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Contents

SPECTRAL VARIABILITY OF THE UNUSUAL AE HERBIG STAR V1295 AQL. I.

H. N. Adigozalzade, U. Z. Bashirova, N. Z. Ismailov

6

ABOUT REGIONAL COSMIC MONITORING OF SNOW COVER IN THE SOUTH-EASTERN REGION OF THE GREATER CAUCASUS

F. I. Ismailov, N. S. Dzhililov, E. E. Humbatova

23

DETERMINING THE PROJECTION OF THE ROTATIONAL VELOCITY OF STARS BY THE SPECTRA OBTAINED AT THE SHAO ECHELLE SPECTROGRAPH

*N. Z. Ismailov, H. N. Adigozalzade, A. B. Hasanova, U. Z. Bashirova,
A. Z. Guliyeva*

30

MHD INSTABILITIES IN SHEAR FLOWS OF ANISOTROPIC COSMIC PLASMAS. I. FIRE HOSE MODES

N. S. Dzhililov, J. H. Samadov

40

THE FUNDAMENTAL PARAMETERS OF THE STAR HR 6725(F2 III)

*Z. A. Samedov, Z. A. Aliyeva, G. M. Hajiyeve
U. R. Rustam, N. H. Samedova*

61

**DYNAMICAL EVOLUTION AND STATISTICS
OF DAMOCLOIDS. 1**

*N. S.Kovalenko, R. A.Guliyev, V. V.Kleshchonok,
A. S.Guliyev*

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SPECTRAL VARIABILITY OF THE UNUSUAL AE HERBIG STAR V1295 AQL. I.

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On the homogenous spectral observations obtained for May-September 2015 season we have obtained some new characteristics of spectral variability of the unusual Herbig Ae star HD190073. It is shown that with an increasing of intensity in the blue absorption component in the profiles of hydrogen lines, the variability of the star's spectrum activated, which indicates the existence at this moment of an increasing in mass ejection from the disk. In a time interval of 98 days of observations, synchronous variability was discovered in these lines with a characteristic time of about 40 days. Monitoring of variations over time in the profiles of the emission components of the H α and H β lines showed that the main variability in the lines occurs on the wings of individual components. The half-width (250 km/s) and full width (350 km/s) at the continuum level of the hydrogen emission lines probably indicate the existence of outflow and accretion of matter from the circumstellar disk.

Keywords: Pre-Main Sequence stars – circumstellar disks –variability – individual HD190073

1. INTRODUCTION

HD190073 (V1295 Aql, MWC325, A2IIIe - B9IIep+sh) is a very remarkable early-type object with emission lines in the visible spectrum. HD 190073 was variously classified as a peculiar Bep star [5] or as an evolved post main sequence A giant [12]. Recently HD190073 has gained recognition as a young Herbig Ae/Be star [10, 26]. In spite of being situated in the constellation of Aquila rather far from well-known regions of star formation, it displays a large far-IR excess due to thermal radiation of cool circumstellar (CS) dust [24]. The energy distribution of

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HD190073 in this spectral region is similar to that of well known Herbig Ae stars, like AB Aur, HD 163296 and HD 31648 [19].

Alicia et al. [4] identified stellar parameters for V1295 Aql. Its magnetic field, $\sim 100\text{G}$, has been detected and confirmed by multiple authors over several years [1, 8, 14, 15]. As described in [4] from MIKE spectra $RV = -1.2 \pm 1.3 \text{ km s}^{-1}$ and $v \sin i = 3.19 \pm 2.45 \text{ km s}^{-1}$, consistent with [3]. Effective temperature is $T_{\text{eff}} = 9250 \pm 250 \text{ K}$, mass is $M = 2.9 \pm 0.5 M_{\odot}$, radius is $R = 3.6 \pm 0.5 M_{\odot}$. With these parameters and assuming