microturbulent velocity, and projected rotational velocity. The emission contribution can then be derived by subtracting the standard spectrum from that of the target star. However, finding such an identical standard star is extremely difficult, and therefore this method is rarely applied. A generally accepted scheme for accurately separating the emission component in spectral-line profiles has not yet been developed for spectra with resolutions of $R = 28\,000$ and $R = 56\,000$ obtained with the 2-m telescope of the Shamakhy Astrophysical Observatory. Taking this into account, the aim of the present work is to describe a method for separating the emission component in hydrogen lines and determining its spectrophotometric parameters, using Herbig Ae/Be stars as an example.

2 THEORETICAL APPROACH

The observed stellar spectrum (flux) can be expressed as the combined effect of the intrinsic spectral distribution of the star and the transmission characteristics of the telescope and

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spectrograph system (e.g. [Allende Prieto 2004](#); [Thorne et al. 1999](#)). Analytically, the observed flux $F_{\text{obs}}(\lambda)$ is given by following formula:

$$F_{\text{obs}}(\lambda) = [F_{\star}(\lambda) T_{\text{atm}}(\lambda) T_{\text{tel}}(\lambda)] * \text{PSF}_{\text{inst}}(\lambda) + N(\lambda) \quad (1)$$

Here $F_{\text{theor}}(\lambda)$ denotes the intrinsic spectral flux emitted by the stellar photosphere. In the absence of an additional circumstellar disc, this quantity represents a single component. However, in the presence of a gas–dust disc, the stellar flux can be written as

$$F_{\star}(\lambda) = F_{\text{theor}}(\lambda) + F_{\text{em}}(\lambda) \quad (2)$$

where $F_{\text{theor}}(\lambda)$ is the pure photospheric radiation and $F_{\text{em}}(\lambda)$ is the additional emission arising from the circumstellar gas disc.

The function $F_{\text{theor}}(\lambda)$ is computed using NLTE model atmospheres, taking into account the fundamental stellar parameters: effective temperature T_{eff} , surface gravity $\log g$, chemical composition, microturbulent velocity, and projected rotational velocity $v \sin i$.

$T_{\text{atm}}(\lambda)$ is the transmission function of the Earth’s atmosphere, including telluric absorption lines. $T_{\text{tel}}(\lambda)$ represents the efficiency of the telescope and optical system (e.g. mirror reflectivity). $*$ denotes the convolution operator. $\text{PSF}_{\text{inst}}(\lambda)$ is the instrumental profile (point spread function), and $N(\lambda)$ represents the detector noise.

The dark frame is used to correct the observed stellar spectrum for detector noise. By subtracting the dark frame from the observed spectrum, the contribution of $N(\lambda)$ is effectively removed. If all remaining instrumental and observational effects are combined into a single response function $G(\lambda)$, then equation (1) can be rewritten as

$$F_{\text{obs}}(\lambda) = F_{\star}(\lambda) T_{\text{atm}}(\lambda) G(\lambda) \quad (3)$$

Since in our case

$$F_{\text{obs}}(\lambda) = F_{\text{theor}}(\lambda) + F_{\text{em}}(\lambda) \quad (4)$$

equation (1) can be rewritten as

$$F_{\text{obs}}(\lambda) = (F_{\text{theor}}(\lambda) + F_{\text{em}}(\lambda)) T_{\text{atm}}(\lambda) G(\lambda) \quad (5)$$

Thus, based on the above expressions, the emission component $F_{\text{em}}(\lambda)$ can, in principle, be determined. For spectral regions free from significant telluric contamination (e.g. $\text{H}\beta$ and $\text{H}\gamma$), the atmospheric transmission function can be approximated as $T_{\text{atm}}(\lambda) \approx 1$. However, in the $\text{H}\alpha$ region ($\lambda = 6563 \text{ \AA}$), this function may introduce noticeable distortions in both the line wings and core.

For stars of spectral type B8Ve–A0Ve, the $\text{H}\alpha$ line is typically very broad, with photospheric absorption widths of approximately 20–50 $\text{\AA}$. In such objects, the emission component usually originates from the circumstellar gas disc, filling the central absorption core or producing a double-peaked profile.

A more detailed expression for separating the emission contribution in this wavelength region, including the effects of

both the instrumental response $G(\lambda)$ and atmospheric absorption, can be written as

$$F_{\text{obs}} = (F_{\text{theor}} + F_{\text{em}}) T_{\text{H}_2\text{O}} G \quad (6)$$

where $T_{\text{H}_2\text{O}}$ is the water vapour transmission function. In conditions of high humidity, this function can reduce the line wings or modify the peak intensity.

To correct for this effect, the observed spectrum is divided by a telluric standard (divisor spectrum) obtained with the same instrumental setup. Thus, we obtain

$$F' \approx \frac{F_{\text{obs}}}{T_{\text{H}_2\text{O}}} \approx (F_{\text{theor}} + F_{\text{em}}) G \quad (7)$$

Equation (4) is then used as the working relation for separating the emission component from the observed profile. For spectral lines other than $\text{H}\alpha$, $T_{\text{H}_2\text{O}}$ can be safely taken as unity. Before applying equation (4) to the $\text{H}\alpha$ line, the observed spectrum must be divided by a divisor spectrum obtained with the same instrument.

3 METHOD I

Suppose that F_{obs} denotes the observed flux in the stellar spectrum and F_{theor} is the synthetic NLTE (non-local thermodynamic equilibrium) spectrum of the star. In Fig. 1, the upper panel shows the observed $\text{H}\beta$ line profile of the spectrum KF1011-12 obtained on 20.05.2017, while the lower panel presents the corresponding synthetic profile of the $\text{H}\beta$ line.

The synthetic hydrogen line profiles were calculated using the STAR program (e.g. [Menzhevitski et al. 2014](#)). In this code, the synthetic spectra are computed using the fundamental stellar parameters: effective temperature T_{eff} , surface gravity $\log g$, microturbulent velocity ($\xi = 2 \text{ km s}^{-1}$), chemical composition, and projected rotational velocity $v \sin i \approx 236 \text{ km s}^{-1}$ [Merín et al. 2004](#). For the instrumental profile of the spectrograph, a value of 0.15 $\text{\AA}$ was adopted, [Ismailov et al. 2024](#). For the Herbig Ae/Be star HD 141569, a solar chemical composition was assumed.

Since the $\text{H}\beta$ line wings are free from emission, the synthetic profiles were directly compared with the observed profiles of HD 141569.

After subtraction of the detector dark signal $N(\lambda)$ and correction for telluric absorption, equation (1) can be reduced to the simplified form

$$F_{\text{obs}} = (F_{\text{theor}} + F_{\text{em}}) G \quad (8)$$

Here F_{theor} represents the stellar photospheric radiation, F_{em} is the flux originating from the circumstellar environment, and G is the response function of the observing instrument. To extract the emission component F_{em} from this expression, we use the theoretically calculated line flux F_{theor} .

Dividing equation (5) by F_{theor} , we obtain

$$D_1 = \frac{(F_{\text{theor}} + F_{\text{em}}) G}{F_{\text{theor}}} \quad (9)$$

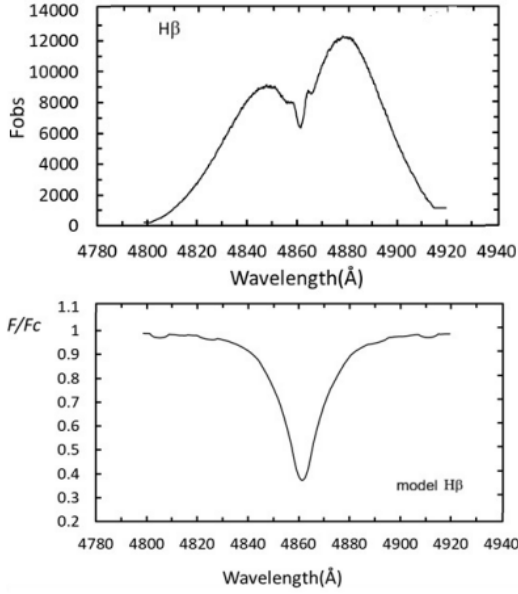


Figure 1. Observational profile (top) and synthetic profile (bottom) for the star HD141569.

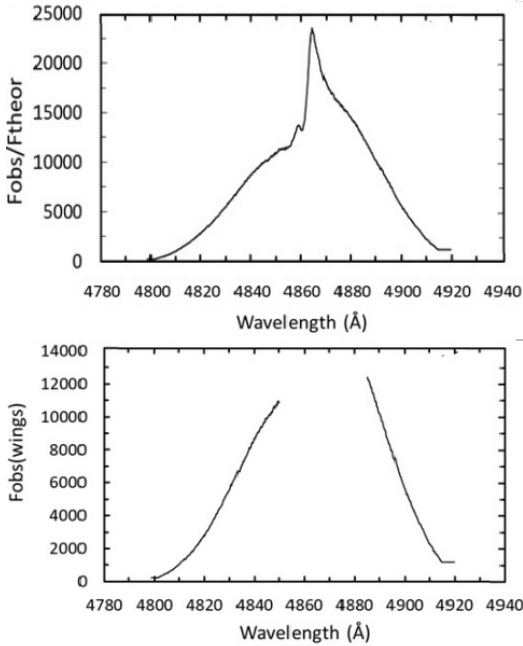


Figure 2. The profile obtained from expression (6) (top) and its case without considering the emission region (bottom).

It is clear that the purely photospheric radiation of the star corresponds to F_{theor} , since the synthetic spectrum is calculated based on the known photospheric parameters of the star. The emission peak is clearly visible in the resulting curve obtained after division (see Fig. 2).

We approximate the continuum curve using a polynomial function, excluding the emission region of the line profile (see Fig. 3). The resulting polynomial function is denoted as F_{pol} . If we assume $F_{\text{em}} = 0$ in equation (2), it follows that $F_{\text{pol}} \approx G$. Thus, the instrumental response function can be

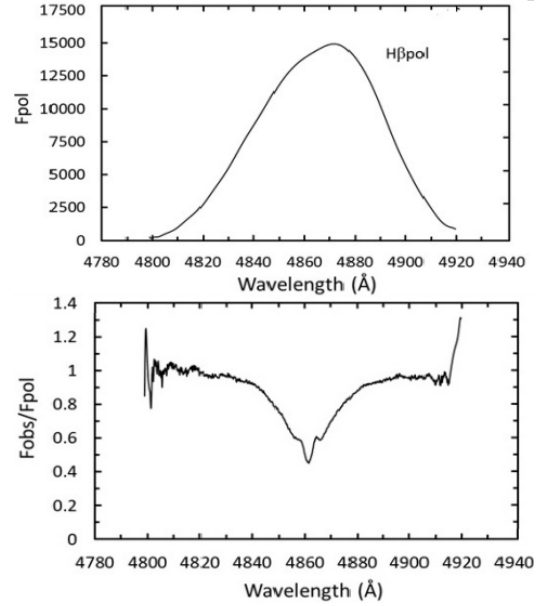


Figure 3. Polynomial distribution constructed after approximation (top). The bottom panel shows the profile obtained from the polynomial division of the observation profile.

represented by a polynomial approximation of the observed continuum (upper panel in Fig. 3).

The polynomial is calculated over the same wavelength range as the observed spectrum, including the line profile region, thereby providing the corresponding values of F_{pol} . In the next step, the observed spectrum F_{obs} is divided by the polynomial function F_{pol} . As a result, a properly normalized spectral line profile is obtained. After this division, the resulting profile is free from continuum distortions (see Fig. 3, lower panel):

$$\frac{F_{\text{obs}}}{F_{\text{pol}}} = \frac{(F_{\text{theor}} + F_{\text{em}})G}{G} = F_{\text{theor}} + F_{\text{em}} \quad (10)$$

After obtaining this profile, the outer wings are selected and compared with the theoretical profile. In Fig. 4 (upper panel), the cut and normalized observed profile (blue line) and the synthetic profile (red line) of the $H\beta$ line are shown. If the wings of the profiles do not match satisfactorily, the atmospheric parameters of the model must be adjusted. This procedure is repeated until a satisfactory agreement between the observed and theoretical line wings is achieved.

Subtracting F_{theor} from equation (7) yields the emission line profile F_{em} (see Fig. 4, lower panel). By adding unity to the intensity of the resulting residual profile, the emission component is normalized.

The resulting clean emission profile can then be exported as an ASCII file to the DECH program and converted into a FITS file. From this profile, the spectrophotometric parameters of the emission line can be determined.

4 METHOD II

This method is similar to Method I; however, to eliminate the instrumental response function G in equation (1), the observed spectral region is divided by a flat-field (lamp) spectrum obtained with the same instrument setup. The instrumental response function is effectively removed when both spectra are recorded using the same instrumental configuration.

By dividing the observed spectrum by the flat-field spectrum, we obtain the following expression (8), which is analogous to equation (7):

$$F_{\text{obs}} = \frac{(F_{\text{theor}} + F_{\text{em}})G}{G} = F_{\text{theor}} + F_{\text{em}} \quad (11)$$

The theoretical profile is then subtracted from the obtained normalized profile, yielding the emission component F_{em} , which can again be determined using equation (8). The procedure is identical to that described in Method I.

As can be seen, Method II is essentially a continuation of Method I and is based on the use of a synthetic stellar spectrum.

5 CONCLUSIONS

Thus, this paper proposes two different methods for extracting the contribution of the emission component from spectral line profiles containing emission features. Method I is based on a polynomial approximation used to eliminate the instrumental response function. Method II employs flat-field lamp spectra obtained with the same instrumental configuration to correct for the instrumental response.

Both methods were tested using spectra of the Herbig Ae/Be star HD 141569, and satisfactory results were obtained. These approaches can be widely applied in future studies of stars exhibiting emission lines in their spectra.

Using the $H\beta$ spectral line from the observed spectrum KF1011-12 as an example, we demonstrated how to isolate the emission component superimposed on the absorption profile. This procedure was also applied to the remaining $H\alpha$ – $H\delta$ hydrogen lines for all spectra of the star prepared for publication. As an example, the resulting spectral components for these lines are shown in the Appendix (Fig. A1).

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APPENDIX A: EXTRACTED EMISSION COMPONENTS IN STELLAR SPECTRAL LINES OF THE $H\alpha$ LINE

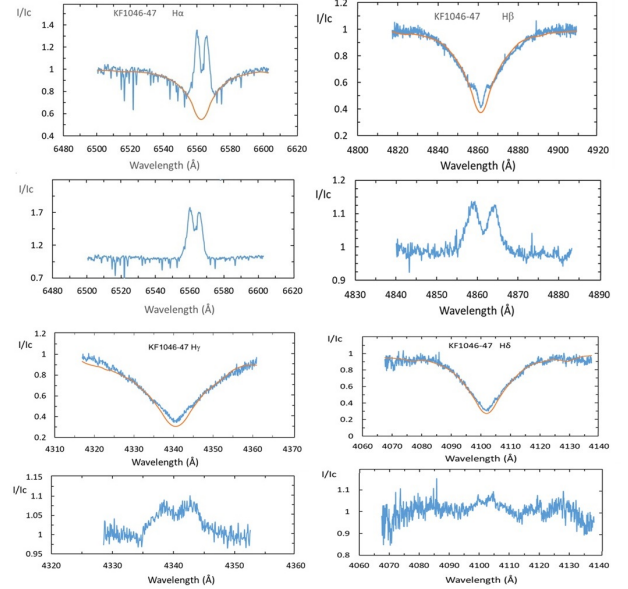


Figure A1: Extracted emission components for the $H\alpha$ – $H\delta$ lines in the KF1046-47 spectra are shown in the lower panels. In the upper panels, the observed line profiles (blue lines) and synthetic spectral lines (red lines) are presented for each transition.



ABOUT THE POSSIBLE RELATIONSHIP BETWEEN LONG-PERIOD COMETS AND TRANSNEPTUNIAN OBJECTS.1

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ABSTRACT

This paper investigates dynamical links between long-period comets (LPCs) and large trans-Neptunian objects (TNOs). Using updated catalogs (1495 LPCs with aphelion > 30 au and 37 bright TNOs with $H < 4.1$), we apply three complementary methods: (i) a statistical test of LPC orbital nodes relative to each TNO's orbital plane, (ii) counting of minimum orbit intersection distance (MOID) events, and (iii) backward numerical integrations. The nodal-plane analysis reveals a highly significant clustering of 53 comet passages near the orbit of TNO 2003 VS₂ and a weaker signal for 2010 KZ₃₉. The MOID statistics confirm that 2003 VS₂ exhibits an excess of encounters (19 comets within 0.1 au), while Salacia and 2010 KZ₃₉ show more modest excesses. Orbital integrations of 31 candidate LPCs and the three selected TNOs indicate that comet C/1969 P1 likely passed ~ 0.05 – 0.20 au from 2003 VS₂ (circa 1951), while C/1937 D1 and C/2024 V2 passed ~ 0.15 – 0.30 au from Salacia. These results are consistent with earlier suggestions of an LPC–TNO association, implying that the largest Kuiper belt bodies may influence the orbital distribution of distant comets. Other possible relationships between these two populations cannot be excluded and should be investigated using more comprehensive datasets in future studies.

Key words: TNO - long-period comets – interrelation - orbit elements

1 INTRODUCTION

The study of comets and their dynamical evolution provides critical insights into the primordial conditions and ongoing processes that have shaped the Solar System. As relics of its early formation, long-period comets carry relatively unaltered material from the protoplanetary disk, allowing us to probe its chemical and physical properties. Likewise, trans-Neptunian objects (TNOs) occupy the distant, dynamically cold reservoir beyond Neptune, preserving records of planetary migration and resonance interactions.

By combining analyses of cometary trajectories and TNO orbital architectures, it is possible to reconstruct the dynamical history of the Solar System and to constrain models of its long-term stability. Such integrated investigations are essential for a comprehensive understanding of both local small-body populations and the broader mechanisms governing planetary system evolution.

The statistical aspects of a possible connection between long-period comets and trans-Neptunian objects have been

addressed in several studies (Guliyev & Guliyev 2012; Guliyev & Nabiye 2014; Guliyev & Guliyev 2017). The potential for a dynamical, kinematical, and possibly genetic relationship between these two populations of Solar System bodies has a number of underlying premises. It is known that a subset of long-period comets — judging by their minimum orbit intersection distance (MOID) values and distant nodes — tends to cluster near the orbits of the giant planets (Guliyev & Guliyev 2020). When the methods used to reveal these trends are applied to Kuiper belt objects, the resulting calculations often display similarly noteworthy patterns. This represents the principal conclusion of the aforementioned studies. However, when analyzing such results for trans-Neptunian objects and long-period comets, any stochastic components must be examined with the utmost rigor, since at first glance such a connection appears highly improbable, if not impossible. Positive statistical findings should therefore be cross-validated using multiple independent approaches. Furthermore, these statistical results ought to be corroborated by numerical calculations of cometary and planetary orbital evolution.

In the search for dynamical interactions, primary focus should

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be directed towards the largest trans-Neptunian bodies. However, if the underlying mechanisms are of a different nature — such as collisional, tidal, or various eruptive processes — then other, purely physical characteristics of these objects may become paramount.

2 PRIMARY OBJECTIVE OF THE PRESENT WORK

Since the publication of the aforementioned studies on a possible connection between trans-Neptunian objects (TNOs) and long-period comets, the catalogs of these two populations have expanded substantially. Consequently, reassessing the results reported in those studies may prove critically important. Moreover, the modeling and statistical methods employed in those works, in the view of the authors, require refinement.

However, such refinement is not the sole objective of the present study. We contend that the findings derived from analyses of the distant nodes of cometary orbits must be independently validated using minimum orbit intersection distance (MOID) calculations. Should these two methodologies yield consistent results, it will then be necessary to undertake detailed investigations of cometary orbital evolution, incorporating the orbital parameters of the relevant TNOs.

We also acknowledge that expectations of identifying close encounters between comets and TNOs — either in the recent past or in the near future — may not always be fulfilled. Such limitations arise not only from temporal constraints but also from the accuracy of the orbital elements available for objects in both populations, which can significantly affect the results.

Despite these challenges, we revisit and rigorously examine the question of a possible dynamical linkage between long-period comets and the largest TNOs. This re-evaluation constitutes the principal aim of the present work.

The present study comprises three stages of computation. In the first stage, the distant nodes of cometary orbits are examined with respect to the planes of motion of the trans-Neptunian objects (TNOs). In the second stage, a minimum orbit intersection distance (MOID) analysis of the cometary orbits relative to Kuiper belt objects is carried out. Finally, in the third stage, orbital evolution simulations are performed for the comets, taking into account the most relevant TNO parameters for this investigation.

3 THE DATA USED

In previous studies (Guliyev & Guliyev 2012; Guliyev & Nabiyeu 2014; Guliyev & Guliyev 2017), the number of comets employed in the calculations ranged from 1040 to 1190. Those works also incorporated orbital parameters for up to 92 trans-Neptunian objects (TNOs) with absolute magnitudes not exceeding $H \leq 5.5$ mag.

In the present study, we use a more extensive sample of 1495 long-period comets observed prior to early 2025, whose aphelion distances exceed 30 au. Low-perihelion comets are

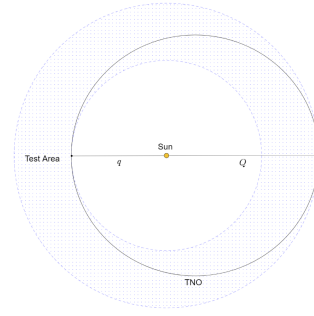


Figure 1. Schematic representation of the testing area for a representative TNO orbit.

excluded, and for any comet that has undergone fragmentation, the orbital elements of its largest component (designated “A”) are adopted. Such selection criteria minimize the risk of spurious correlations and enhance the robustness of the results within the scope of our objectives.

For the TNO sample, we initially impose a stricter upper limit on absolute magnitude of $H \leq 4.1$ mag, yielding 37 objects observed through 2025. Their orbital data are retrieved from the JPL Small-Body Database¹. Cometary orbital elements are sourced from the Marsden (2007) catalog and relevant issues of the Minor Planet Electronic Circulars (MPEC)² archive, covering the period 2007–2025.

4 FEATURES OF THE DISTRIBUTION OF COMETARY ORBITAL NODES RELATIVE TO THE PLANE OF TNOs

The methodology and computational scheme in this part of the study closely follow those described in Guliyev & Guliyev (2012) and Guliyev & Nabiyeu (2014). The number of cometary passages within the orbital zone of a selected trans-Neptunian object (TNO) is compared with that obtained for 205 simulated (“dummy”) zones (67 in the cited works), which differ from the actual zone only in their fundamental plane parameters — the longitude of ascending node Ω_p and the inclination i_p .

In all cases, comet–TNO intersections are analyzed strictly within the heliocentric distance interval $[q, Q]$, corresponding to the perihelion and aphelion distances of the selected TNO (see Fig. 1). In contrast, earlier studies allowed a contraction of this interval in order to optimize the statistics of intersections. Specifically, Ω_p is varied from 0° to 330° in 15° increments (previously 30°), and i_p from 0° to 90° in such a way that the poles of the corresponding planes are equally spaced on the celestial sphere. This equal-spacing condition is achieved by dividing the interval into equal parts of $\cos i$. Note that the reference plane (for each zone, including dummy ones) is not the ecliptic, but the orbital plane

¹ <https://ssd.jpl.nasa.gov/sb/orbits.html>

² <https://projectpluto.com/mpecs.htm>

of the TNO itself, with its ascending node taken as the zero point.

For each TNO (real or dummy), we compute:

- N — the number of cometary passages within its q - Q zone;
- $\bar{n}$ — the mean number of passages across the 205 dummy zones;
- σ — the standard deviation of those 205 counts;
- t — the normalized difference, $t = (N - \bar{n})/\sigma$;
- α — the one-sided confidence level associated with t .

The reliability of t and α is assessed using a one-sample Student's t -test. Values exceeding $t = 1.67$ (corresponding to $\alpha = 0.95$) indicate statistical significance at the 5% level.

As an independent test of the method, we apply it to a fictitious TNO defined by

$$q = 30 \text{ au}, \quad Q = 40 \text{ au}, \quad \Omega_p = 100^\circ, \quad i_p = 20^\circ$$

using the same comet dataset. The results are:

$$N = 76, \quad \bar{n} = 70.07, \quad \sigma = 8.08, \quad t = 0.73, \quad \alpha \ll 0.95$$

At this stage, one might argue that, owing to the moderate eccentricity of the orbit, the “width” of the tested region — only 10 au — is too narrow. However, if we increase the aphelion distance to 50 or 60 au, the resulting t -values become 0.37 and 0.43, respectively.

Thus, for the simulated TNO, the criterion is not met, confirming that the procedure does not produce false positives under these conditions.

If any apparent correlation between a TNO and long-period comets is purely coincidental and lacks a physical basis, we would consistently obtain t -values below the critical threshold in all cases.

However, when the test was applied to the 37 selected trans-Neptunian objects, one body exhibited highly significant results. This object, designated 2003 VS₂, has the following orbital parameters used in the base calculations:

$$q = 36.46 \text{ au}, \quad Q = 42.98 \text{ au}, \quad \Omega_p = 302.77^\circ, \quad i_p = 14.77^\circ$$

The specific outcomes for 2003 VS₂ are:

$$N = 53, \quad \bar{n} = 37.06, \quad \sigma = 5.87, \quad t = 2.72, \quad \alpha = 0.996$$

The positive result of the applied test is likewise apparent for the TNO 2010 KZ₃₉, whose statistical parameters are:

$$N = 33, \quad \bar{n} = 23.45, \quad \sigma = 4.79, \quad t = 1.99, \quad \alpha = 0.976$$

If the lower bound for the confidence parameter α is relaxed to 0.90, then Salacia and 2018 VG₁₈ also emerge as noteworthy, with α -values of 0.90 and 0.93, respectively.

The proposed testing scheme was also applied to the hypothetical planet advocated by Guliyev (2019). The calculations indicate that a planet with parameters $\Omega_p = 271.7^\circ$, $i_p = 86.2^\circ$, within the semi-major axis range 268–378 au, would yield a value of N exceeding $\bar{n}$ with a confidence level of 0.98.

While periodic application of this methodology to other

planetary hypotheses — such as those proposed by Batygin & Brown (2016b) — is scientifically justified, such investigations extend beyond the scope of this study.

In summary, the quantitative results obtained for the trans-Neptunian objects (TNOs) considered herein — particularly for 2003 VS₂ — provide sufficient justification for undertaking more detailed analyses within the framework of the stated objective.

5 MOID ANALYSIS IN THE CONTEXT OF THE RELATIONSHIP BETWEEN TNOS AND LPCS

Within the framework of the present investigation into the relationship between trans-Neptunian objects (TNOs) and long-period comets (LPCs), the MOID analysis represents a more precise method. Accordingly, in the second phase of the study, MOID values were computed for 1495 comets with respect to 37 selected planetary bodies, yielding a total of 55 315 individual calculations. As regards the computational approaches used to determine the MOID, we employed the numerical method of Wiśniowski & Rickman (2013) and the “classical” method of Gronchi (2005). The former is applied to elliptical orbits (including comets with extreme eccentricities, $e \approx 0.99$), whereas the latter is used for nearly parabolic ($e = 1.0$) and hyperbolic ($e > 1$) cometary orbits. As the limiting distances in our analysis for each TNO, we adopted the radii of the sphere of influence (Abalakin 1977), which are determined from the relation

$$h = a \left(\frac{m_{\text{pl}}}{M_{\text{S}}} \right)^{2/5} \quad (1)$$

where a is the semi-major axis of the planet's orbit, m_{pl} is its mass, and M_{S} is the mass of the Sun.

When conducting the MOID analysis in the context of our investigation, it is difficult to rely on the parameter r (gravitational sphere) for planetary bodies, since their masses are known with insufficient precision. The same uncertainty applies to the orbital elements of long-period comets.

Quantitative estimates demonstrate that a trans-Neptunian object with a mass of 10^{20} – 10^{21} kg at a heliocentric distance of 40 au has a sphere of influence ranging from approximately 0.003 to 0.008 au. Nevertheless, we restrict ourselves to analyzing only the aggregate MOID values for various choices of the parameter r .

The final results of this analysis are compiled in Table 1.

Applying statistical criteria to ascertain the degree of randomness in the data of Table 1 proves methodologically challenging. However, an analysis of the distribution $r(N)$ nonetheless underscores the relevance of the present investigation. It emerges that close and minimal-distance encounters between long-period comets and trans-Neptunian objects are, in fact, rather common. Meanwhile, within the broader field of Solar System small-body research, this issue has not yet received sufficient attention.

As anticipated from prior analyses, 2003 VS₂ dominates the statistics: it exhibits the highest frequency of MOID val-

Table 1. Number of MOID values for 1495 comets and 37 TNOs at different r

r [au]	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
N	3	5	6	9	12	17	17	18	18
r [au]	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
N	19	45	75	97	121	146	175	198	219
r [au]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
N	235	513	767	1047	1316	1562	1820	2073	2318

ues across all thresholds of r , significantly outperforming the other 36 TNOs.

Table 2 shows the number of MOID values for long-period comets relative to 2003 VS₂ at r up to 0.1 au.

At the upper limit $r = 0.10$ au, the number of MOID values among the 37 trans-Neptunian objects ranges from 2 to 19. In particular, for 2003 VS₂ the outcomes are:

$$N = 19, \quad \bar{n} = 6.35, \quad \sigma = 3.85, \quad t = 3.28, \quad \alpha = 0.999$$

The next TNO exhibiting a notable excess of small MOID values is Salacia. Across the interval $r = 0.10$ au, the count of comet–Salacia MOID pairs ranges from 1 to 13. At the upper limit, its statistics are:

$$N = 13, \quad \bar{n} = 6.35, \quad \sigma = 3.85, \quad t = 1.72, \quad \alpha = 0.953$$

Table 2 presents the number of MOID values for long-period comets relative to 2003 VS₂ for different values of r up to 0.1 au.

6 PRELIMINARY ORBITAL EVOLUTION ANALYSIS OF THREE TNOS AND 31 LPCS

This section presents backward integrations of the orbits of the selected comets, including three trans-Neptunian comets, over a 10,000-year interval. The goal of these computations is to identify Actual close encounters between the two categories of small bodies are considered. Comets were selected using a MOID threshold of ≤ 0.1 au; the resulting sample of 31 objects is listed in Table 3.

In the course of our dynamical study of comets, we deliberately excluded certain bodies — in particular, historical comets such as C/1880 G1, whose last recorded observations date back more than a century, as well as objects for which the observational arc is demonstrably insufficient or lacking reported uncertainties (“sigmas”), which makes it impractical for the proper construction of orbital clones.

Although these objects satisfy our selection by the MOID criterion, their uncertainties are too large to permit reliable dynamical modelling. As the basis for our simulations, we adopted a heliocentric model of the Solar System including the four Jovian planets and the three trans-Neptunian objects (TNOs) under consideration. For numerical integration, we employed the Bulirsch–Stoer algorithm as implemented in the MERCURY N -body simulations package (Chambers 1999). To account for the uncertainties in the cometary orbits and to ensure the robustness of the results, we generated a swarm of virtual orbits (1000 so-called clones) for each massless test particle.

To generate a set of orbital “clones” for each nominal

Cartesian state vector (X, Y, Z, V_X, V_Y, V_Z) , we proceeded as follows:

- (i) We denote the nominal state vector by

$$\mathbf{x}_0 = [X_0, Y_0, Z_0, V_{X,0}, V_{Y,0}, V_{Z,0}]^T,$$

and the one-sigma uncertainties for each component by

$$\boldsymbol{\sigma} = [\sigma_X, \sigma_Y, \sigma_Z, \sigma_{V_X}, \sigma_{V_Y}, \sigma_{V_Z}]^T.$$

- (ii) We assume that the six components are uncorrelated, so that the covariance matrix is diagonal:

$$\mathbf{C} = \text{diag}(\sigma_X^2, \sigma_Y^2, \sigma_Z^2, \sigma_{V_X}^2, \sigma_{V_Y}^2, \sigma_{V_Z}^2).$$

- (iii) Each $\mathbf{x}_k$ is drawn from the multivariate normal distribution

$$\mathbf{x}_k \sim \mathcal{N}(\mathbf{x}_0, \mathbf{C}),$$

which, under the diagonal-covariance assumption, is equivalent to sampling each component independently:

$$X_k \sim \mathcal{N}(X_0, \sigma_X^2), \quad \dots \quad V_{Z,k} \sim \mathcal{N}(V_{Z,0}, \sigma_{V_Z}^2).$$

- (i) Each sampled vector $\mathbf{x}_k$ thus represents one “clone” of the original orbit, preserving the prescribed one-sigma uncertainties in each Cartesian component.

This procedure yields a statistically representative ensemble of clones around the nominal state, suitable for Monte Carlo propagation under the assumption of independent Gaussian errors.

As a result of the integrations, we indeed identified several relatively close approaches between comets and TNOs. Of particular interest is comet C/1969 P1, which, with high probability, approached the object 2003 VS₂ in 1951 at a distance of approximately 0.05–0.20 au. We also recorded two moderate encounters with Salacia — specifically involving comets C/1937 D1 and C/2024 V2 — at distances of ≈ 0.15 –0.35 au.

Naturally, the orbital uncertainties of the TNOs themselves and the limitations of the numerical methods must be taken into account before drawing firm conclusions.

Nevertheless, the calculations demonstrate that close encounters between long-period comets and TNOs are plausible.

7 DISCUSSION

Our analysis indicates a statistically robust association between certain long-period comets and trans-Neptunian objects. In particular, 2003 VS₂ stands out: both the nodal-plane test ($N = 53$ comet passages, $t = 2.72$, confidence

Table 2. Number of LPC–2003 VS₂ pairs with MOID ≤ 0.1 au

r [au]	0.006	0.007	0.008	0.009	0.01	0.02	0.03
N	1	1	1	1	2	4	5
r [au]	0.04	0.05	0.06	0.07	0.08	0.09	0.1
N	9	10	13	16	18	18	19

Table 3. List of integrated comets and transneptunian objects

Comet	MOID [au]	Comet	MOID [au]	Comet	MOID [au]
C/2002 J4	5.08×10^{-2}	C/1984 U1	1.16×10^{-2}	C/2005 G1	5.64×10^{-5}
C/2015 Y1	5.53×10^{-3}	C/2019 T3	2.19×10^{-2}	C/2006 A2	2.28×10^{-4}
C/2021 V1	9.79×10^{-3}	C/1942 C1	2.44×10^{-2}	C/2020 J1	3.15×10^{-2}
C/1997 P2	1.14×10^{-2}	C/1937 D1	4.07×10^{-2}	C/2004 P1	3.35×10^{-2}
C/2014 M3	2.41×10^{-2}	C/2021 A4	4.15×10^{-2}	C/2011 O1	3.38×10^{-2}
C/2010 H1	0.03280725	C/1992 B1	0.060198	C/2020 M5	4.67×10^{-2}
C/1906 E1	3.40×10^{-2}	C/2004 L1	6.52×10^{-2}	C/1981 H1	5.09×10^{-2}
C/1999 K4	0.03864269	C/1994 T1	7.46×10^{-2}	C/2021 D2	5.37×10^{-2}
C/2007 W1	4.09×10^{-2}	C/1996 J1-A	8.66×10^{-2}	C/1945 L1	0.065135
C/1998 T1	6.41×10^{-2}	C/1909 L1	8.91×10^{-2}		
C/2011 Q3	0.0643297	C/2024 V2	9.52×10^{-2}		
C/1969 P1	0.06669534	C/2024 V2	9.52×10^{-2}		
C/2019 K4	7.07×10^{-2}	C/2024 V2	9.52×10^{-2}		
C/1998 K2	7.34×10^{-2}				

99.6%) and the MOID count (19 comets within 0.1 au, $t = 3.28$, confidence 99.9%) show a highly significant clustering of LPC orbits near 2003 VS₂'s orbital path.

We also detect weaker but notable signals for 2010 KZ₃₉ and Salacia ($t \approx 2.0$), suggesting these bodies may similarly influence or align with the LPC population.

Importantly, our findings qualitatively confirm and extend earlier studies by Guliyev and colleagues. For example, [Guliyev & Nabiyeu \(2014\)](#) and related works reported non-random clustering of LPC orbital elements near the orbits of large Kuiper-belt objects. The present, much larger dataset isolates 2003 VS₂ as the dominant case, providing stronger evidence that the long-standing hypothesis of an LPC–TNO connection has merit.

We note that obtaining $t > 2$ for two of 37 tested TNOs is well beyond the 5% significance threshold, making random coincidence highly unlikely.

If these statistical correlations reflect a physical connection, what mechanism could underlie them?

The large TNOs identified (2003 VS₂, 2010 KZ₃₉, Salacia) are massive ($\sim 10^{20}$ – 10^{21} kg) but still much smaller than planets. Their instantaneous action spheres at ~ 40 au are only a few thousand km in radius (~ 0.003 – 0.008 au), far smaller than the observed encounter distances (e.g. ~ 0.05 – 0.20 au for C/1969 P1–VS₂).

Notably, we found a few even closer encounters down to ≈ 0.005 au — formally within the estimated influence sphere of the TNO — but these are isolated cases amid several hundred recorded approaches and should be regarded as singular outliers, especially in light of the uncertainties in the orbital elements. Thus, a single “flyby” would impart only a minor impulse.

Instead, these alignments may stem from shared dynamical history. For example, recent models suggest the Oort cloud initially contained a flattened disk-like component of comets originating near the giant planets, possibly retaining a memory of its primordial plane (see, e.g., [Zwart \(2021\)](#), [Fouchard \(2019\)](#), [Nesvorný \(2024\)](#)).

Likewise, secular or resonant perturbations in the early Solar System might have preferentially placed comets into orbital planes near those of large TNOs. The very high t -values for 2003 VS₂ and 2010 KZ₃₉ indicate that random chance is unlikely, pointing to an underlying cause beyond statistical fluctuation.

Collisions among TNOs could also contribute. The Haumea collisional family in the Kuiper belt demonstrates that giant impacts can shatter large bodies, creating swarms of fragments ([Brown 2007](#); [Leinhardt & Stewart 2010](#); [Carry 2012](#)). If 2003 VS₂ or Salacia experienced such an event, debris could be injected onto nearly parabolic orbits and later appear as LPCs.

To date, no definitive “comet family” linked to 2003 VS₂ is known, but compositional similarities between some comets and TNOs might hint at a common origin. In any case, a collisional debris cloud would initially be planar, so fragments sharing 2003 VS₂'s orbital plane could produce the observed clustering. Thus, while direct gravitational scattering by these TNOs is weak, collisional or collective dynamical effects in the Kuiper belt cannot be ruled out.

Our backward integrations provide further context. We generated 1000 clones for each of the 31 candidate comets and integrated them with the four giant planets and the three selected TNOs. Several relatively close approaches emerged. Notably, comet C/1969 P1 likely passed within ~ 0.05 – 0.20 au of 2003 VS₂ around 1951.

We also observed moderately close approaches to Salacia: comets C/1937 D1 and C/2024 V2 approached within ~ 0.15 – 0.35 au during their respective perihelion passages. While these distances remain larger than the TNOs' Hill spheres, they demonstrate that LPC and TNO orbits can indeed come into proximity. We stress that the clones carry orbital uncertainties (older comets and some TNOs have imprecise elements), so exact distances are uncertain, but the occurrence of such near-encounters lends credence to the statistical associations.

As with any statistical study, selection effects and uncer-

tainties warrant discussion. Our LPC sample excludes objects with very short observation arcs or known fragmentation, and our 37 TNOs are limited to the brightest ($H < 4.1$) to avoid spurious hits. Nevertheless, the orbital elements of some TNOs carry large uncertainties, and a few comets have poorly constrained orbits. We have attempted to mitigate these biases: for instance, a simulated “dummy” TNO produced no signal ($t = 0.73$) under the same nodal test, and the MOID results are qualitatively similar across reasonable encounter radii.

In particular, 2003 VS₂’s excess encounters persist even at smaller radii (Table 2), always significantly above the mean. These consistency checks increase our confidence that the patterns for 2003 VS₂ (and to a lesser extent Salacia and 2010 KZ₃₉) are not artifacts of data selection or method.

Comparing with other research on outer Solar System dynamics, our findings fit a broader pattern: massive TNOs can shepherd smaller bodies. For example, [Muñoz-Gutiérrez et al. \(2025\)](#) showed that Pluto (the largest TNO) significantly affects the evolution of Neptune-resonant Kuiper belt objects. By analogy, a mid-sized dwarf planet like 2003 VS₂ (~ 520 km diameter) could exert a subtler influence on the comet population.

2003 VS₂ occupies an intermediate mass regime — not as dominant as Pluto but large enough to leave statistical traces — and our results suggest it does impact the LPC flux. While we did not directly test hypothetical distant planets (e.g. a “Planet Nine”), the methods used here could be extended to evaluate such scenarios in future work.

Looking forward, these results open new avenues for exploration. If large Kuiper belt bodies influence the delivery or perturbation of Oort-cloud comets, then models of comet flux and Solar System evolution will need revision. Upcoming surveys (e.g. the Vera Rubin Observatory’s LSST) will greatly expand the LPC catalog, enhancing the statistical power of these tests. Likewise, continued searches and orbit refinement for distant TNOs may reveal additional massive bodies whose orbital planes correlate with comets.

Detailed N -body simulations including all known TNOs and planets should be performed to attempt to reproduce the observed associations. For now, our study provides the most extensive statistical evidence to date that some LPC orbital elements are not randomly distributed with respect to the orbits of the largest trans-Neptunian objects, hinting at a subtle interplay between these distant populations.

8 CONCLUSION

In summary, our analysis of 1,495 long-period comets and 37 large trans-Neptunian objects reveals statistically significant correlations. Both the nodal-plane test and the MOID encounter statistics identify 2003 VS₂ as having an anomalously high number of comet interactions, well above random expectation. Salacia and 2010 KZ₃₉ also show moderate excesses.

Our numerical integrations further suggest that these

comets did indeed have relatively close approaches to their respective TNOs (e.g. C/1969 P1 with 2003 VS₂), lending dynamical support to the statistical findings. These results corroborate and extend earlier proposals of an LPC–TNO association.

These findings have important implications. If the largest Kuiper belt bodies influence the orbits of some Oort-cloud comets, models of comet delivery and Solar System evolution may need revision. Possible mechanisms could include collisional fragmentation of TNOs that produces cometary fragments, or long-range perturbations via resonances aligned with the planes of these TNOs.

Distinguishing among these scenarios will require additional study. In light of these results, our analyses provide substantial statistical evidence that the orbital distributions of long-period comets correlate with several major trans-Neptunian objects, motivating targeted dynamical and observational follow-ups to clarify the causal mechanisms.

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THE REFLECTANCE SPECTRUM AND TAXONOMIC TYPE OF ASTEROID (704) INTERAMNIA

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ABSTRACT

This study presents new evidence supporting the periodic occurrence of sublimation-driven activity on the main-belt asteroid (704) Interamnia, initially detected near perihelion in 2012. New low-resolution $R \approx 600$ reflectance spectra of Interamnia were obtained on 10 February 2025 at the Assy-Turgen Observatory using the 1.5-meter AZT-20 telescope, covering the 3500–7500 Å spectral range. At the time of observation, the asteroid’s heliocentric distance was approximately 3.499 AU, placing it near aphelion (≈ 3.53 AU). The spectra reveal a broad absorption feature centered around 0.45–0.50 μm and an overall negative spectral slope. The observed spectrum was compared with averaged data from the SMASSII and Gaia DR3 surveys. Taxonomic classification using a template-matching approach identifies the asteroid as belonging to the F-type group, with weak spectral indications of sublimation activity. A comparison with modeled spectra of carbonaceous chondrite analogs suggests a composition dominated by CM and CI chondrites, which are rich in volatiles and hydrated minerals. These findings indicate that Interamnia is a dark, carbonaceous body with a primitive composition. The presence of transient sublimation activity, along with its low albedo and thermal properties, supports the hypothesis that (704) Interamnia is a large, partially degassed primitive object. Continued spectroscopic monitoring will be essential to further constrain the nature and extent of its activity.

Key words: Minor planets, asteroids: individual: (704) Interamnia – asteroid surfaces – sublimation – reflectance spectroscopy

1 INTRODUCTION

While Main Belt Asteroids (MBAs) were traditionally considered inert remnants from the early Solar System, recent observations—including spectroscopic analyses, infrared data, and direct missions—have revealed a more complex nature. Evidence suggests the presence of hydrated minerals, seasonal or intermittent activity (such as dust ejection and sublimation), and comet-like behaviors in some of these bodies. The observed sublimation activity, in particular, indicates a more intricate thermal and dynamical evolution for MBAs. Consequently, these objects are now recognized as crucial for understanding the origin of water, the evolution of the early Solar System, and for informing future space missions.

(704) Interamnia, one of the largest Main Belt Asteroids (MBA), is classified as a dark carbonaceous body. The mean diameter and geometric albedo of (704) Interamnia are 307.31 km and 0.08, respectively, according to WISE spacecraft data [Masiero et al. \(2014\)](#). Its semimajor axis and or-

bital eccentricity are 3.059 AU and 0.155, respectively. Interamnia is classified spectrally as either type “F” [Tholen \(1989\)](#) or type “B” [Bus & Binzel \(2002\)](#), both of which are characterized by a broad absorption band beyond $\sim 0.5 \mu\text{m}$ in combination with an overall negative spectral slope.

Recent advancements in observational spectroscopy, thermal modeling, and shape reconstruction have provided compelling evidence of complex surface processes, including episodic sublimation activity [Busarev et al. \(2016\)](#); [Savelova et al. \(2023\)](#). Table 1 presents a list of objects exhibiting spectral features of an intermediate type or transitional morphology between C-type and B/F-type asteroids. With an estimated volume comparable to that of (10) Hygiea (another MBA and candidate dwarf planet) and a low albedo (~ 0.05) [Masiero et al. \(2014\)](#); [Vernazza et al. \(2020\)](#), it has garnered interest as a transitional object between the taxonomic C-type group and the more bluish B/F-types.

Sublimation activity on Interamnia is considered atypical for a MBA, suggesting it may be a partially devolatilized body that retains primordial material in its subsurface layers. Research indicates that sublimation on Interamnia oc-

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curs unevenly and sporadically [Busarev et al. \(2016\)](#), pointing to a seasonal or trigger-driven nature of the activity. As the asteroid approaches perihelion, increased solar insolation may heat deeper surface layers, causing subsurface volatiles to sublimate. The resulting gas pressure beneath the surface crust can lead to fracturing of the asteroid and the ejection of dust and gas into the near-surface environment, resembling weak cometary activity. These outbursts likely occur locally within fractures or craters where the regolith layer is thinner.

All of this supports the interpretation of Interamnia as a potentially transitional object, not only in terms of composition, but also in terms of its evolutionary status. Interamnia occupies an intermediate position between typical B-type asteroids (characterized by carbonaceous surfaces and low albedo) and dormant comets that have lost most of their surface volatiles [Busarev et al. \(2016\)](#); [Savelova et al. \(2023\)](#). Such bodies are of particular interest for understanding the distribution of water and organic compounds in the early Solar System.

2 OBSERVATION AND METHODS

Spectral observations of the asteroid were conducted on April 4, 2024 and February 10, 2025 at the Assy-Turgen Observatory using a long-slit spectrograph based on volume-phase holographic gratings (VPHG), mounted at the prime focus of the AZT-20 telescope with an aperture of 1.5 meters and a focal length of 5.72 meters (f/3.8). The focal lengths of the spectrograph's collimator and camera are 130 mm and 85 mm, respectively. The spectrograph is equipped with an iXon Ultra 888 EMCCD detector, featuring a resolution of 1024×1024 pixels and a physical pixel size of $13 \mu\text{m}$, resulting in an image scale of 0.717 arcseconds per pixel.

The observations were carried out in low spectral resolution mode ($R = 600$) using a 360 lines/mm VPHG with a dispersion of $4.25 \text{ \AA}$ per pixel, in first binning mode with the EMCCD operated at a gain factor of 2.4 and an exposure time of 60 seconds. The slit width was set to 9 arcseconds. Wavelength calibration was performed using spectra of a standard He–Ne–Ar lamp. The asteroid spectrum was measured using a differential method, comparing the radiation flux from the object to that of a standard star. Solar analog stars (G-type) were used as spectrophotometric standards.

Asteroid's orbital data at the time of the observations are provided according to the Minor Planet Center and summarized in Table 2 (columns 3–9). The last rows of the table contain the details of the EMCCD operating mode used during observations. According to the orbital data for Interamnia, its perihelion distance is $q = 2.58 \text{ AU}$, and its aphelion is approximately $Q \approx 3.53 \text{ AU}$.

The primary research method involves the accurate acquisition and analysis of spectra of sunlight reflected by the asteroid, as well as spectra of solar-type stars. Data reduction was carried out using the Image Reduction and Analysis Facility (IRAF) software package. Wavelength calibration was performed using spectra from a standard He–Ne–Ar lamp. The

spectra of the asteroid and the calibration source were processed using identical procedures, with consideration given to changing air mass during the observations.

The calibrated spectra of standard stars and asteroids, observed on the same night, were normalized to the flux at a wavelength of $0.55 \mu\text{m}$. The resulting normalized reflectance spectra of the asteroids were obtained by dividing the asteroid spectrum by the spectrum of a standard star, or by an averaged spectrum of several standard stars. This procedure introduces additional noise into the final result due to the intrinsic noise present in the spectra of solar analog stars.

A Butterworth filter was utilized to smooth the reflectance spectra [Serebryanskiy et al. \(2022\)](#). Reflectance spectra errors were estimated through the averaging of multiple spectra, rather than derived from the formal signal-to-noise ratio of individual spectra, thereby incorporating fluctuations due to varying observational conditions. The ultimate error, even with the smoothing procedure, remains below 10% of the reflectance spectrum value. A substantial increase in error at wavelengths shorter than $4000 \text{ \AA}$ imposes corresponding limitations on the usable wavelength range of the analyzed spectra.

3 RESULTS AND DISCUSSION

Figure 1 shows the reflectance spectra obtained with the AZT-20 telescope, as well as the averaged spectra obtained with SMASSII and the Gaia DR3 catalog [Gaia Collaboration et al. \(2023\)](#). These reflectance spectra are in good agreement with each other.

Figure 2 illustrates a comparison between the reflectance spectrum observed in this work on February 10, 2025, and the average spectrum obtained on September 13, 2012, by [Busarev et al. \(2016\)](#), with corresponding designations provided in the figure legend. The green-shaded area in the figure highlights the template range for the F-type taxonomic class. This range is based on the maximum and minimum albedo values reported by [Tholen \(1989\)](#).

It should be mentioned that the observations of Interamnia on September 13, 2012 were conducted near perihelion. According to JPL Horizons (or equivalent ephemerides), the heliocentric distance of Interamnia around midday on that date was approximately 2.59 AU, indicating that the object had either just passed or was approaching perihelion. On February 10, 2025, at the time of our observations, the heliocentric distance was $r \approx 3.499 \text{ AU}$, which is close to aphelion $Q \approx 3.53 \text{ AU}$, as expected for the midpoint between the 2023 perihelion and the next one, anticipated around 2028.

Figure 2 illustrates that Interamnia exhibits signs of sublimation as it approaches perihelion, as evidenced by the reflectance spectrum from [Busarev et al. \(2016\)](#). Conversely, our observations on February 10, 2025 suggest it remains in a quiescent state near aphelion.

In the study by [Savelova et al. \(2023\)](#), the authors estimated the asteroid composition by modeling its reflectance spectra using meteorite analogs. According

Table 1. Asteroids exhibiting transitional properties between C-type and B/F-type

Asteroid	<i>D</i> (km)	Type	Sublimation activity	Peculiarities
(1) Ceres	940	G/C	Yes	Dwarf planet, icy mantle Park et al. (2016) .
(10) Hygiea	~434	C/B	No (possibly in the past)	Almost spherical, potentially a dwarf planet candidate Vernazza et al. (2020) .
(24) Themis	~202	B/C	Yes	Presence of ice, comet-like activity Campins et al. (2010) ; Rivkin & Emery (2010) .
(52) Europa	~314	B/C	Not detected	Evidence of differentiation Hanuš et al. (2017) .
(65) Cybele	~290	P/B?	Assumed	Low density, possibility of ice presence Licandro et al. (2011) .
(145) Adeona	~150	C	Yes	Sublimation features in the spectra Busarev et al. (2016) .
(704) Interamnia	~332	F/B/ C	Yes	Almost spherical, icy, active Busarev et al. (2016) ; Savelova et al. (2023) .
(779) Nina	~80	F	Yes	Reflection surges in the blue spectral range Busarev et al. (2016) .
(1474) Beira	~78	C/F?	Yes	Anomalous spectral features Busarev et al. (2016) .

Table 2. Log of observations. All observations were obtained at $\Delta = 2.509$ AU and $r = 3.408$ AU for 704 Interamnia.

Date (y m d)	UT (h m s)	R.A. (h m s)	Decl. (° ' ")	Elong (°)	Ph (°)	V (mag)	Airmass	Exp Time (s)	Standards HD / Type
704 Interamnia									
2025 02 10	17:20:52	10 25 44.2	-11 41 42	151.4	8.0	11.6	2.400	60	81809
2025 02 10	17:21:57	10 25 44.1	-11 41 42	151.4	8.0	11.6	2.388	60	81809
2025 02 10	17:23:47	10 25 44.1	-11 41 42	151.4	8.0	11.6	2.367	60	81809
2025 02 10	17:24:51	10 25 44.1	-11 41 42	151.4	8.0	11.6	2.356	60	81809
HD 81809									
2025 02 10	17:43:40.5	09 27 43.2	-06 04 15.6	–	–	–	1.628	5	G1.5IV–V
2025 02 10	17:43:52.5	09 27 43.2	-06 04 15.6	–	–	–	1.628	5	G1.5IV–V
2025 02 10	17:44:53.5	09 27 43.2	-06 04 15.6	–	–	–	1.625	3	G1.5IV–V
2025 02 10	17:45:00.5	09 27 43.2	-06 04 15.6	–	–	–	1.625	3	G1.5IV–V
TEMP = -60°C (matrix cooling temperature)									
READTIME = 1.0×10^{-6} s (pixel readout time)									
GAIN = 5 (signal gain factor)									

to the modeling results, Interamnia belongs to the F class. The asteroid composition was modeled as a mixture of three carbonaceous chondrites: CM2, CI1 and C1/2, corresponding to possible meteorite analogs of F-type asteroids [Gaffey et al. \(1989\)](#); [Savelova et al. \(2023\)](#). CI chondrites are the most primitive and water-rich carbonaceous chondrites. They contain a high proportion of water and other volatiles and very few chondrules. CM chondrites contain chondrules, but are also rich in water and organic compounds, a prominent example of which is Murchison. Ivuna, a CI-type carbonaceous chondrite, is one of the most primitive known meteorites, with a composition similar to that of the solar photosphere. It is characterized by a high water content and a fine-grained matrix consisting of phyllosilicates, magnetite, sulfides, and sulfates. According to [Savelova et al. \(2023\)](#), the composition of asteroid (704) Interamnia can be described as follows: approximately 55% Murchison (CM2), 43% Ivuna 700 (CI1), and 2% Yamato 82162 (C1/2). Figure 3 presents the data from the study by [Savelova et al. \(2023\)](#), where the solid black line is the

normalized reflectance spectrum of the asteroid (704) Interamnia from the SMASSII database, the solid red line corresponds to the modeled spectrum based on meteorite analogs, and the green curve is the reflectance spectrum of Interamnia obtained in this study. Comparative analysis shows that the normalized reflectance spectrum of the asteroid (704) Interamnia obtained in this work and from the SMASSII database have similar features in the region of $\sim 0.45\text{--}0.5\mu\text{m}$ and a negative gradient and are close to the model reflectance spectrum [Gaffey et al. \(1989\)](#); [Savelova et al. \(2023\)](#).

The complex composition of (704) Interamnia—represented as a mixture of CM2, CI1, and C1/2 chondrites—may contribute to its spectral variability and heterogeneous sublimation behavior [Busarev et al. \(2016\)](#); [Gaffey et al. \(1989\)](#); [Savelova et al. \(2023\)](#). Each chondrite type contains differing proportions of hydrous minerals, organics, and other volatile-rich phases that sublimate or thermally decompose at different temperatures and depths. For example, CI-type material such as Ivuna is rich in phyllosilicates and sulfates, which can release water vapor and sulfur-bearing

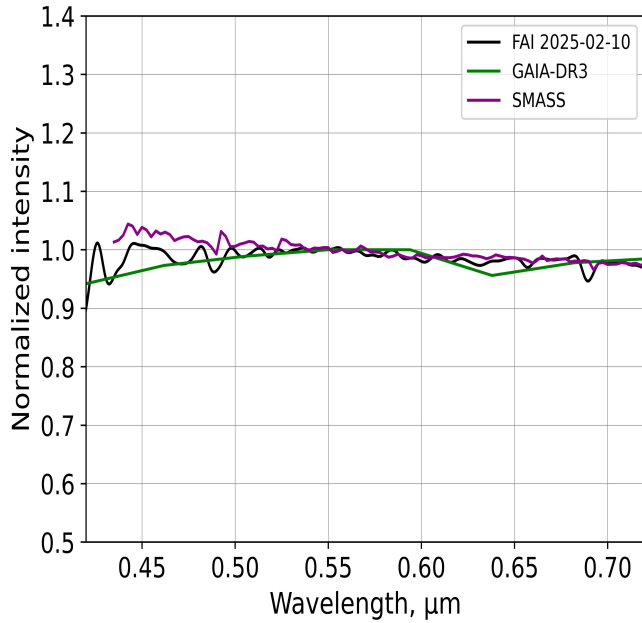


Figure 1. Comparison of averaged spectra from SMASSII and Gaia DR3 [Gaia Collaboration et al. \(2023\)](#) for taxonomic class F and the reflectance spectrum obtained on February 10, 2025 on AZT-20

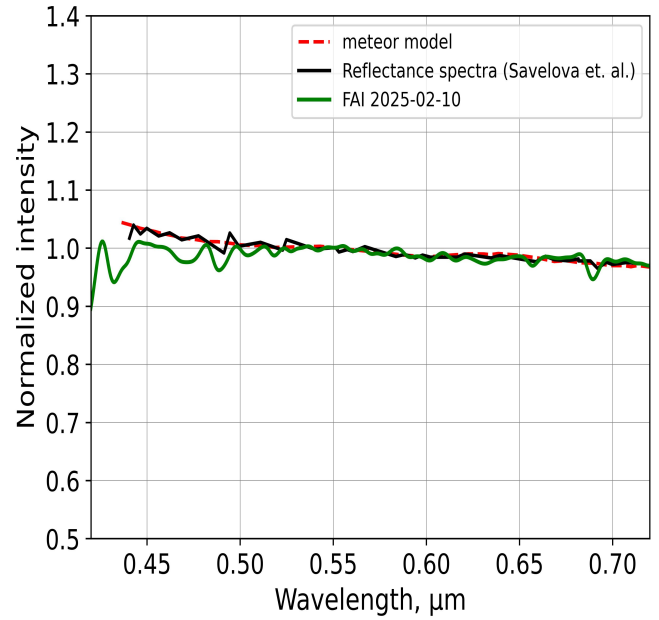


Figure 3. Comparison of the composition of asteroid (704) Interamnia based on reflectance spectra using meteorite analogs [Savelova et al. \(2023\)](#) and the reflectance spectrum obtained on February 10, 2025 using AZT-20

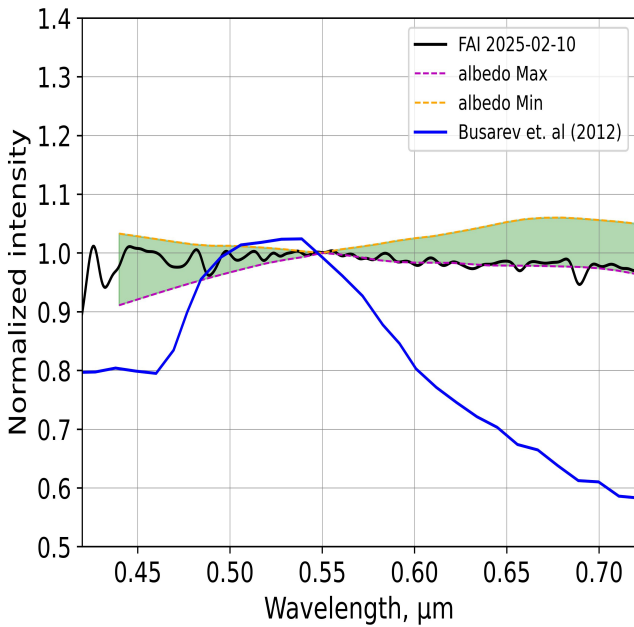


Figure 2. A comparison of the reflectance spectra of (704) Interamnia near perihelion [Busarev et al. \(2016\)](#) and aphelion (FAI data 2025-02-10) and the spectral range for taxonomic class F [Tholen \(1989\)](#)

gases at moderate heating. In contrast, CM-type chondrites, while also hydrated, may contain more refractory organic compounds and carbonates that sublime under slightly different thermal conditions. C1/2-type meteorites (e.g., Yamato 82162) may include transitional material with intermediate thermal stability.

As a result, the surface or near-surface layers of Interamnia may undergo localized or transient degassing processes depending on the spatial distribution and burial depth of each volatile phase. This heterogeneity may lead to spectrally variable features, especially in the visible and near-infrared range. Differences in the depth and shape of absorption bands (e.g., near 0.45–0.5 μm) may explain the episodic and irregular sublimation activity observed in different studies [Busarev et al. \(2016\)](#); [Savelova et al. \(2023\)](#). These findings support the hypothesis that volatiles on Interamnia are distributed heterogeneously and that sublimation is not a uniform process across the surface, but rather dependent on local activation conditions such as solar heating.

4 CONCLUSIONS

The reflectance spectrum of asteroid (704) Interamnia, obtained on February 10, 2025 using the AZT-20 telescope at Assy-Turgen Observatory, exhibits a broad absorption band in the $\sim 0.45\text{--}0.5\ \mu\text{m}$ range along with an overall negative spectral slope. Template-based taxonomic analysis indicates that the asteroid belongs to the F-type class [Tholen \(1989\)](#);

Bus & Binzel (2002); Gaia Collaboration et al. (2023); Gaffey et al. (1989); Savelova et al. (2023). Interamnia is a dark, carbonaceous body composed primarily of CM and CI chondrites, which are rich in water and other volatiles Gaffey et al. (1989); Savelova et al. (2023). Comparison with the data from Busarev et al. Busarev et al. (2016) confirms that sublimation activity on (704) Interamnia occurs in an irregular and episodic manner, suggesting a seasonal or trigger-driven activation mechanism.

Further spectroscopic monitoring of Interamnia at perihelion in 2028 will be necessary to confirm the nature and extent of this activity, as this will allow a more detailed study of the sublimation activity of this class of objects and shed light on their nature.

5 ACKNOWLEDGEMENTS

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FLARE X-RAY ACTIVITY OF THE γ CAS TYPE STAR HD 110432

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ABSTRACT

The X-ray light curves of the γ Cas type star HD 110432 (BZ Cru, B0.5IVpe) are analysed. In the present paper, the method for searching fast flares in the X-ray light curves proposed by Smith et al. (2012) is augmented and used to look for such flares from HD 110432 light curves with bin 5 s. The profiles, powers and numbers of flares in different energy ranges are examined. It has been established, that stellar X-ray light curve consist of fast flares and a base level without flares. We hypothesize that both mechanisms of flares generation proposed by Smith et al. (2012): accretion of disk matter onto a degenerate component and reconnection of magnetic field lines of the decretion disk and the star are effective for γ Cas type stars are effective.

Key words: stars: emission-line, Be – stars: binaries: individual: γ Cas – stars

1 INTRODUCTION

The enigmatic subclass of Be-stars named γ Cas analogues includes stars with power and hard X-rays. X-ray luminosity of such objects is higher than that of typical Be-stars, but lower than X-ray luminosity of high massive X-ray binaries. Assuming a completely thermal X-rays from γ Cas analogues, the temperature of the emitting plasma reaches 10-20 keV and even more. The first list of these objects is given by Smith et al. (2016a). Most of the γ Cas analogues are probably binaries with a low-mass companion (Naze et al. (2022)). Accordingly to Gies et al. (2023) γ Cas analogues are binary Be star accompanied by a white dwarf.

The formation of X-rays emitted by these mysterious stars is enigmatic and can, in a principle, be explained by following hypotheses:

- 1) An accretion onto a compact component, being either a neutron star in the propeller mode (Postnov et al. 2017) or a white dwarf (Gies et al. 2023);
- 2) an interaction between the magnetic field of the decretion disk and the local magnetic field of the star (Smith et al. 2016b);
- 3) the contribution of the possible non-thermal X-ray emission resulting from the inverse Compton scattering of UV photons by relativistic electrons in the framework of the Chen & White (1991) model as suggested by Ryspaeva & Kholtygin (2020, 2021)

According to the second scenario X-ray emission from

γ Cas analogs should consist of a lot of the short flares. Smith et al. (2012) inspected this scenario on star HD 110432 (BZ Cru, B0.5IVpe) being the first discovered analog of γ Cas. Authors studied stellar light curves from the observations on *XMM-Newton* and *RXTE* satellites and revealed three kinds of X-ray variations of the object: long cycles of a few months, intermediate variations of a few hours, and rapid flares having lifetimes from 1.5 minutes down to several seconds. Authors found 1615 "fast flares" ("flare-like events").

Smith et al. (2012) explained these flares either by reconnecting the magnetic field lines of the decretion disk and of the star, or by accretion to a compact component. In the present paper we perform deeper investigation of X-ray fast flares on HD 110432. We use method by Smith et al. (2012) with our corrections and apply this for light curves with different steps and in various energy intervals. In addition, we test the hypothesis that fast flares, particularly those occurring at low energies, may be similar to solar nanoflares generated in the solar corona accordingly to (Cargill & Klimchuk 2006).

Present paper is organized by the following manner. Section 2 contain the detailed description of observational data reduction. The flares searching method is described in Section 3. The results of searching the fast flares in the X-ray light curves of HD 110432 are presented in Sections 4. General conclusions are given in Section 5.

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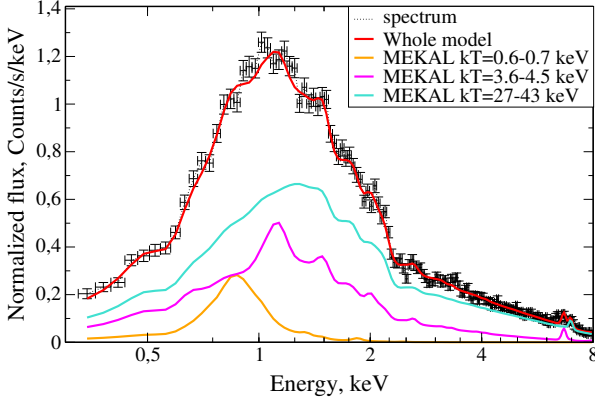


Figure 1. The best fit of X-ray spectra on September 4, 2007 by thermal models (thick red line). The contributions of individual model components are shown by other color lines.

2 OBSERVATION AND DATA REDUCTION

Log of observation of studied star is given in Table 1. X-ray luminosities for observations in 2002-2003 are taken from paper by Ryspaeva (2024). We reanalyzed archival X-ray observations, obtained by *European Photon Imaging Camera* (EPIC) onboard the *XMM-Newton* space observatory. We process data in *SAS v.20*¹ (Scientific Analysis Software) package following the recommendations of the SAS team. The pipeline of observation data includes the *emproc* script for EPIC-MOS data and by the *epproc* script for EPIC-PN data. The filtration of the EPIC-images from background flares is performed with the *tabgtigen* and *esfilter* tasks. We convert times of EPIC-images from the local satellite frame to Barycentric Dynamical Time (TDB) whose spatial origin lies at the solar system barycenter by *barycen* task. The stellar light curves are extracted from filtered and barycentred EPIC-PN images.

This is done from the circle region with a radius of not less than 15' centred on the stellar coordinates. They are taken from the SIMBAD² database and corrected for the X-ray image position. The background light curves are obtained from the regions of the same size in the places free of other bright sources. The background light curve correction is performed using the *epiclccorr* task. We extract light curves with binning 500-1000 s to reveal possible big flares. There are no big flares in examined light curves are found. The light curves with bin 5 s and 1 s in energy bands 0.2-10 keV, 0.2-1 keV, 1-2 keV, 2-4 keV, 4-8 keV are extracted for searching fast flares. We remove points with zero count rate and with errors more than count rates from these light curves.

In the present paper we analyse X-ray spectrum of HD 110432 from the observation on 4.09.2007 cited in Table 1. The stellar and background spectra are extracted from the same regions on EPIC-images, as for light curve by *evselect*, *arfgen*, *rmfgen* tasks. The background spectrum correction is made using the *epicspeccombine* procedure.

Table 1. Log of observation. First column contains ObsID, observation dates and exposures are presented in 2nd and 3rd (in seconds) columns respectively. Observed X-ray luminosities (in 10^{32} erg s⁻¹) are given in the last column (see text)

ObsID	Date	Exposure	$L_X(0.2 - 8 \text{ keV})$
109480101	3.07.2002	53046	8.77 ± 0.76
109480201	26.08.2002	48690	7.75 ± 1.03
109480401	21.01.2003	48015	7.39 ± 0.52
504730101	4.09.2007	80677	3.52 ± 0.05

Table 2. Parameters of fitting the spectrum from 4.09.2007 (see text).

Parameter	Value
kT_1 , keV	$0.64^{+0.04}_{-0.04}$
$\log EM_1$, cm ⁻³	$53.71^{+0.08}_{-0.08}$
kT_2 , keV	$4.1^{+0.4}_{-0.4}$
$\log EM_2$, cm ⁻³	$54.72^{+0.07}_{-0.07}$
kT_3 , keV	$33.8^{+9.6}_{-6.9}$
$\log EM_3$, cm ⁻³	$55.15^{+0.02}_{-0.02}$
N_H , 10^{22} cm ⁻²	$0.226^{+0.007}_{-0.007}$
Abundance, sol. un.	$0.81^{+0.11}_{-0.10}$
χ^2 (d.o.f)	1.15 (475)

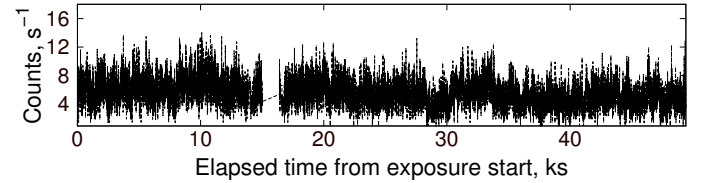


Figure 2. X-ray light curve of HD 110432 on July 3, 2002 (bin 5 s). The gap between 10 and 20 ks is caused by the removal of a fragment with background emission flare.

Low-resolved stellar spectra from the EPIC images were fitted using the by three-temperature MEKAL model by Mewe et al. (1985, 1986) and Liedahl et al. (1995) in the XSPEC 12.10.0 package³ for the 0.2-8 keV energy band. EPIC-PN, EPIC-MOS1, and EPIC-MOS2 spectra were fitted simultaneously. These models were multiplied on model TBABS by Wilms et al. (2000) describing the interstellar absorption.

Spectral fit parameters are presented in Table 2. For each thermal component the plasma temperature kT_i and the emission measures EM_i , where i is the component number. Stellar element abundance is given in solar units by Anders & Grevesse (1989). The good quality of the fit is confirmed to low value of the reduced χ^2 statistics also given in Table 2. The graphs of observed and model spectra are shown in Fig. 1. The temperatures kT_i and emission measures EM_i in the models for all remaining observations presented in Table 1 seems to be close to those given in Table 2.

As one can see in Fig. 1, the model spectra fits both the Fe K line complex at ~ 6.4 keV and the lines of Hydrogen-like and the Helium-like Fe.

¹ www.cosmos.esa.int/web/xmm-newton

² <http://simbad.u-strasbg.fr/Simbad>

³ <https://heasarc.gsfc.nasa.gov/xanadu/xspec/>

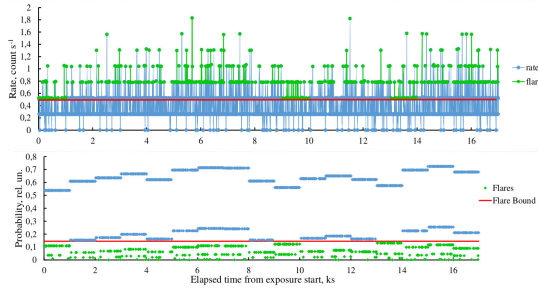


Figure 3. Illustration of looking for the flares in the light curves for the Poisson distribution of counts. *Top panel:* the fragment of light curve, flare points are shown by green colour. *Bottom panel:* The probabilities of the registered counts in the same fragment. The red line shows the level above which points are considered as the flares.

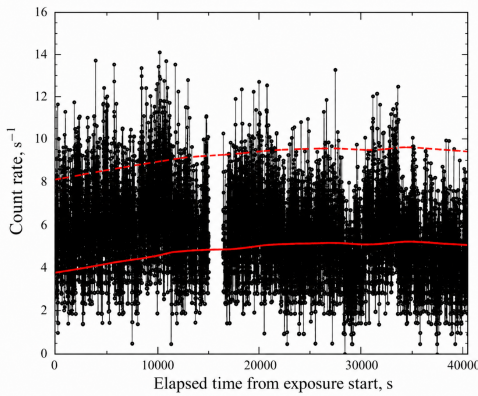


Figure 4. Illustration of searching the flares in the light curve on 3.07.2002, where the base level corresponds to the exponential moving average of 1st order. This is shown by red line. The dashed red line shows the the exponential moving average with additional 2σ (see text).

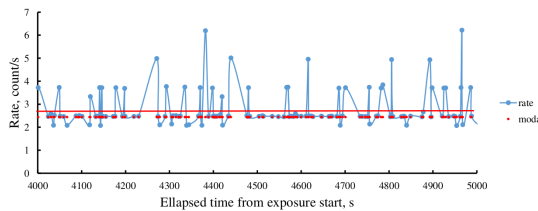


Figure 5. Illustration of searching the flares in the light curves, where the base level corresponds to the most common count rate (see text). Base level is marked by red points. Counts above the red line are supposed as belonging to flares.

3 FLARES IN THE X-RAY LIGHT CURVES

3.1 Flares detection

We propose that the total X-ray flux in some energy interval in light curve of the star can be presented as

$$F(E) = F_{\text{base}}(E) + F_{\text{flare}}(E), \quad (1)$$

where $F_{\text{base}}(E)$ is slowly varying base flux component. The

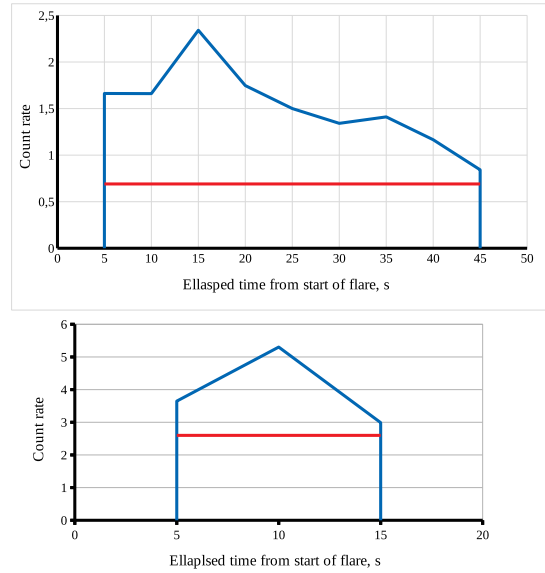


Figure 6. The examples of flares with simple profiles. Count rates are shown by blue lines, horizontal red lines show base count rate level.

second component $F_{\text{flare}}(E)$ includes only flaring part of the X-ray flux.

Our analysis of the HD 10432 light curves with different bin values shows that the extraction of flaring events from the light curves is most efficient with a bin size of 5 seconds. Searching for fast flares in light curves with both smaller and large bins do not allow to investigate the exact profiles of the flares in the light curves. The typical light curve on July 3, 2002 with 5 s bin is illustrated in Fig. 2.

The methodic of flares extractions depends on the statistics of the X-ray counts. The light curve have been divided into intervals lasted about of 1 ks in which the base flux is supposed to be constant. For weak sources, one can assume that a number of counts in the light curve within each bin can be described by a Poisson statistics. The expected value of the number of arrived photons or parameter λ of the Poisson distribution of X-ray counts in the bin is estimated as the average value of counts in the interval 1 ks multiplied by the length of the bin in seconds. For the Poisson statistics we accept the level of counts corresponding to the parameter λ as the base level. Our numerical experiment for bins of 0.2 ks, 0.5 ks, 0.8 ks, and 2 ks have shown that the results of the flare detections practically do not changed for these bins in a comparison with bin of 1 ks.

Next, we fix the probability α defining whether the considered count number belongs to flare or not. If the registered count rate for a point in the light curve $R_{\text{flare}} > R_{\alpha}$, where R_{α} is the count rate corresponding to the probability α , then it is supposed that the X-ray flare in that bin has occurred. Parameter α is estimated supposing that the number of false-positive rates do not exceed 10%.

For the light curves with high count rates we can consider the 1st order exponential moving average as the base level.

The points exceeding this level by 2 standard deviations σ are considered as flares as it is demonstrated in Figure 4.

In some light curves, the base level is visible by eye. For these curves we consider the mode of the distribution as the base level. The points in the curve with count rates above the 1.1 of the base level are considered as flares. Figure 5 illustrates this case.

Flare points can be either isolated or be the groups of adjacent points without gaps between them. Both isolated flare points and groups of such points we consider as the separate flares (flare events). The detected flares have very different shapes, examples of which are shown in Figs. 6 and 7. We classify three types of flares: the ultrafast consisting one flare point only; the simple including the group of flare points without local minima; and the combined, which are also the group of such points but with at least one deep local minima within the profile. The latter most likely can be superimposing of several shorter flares.

We introduce next criterion for identifying the combined flares:

$$\frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} > 0.3, \quad (2)$$

where $R_{\max}$ and $R_{\min}$ are the biggest and the smallest count rate in the flare profile respectively. The combined flares can be presented as a combination of the shorter subflares. Local minima probably separate individual sub-flares contributed in the combined flare as it shown in Fig 7. But we should keep in mind the different possibilities to divide the combined flare onto the individual sub-flares.

According to our preliminary suggestion on an analogy the stellar with solar nanoflares, all fast X-ray flares should have similar shapes. From the above described analysis and examples of flares shown in Figs. 6 and 7 one can conclude that this suggestion is probably wrong.

3.2 Parameters of flares

For each flare we estimate the following characteristics: duration (in seconds), integral power and relative power. For all of the considered light curves the total numbers of flares and relative contribution of flares in whole X-ray stellar flux are calculated.

The integral power of flare in units of detector counts is determined by next expression:

$$P_{\text{flare}} = \frac{1}{2}h \cdot \sum_{i=1}^{N-1} (R_i + R_{i+1}), \quad (3)$$

where R_i is a flare count rate for the time interval with a number i , N is a full number of counts within a flare, and h is the bin size (time interval between subsequent flare counts).

The relative power of flare is calculated as a ratio

$$Q_{\text{flare}} = \frac{P_{\text{flare}} - P_{\text{base}}}{P_{\text{base}}}. \quad (4)$$

Here P_{base} is a sum of the counts of the base level for all bins corresponding to the flare.

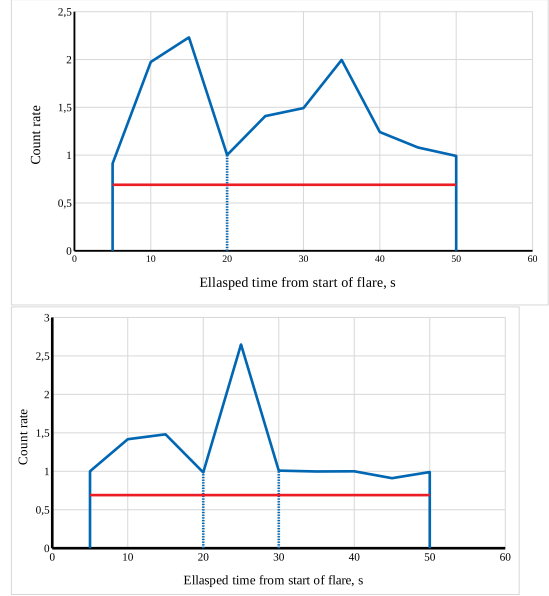


Figure 7. The same as in Fig. 6, but for combined flares. Vertical dashed lines indicate the division of the flare into subflares.

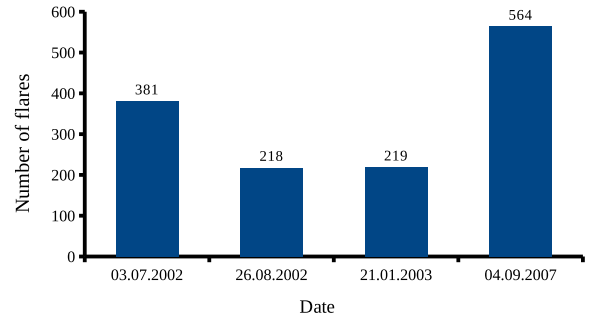


Figure 8. Numbers of flares in light curves for 0.2–10 keV energy band with 5 s bin.

For each individual observations the fraction of the flares contribution into the full stellar X-ray flux is estimated as

$$f_{\text{flare}} = \frac{\sum_{k=1}^M P_{\text{flare}}^k}{P_{\text{LC}}}, \quad (5)$$

where M is the number of flares in the light curve, P_{flare}^k is the power of flare with number k , and P_{LC} is an integral power of the whole Light Curve, which is the sum of all counts registered during the considered observation.

Our calculations show that from tens to thousands of fast flares with various integral powers and durations are registered for each of the analysed light curves corresponding the observation cited in Table 1.

Ultrafast flares were not taken into account by Smith et al. (2012) and need special consideration. Such flares make up a large part of all fares. We will consider ultrafast flares with $Q_{\text{flare}} > 0.8$ only.

This inequality corresponds to the condition $P_{\text{flare}} > 1.8P_{\text{base}}$. Our numerical experiment shows that this condi-

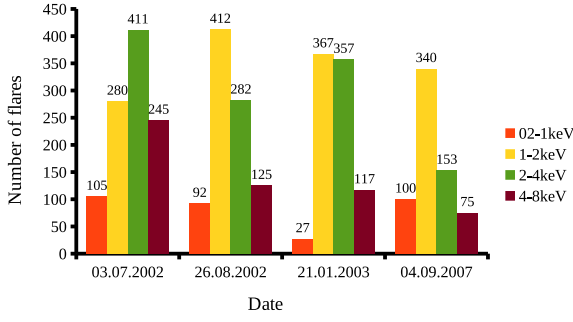


Figure 9. Numbers of flares in the light curve for different energy intervals.

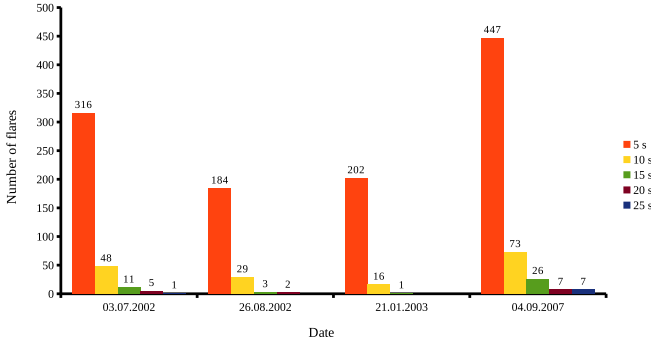


Figure 10. Numbers of flares in the light curves in the full 0.2-10 keV energy band with durations from 5 s to 25 s.

tion allows us to identify the majority of flare events with a false-positive rate do not exceeding 1%.

4 RESULTS

Fig. 8, demonstrate the numbers of fast flares in the total energy interval [0.2 – 10] keV detected for four observations of HD 110432 with using the procedure described in subsection 3.1.

In Fig. 9 the numbers of flares in different energy bands are given. In the light curves for all observations many fast flares appears to be combined with the small local minima. Durations of these flares reach 55 s. At the same time the larger part of flares extracted from the light curves seems to be simple. There are very small number of flares with durations up to 25 s. (see Fig. 10).

All registered flares in the light curves have a wide range of integral powers from 1 to 289 counts. The most of flares extracted from the light curves looks like a superposition of shorter flares. The relative powers of the flares including two and more flare points have relative powers Q_{flare} up to 0.2 rel. un.

As mentioned above, the temperature of the X-ray emitted plasma remained practically do not changed though X-ray luminosity of star reduced from 2002 to 2007. Our searching the fast X-ray flares evidenced the decreasing of the X-ray luminosity of HD 110432 leads to reducing the number and contri-

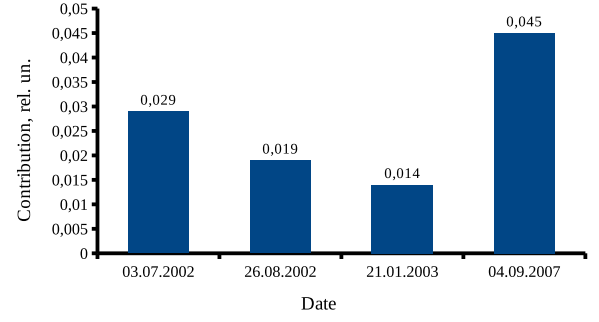


Figure 11. Contributions of flares in the X-ray light curves for different observations.

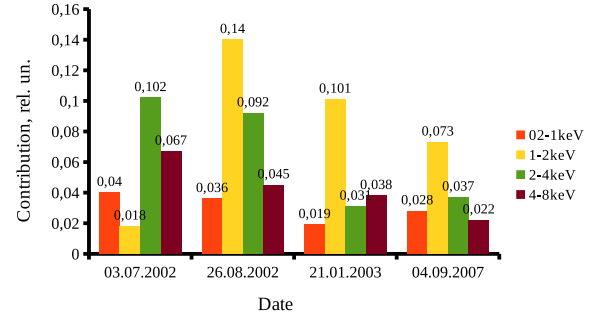


Figure 12. Contributions of flares in the total X-ray light curves energy for different energy bands.

bution of fast flares only in 4-8 keV X-ray interval. Numbers and contributions of flares in whole examined range 0.2-10 keV and other narrow ranges do not depend on stellar X-ray luminosity or emitted plasma temperature.

Fig 11 show the contribution of the flares in total X-ray flux emitted during the considered observation for different dates. This parameter can reach only 4.5% for the observation with the lowest X-ray luminosity. In Fig 12 the same value is plotted, but for different energy bands. The fractions of flares in the bands are decreased with X-ray luminosity excluding the case of soft [0.2 – 1] keV band.

5 CONCLUSIONS

The contribution of fast flares in the total X-ray luminosity is rather small as it is seen on figures 11 and 12. This result is in favor of the hypothesis about the interaction between the magnetic fields of the decretion disk and the local magnetic fields of the star. Most probably the X-ray light curves contain both fast flares and a slowly changing base level without flares.

The nature of the base level is not entirely clear. In binary γ Cas analogues, this part of the X-ray fluxes can be resulted from the accretion of the matter of decretion disk onto a compact component. The contribution of the non-thermal component to the spectrum of HD 110432 is still possible but remains unproven.

Our analysis demonstrates that fast flares predominate at energies of 1-4 keV. This means that they are most probably not similar to solar nanoflares. We may suppose that the changes in the mass and density of the HD 110432 decretion disk affect the features of the star's X-rays. The proposed method for detecting fast flares in the X-ray light curves can be used to analyse the X-ray light curves of not only γ Cas analogs, but those of other astrophysical objects.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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DIFFERENTIAL ROTATION OF CELESTIAL BODIES AND THE CORIOLIS FORCE

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ABSTRACT

Differential rotation is a central organising mechanism in rotating planets, stars, and magnetised plasma envelopes. This article treats the problem as a comparative dynamical analysis and asks how latitudinal and radial shear, Coriolis deflection, and wave-mediated angular-momentum transport form a single physical chain across planetary atmospheres, the solar convection zone, and magnetically active stellar interiors. Starting from the momentum equation in a rotating frame, the paper derives the role of the Coriolis term, introduces the Rossby number and the latitudinal beta effect as diagnostic parameters, and relates these quantities to observed solar differential rotation, tachocline shear, solar-like stellar rotation, and Rossby or r-mode oscillations. The analysis shows that differential rotation should not be interpreted simply as a surface rotation law; it is a maintained non-equilibrium state in which Reynolds stresses, baroclinicity, meridional circulation, Lorentz forces, and global waves compete to redistribute angular momentum. The Sun is used as the principal astrophysical case because helioseismology constrains its internal angular velocity profile, while the Earth-atmosphere system provides the clearest geophysical analogue for Coriolis-controlled wave dynamics. A synthesis table is proposed to classify rotating celestial systems according to dominant force balance, expected shear morphology, and wave response. The resulting framework clarifies why Rossby-type modes can appear in both neutral planetary fluids and magnetised stellar plasmas, although their restoring mechanisms and observational tracers differ.

Key words: differential rotation – Coriolis force – Rossby number – Rossby waves – solar rotation – tachocline – helioseismology – stellar convection – angular momentum transport.

1 INTRODUCTION

Rotation enters astrophysical and geophysical fluid dynamics not as a secondary kinematic detail but as a force-organising constraint. Once a body rotates rapidly enough for the Coriolis acceleration to be comparable with inertial acceleration, the motion of gas, plasma, atmosphere, or ocean no longer follows the intuition of a non-rotating frame. The flow tends to align with the rotation axis, angular momentum becomes redistributed by correlated velocity fluctuations, and large-scale waves appear because the effective vorticity changes with latitude. These effects are especially important in the Sun and in solar-type stars, where convection, magnetic fields, and rotation jointly determine the observed pattern of differential rotation and the operation of magnetic dynamos (Tassoul 1978; Thompson et al. 2003; Miesch 2005; Miesch and Toomre 2009).

The term differential rotation describes the situation in which angular velocity is not spatially uniform. It may

vary with latitude, radius, depth, or time. The solar photosphere provides the classical example: equatorial regions rotate faster than higher latitudes, and helioseismic inversions show that this surface pattern is connected to a structured internal rotation profile rather than to a shallow surface phenomenon alone (Schou et al. 1998; Howe 2009). In planetary atmospheres the same general issue appears in a different form. The solid planet may have a well-defined rotation rate, but the atmosphere and ocean organise themselves into jets, cells, gyres, and planetary waves because the Coriolis parameter varies with latitude (Holton and Hakim 2012; Vallis 2017). Thus, the physics of differential rotation links apparently separate systems: stellar convection zones, planetary atmospheres, giant-planet envelopes, accretion flows, and magnetised plasma layers.

The scientific difficulty is that differential rotation is both a cause and a consequence of angular-momentum transport. Shear can amplify magnetic field by the omega effect, but magnetic stresses can feed back on shear. Convection can generate Reynolds stresses that maintain latitudinal angular-velocity gradients, but the Coriolis force modifies the convec-

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tive cells that generate those stresses. Rossby waves can redistribute angular momentum, but their propagation depends on the very rotation profile that they help to alter. A coherent treatment therefore requires more than a descriptive list of examples. It requires an explicit chain of dynamical reasoning from the rotating-frame momentum equation to the observed morphology of planetary and stellar flows.

A related extension is provided by the epsilon-mechanism interpretation of solar variability discussed by [Dzhililov and Staudé \(2005\)](#). In that view, radiation energy generated in the nuclear core may interact with the differentially rotating central solar region and excite Rossby-type vortical structures. If such vortices locally disturb the efficiency of nuclear energy generation, the solar luminosity integrated over the visible disk may acquire a weak quasi-periodic modulation. This idea is not treated here as an established observational result; rather, it is used as a motivating hypothesis connecting internal rotation, Rossby-type dynamics, nuclear-fusion sensitivity, and possible long-timescale solar forcing relevant to climate-variability models.

The aim of this article is to provide that chain. The paper has four specific objectives. First, it formulates the Coriolis force, Rossby number, beta effect, and differential-rotation measures in a common notation. Second, it interprets solar differential rotation as a maintained dynamical state rather than a static observational fact. Third, it compares planetary Rossby waves with solar Rossby-like modes and stellar r-modes, emphasising both the shared vorticity principle and the differences introduced by stratification and magnetism. Fourth, it proposes a compact classification of rotating celestial bodies according to dominant force balance, expected shear structure, and wave response. In this sense the contribution of the paper is analytical synthesis: it reorganises established observational and theoretical material into a comparative framework that can be used to interpret rotating celestial systems without treating each system in isolation.

2 DYNAMICAL FORMULATION IN A ROTATING FRAME

Consider a fluid element described in a reference frame rotating with angular velocity Ω . The momentum equation may be written as

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \rho \mathbf{g} - 2\rho \Omega \times \mathbf{u} - \rho \Omega \times (\Omega \times \mathbf{r}) + \mathbf{F}_{\text{visc}} + \mathbf{F}_{\text{mag}}, \quad (1)$$

where ρ is density, $\mathbf{u}$ is velocity in the rotating frame, p is pressure, $\mathbf{g}$ is gravity, $\mathbf{F}_{\text{visc}}$ denotes viscous or turbulent stresses, and $\mathbf{F}_{\text{mag}}$ denotes the Lorentz force when the medium is conducting. The term $-2\rho \Omega \times \mathbf{u}$ is the Coriolis force per unit volume. It does no mechanical work because it is perpendicular to the instantaneous velocity, yet it changes the direction of motion and thereby reorganises circulation, convection, and wave propagation.

A useful nondimensional measure of rotational control is the Rossby number,

$$Ro = \frac{U}{2\Omega L}, \quad (2)$$

where U and L are characteristic velocity and length scales. When $Ro \ll 1$, Coriolis effects dominate inertial advection and the flow tends to become rotationally constrained. When $Ro \gtrsim 1$, inertial and buoyant motions can cross the rotational constraint more freely. In stellar convection zones this number is not uniform: near-surface granulation, deep convection, and global meridional circulation occupy different dynamical regimes. This is one reason why a star can exhibit near-surface shear, deeper conical rotation contours, and tachocline shear in the same object ([Miesch 2005](#); [Miesch and Toomre 2009](#)).

Differential rotation may be described through an angular-velocity field $\Omega(r, \theta, t)$, where r is radius and θ is colatitude. A commonly used surface representation is

$$\Omega(\lambda) = A + B \sin^2 \lambda + C \sin^4 \lambda, \quad (3)$$

where λ is latitude and the coefficients express equatorial rotation and latitudinal shear. For the solar interior, however, Eq. (3) is insufficient because helioseismology reveals radial as well as latitudinal gradients. A more physically meaningful diagnostic is the relative shear,

$$\alpha = \frac{\Omega_{\text{eq}} - \Omega_{\text{pole}}}{\Omega_{\text{eq}}}, \quad (4)$$

combined with radial gradients such as $\partial\Omega/\partial r$ across the near-surface shear layer and the tachocline.

The beta effect is the wave counterpart of the same rotational geometry. On a spherical body the vertical component of planetary vorticity changes with latitude. In a local beta-plane approximation,

$$f = f_0 + \beta y, \quad \beta = \frac{2\Omega \cos \phi_0}{R}, \quad (5)$$

where $f = 2\Omega \sin \phi$ is the Coriolis parameter, R is the radius, and ϕ_0 is a reference latitude. This gradient supplies the restoring mechanism for Rossby waves in atmospheres and oceans ([Rossby 1939](#); [Gill 1982](#); [Pedlosky 1987](#); [Vallis 2017](#)). In stars, analogous global r-modes arise because rotating spherical fluids possess vorticity-conserving oscillations whose dynamics are modified by stratification, compressibility, differential rotation, and magnetic fields ([Papaloizou and Pringle 1978](#); [Zaqarashvili 2021](#); [McIntosh et al. 2017](#); [Lop-tien et al. 2018](#)).

3 DIFFERENTIAL ROTATION AS AN ANGULAR-MOMENTUM TRANSPORT PROBLEM

A uniformly rotating self-gravitating body is dynamically simple only in an idealised limit. Real celestial bodies contain

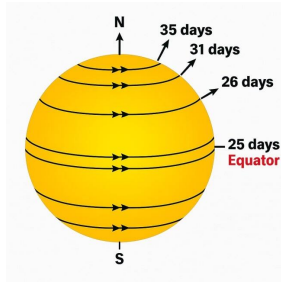


Figure 1. Schematic representation of solar differential rotation. The equatorial region rotates faster than high latitudes, producing a latitude-dependent angular velocity that is central to solar dynamo models. *Source:* Authors' schematic based on Schou et al. (1998), Thompson et al. (2003), and Howe (2009).

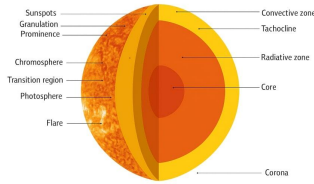


Figure 2. Illustrative internal structure of the Sun and its rotation profile. The radiative interior, convection zone, near-surface layers, and tachocline participate differently in the redistribution of angular momentum. *Source:* Authors' schematic based on Schou et al. (1998), Thompson et al. (2003), and Howe (2009).

turbulence, stratification, convection, radiative zones, magnetic stresses, and boundary layers. The observed angular velocity is therefore the outcome of transport processes rather than an arbitrary profile. In a rotating convection zone, correlations such as $\langle u_r u_\phi \rangle$ and $\langle u_\theta u_\phi \rangle$ transport angular momentum. These Reynolds stresses compete with meridional circulation and turbulent diffusion. When the medium is ionised, Maxwell stresses add another channel for angular-momentum redistribution.

The Sun illustrates the problem with exceptional clarity because the internal rotation profile is observationally constrained. Helioseismic measurements show that the solar convection zone rotates differentially, that the radiative interior is closer to solid-body rotation, and that a sharp transition occurs near the base of the convection zone in the tachocline (Schou et al. 1998; Thompson et al. 2003; Howe 2009). The tachocline is important not merely as a structural boundary but as a shear layer in which toroidal magnetic field can be produced from poloidal field. This links differential rotation directly to dynamo theory (Parker 1955; Charbonneau 2010).

The qualitative statement that the solar equator rotates faster than the poles is therefore only the visible endpoint of a deeper dynamical balance. In the bulk of the convection zone, rotating convection tends to generate angular-momentum transport that favours solar-like differential rotation under suitable Rossby-number conditions. In the tachocline, radial shear and stable stratification confine strong gradients to a thin region. Near the photosphere, thermal stratification and

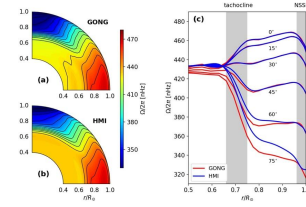


Figure 3. Conceptual view of the tachocline as a shear interface between the differentially rotating convection zone and the more uniformly rotating radiative interior. This layer is widely regarded as important for solar magnetic-field generation. *Source:* Authors' schematic based on Thompson et al. (2003) and Charbonneau (2010).

small-scale convection contribute to a separate near-surface shear layer. A complete interpretation must therefore combine latitudinal shear, radial shear, and temporal modulation.

The role of the Coriolis force is indirect but decisive. Rising and sinking convective parcels are deflected, producing tilted convective structures. These tilts create systematic correlations in velocity fluctuations, which then transport angular momentum. If rotation is weak relative to convection, the correlation is reduced and the differential rotation can change sign or become less coherent. Numerical simulations and stellar observations suggest that the transition between solar-like and anti-solar differential rotation is controlled substantially by the convective Rossby number, although details depend on luminosity, mass, age, and magnetic feedback (Gastine et al. 2014; Brun and Browning 2017).

4 CORIOLIS FORCE IN PLANETARY AND STELLAR CONTEXTS

On Earth, the Coriolis force is most familiar through the deflection of winds and ocean currents. In the Northern Hemisphere large-scale horizontal motion is deflected to the right of its direction of travel; in the Southern Hemisphere it is deflected to the left. This rule is only a surface manifestation of a more general vorticity constraint. Geostrophic balance, in which pressure-gradient force and Coriolis force approximately balance, explains the prevalence of large-scale atmospheric flows parallel to isobars. Departures from this balance allow vertical motion, cyclogenesis, jet-stream meanders, and wave propagation (Holton and Hakim 2012; Vallis 2017).

The solar case is less intuitive because the moving medium is conducting plasma rather than neutral air or water. Nevertheless, the Coriolis term in Eq. (1) remains present. It deflects convective motions, contributes to helicity, influences meridional circulation, and helps determine the sign and strength of Reynolds stresses. In mean-field dynamo language, rotationally influenced convection contributes to the generation of poloidal field from toroidal field, while differential rotation contributes to toroidal-field amplification from poloidal field. The Coriolis force therefore participates in the dynamo indirectly by shaping the geometry and statistical

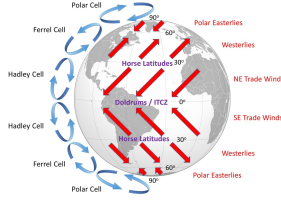


Figure 4. Schematic illustration of Coriolis deflection in a rotating planetary atmosphere. The same mathematical term that organises atmospheric circulation also affects plasma motion in rotating stellar envelopes, although the force balance differs in magnetised plasma. *Source:* Authors' schematic based on Holton and Hakim (2012) and Vallis (2017).

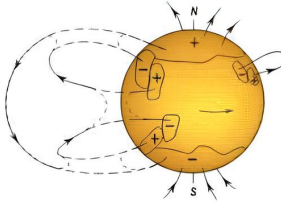


Figure 5. Schematic representation of rotational deflection in solar plasma motion. Convective upflows and downflows are deflected by rotation, contributing to helicity and angular-momentum transport. *Source:* Authors' schematic based on Stix (2002), Charbonneau (2010), and Brun and Browning (2017).

properties of turbulence (Stix 2002; Charbonneau 2010; Brun and Browning 2017).

A useful way to compare Earth and the Sun is not to ask whether their flows look the same; they plainly do not. The appropriate question is whether their governing balances contain homologous terms. Earth-atmosphere dynamics are often approximated by hydrostatic and geostrophic balances with moist thermodynamics, while solar convection involves compressibility, ionisation, radiative transport, and magnetohydrodynamics. Yet both systems contain a rotating-frame vorticity equation in which planetary or stellar rotation supplies a preferred axis and a latitude-dependent background vorticity. This shared structure explains why Rossby-type phenomena appear in both systems despite different material properties.

5 ROSSBY WAVES, R-MODES, AND THE BETA EFFECT

Rossby waves arise because a displaced fluid element must conserve potential vorticity while moving across a background vorticity gradient. In a simple barotropic beta-plane model, the dispersion relation is

$$\omega = Uk - \frac{\beta k}{k^2 + l^2}, \quad (6)$$

where ω is angular frequency, U is background zonal flow, and k and l are zonal and meridional wavenumbers. The intrinsic phase propagation is westward relative to the mean flow. This

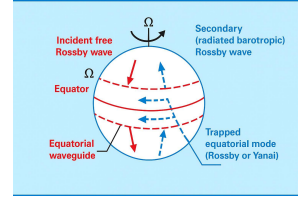


Figure 6. Schematic geometry of Rossby-wave propagation. Latitudinal variation of planetary vorticity provides the restoring mechanism and leads to characteristic retrograde phase propagation. *Source:* Authors' schematic based on Rossby (1939), Gill (1982), and Vallis (2017).

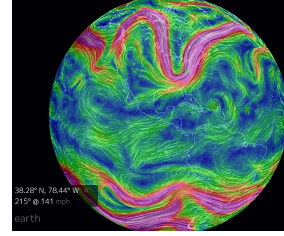


Figure 7. Planetary-scale wave organisation in a rotating atmosphere or ocean. Such patterns provide the geophysical analogue for interpreting Rossby-like behaviour in rotating stellar envelopes. *Source:* Authors' schematic based on Gill (1982), Holton and Hakim (2012), and Vallis (2017).

property underlies the slow meandering of planetary waves and the redistribution of angular momentum in atmospheres and oceans (Rossby 1939; Gill 1982; Pedlosky 1987; Vallis 2017).

In stars, the equivalent family of oscillations is usually discussed as r-modes or Rossby-like waves. In a uniformly rotating, inviscid spherical shell, the simplest sectoral r-mode frequencies in the co-rotating frame scale with rotation as

$$\omega_{co} \simeq -\frac{2m\Omega}{\ell(\ell+1)}, \quad (7)$$

where ℓ and m are spherical harmonic degree and azimuthal order. Real solar modes deviate from this simple relation because the Sun is differentially rotating, stratified, magnetised, and turbulent. Nevertheless, the negative sign captures the essential retrograde character of Rossby-like modes in the rotating frame.

Observational evidence for solar Rossby-like waves has developed through tracking of photospheric and coronal tracers. The detection of large-scale Rossby-like waves using coronal bright points observed by SDO and STEREO provided a direct connection between solar magnetic structures and global rotating-fluid dynamics (McIntosh et al. 2017). Subsequent helioseismic and feature-tracking studies have strengthened the view that global-scale retrograde modes are a real component of solar dynamics (Loptien et al. 2018). These observations are significant because they suggest that angular-momentum redistribution in the Sun is partly wave-mediated, not only turbulence-mediated.

The conceptual bridge between planetary Rossby waves and solar r-modes must be drawn carefully. In a neutral plan-

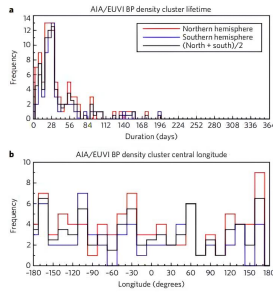


Figure 8. Coronal bright points used as tracers of large-scale solar wave patterns. Tracking magnetic tracers across longitude and latitude allows Rossby-like oscillations to be inferred from coherent retrograde structures. *Source:* Authors’ schematic based on McIntosh et al. (2017) and Loptien et al. (2018).

etary atmosphere, the primary restoring mechanism is the conservation of potential vorticity in the presence of the beta effect and stratification. In the Sun, the same rotational geometry is present, but magnetic tension, turbulent stresses, and radial shear modify both the dispersion and damping of modes. Hence the phrase Rossby-like is physically appropriate: the modes are homologous in their vorticity foundation but not identical in their full force balance.

6 COMPARATIVE CLASSIFICATION OF ROTATING CELESTIAL BODIES

The following synthesis table summarises the analytical framework proposed here. It classifies systems not by appearance but by dominant force balance and expected dynamical response. The classification is necessarily simplified, but it makes explicit what is often implicit in descriptive treatments of differential rotation.

The table yields three interpretive conclusions. First, differential rotation is best understood as a transport problem. The visible angular-velocity profile is an outcome of competing fluxes of angular momentum. Second, the Coriolis force is not merely a deflection term; by shaping the correlations of turbulent motion it controls how angular momentum is transported. Third, Rossby-type waves are a natural response of rotating spherical fluids and plasmas because latitude-dependent background vorticity is geometrically unavoidable on a rotating sphere.

7 IMPLICATIONS FOR SOLAR AND STELLAR ACTIVITY

Differential rotation is essential to solar and stellar magnetic activity because it converts poloidal magnetic field into toroidal field through shear. In the Sun, this process is associated with the 11-year sunspot cycle and the 22-year magnetic cycle. The tachocline has traditionally been emphasised as a storage and amplification region, although modern dynamo models also recognise the importance of dis-

tributed convection-zone processes and near-surface shear (Parker 1955; Charbonneau 2010; Brun and Browning 2017).

Rossby-like waves add another layer to this picture. If global modes redistribute angular momentum or modulate the emergence of magnetic flux, they may help explain quasi-periodic patterns in solar activity. The 90–200 day periodicities reported in coronal bright-point studies are not a replacement for the dynamo cycle, but they may represent an intermediate timescale on which rotation, magnetic fields, and wave dynamics interact (McIntosh et al. 2017). This suggests that the solar cycle should not be interpreted only as a mean-field magnetic oscillator; it is also embedded in a spectrum of rotating-fluid modes.

For stars beyond the Sun, the problem is harder because internal rotation profiles are not normally resolved. Surface spot modulation, chromospheric activity, and asteroseismic rotational splittings provide partial constraints. The same framework remains useful, however, because it predicts that stars with different Rossby regimes should display different relationships among rotation rate, differential shear, magnetic activity, and global oscillations. Rapid rotators are expected to be more strongly rotationally constrained; slowly rotating convective stars may approach regimes in which anti-solar differential rotation becomes possible (Gastine et al. 2014; Brun and Browning 2017).

8 DISCUSSION

The central result of this article is a conceptual reclassification of differential rotation. Rather than treating the Coriolis force, Rossby waves, solar rotation, and stellar dynamos as separate topics, the paper places them in a single causal sequence. Rotation introduces Coriolis acceleration; Coriolis acceleration constrains convection and circulation; constrained flows transport angular momentum anisotropically; anisotropic transport maintains differential rotation; differential rotation and latitude-dependent vorticity support global waves; waves and magnetic stresses feed back on the angular-momentum budget.

This sequence also clarifies the limits of analogy. The Earth and the Sun are not dynamically identical. The Earth has a solid lower boundary, a thin atmosphere, oceans, moisture, topography, and comparatively weak ionisation. The Sun has a deep compressible convection zone, no solid surface, strong magnetic feedback, and a radiative interior. Nevertheless, both systems are rotating spherical fluids in which vorticity conservation and Coriolis deflection structure large-scale motion. The analogy is therefore not morphological but dynamical.

The framework has practical implications for future work. Observationally, simultaneous use of helioseismic rotation inversions, magnetic tracers, and coronal bright-point tracking can separate advection by mean flows from true wave propagation. Theoretically, models should report not only the resulting angular-velocity maps but also the associated angular-momentum flux decomposition. For stellar applications, the

Table 1. Comparative dynamical regimes of rotating celestial systems.

System class	Dominant balance	Differential-rotation morphology	Wave response	Principal diagnostic
Terrestrial atmospheres and oceans	Pressure gradient, Coriolis force, stratification, friction	Zonal jets and gyres relative to solid-body rotation	Rossby waves and jet meanders	Wind, pressure, temperature, sea-surface height
Giant-planet atmospheres	Rotation, convection, stratification, internal heat flux	Strong banded zonal jets	Planetary waves, vortices, normal modes	Cloud tracking and thermal emission
Solar convection zone	Rotating convection, Reynolds stress, meridional flow, Lorentz feedback	Equator-fast latitudinal shear with radial structure	Rossby-like modes, inertial waves, torsional oscillations	Helioseismology, Doppler rotation, magnetic tracers
Tachocline and stable stellar interfaces	Shear, stratification, magnetic tension, thermal wind balance	Thin radial shear layer	Magneto-Rossby and shear-modified modes	Helioseismic inversion and activity-cycle modulation
Rapidly rotating solar-like stars	Strong rotational constraint and magnetic feedback	Solar-like or anti-solar shear depending on Rossby regime	Global r-modes and activity-linked modulation	Asteroseismology, spot modulation, activity indicators

Rossby number should be treated as a depth-dependent and process-dependent diagnostic rather than as a single global number derived from rotation period alone.

9 CONCLUSIONS

This paper examines differential rotation and the Coriolis force as an analytical synthesis. The main conclusions are as follows:

- (i) Differential rotation is a maintained non-equilibrium state produced by angular-momentum transport, not merely an observed latitude-dependent rotation law.
- (ii) The Coriolis force controls differential rotation indirectly by shaping convective tilts, Reynolds stresses, meridional circulation, and global vorticity balance.
- (iii) The Sun is the key astrophysical reference case because helioseismology demonstrates radial and latitudinal internal rotation structure, including the tachocline.
- (iv) Rossby waves in planetary atmospheres and Rossby-like r-modes in stellar plasmas share a vorticity foundation, but solar and stellar cases are modified by magnetic fields, stratification, shear, and turbulence.
- (v) A comparative regime classification based on force balance shear morphology, and wave response provides a more original and analytically useful structure than a descriptive listing of known examples.
- (vi) The epsilon-mechanism hypothesis adds a further interpretive possibility: Rossby-type vortices generated in differentially rotating inner solar layers may modulate the nuclear-fusion rate and, consequently, the integrated solar luminosity on quasi-periodic timescales. In this limited sense, the mechanism may offer a new theoretical link between internal solar dynamics and climate-variability modelling (Dzhalilov and Staude 2005).

The contribution of this study is not the presentation of new observational data, but the construction of an integrated dynamical framework that links differential rotation, Coriolis forcing, and Rossby-type wave dynamics across celestial bodies.

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dynamics, and stellar magnetohydrodynamics on which this synthesis is based.



THERMAL STRESSES IN SMALL BODIES APPROACHING THE SUN

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ABSTRACT

This study examines thermal stresses as one of the key physical mechanisms leading to the destruction of small Solar System bodies as they approach the Sun. The thermal destruction mechanism and its evolution are investigated in bodies of icy and silicate compositions of various sizes, along with their role in initiating cracking, fragmentation, and subsequent mass loss. Analytical and numerical solutions of the heat conduction equation for spherical bodies moving in highly eccentric orbits are used to describe temperature fields and resulting stresses. The analytical approach is based on the assumption of constant thermal diffusivity, whereas the numerical model accounts for its temperature dependence and the actual thermophysical properties of crystalline ice and meteoritic matter. A systematic comparison of the two methods was conducted for bodies ranging in size from decimeter-sized meteoroids to kilometer-sized cometary nuclei. It is shown that thermal stresses can exceed the material strength limits at significant heliocentric distances that is, well before reaching the tidal disruption zone. It is also shown that the analytical method performs effectively and exhibits minor discrepancies when compared with the numerical method. It was found that intermediate-sized bodies are the most vulnerable, as strong temperature gradients form between the cold core and heated surface layers. Small bodies heat up almost entirely and do not accumulate significant internal stresses, while large objects maintain stability due to the low penetration of heat into the interior. The results obtained confirm the significant role of thermal stresses in the evolution, activity, and destruction of both cometary nuclei and small asteroid bodies.

Key words: Small bodies – Comets – Asteroids – Thermal stresses – Numerical calculations

1 INTRODUCTION

This chapter provides a general overview of the key aspects related to the disintegration of small Solar System (SS) bodies.

Despite the large number of observed comets, the mechanisms of their formation, evolution, and disintegration remain not fully understood. Agglomeration models suggest that comets are loose bodies with high porosity (up to ~80%) and low density of approximately 0.2 g/cm³ making them vulnerable to destruction by tidal forces [Sekanina et al. \(1994\)](#). At the same time, a number of studies point to higher density values, reaching 0.5–0.6 g/cm³ [Solem \(1995\)](#).

Significant discrepancies also exist in estimates of the initial sizes of cometary nuclei. A survey of long-period comets shows that disintegrating nuclei have substantially smaller sizes (average radius ~0.4 km) compared to surviving ones (~1.6 km), as well as smaller perihelion distances [Jewitt](#)

[\(2022\)](#). This indicates an increased probability of the destruction of small nuclei during their approach to the Sun. In a number of works, the destruction of comets near the Sun is attributed to breakup caused by the rotation of the nucleus [Sekanina \(1997\)](#). Additionally, other possible mechanisms of comet disintegration are discussed, including disruption by centrifugal forces, destruction due to internal gas pressure during intense sublimation, and collisions with other small bodies [Boehnhardt \(2005\)](#). Collectively, these processes are considered the primary causes of comet decay in the Solar System.

Regarding small bodies composed of silicate rocks, the origin regions of most meteorites and kilometer-sized near-Earth objects (NEOs), including some minor classes, have been identified to date [Brož et al. \(2024\)](#). The authors of that work examined 38 individual asteroid families, both young and old, and determined their contribution to the populations of near-Earth objects ranging in size from meters to kilometers using collision and orbital models. In work [Brož et al. \(2024\)](#), three young asteroid families (Karin, Koronis,

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Massalia) were identified as the source of the majority of ordinary chondrite falls. The origin regions of various classes of meteorites and near-Earth objects have been determined, with an emphasis on various classes of carbonaceous chondrites. Some well-known annual meteor showers are formed as a result of the destruction of comets or active asteroids such as 3200 Phaethon, which is the parent body of the Geminid meteor shower [Jewitt \(2010\)](#).

In this work, we propose a mechanism for the destruction of small bodies made of crystalline ice and silicates due to thermal stresses. As cometary bodies approach the Sun, surface layers heat up, and heat is transferred inward. In bodies of homogeneous composition, this process can generate strong stresses exceeding the strength limits of the materials. This process was examined in [Shestakova & Serebryanskiy \(2023\)](#) for homogeneous bodies of water ice and with the inclusion of silicate inhomogeneities composed of ice and silicates. An analytical solution of the linear heat conduction equation for spherical bodies approaching the Sun along parabolic orbits was obtained in [Shestakova & Tambovtseva \(1997\)](#). Thermal stress has emerged as a probable fragmentation mechanism capable of operating far from the Sun without requiring tidal forces; studies show that thermal stresses can exceed the tensile strength of terrestrial materials. For small bodies of cometary and asteroidal origin, this mechanism operates at various heliocentric distances, which is due to significantly different thermal and physico-mechanical properties. This mechanism is responsible for the formation of near-surface cracks followed by material release and even complete fragmentation. What might happen next? A cracked object may enter the Roche limit and undergo complete disintegration, as was the case with comet SL9 [Shestakova et al. \(2025\)](#), or in the case of dust clouds, enter the sublimation zone. In such instances, thermal stresses determine the initial gradual splitting of the body. The subsequent evaporation of small bodies under the influence of solar heat allows for the acquisition of information regarding their chemical composition through infrared (IR) observations. Despite the unfavorable conditions for the existence of crystalline ice in space, recent spectroscopic studies of planetary satellites and Kuiper Belt objects have revealed signs of its presence. According to [Priyalnik & Jewitt \(2022\)](#), modeling has demonstrated the possible crystallization of matter deep within the body under various orbital parameters. The spectral band of crystalline ice at $1.65 \mu\text{m}$ was detected in the satellites of Jupiter (Europa), Uranus [Grundy et al. \(2006\)](#); [Guilbert et al. \(2009\)](#); [de Bergh et al. \(2009\)](#), and Charon the satellite of Pluto [Brown & Calvin \(2000\)](#). Analysis of the spectrum of Phaethon in the mid-infrared region, obtained from the Spitzer Space Telescope, showed that Phaethon is associated with rare carbonaceous chondrites containing olivine, Mg-rich carbonates, and Fe-sulfides [MacLennan & Granvik \(2023, 2024\)](#). These minerals decompose at temperatures of approximately 1000 K, which 3200 Phaethon reaches at perihelion. The role of thermal stresses in the physics of small Solar System bodies has been studied by many authors [Shestakova & Tambovtseva \(1997\)](#); [Tambovtseva & Shestakova \(1999\)](#); [Täuber &](#)

[Kührt \(1987\)](#); [Čapek & Vokrouhlický \(2010\)](#). We apply both analytical methods [Shestakova & Tambovtseva \(1997\)](#) and a new method for the numerical solution of the heat diffusion equation with one initial and two boundary conditions. The analytical approach assumes constant thermal diffusivity, whereas the numerical model accounts for temperature-dependent thermal diffusivity. The remaining structure of the article is as follows: the second section will consider the thermal and elastic properties of crystalline ice and silicate rocks. In the third section, a numerical model for the destruction of small bodies will be proposed; the fourth section will present the results of comparing the analytical and numerical models along with a statistical analysis and the conclusion.

2 THERMAL AND ELASTIC PROPERTIES OF CRYSTALLINE ICE AND SILICATE MATERIALS FRAGMENTS OF SMALL BODIES

Icy and silicate materials possess a diverse range of properties. Overall, they can be characterized by thermophysical (c_v, k, a^2) and physico-mechanical (E, μ) parameters as they vary with temperature. Here, c_v denotes the heat capacity at constant volume, and k represents thermal conductivity. E is the Young's modulus of elasticity (MPa), α is the coefficient of linear thermal expansion (expressed in K^{-1}), and μ is Poisson's ratio. These parameters allow for the determination of the critical value of the temperature function T_{rr} and the corresponding onset of tensile stresses σ^+ . Similarly, when using the compressive strength limit σ^- , the critical value of the temperature function $T_{\phi\phi}$, which is responsible for compressive stresses, is defined. These stresses allow for a quantitative assessment of the probability of failure in the surface layers of small bodies. Below, Table 1 presents the thermal and elastic properties of crystalline ice at low temperatures.

In work [Klinger \(1981\)](#), the thermal conductivity of crystalline ice for temperatures above 25 K was defined as a temperature function, while the heat capacity was determined from experimental data in the temperature range of $16.43 \text{ K} \leq T \leq 267.77 \text{ K}$ and is approximated by the expression provided in work [Klinger \(1980\)](#). Consequently, the thermal diffusivity of crystalline ice can be obtained using the formula $a^2 = \frac{k}{c_v}$ and the final expression is written as a temperature function:

$$a^2 = \frac{5.67}{0.92T(7.49 * 10^{-3}T + 0.09)} \text{ cm}^2\text{sec}^{-1}, \quad (1)$$

Subsequently, Table 2 presents the adopted values of the material parameters and their corresponding temperature functions for minerals, rocks, basalt, and chondrites [Shestakova et al. \(2019\)](#).

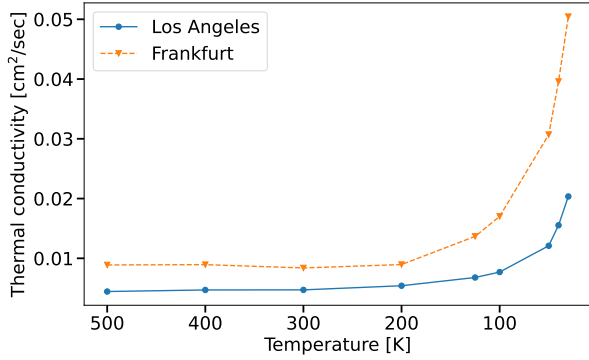
In our research, the data for thermal conductivity and heat capacity were sourced from the findings in [Opeil et al. \(2012\)](#), where thermal conductivity was measured for seventeen stony meteorites across a temperature range from 5 K to 300 K. The

Table 1. Material parameters for ice in SI units

	c_v	κ	a^2	α	μ	E	T_-	σ_-	T_+	σ_+
T (K)	erg/cm ³ K	erg/(s cm K)	cm ² /s	1/K	–	MPa	K	MPa	K	MPa
30	0.3147×10^7	1.89×10^6	0.6	–	–	–	–	–	–	–
125	1.026×10^7	0.4536×10^6	0.0442	3.8×10^{-5}	0.33	9×10^3	-10	-5	4	2

Table 2. Physico-mechanical parameters of stone meteorites

Parameter	a^2 cm ² /s	α 1/K	μ –	E MPa	T_- K	σ_- MPa	T_+ K	σ_+ MPa
Minerals								
Rocks	0.0058		0.15	72000	-1300	-800	130	80
Basalt	0.0167	7.5×10^{-6}		26000	-800	-180	90	20
Carbon chondrites			0.25	7×10^4	-300	-160	7	4.5
Ordinary chondrites	0.0118				-86	-60	13	9
					-214	-150	36	25

**Figure 1.** Thermal diffusivity a^2 for meteorite samples

selection of this specific rock type is based on the fact that, for instance, the Frankfurt meteorite (a howardite) serves as a typical sample of the material found on the surface of the asteroid Vesta. The thermal conductivity of these meteorites, as measured by Opeil [Opeil et al. \(2012\)](#), is described by a fourth-order equation of the following form:

$$K = A + BT + CT^2 + DT^3 + ET^4 \quad (2)$$

The coefficients for the Frankfurt basaltic chondrite sample at temperatures of 300 K and below were utilized [Opeil et al. \(2012\)](#). The selected parameters are listed in Table 3.

For numerical simulations, data from the bottom row of Table 3 for the Los Angeles sample is used, while analytical calculations are based on Table 3. The temperature dependencies are illustrated in Fig. 1.

Approximating a^2 (Los Angeles) by a polynomial, we obtain:

$$a^2(T) = (3.7404 \cdot 10^{-12}T^4 - 4.6002 \cdot 10^{-9}T^3 + 1.9825 \cdot 10^{-6}T^2 - 3.5451 \cdot 10^{-4}T + 2.7446 \cdot 10^{-2}) \text{ cm}^2\text{s}^{-1} \quad (3)$$

3 NUMERICAL SOLUTION OF THE THERMAL DIFFUSION EQUATION AND CALCULATION OF THERMAL STRESSES FOR SMALL BODIES

The boundary value problem for the thermal diffusion equation (HDE) for a spherical body according to [Shestakova & Tambovtseva \(1997\)](#) is written as:

$$\frac{\partial T}{\partial t} = a^2 \frac{\partial^2 T}{\partial x^2} + \frac{2a^2}{x} \frac{\partial T}{\partial x} \quad (4)$$

$$T(r, 0) = T_0, \quad (5)$$

$$\frac{dT(0, t)}{dx} = 0, \quad (6)$$

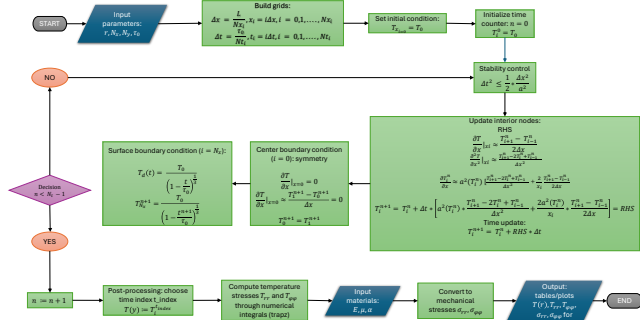
$$T_d(r, t) = \frac{T_0}{(1 - \frac{t}{\tau_0})^{\frac{1}{3}}} \quad (7)$$

Equation 4 defines the initial condition for the surface temperature at the initial moment of time. Expressions 6 and 7 represent the boundary conditions, where the former accounts for the spherical symmetry of the heat flux, and the latter 5 defines the surface temperature of the small body in the blackbody approximation: $T_0 = T_* \sqrt{\frac{R_*}{2R}}$. Equation 4 is solved numerically, where $T(x, t)$ is the temperature, and the thermal diffusivity $a^2(T)$, is determined by empirical formulas depending on temperature for crystalline ice Eq. 1 and silicate rock Eq. 3. The numerical scheme employed is the explicit Euler method. After obtaining the temperature profile $T(x, t) \rightarrow T(y)$ from the surface to the center of the spherical body, $T(y)$ is substituted into the expressions for thermal stresses.

$$T_{\phi\phi}(x) = \frac{2}{r^3} \int_0^r T(y)y^2 dy + \frac{1}{x^3} \int_0^x T(y)y^2 dy - T(x), \quad (8)$$

Table 3. Thermal parameters of meteorite samples Frankfurt and Los Angeles

Temperature (K)	500	400	300	200	125	100	50	40	30
k (W/m) Frankfurt	2	1,9	1,6356	1,2876	1,2648	1,2336	0,9214	0,7916	0,6305
k (W/m) Los Angeles	1,1	1	0,9204	0,7774	0,6284	0,5584	0,36209	0,310748	0,254429
c_p (J/(kg K))	900	850	780	575	370	290	120	80	50
a^2 Los Angeles	0,00444	0,004706	0,00472	0,00541	0,0067	0,00770	0,0121	0,0155	0,0203
a^2 Frankfurt	0,0088	0,0089	0,0083	0,0089	0,013	0,017	0,030	0,0395	0,0504


Figure 2. Block diagram of the numerical solution of the HDE and calculation of thermal stresses

$$T_{rr}(x) = \frac{2}{r^3} \int_0^r T(y)y^2 dy - \frac{2}{x^3} \int_0^x T(y)y^2 dy, \quad (9)$$

By using temperature functions as analogues of thermal stresses, we can readily convert them to the actual stresses using the following simple relationship:

$$\sigma_{\phi\phi}(x) = \frac{E\alpha}{1-\mu} T_{\phi\phi}(x), \quad \sigma_{rr}(x) = \frac{E\alpha}{1-\mu} T_{rr}(x), \quad (10)$$

The notations are provided in Section 2, and the results for the temperature profiles and stresses will be presented in Section 3. Below is the numerical algorithm for solving Equation 4 using the explicit Euler scheme with the initial condition Eq. 5 and two boundary conditions Equations 6 and 7, followed by the calculation of stresses using formulas 8, 9 and 10 Tambovtseva & Shestakova (1999); Boley & Weiner (1960).

The analytical calculation of HDE and thermal stresses is presented in Shestakova & Tambovtseva (1997). Further in the next section, comparisons of analytical and numerical approaches will be presented.

4 COMPARISON OF ANALYTICAL AND NUMERICAL METHODS FOR SMALL BODIES. DISCUSSION.

Analytical method: This method is based on a simplified model where thermal conductivity and diffusivity are assumed to be temperature-independent. It allows for the rapid acquisition of temperature functions and thermal stresses. The model accurately describes the behavior of temperature and stress near the surface and in the center of the bodies.

The primary limitation is inaccuracy in the intermediate layers, particularly for large bodies (radius > 1 km).

Numerical method: This method solves the nonlinear heat conduction equation with temperature-dependent thermal diffusivity $a^2(T)$. This approach is suitable for large bodies as well. Below, the simulation results of both approaches for bodies composed of crystalline ice and silicates are presented.

Crystal Ice: For the numerical calculation of crystalline ice, the variable coefficient from Eq. 1 was used, while for the analytical solution, a constant a^2 was adopted according to Table 1. For small cometary bodies, the value of a^2 was taken at $T = 30$ K; for large bodies, the value was taken at $T = 125$ K; and for medium-sized bodies, a^2 was averaged over the temperature range $T = (30 - 125)$ K. The calculated temperature and stress profiles are presented below in Figure 3.

As shown in Figure 3, when the radius of the ice bodies reaches 1 km or 3.5 km, the results of the analytical and numerical methods practically coincide. However, as the body size decreases for instance, to 200 m and 30 m a certain divergence in the results is observed, although the error remains relatively small. Figure 3 presents a comparison of the numerical and analytical solutions for bodies of various sizes. For all bodies, a high degree of agreement is observed in the near-surface zone. For a cometary body with a radius of 30 m, the average discrepancy between the analytical and numerical methods is 1.56 K, which corresponds to a 5% relative error; the maximum discrepancy is 4 K near the center. Discrepancies are minimal (less than 1 K) at a 10% relative depth x/r . For a 200 m cometary body, the average discrepancy is 2.1 K, with a maximum of approximately 5 K near the center. For a 1 km body, the average discrepancy is approximately 1.09 K, with a maximum of about 2.5 K near the center. For a 3.5 km body, the discrepancy is negligible, remaining less than 1 K across the entire profile. For small bodies (less than 30 m), discrepancies arise at depth due to the finite size of the body and effects associated with rapid heating.

Subsequently, Figure 4 illustrates the dependence of radial stresses at the center and tangential stresses at the surface as a function of distance, obtained by both analytical and numerical methods.

The solutions obtained for small bodies demonstrate good agreement between the numerical and analytical approaches, as only minor discrepancies in stresses are observed at different distances, as shown in Figure 4. For a cometary body with a radius of 30 m, the discrepancies in radial stresses at the center are less than 0.5 K from the starting position to the final distance; however, at the final distance, a difference of approximately 5 K is observed. This result is consis-

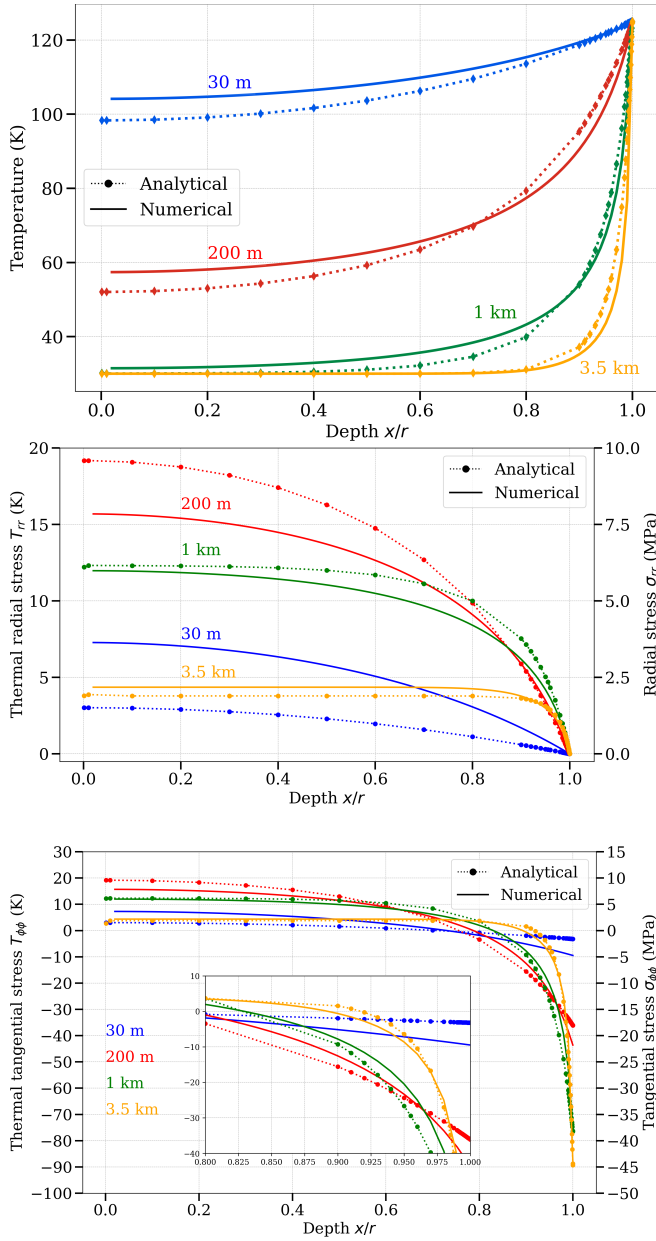


Figure 3. Profiles of temperature, as well as radial and tangential thermal stresses, from the surface to the center of the crystal ice small bodies at a final distance of 4.95 AU, obtained by both analytical ($a^2 = \text{const}$) and numerical methods.

tent with the stress discrepancies shown in Figure 3. For a cometary body with a radius of 200 m, the average discrepancy in stresses at the center is about 1 K from the start to the final distance, while at the final distance the discrepancy reaches approximately 4 K. For a cometary body with a radius of 1 km, stress discrepancies are observed at almost all distances, with an average discrepancy of about 5 K and a maximum discrepancy at the final distance of approximately 10 K. For a cometary body with a radius of 3.5 km, the average discrepancy is about 1.5 K, with a maximum discrepancy at the final distance of approximately 2 K. Such minimal discrepancies can be explained by the fact that, in the analytical

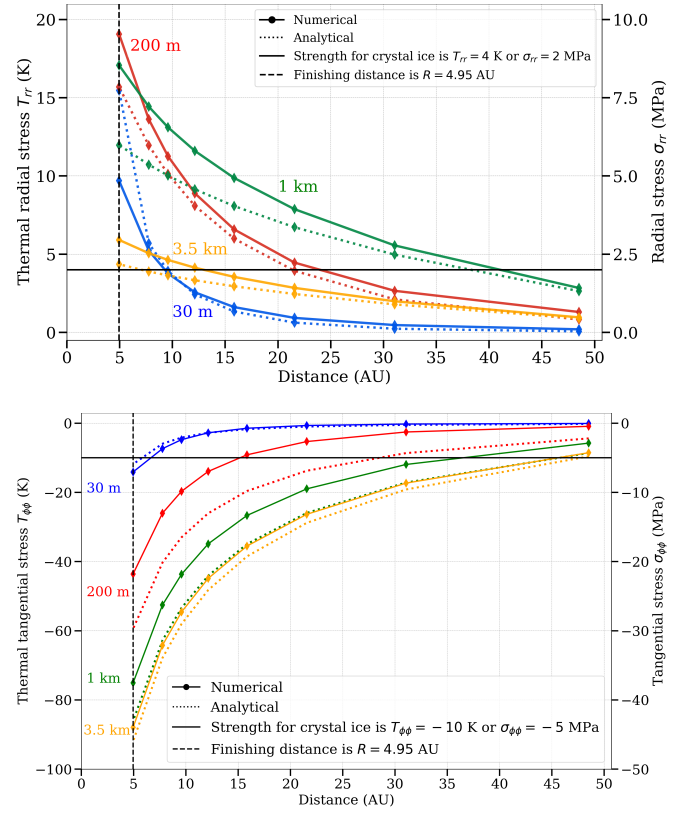


Figure 4. Thermal stresses at the center of the body ($x/r=0$) for the radial component (left) and at the surface ($x/r=1$) for the tangential component (right), calculated by analytical and numerical methods at various heliocentric distances from the initial position of 86 AU to the final distance of 4.95 AU.

solution (HDE), a constant value of the a^2 parameter is used at $T = 30$ K for bodies larger than 1 km, since they retain an initially low temperature in their central regions up to the moment of destruction. For bodies with radii of approximately 30 m, a^2 - constant value is used at $T = (125-200)$ K, corresponding to the blackbody temperature at the final distance, as heating in such bodies occurs throughout the entire volume. However, for sub-kilometer bodies, this parameter is averaged over the temperature range between the start and final distances, $T = (30-200)$ K, since pronounced temperature gradients are observed throughout the entire profile. Further, Figure 5 show the temperature profile, thermal radial and tangential stresses in the near-surface layer at a depth of 10 m.

As shown in Figure 5, heating occurs more effectively for the cometary body with a radius of 30 m, while the results for radii of 200 m, 1 km, and 3.5 km are comparable. The temperature discrepancy at a depth of 10 m between the two methods is approximately 10 K. The temperature discrepancy at a depth of 10 m between the two methods is approximately 10 K. For the stresses shown in Figure 5, the discrepancy between the analytical and numerical methods at a depth of 10 m is about 1 K for the 30 m and 200 m bodies, whereas for the 1 km and 3.5 km bodies the discrepancy is minimal (less than 0.1 K). For the stresses in Figure 5,

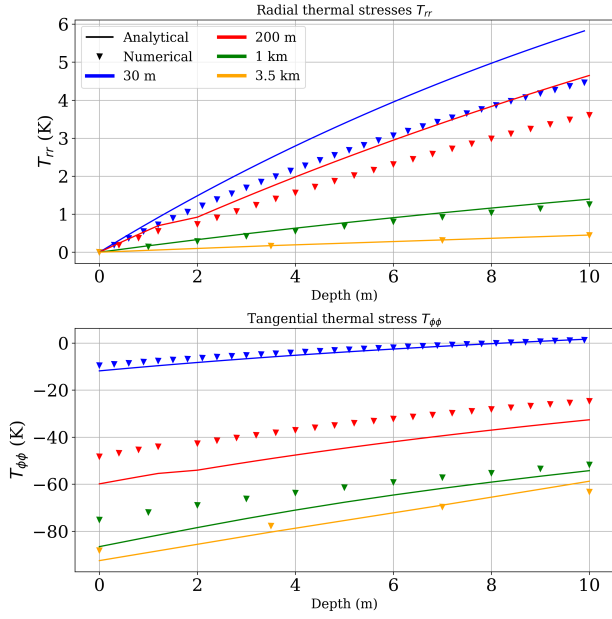


Figure 5. Profiles of radial and tangential thermal stresses in the near-surface layer at a depth of 10 m at a final distance of 4.95 AU, obtained by analytical (solid curve) and numerical (dotted curve) methods for cometary bodies of various sizes.

the discrepancy for the 30 m body is less than 1 K, while for the 200 m, 1 km, and 3.5 km bodies it is approximately 10 K. It is also important to note with regard to Figure 5, which is also applicable to silicate rocks, that at the surface $|x = r|$ the radial stress is $T_{rr} = 0$, whereas the tangential stress is $T_{\varphi\varphi} < 0$. However, as depth increases toward the center, the stresses T_{rr} and $T_{\varphi\varphi}$ should begin to equalize, a behavior that should be consistent for both methods. An analysis of crystalline ice clearly demonstrates this trend for a cometary body with a radius of 30 m, since a depth of 10 m constitutes one-third of its profile. A comparison of the results shows that at a depth of 10 m $T_{rr} \approx T_{\varphi\varphi}$, with values of approximately 5 K for the analytical method and 6 K for the numerical method. For cometary bodies with radii of 200 m, 1 km, and 3.5 km, such equalization is not observed, because a depth of 10 m represents only a small fraction of the total profile. The analytical solution performs well for large bodies, for which thermal diffusion does not reach the center and the temperature distribution remains relatively stable. However, for small bodies, where the entire volume heats up rapidly, only the numerical model accurately reflects the temporal and spatial variations in temperature.

Silicates: For the numerical calculations of silicate rocks, the variable coefficient from Equation 3 was used, whereas a constant value was adopted for basalt and chondrites in the analytical solution in accordance with Table 2. Figure 6 illustrates the temperature profiles, as well as the radial and tangential thermal stresses, within meteoroid bodies.

Figure 6 presents a comparison of the numerical and analytical solutions of the heat diffusion equation for small bodies with radii of 10 cm, 50 cm, 1 m, 5 m, 10 m, and 100 m composed of silicate chondritic and basaltic material. For a 100

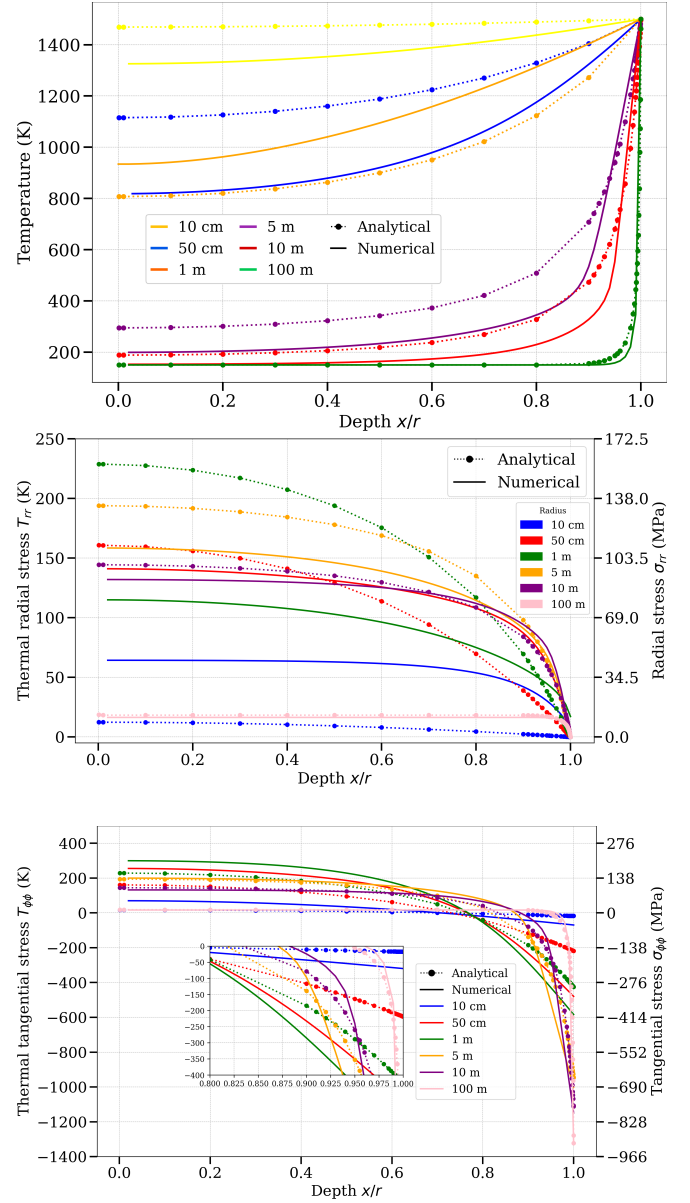


Figure 6. Profiles of temperature, as well as radial and tangential thermal stresses, from the center ($x/r=0$) to the surface ($x/r=1$) within bodies of various sizes at a final heliocentric distance of $0.0345 \text{ AU} \approx 7.4 R_{\odot}$ for chondritic material, obtained by both analytical ($a^2 = \text{const}$) and numerical methods.

m meteoroid, a nearly complete coincidence of the numerical and analytical temperature and stress profiles is observed, with differences of less than 1 K. For radii of 1 m and 5 m, the average discrepancy is approximately 20 K. For bodies of 10 cm and 50 cm, the average discrepancy is about 200 K, which is considered a reasonable result given that the black-body temperature at the final distance is 1500 K. The highest level of agreement (with discrepancies of less than 20 K) occurs in the near-surface region, extending up to 5% of the total profile. However, the maximum discrepancies occur at the center: 150 K for 10 cm, 300 K for 50 cm, 100 K for 1 m, 100 K for 5 m, 50 K for 10 m, and 5 K for 100 m. Significant

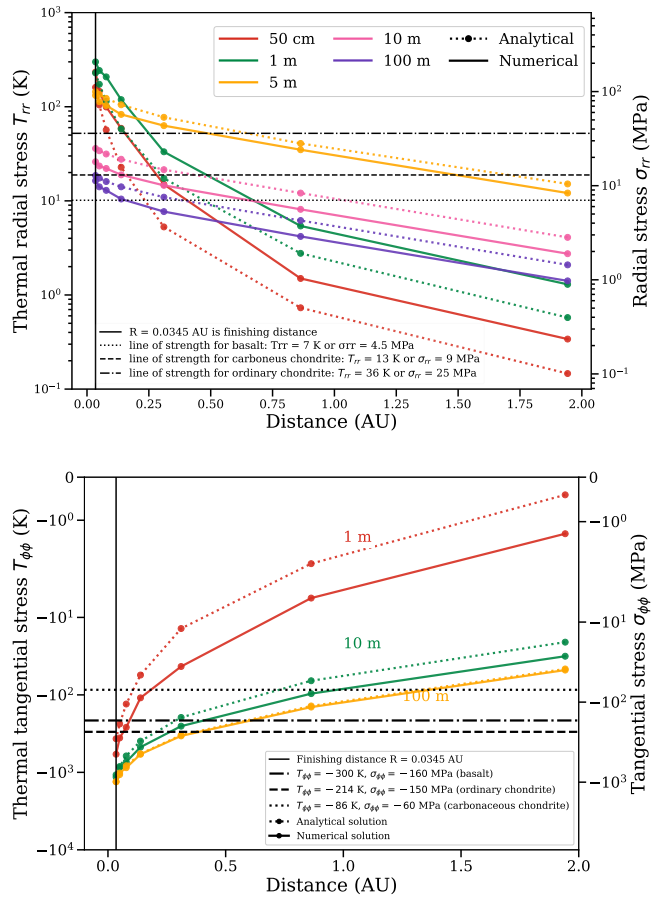


Figure 7. Thermal stresses at the center of the body ($x/r=0$, radial component) and at the surface ($x/r=1$, tangential component), calculated using analytical and numerical methods at various heliocentric distances from the initial position of 3.45 AU to the final distance of $0.0345 \text{ AU} \approx 7.4 R_{\odot}$ for chondritic and basaltic bodies.

discrepancies are observed throughout the entire volume for bodies with radii of 10 cm and 50 cm. Due to their small size, heating encompasses nearly the entire volume, and the temperature gradient equalizes rapidly. Thus, as with icy bodies, the analytical solution for silicate meteoroids proves accurate only when there is a sufficient thickness of the uncooled layer, whereas the numerical model is necessary for an adequate description of thermal processes in small bodies.

Subsequently, Figure 7 illustrates the dependence of radial stresses at the center and tangential stresses at the surface on the distance from the star, obtained by both analytical and numerical methods. These dependencies are calculated specifically for silicate bodies.

Analysis of Figure 7 shows that for bodies with radii from 1 m to 100 m, both stress calculation approaches at different distances demonstrate good agreement, and discrepancies in distances are minimal. For a body with a radius of 50 cm, the average discrepancy is approximately 100 K; for 1 m, it is 80 K; for 5 m, 20 K; for 10 m, 50 K; and for 100 m, 45 K. The stresses at the final distance also differ for all sizes. The discrepancy between the two methods varies: for 50 cm, it is about 50 K; for 1 m, 100 K; for 1 m and 5 m, approximately

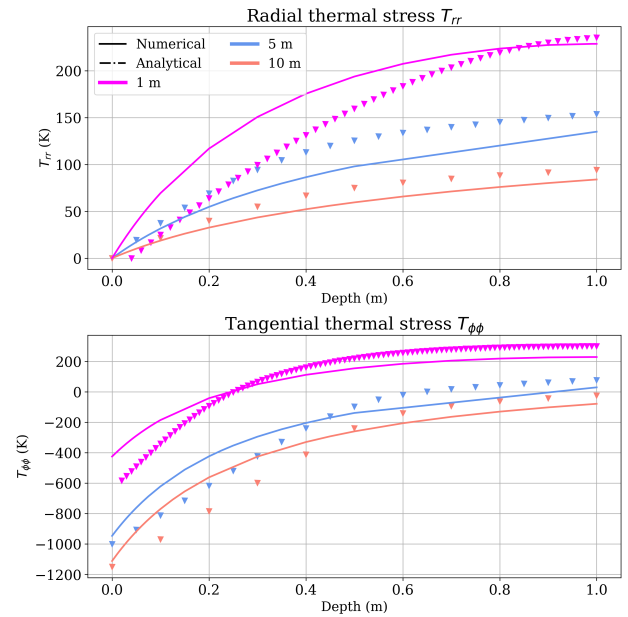


Figure 8. Profiles of radial and tangential thermal stresses in the near-surface layer at a depth of 1 m at a final heliocentric distance of $0.0345 \text{ AU} \approx 7.4 R_{\odot}$, obtained by analytical (solid curve) and numerical (dotted curve) methods for meteoroids of chondritic and basaltic material of various sizes.

100 K; for 10 m, 50 K; and for 100 m, about 10 K. Subsequently, Figure 8 presents the profiles of temperature, as well as radial and tangential thermal stresses, in the near-surface layer at a depth of 1 m for small silicate bodies. An analysis of the near-surface layer presented in Figure 8 was carried out in a manner similar to that described for Figure 5. The main difference lies in the fact that the near-surface layer was considered at a depth of 1 m, which is associated with the lower thermal conductivity of silicates compared to crystalline ice. As shown in Figure 8, the temperature discrepancies between the analytical and numerical methods are small: approximately 5 K for a meteoroid with a radius of 1 m, 15 K for a radius of 5 m, and 10 K for a radius of 10 m. Regarding the stresses in Figure 8, the discrepancy is about 50 K for the 1 m body, approximately 10 K for the 5 m body, and about 30 K for the 10 m body. Furthermore, the equalization condition $T_{rr} \approx T_{\varphi\varphi}$ occurs at a depth of 40 cm for a 1 m radius meteoroid at a temperature of approximately 150 K according to the numerical method, and at a depth of 50 cm at the same temperature for the analytical method. For the 5 m and 10 m bodies, this equalization is expected to occur at depths greater than 1 m from the surface. The numerical model is applicable to silicate bodies and shows consistency with the analytical solution. For large silicate bodies with radii exceeding 10 m, the temperature distribution remains stable in both the deep interior and near-surface layers, since thermal diffusion does not reach the center due to the low thermal conductivity of silicates, whose thermal diffusivity is approximately an order of magnitude smaller than that of crystalline ice. For this reason, a narrower size range from 10 cm to 100 m was selected, as even a 10 m fragment re-

tains its initial temperature in the central region. For small silicate bodies (less than 1 m), where the entire volume heats rapidly, only the numerical model accurately describes the temporal and spatial evolution of temperature. The proposed numerical model is applicable to both silicate and icy bodies. Similarities and discrepancies follow the same general trends for both large and small bodies; the primary difference lies in the selected size range: from 10 cm to 100 m for silicates and from 30 m to 3.5 km for icy bodies.

To address the physical interpretation of the comparison, it should be noted that the observed minor discrepancies between the two approaches are primarily driven by the temperature dependence of the thermal diffusivity $a^2(T)$, rather than numerical artifacts. In the numerical approach, the non-linear heat conduction equation is solved using the explicit Euler finite-difference scheme (first-order in time and second-order in space, FTCS) to account for the dynamically changing $a^2(T)$, and the resulting temperature field is subsequently used to calculate thermal stresses. Despite the differences in the mathematical treatment, the analytical method demonstrates very good overall agreement. This is due to the careful selection of the constant a^2 based on the physical characteristics of the bodies. Specifically, for very large bodies, a^2 was chosen at the initial temperature, since their internal regions remain cold until the final distance. For small bodies, which heat up entirely, a^2 was taken at the temperature corresponding to the final distance. For medium-sized bodies, an averaged a^2 between the initial and final temperatures was used. Because of this size-dependent parametrization, the analytical model successfully minimizes deviations from the numerical solution, resulting in only slight differences in the evaluated thermal gradients and stresses.

5 CONCLUSIONS

This study formulates and solves a comprehensive problem addressing the mechanism of thermal destruction of small bodies (SB) of various compositions (icy and silicate) during their approach to the Sun.

Key Results

The following dependencies of destruction on the size and composition of stony bodies have been established:

- Basaltic and carbonaceous bodies begin to disintegrate at heliocentric distances between Earth's orbit and Mars's orbit (1–2.5 AU).
- Ordinary chondrites disintegrate closer to Venus's orbit (~ 0.7 AU).
- Small stony bodies (< 10 m) disintegrate in the region between the orbits of Mars and Mercury, while larger bodies (~ 40 – 100 m) disintegrate between the orbits of Mercury and Venus.
- Very large silicate bodies (> 100 m) disintegrate closer to the Sun, producing dust clouds observable in the infrared and optical ranges.

For cometary nuclei moving along highly eccentric orbits, thermal stresses generated by the heating of surface layers are shown to be a critical factor in their destruction. Bodies with radii from 100 m to 3 km are most susceptible to internal cracking due to strong temperature gradients between the cold interior and the heated surface. Small bodies (radius up to 10 m) heat throughout their entire volume without accumulating significant internal stresses, whereas large bodies (radius greater than 10 km) retain a cold interior and experience heating only in a thin surface layer, remaining resistant to thermal destruction.

- For small bodies composed of silicates (0.1–5 m) and crystalline ice (less than 30 m), the analytical solution may significantly deviate in the central regions, whereas the numerical solution accurately accounts for volumetric heating.
- For icy bodies (30–200 m) and silicate bodies (10–100 m), the analytical solution remains applicable in the near-surface zone (up to 10–20% of the radius), but numerical modeling is required at greater depths.
- For large bodies (1–3.5 km for cometary nuclei and ~ 100 m for silicates), discrepancies between the analytical and numerical approaches are minimal throughout the entire profile.

Both approaches complement each other effectively, and their combined application provides a reliable and accurate assessment of the stability of small bodies during solar approach.

In the long term, this research may be extended by incorporating elliptical orbits and modeling multiple orbital revolutions up to the complete destruction and subsequent evaporation of cometary nuclei. This would allow for consideration of thermal stresses arising both during the approach to and recession from the star. Future developments include more detailed calculations of mass loss during stellar approaches and subsequent material accretion. Additional modeling will account for various heat balance boundary conditions, internal sublimation processes, and other relevant physical factors. Further refinement may be achieved by integrating multiple destruction mechanisms and orbital dynamics into a comprehensive simulation framework describing the environment of both the star and the small body. The model is planned to be extended to three dimensions with implementation of the full thermal stress tensor. Moreover, diurnal rotation effects will be incorporated, including azimuthal and latitudinal (equatorial) profiles and their influence on thermal stress distribution.

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RELATIONSHIP BETWEEN THE CONFORMAL GROUP AND MAXIMAL GROUPS OF MOTIONS IN COSMOLOGY

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ABSTRACT

The maximal groups of motions of the Minkowski, de Sitter, and anti-de Sitter spacetime are the Poincaré group, the inhomogeneous Lorentz group, and the de Sitter groups of the first and second kind, respectively. It has been proven that these groups are subgroups of the conformal group locally and globally.

Key words: $ISO_0(3,1)$ – Poincaré group, $SO(3,2)$, $SO(4,1)$ – de Sitter groups, $SO(4,2)$ – conformal group.

AMS Subject Classification: 22-22E, 83-83C, 83-83F

1 INTRODUCTION

There are only three cosmological models with maximal groups of motions - the Minkowski, de Sitter, and anti-de Sitter worlds, Tolman (1969); Weinberg (1972). These worlds' maximal groups of motions are the Poincaré group, i.e., the inhomogeneous Lorentz group, and the de Sitter groups of the 1st and 2nd kind, respectively. Recall that according to Wigner's theorem, the main quantum numbers of elementary particles are determined by the invariants of the maximal groups of motions.

It is well known that these groups are local subgroups of the conformal group. In other words, the Lie algebras of the Poincaré group, de Sitter groups of the 1st and 2nd kind are subalgebras of the Lie algebra of the conformal group. Moreover, a stronger statement is true: the Poincaré and de Sitter groups of both kinds are subgroups of the conformal group not only locally, but also globally. The proof is based on the decomposition of the elements of the conformal group by the stationary subgroup of the 5-dimensional cone, which is a transitive surface.

2 THE VACUUM SOLUTIONS OF EINSTEIN'S EQUATIONS

According to Einstein's general relativity, the metric properties of space-time are determined by the distribution and motion of matter, Einstein (1965-1967); Moeller (1972):

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}; \quad R = R^\mu_\mu \quad (1)$$

where

$R_{\mu\nu}$ – Ricci tensor, $g_{\mu\nu}$ – metric tensor, Λ – cosmological constant, G – the gravitational constant of Newton, $T_{\mu\nu}$ – energy-momentum tensor and $\mu, \nu = 0, 1, 2, 3$.

This equation can be rewritten in an equivalent form:

$$R_{\mu\nu} = \Lambda g_{\mu\nu} - \frac{8\pi G}{c^4}(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T); \quad T = T^\mu_\mu \quad (2)$$

Einstein's equations for vacuum are as follows:

$$R_{\mu\nu} = \Lambda g_{\mu\nu}. \quad (3)$$

It is clear from (3) that the Λ -term, even in the absence of matter ($T_{\mu\nu} = 0$), changes the space-time geometry and $g_{kl}\Lambda$ is the energy-momentum tensor of the vacuum.

For the zero value of the cosmological constant, the solution of this equation is the flat world of Minkowski, for which the Poincaré group is the maximal group of motion.

$$ds^2 = dr^2 + r^2(d\vartheta^2 + \sin^2\vartheta d\varphi^2) - c^2 dt^2. \quad (4)$$

In the general case, the solutions of the Einstein equations do not have a maximal group of motions.

In 1917 Willem de Sitter found two solutions with different global groups of movements:

$$ds^2 = \frac{dr^2}{1 - r^2/R^2} + r^2(d\vartheta^2 + \sin^2\vartheta d\varphi^2) - \left(1 - \frac{r^2}{R^2}\right) c^2 dt^2, \quad (5)$$

if $\Lambda > 0$;

$$ds^2 = \frac{dr^2}{1 + r^2/R^2} + r^2(d\vartheta^2 + \sin^2\vartheta d\varphi^2) - \left(1 + \frac{r^2}{R^2}\right) c^2 dt^2, \quad (6)$$

if $\Lambda < 0$.

Here R is the radius of curvature and is related to the cosmological constant Λ :

$$\Lambda = \pm \frac{3}{R^2}.$$

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Using stereographic projections:

$$\xi_1 = r \cos \varphi; \quad \xi_2 = r \sin \vartheta \cos \varphi; \quad \xi_3 = r \sin \vartheta \sin \varphi; \\ \xi_4 = R \sqrt{1 - \frac{r^2}{R^2}} \cosh \left(\frac{ct}{R} \right); \quad \xi_0 = R \sqrt{1 - \frac{r^2}{R^2}} \sinh \left(\frac{ct}{R} \right)$$

and

$$\eta_1 = r \cos \varphi; \quad \eta_2 = r \sin \vartheta \cos \varphi; \quad \eta_3 = r \sin \vartheta \sin \varphi; \\ \eta_4 = R \sqrt{1 + \frac{r^2}{R^2}} \cosh \left(\frac{ct}{R} \right); \quad \eta_5 = R \sqrt{1 + \frac{r^2}{R^2}} \sinh \left(\frac{ct}{R} \right)$$

de Sitter solutions can be isometrically embedded as sub-manifolds in 5-dimensional pseudo-Euclidean spaces:

$$\xi_0^2 - \xi_1^2 - \xi_2^2 - \xi_3^2 - \xi_4^2 = -R^2 \quad (7)$$

and

$$\eta_1^2 + \eta_2^2 + \eta_3^2 - \eta_4^2 - \eta_5^2 = -R^2, \quad (8)$$

respectively.

These are the worlds of de Sitter of the 1st and 2nd kind, in other words, the worlds of de Sitter and anti-de Sitter, (Rajabov 2021).

These spaces have global symmetry groups $SO(4, 1)$ and $SO(3, 2)$, which leave the metric unchanged and are called de Sitter groups. These are the worlds of de Sitter of the 1st and 2nd kind, in other words, the worlds of de Sitter (DS) and anti-de Sitter (AdS), respectively.

Of particular interest is the connection of these groups with the conformal group, which H.Weyl introduced in connection with the conformally invariant theory of gravitation.

3 $SO(4, 2)$ -CONFORMAL GROUP AND ITS SUBGROUPS

The group $SO_0(4, 2)$ is a connected component of the unit of the group of motions of the 6-dimensional pseudo-Euclidean space, which leaves the quadratic form invariant, Barut and Raczka (1977); Gursey (1964):

$$[k, k] = k_1^2 + k_2^2 + k_3^2 + k_4^2 - k_5^2 - k_6^2.$$

Elements of $g \in SO(4, 2)$ are represented by 6×6 -matrices that perform linear transformations over $k = (k_1, k_2, k_3, k_4, k_5, k_6)$. From the definition it follows that the following relations are satisfied:

$$g^\top \eta g = \eta, \quad \det g = 1, \quad (9)$$

where the $\top$ means transposition and η is the diagonal 6×6 -matrix:

$$\eta = \text{diag}(1, 1, 1, 1, -1, -1)$$

We will number the matrix elements with indices: $a, b, c = 1, 2, 3, 4, 5, 6$.

The groups $SO(4, 1)$ and $SO(3, 2)$ are subgroups of the conformal group $SO(4, 2)$. Let us show that the Poincaré group is also a subgroup of $SO(4, 2)$ globally.

Transitivity surfaces of the group $SO_0(4, 2)$:

$$[k, k] = k_1^2 + k_2^2 + k_3^2 + k_4^2 - k_5^2 - k_6^2 = c,$$

pass into themselves under transformations from the group $SO_0(4, 2)$. Depending on the sign of c , there are three types of transitive surfaces: a hyperboloid, if $c > 0$ or $c < 0$, and a cone with a punctured vertex, if $c = 0$, because the point $k_1 = k_2 = k_3 = k_4 = k_5 = k_6 = 0$ is the vertex of the cone and forms a homogeneous space.

A cone with a punctured vertex plays an exceptional role in our study, so we restrict ourselves to the study of invariant measures and coordinate systems on the cone.

We introduce a spherical coordinate system on the cone $[k, k] = 0$:

$$k = \omega \mathbf{n}, \quad \mathbf{n} = (\xi, \zeta), \quad 0 < \omega < \infty, \quad [\mathbf{n}, \mathbf{n}] = 0.$$

Here ξ and ζ are 4-dimensional and 2-dimensional unit vectors, respectively¹:

$$\zeta = (\sin \psi, \cos \psi), \quad \zeta^2 = 1, \quad 0 \leq \psi < 2\pi; \\ \xi = (\cos \chi, \sin \chi \cos \vartheta, \quad, \quad \xi^2 = 1; \quad (10)$$

$$\sin \chi \sin \vartheta \cos \varphi,$$

$$\sin \chi \sin \vartheta \sin \varphi)$$

$$0 \leq \varphi < 2\pi, \quad 0 \leq \vartheta, \chi \leq \pi.$$

As a fixed point $\overset{\circ}{k}$ it is convenient to choose point with spherical coordinates $\omega = 1; \psi = \vartheta = \varphi = \chi = 0$:

$$\overset{\circ}{k} = (1, 0, 0, 0, 0, 1).$$

The transformation $h(k)$ (the so-called "boost" or the Wigner operator) that maps a fixed point $\overset{\circ}{k}$ to a given point k is defined as follows:

$$h(k) = g_{34}(\varphi)g_{23}(\vartheta)g_{12}(\chi)g_{56}(\psi)g_{16}(\beta), \quad \beta = \ln \omega \quad (11)$$

The stationary group W of the point $\overset{\circ}{k}$ is isomorphic to the group of motions of the 4-dimensional pseudo-Euclidean space M_4 , that is, Poincaré group $ISO(3, 1)$:

$$W \simeq ISO(3, 1).$$

Each element of $w \in W$ uniquely represented as:

$$w = R(r)B(\vec{z}), \quad (12)$$

where $\vec{z}$ is a 4-dimensional vector, and r is the pseudo-orthogonal 4×4 -matrix:

$$r^\top \tilde{\eta} r = \tilde{\eta}; \quad \tilde{\eta} = \text{diag}(1, 1, 1, -1).$$

The matrices $R(r)$ and $B(\vec{z})$ are elements of the rotation and translation subgroups, respectively:

$$R(r) \in SO(3, 1) \subset SO(4, 2),$$

$$B(\vec{z}) \in W \simeq ISO(3, 1), \quad z = \vec{z}^2 = \vec{z}^\top \tilde{\eta} \vec{z} = z_1^2 + z_2^2 + z_3^2 - z_4^2.$$

The matrices $B(\vec{z})$ form an Abelian subgroup, which is a normal divisor of the stationary subgroup $W \simeq ISO(3, 1)$:

¹ The spherical coordinate system does not constitute an atlas. Therefore, all of the following relations hold almost everywhere or for almost all elements of the group.

$$B(\vec{z}_1)B(\vec{z}_2) = B(\vec{z}_1 + \vec{z}_2), \quad R(r^{-1})B(\vec{z})R(r) = B(r^{-1}\vec{z}).$$

Thus, for $g \in SO(4, 2)$ we have:

$$g = h(k)w. \quad (13)$$

Using the last formulas, we obtain the expansion for the elements of the group $SO(4, 2)$:

$$g = g_{34}(\varphi)g_{23}(\vartheta)g_{12}(\chi)g_{56}(\psi)g_{16}(\beta)R(r)B(\vec{z}). \quad (14)$$

Thus, we have proven the following proposition:

The groups $SO(4, 1)$, $SO(3, 2)$, and $ISO(3, 1)$ are, up to isomorphism, subgroups of the conformal group $SO(4, 2)$, globally.

4 CONCLUSION

The principle of general covariance in general relativity makes the interpretation of solutions and the definition of the energy-momentum tensor ambiguous. The complexity of this problem is related, among other things, to the non-trivial symmetry properties of vacuum solutions to Einstein's equations, which create serious difficulties in defining the quantum vacuum, [Rajabov \(2022\)](#).

Without the maximal group of motions, using the methods of relativistic quantum field theory is impossible. Thus, the gravitational field is not amenable to quantization, and the unification of general relativity with quantum mechanics is a pressing problem in modern physics. A reasonable question arises: is it possible to apply quantum mechanics on the scale of the Universe? All this forces us to look for other possibilities for solving the problems of high-energy physics and cosmology, [Rajabov \(2021\)](#).

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JUPITER IN THE 890 NM METHANE ABSORPTION BAND: A RESEARCH REVIEW

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ABSTRACT

Jupiter's atmosphere is a complex dynamic system with a multilayered cloud structure and intense circulation processes. Near-infrared observations, particularly in the methane absorption band around 890 nm, provide a powerful diagnostic tool for the upper atmosphere. This paper presents a comprehensive analysis of observational data in the 890 nm band, including a comparison with brightness temperatures in the far-infrared and microwave ranges. Observations show that the central depth of the methane absorption band closely correlates with stratospheric temperatures at pressure levels of 3.5–8.6 mbar. The largest deviations are observed in the Great Red Spot (GRS) region, reflecting its unique vertical and dynamic structure. High latitudes and equatorial anticyclonic formations, as well as variations in aerosol optical depth, contribute to the observed photometric contrasts. The results demonstrate that the 890 nm methane absorption band is a sensitive tool for studying stratospheric haze and upper tropospheric dynamics, providing important constraints for atmospheric modeling and interpretation of high-resolution ground-based and space-based observations.

Key words: Jupiter – atmosphere – methane absorption – near infrared – aerosols – Great Red Spot – stratosphere – troposphere – planetary spectroscopy.

1 INTRODUCTION

Jupiter's atmosphere is a complex dynamic system with a multilayered cloud structure and intense circulation processes. One of the key methods for diagnosing its upper layers is observations in the near-infrared spectral region, in particular in the strong methane absorption band around 890 nm. Diffuse reflectance levels of solar radiation in this spectral region correspond to pressures from 5–70 mbar in the polar regions to 100–200 mbar in the equatorial zone (Morales-Juberias et al. 2003; Banfield et al. 1998). This pressure range reflects the altitudes at which the observed radiation is formed and allows this band to be used as a diagnostic tool for studying the upper troposphere and lower stratosphere of the planet. This method allows one to study the properties of aerosols, the thermal structure, and the dynamics of high atmospheric layers inaccessible to observations in the visible range. This is due to the fact that in the region of strong methane absorption, the contribution of deeper atmospheric layers is significantly weakened, and the recorded radiation is formed predominantly at high altitudes.

Methane absorption band and a brief analysis of the absorption in this band compared to brightness temperatures in the far infrared and microwave ranges. This comparison is

of particular interest because it allows us to establish a possible relationship between the radiative characteristics of the atmosphere and its thermal structure at different altitudes. Analysis of such relationships is important for a deeper understanding of the physical processes that determine the vertical and latitudinal structure of Jupiter's atmosphere, as well as for refining existing atmospheric models of the planet.

2 A REVIEW OF PUBLISHED FILTER OBSERVATIONS OF JUPITER IN THE METHANE ABSORPTION BAND OF 890 NM

Images obtained at 890 nm reflect changes in high clouds and the upper haze layer at a pressure level of 150–200 mbar (Morales-Juberias et al. 2003). This means that observations in this spectral region are predominantly sensitive to the upper troposphere and lower stratosphere, where the main aerosol structures are formed. In polar regions, data at 889 nm are an indicator of the highest formations of stratospheric aerosol, concentrated between the levels of 5 and 70 mbar (Banfield et al. 1998). Thus, observations in this band make it possible to reveal the distribution of high-lying aerosol haze, especially in regions characterized by intense stratospheric dynamics. High cloud tops and thick clouds at the tops of plumes explain the anomalously low equivalent width of the 890 nm methane absorption band (Banfield et al.

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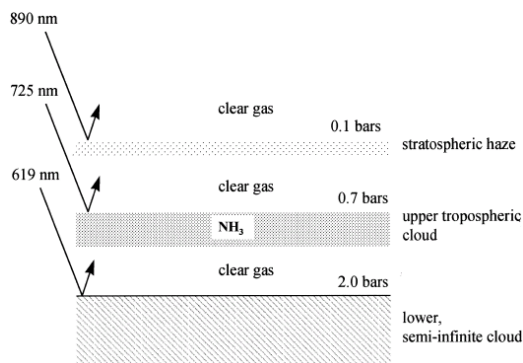


Figure 1. Model of Jupiter's atmosphere. Different layers of the atmosphere are sensitive to radiation at different wavelengths (Bellini et al. 1998).

1998). This is due to the fact that an increase in the height of cloud tops reduces the effective path length of the absorbing gas, which leads to a weakening of the observed absorption.

The stratification of Jupiter's atmosphere, not only meridionally but also vertically, leads to significant differences in observational data obtained at wavelengths of 619 and 890 nm, as demonstrated by West et al. in their analysis of data for 619, 725, and 890 nm (West et al. 1986). These differences are due to the fact that each of these wavelengths is characterized by different radiation penetration depths and, therefore, is sensitive to different atmospheric altitudes. As a result, observations at different wavelengths provide information on the vertical structure of the atmosphere and the distribution of aerosol and gaseous components. In the work of Bellini et al. (1998) a diagram of the penetration of radiation of different wavelengths with subsequent reflection from different layers of the atmosphere of Jupiter is presented (Bellini et al. 1998). This diagram is shown in Fig. 1. The presented model allows us to clearly illustrate which atmospheric layers make the main contribution to the formation of the observed radiation at different wavelengths. As can be seen from Fig. 1, this model consists of a lower semi-infinite cloud with an upper boundary at a pressure of about 2.0 bar, an upper tropospheric ammonia cloud with a base at 0.7 bar, and stratospheric haze above them at a pressure of about 0.1 bar. Pure gas fills the space between all layers. This multilayered structure of the atmosphere determines the complex nature of the interaction of radiation with cloud and gas components. While the 890 nm wavelength is sensitive to stratospheric haze and gas above the upper clouds, the 725 nm wavelength is sensitive to the upper layers of ammonia clouds and everything located above them, and the 619 nm wavelength also captures gas between the upper and lower clouds at a level of 2 bar (Bellini et al. 1998), and possibly penetrates deeper - to the third ammonia-water cloud layer at a level of 4-5 bar. Thus, a combination of observations at different wavelengths allows for multi-level diagnostics of Jupiter's atmosphere. According to other authors, the atmospheric level sensitive to the 890 nm band differs somewhat. Hill et al. believe that it is at a level of approximately 0.6 bar (Hill et al. 2023). Wong et al. establish it at a level of 0.3-0.5

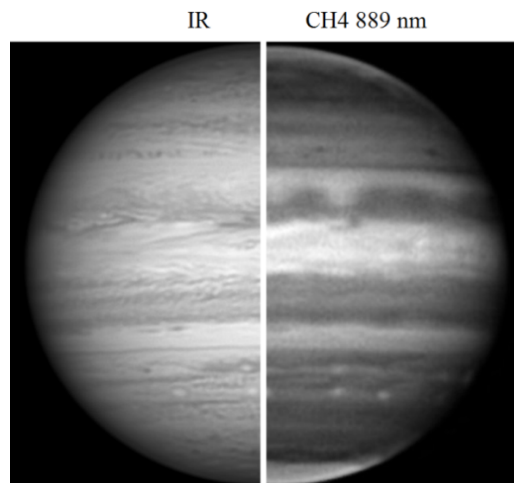


Figure 2. Jupiter's appearance in the infrared (IR) continuum (left) and in the methane absorption band at 889 nm (right), based on images obtained by Christopher Go on May 24, 2018 (<https://alpo-j.sakura.ne.jp/kk18/j180524z.htm>).

bar (Wong et al. 2023). Differences in these estimates may be due to the use of different atmospheric models, as well as the peculiarities of the processing of observational data. Apparently, the latter estimate is the most probable, since it is confirmed by the great external similarity of the zonal-striped structure of Jupiter's atmosphere in images in the continuous spectrum (IR) and in the CH_4 absorption band of 890 nm (Figure 2). This similarity indicates that the bulk of reflected radiation in these spectral regions is generated at similar atmospheric altitudes. The observed differences can be explained by variations in the thickness of the purely gaseous atmosphere above the belts and zones, or by variations in the density and scattering properties of the upper cloud layers, to which the center of the deep 890 nm CH_4 absorption band is very sensitive. Thus, the observed variations reflect real physical differences in the structure of the planet's atmosphere. Wallace and Smith (1977) modeled near-infrared spectra and center-to-limb oscillation observations for the 0.49 and 0.89 μm bands using newly measured methane absorption coefficients. This suggested that the cloud-top pressure of 200-300 mbar is too high to correspond to the condensation level of ammonia ice (West et al. 1986). This points to the need to refine models of Jupiter's cloud structure and the possible presence of additional aerosol chromophore components formed by photochemical reactions.

In the late 1970s and early 1980s, West and others interpreted the band/continuum ratios and center-to-limb brightness variations using high-signal-to-noise CCD images in the 0.619, 0.725, and 0.89 μm bands. They also found suitable conditions for two types of models: one with a gas layer above a semi-infinite homogeneous scattering/absorbing layer, and the other with two discrete, physically thin tropospheric clouds plus a thin stratospheric haze (West et al. 1986). Both models explain the observed photometric characteristics of the planet's disk and confirm the complex vertical structure of the atmosphere.

Similar work was conducted by Vdovichenko and Teifel and colleagues on spectral observations in the 600–1000 nm range (Atai et al. 2022; Vdovichenko et al. 2017; Teifel et al. 2017; Vdovichenko et al. 2016, 2014, 2015; Teifel et al. 2018). Overall, the difference in absorption in the 619 and 890 nm bands indicates a difference in the thermal balance of Jupiter’s troposphere and stratosphere. This is due to the fact that these spectral regions are sensitive to different atmospheric altitudes, characterized by different thermodynamic conditions.

3 ABSORPTION COEFFICIENTS

Owen and Manson determined the absorption coefficients for the 890 nm band using the Beer–Lambert law:

$$I = I_0 e^{-kx} \quad (1)$$

Here, I_0 is the solar energy flux at the top of the atmosphere, e is the base of the natural logarithm, k is the absorption coefficient, and x is the equivalent path length. The following values of the absorbing layer per unit pressure (equivalent path) were used: 60 ± 30 m/atm for the north polar region, 40 m/atm for the equatorial zone (EZ), and 34 m/atm for the Great Red Spot (GRS) (Owen & Mason 1969). These values indicate significant differences in the optical properties of the atmosphere at different latitudes of the planet.

The basic information on the absorption coefficients in the 890 nm methane band was obtained from a 1994 study by Karkoschka (Karkoschka 1994). It was noted that “the narrowing of methane absorption bands toward lower temperatures leads to strong temperature dependencies at the band edges, where the methane spectrum exhibits a steep gradient.” This implies that the spectral characteristics of methane vary significantly with environmental temperature, which is particularly important when interpreting observations of giant planet atmospheres. The steepest linear gradient at wavelengths shorter than 1000 nm occurs near 880 nm. At this wavelength, the absorption coefficient of methane decreases by approximately a factor of 4 when transitioning from room temperature to the temperature of Jupiter’s atmosphere. Such a change indicates a high sensitivity of methane spectral characteristics to temperature conditions. Additional steep gradients are observed near 980 nm, where the decrease is approximately threefold, and near 905 nm, where it is approximately twofold. At these wavelengths, the temperature dependence is sufficiently strong that the temperature differences between the atmospheres of Jupiter and Saturn become significant (Karkoschka 1994). At 880 nm, the absorption coefficient of methane is approximately 20% higher for Jupiter than for Saturn. Although this difference is notable, it is significantly smaller than the variation factor of 4. Therefore, temperature effects must be taken into account in the quantitative analysis of observational data. Once methane absorption at these wavelengths is definitively established by laboratory measurements, these wavelengths may be able to be used as an effective thermometric indicator of Jupiter’s atmosphere (Karkoschka 1994). This opens the prospect of using

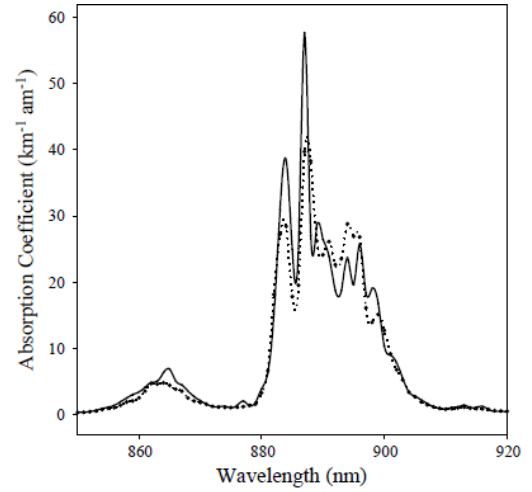


Figure 3. Absorption coefficients (averaged over a 1 nm interval) for methane at 77 K compared with Karkoschka values (Teifel et al. 2017).

spectral observations of methane to remotely determine the atmospheric temperatures of giant planets.

A comparison of laboratory data with the results of Karkoschka is presented in the study by O’Brien and Cao (2002), where the distribution of the methane absorption coefficient in the 890 nm band at a temperature of 77 K is shown graphically (O’Brien & Cao 2002). Figure 3 from that paper (O’Brien & Cao 2002) is presented below. The obtained results serve as an important reference for interpreting observations of the atmospheres of Jupiter and Saturn, whose temperatures are close to the indicated values. When adapting the absorption coefficient data to the temperature conditions of Jupiter, it is necessary to account for temperature corrections at temperate, tropical latitudes, and in the equatorial zone (EZ). This is due to the fact that the temperature structure of the atmosphere varies with latitude and altitude, which in turn affects the observed absorption. The laboratory spectrum of the methane absorption band at 890 nm is presented in the paper by O’Brien and Cao (2002) (O’Brien & Cao 2002). In the same paper, based on the Karkoschka data, numerical tabulated values of the absorption coefficient of methane in the range of 848.6–920.5 nm with a step of 1 at a temperature of 77 K are presented, which is an important source of data for various calculations related to the absorption band at 890 nm (Karkoschka 1994). The availability of such detailed spectral data allows for more accurate modeling of radiative transfer processes in the atmosphere. This paper also presents data on the absorption band of methane at 861 nm. The synthetic spectrum of the methane band at 890 nm is also presented in the paper by Fink, Benner and Dick (1977) (Fink et al. 1977). The spectrum is given with a resolution of 10. This allows it to be used for comparative analysis with observational spectra and for refining the parameters of atmospheric models.

According to Fink et al., the methane absorption band at 890 nm occupies a wavelength range of 872.5–923.5 nm (Fink et al. 1977). Giver reported the range of this band

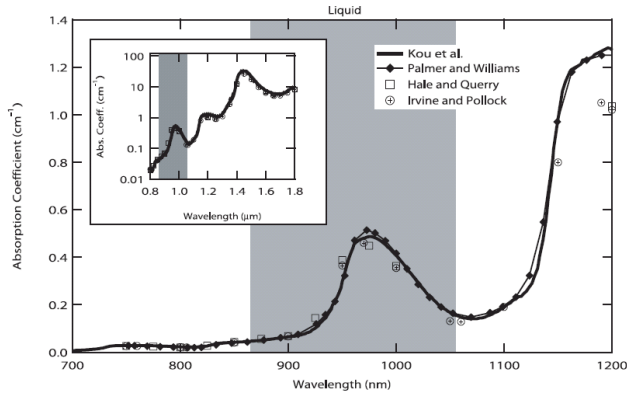


Figure 4. Near infrared water vapor absorption profile. The wavelength range used in this work is shown by the shaded area (Daniel et al. 2002).

to be 872.8–928.3 nm (Giver 1978). Minor differences in the reported ranges may be due to differences in measurement methods and criteria for determining band boundaries.

The accuracy of ground-based observations in the 890 nm band is virtually unaffected by water vapor in the Earth’s atmosphere. This is confirmed by data published by (Daniel et al. 2002) which presents the distribution of water vapor absorption. As can be seen from Figure 4, in the 890–905 nm region, there is only minor water vapor absorption with a gradual increase in the longer wavelength part of the spectrum. This makes this spectral region particularly favorable for ground-based observations of Jupiter’s atmosphere. Similar results are presented in a report by the Max Planck Institute (Bartsch et al. 1997), which shows virtually zero absorption in the region of the methane absorption band at 890 nm, followed by an increase in the near-infrared region. This further confirms the high suitability of this spectral region for astronomical observations.

Observations of Jupiter using the 890 nm filter make it possible to identify features in its atmosphere that are not distinguishable at other wavelengths (Minton 1972; Moreno et al. 1991; Morales-Juberías et al. 2002; Sanchez-Lavega et al. 1998; Hueso et al. 2017). This is due to the fact that strong absorption of methane limits the contribution of deeper layers of the atmosphere and enhances the contrast of high-lying cloud structures. A characteristic feature of Jupiter is the presence of bright polar regions in the 890 nm band (see Figure 2). Figure 5 shows a comparison of photometric profiles of Jupiter’s disk along the central meridian, obtained using the SBIG SGS spectrometer at a wavelength of 890 nm (Almaty, Kazakhstan, November 3, 2023, during opposition) and using the 889 nm filter on the Hubble Space Telescope (May 22, 2022) (Wong et al. 2023).

Red arrows indicate increased brightness in the polar regions. This increased brightness can be explained by the presence of high-altitude aerosol haze, likely caused by cosmic dust precipitation near the planet’s magnetic poles. This phenomenon indicates active interactions between Jupiter’s magnetosphere and atmosphere.

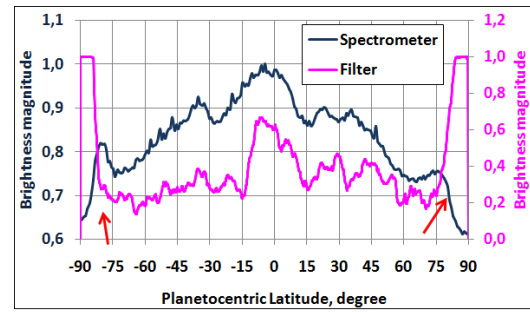


Figure 5. Comparison of brightness profiles of Jupiter’s central meridian in the 890 nm band (see text for details).

4 ANTICYCLONIC FORMATIONS AND THE GREAT RED SPOT (GRS)

Anticyclonic formations are observed at Jupiter’s temperate and equatorial latitudes, appearing as highly bright in images in the 890 nm methane band. This intensity of reflected light can be explained either by an increased aerosol density in cloud structures or by a reduced thickness of the purely gaseous layer above the cloud top. According to Pérez-Hoyos et al. (2012), in the temperate latitudes of the southern hemisphere in 2009, the optical thickness of the above-cloud atmosphere was 0.2–0.9 (Pérez-Hoyos et al. 2012a), while according to Satoh & Kawabata, it did not exceed 0.32 (Satoh & Kawabata 1992). It should be noted that the studies by Pérez-Hoyos et al. took into account the impact of the collision with Comet Shoemaker–Levy. In addition to the given values, for some models Pérez-Hoyos et al. obtained an optical thickness of up to 1.3, which is associated with the consideration of deeper layers of the atmosphere (Pérez-Hoyos et al. 2012b).

Observations in the 890 nm band make it possible to detect haze above the cloud layer and compare it with data in the ultraviolet range of 410 nm (Banfield et al. 1998) and 325–375 nm (Owen & Mason 1969). However, strong variations at these wavelengths are masked by methane absorption (890 nm), aerosol absorption (410 nm), and Rayleigh scattering (325–375 nm), respectively.

The work of Satoh and Kawabata (1992) provides the parameters of atmospheric calculations and the results of modeling for the equatorial zone (EZ) and belts under various cloud models (Satoh & Kawabata 1992). In general, the values of the absorption coefficient are consistent with the data of O’Brien and Cao (O’Brien & Cao 2002). A number of other quantities characterizing the methane absorption band at 890 nm should also be taken into account.

According to Simon et al. the optical depth of the stratospheric haze layer in the 890 nm band is about 0.01, and the albedo of a single scattering of tropospheric haze at the same wavelength is 0.96 (Simon et al. 2015). Bardet et al. presented a map of brightness temperatures along the central meridian in the latitude range of $\pm 70^\circ$ for layers of 0.1 mbar–1 bar (Bardet et al. 2024). The map was constructed based on 281 observations made on May 24–27, 2018, using VISIR on the Very Large Telescope (VLT, Chile). Stratospheric tem-

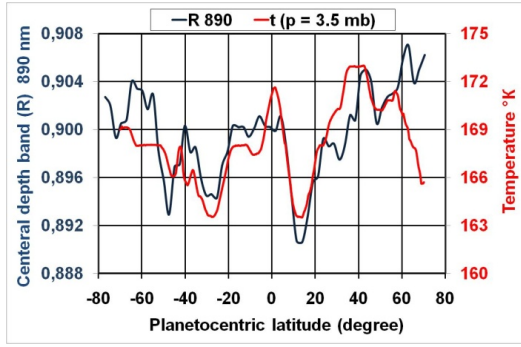


Figure 6. Central depth of the methane absorption band (890 nm) and Jovian brightness temperature at the 3.5 mbar pressure level between $\pm 75^\circ$ latitude.

perature was measured by methane emission at a wavelength of $7.9 \mu\text{m}$. The observations covered the planet from pole to pole and were synchronized with the 13th perijove Juno mission, which allowed the comparison of ground-based infrared measurements with high-resolution Juno Cam images.

The use of 11 narrow-band filters in the range of $7.9\text{--}19.5 \mu\text{m}$ made it possible to reconstruct vertical profiles of temperature, NH_3 , C_2H_2 , C_2H_6 concentrations and aerosol characteristics using the nonlinear optimal estimation method (NEMESIS) Irwin et al., 2008 (Bardet et al. 2024).

Our spectral observations of Jupiter’s central meridian showed a good correspondence between the meridional variation of the central depth of the 890 nm methane absorption band and the brightness temperature at a pressure level of 3.5 mbar (Bardet et al. 2024) on May 25, 2018, which will be presented and discussed in our next article.

The Great Red Spot (GRS) is a massive, cold-core anticyclonic structure surrounded by a warm cyclonic ring. The ring, known as a trough, has a high albedo. Anticyclonic circulation within the GRS, combined with interaction with the Jovian zonal wind system, can cause material from the trough to move into a triangular shape north of the GRS with an upper boundary at $\sim 15^\circ \text{S}$. Anticyclonic winds within the GRS gradually decay with height in the lower stratosphere. Cloud clearing within the cyclonic ring at $5 \mu\text{m}$ wavelength suggests that localized lifting within the GRS causes particle deposition at its periphery (Harkett et al. 2024).

Since methane is uniformly distributed in Jupiter’s atmosphere, the 890 nm absorption band serves as a qualitative indicator of cloud-top pressure (Hill et al. 2024). Variations in the height of the atmospheric layer determined by the 890 nm methane band depend on the thermodynamic state of the stratosphere. The near infrared image of the vortex at 890 nm reveals a region of high aerosol reflectivity within the GRS (Harkett et al. 2024). The 890 nm band is sensitive to low pressures and is strongly influenced by high-level haze (Hill et al. 2024). Stratospheric haze absorption is stronger than tropospheric haze at wavelengths longer than 300 nm , since tropospheric haze exhibits relatively weak absorption in the visible range (Harkett et al. 2024). Consequently, tropo-

spheric haze particles act as effective light scatterers (Fletcher 2020).

The 890 nm spectral region is dominated by CH_4 absorption at a level of $\sim 100 \text{ mbar}$; such observations indicate that the bulk of the aerosol within the GRS is lifted to the upper troposphere or lower stratosphere (Harkett et al. 2024). Increasing the lower pressure of the stratospheric haze reduces the reflectivity in the 890 nm filter, since the light travels a longer path and is subject to greater absorption by methane (Anguiano-Arteaga et al. 2023). If we consider the coincidence of the latitudinal variation of temperature and the distribution of methane absorption, it can be noted that the layer of the atmosphere with a pressure less than 10 mbar is sensitive to the 890 nm band.

For the core of the Great Red Spot, the optical thicknesses of the stratospheric and tropospheric haze ($\tau_{\text{stratum}} = 0.25$; $\tau_{\text{tropum}} = 3.85$) and the optical thickness of the lower cloud ($\tau_{\text{cloud}} = 13$) were adopted (Anguiano-Arteaga et al. 2023). In general, for Jupiter, optically thin layers ($\tau \sim 0.1$) above the main tropospheric cloud ($\tau \sim 10$) are considered (Anguiano-Arteaga et al. 2023). The most reliable calculation results are achieved with a variable imaginary refractive index $\lambda < 400 \text{ nm}$, $\tau_{\text{chromophore}}(900 \text{ nm}) = 0.16 \pm 0.05$ for the GRS core and $\tau_{\text{chromophore}}(900 \text{ nm}) = 0.14 \pm 0.06$ for the South Tropical Zone (STrZ) (Anguiano-Arteaga et al. 2023). In all cases, the overlying haze and chromophore layers are taken into account. For comparison, in the single scattering cloud layer model the layer range is from $\sim 780 \text{ mbar}$ to $\sim 900 \text{ mbar}$ (Hill et al. 2024; Anguiano-Arteaga et al. 2023).

The most optimal model includes the following parameters: stratospheric haze with a base at about 110 mbar , $r_{\text{eff}} \approx 0.3 \mu\text{m}$, $\tau \sim 1$, and optically thick tropospheric haze with a base at 500 mbar , average particle size of $0.5\text{--}6 \mu\text{m}$, τ up to 25. Most of the light attenuation occurs at levels above 500 mbar (Irwin et al. 2025). Harkett et al. note that the characteristic of ammonia ice NH_3 is strongly dependent on particle size: smaller radii create sharper absorption, while larger ones create a broad absorption characteristic (Harkett et al. 2024).

5 DISCUSSION

The obtained results demonstrate the complex nature of the interaction of the 890 nm methane band with Jupiter’s atmosphere. The observed correlation between the central absorption band depth and the brightness temperature at levels of $3.5\text{--}8.6 \text{ mbar}$ indicates that variations in the aerosol optical depth in this spectral range are largely controlled by the thermal structure of the atmosphere.

The Great Red Spot region deserves special attention, as the largest discrepancies between the temperature and methane absorption distributions were detected. This highlights the need to account for the unique dynamic structure of the GRS, including vertical and horizontal temperature gradients, updrafts and downdrafts, and local variations in aerosol concentration.

A comparison of ground-based observations (VLT/VISIR) and Juno mission results shows that the GRS is a deep baroclinic structure with a vertical extension from cloud tops to hundreds of kilometers into the atmosphere. This structure has a significant influence on stratospheric dynamics, is supported by a system of zonal jets, and exhibits a stable radiative-dynamical balance.

Overall, the data confirm that the 890 nm methane absorption band is a sensitive tool for studying the upper troposphere and lower stratosphere. The use of multiparameter models, including variations in optical depth, cloud height, and aerosol concentration, allows for a more accurate interpretation of the observed photometric and spectroscopic characteristics.

6 CONCLUSIONS

1 Observations in the 890 nm methane absorption band provide a highly effective method for diagnosing Jupiter's stratospheric haze and upper troposphere, with sensitivity to pressure levels from ~ 5 to 200 mbar.

2 Spectrophotometric measurements of the central depth of the 890 nm band revealed a stable correlation with the brightness temperature of the atmosphere at levels of 3.5–8.6 mbar, which indicates a close relationship between the thermal state and optical properties of the aerosol layer.

3 The largest deviations from the general absorption-temperature relationship are found in the region of the Great Red Spot, which is due to its complex vertical structure and dynamics, requiring the use of multi-layer atmospheric models for interpretation.

4 To further deepen our understanding of the physics of Jupiter's atmosphere, we need joint observational campaigns combining spectrophotometric and filter methods with high spatial resolution, as well as their comparison with data from space missions (Juno, JWST).

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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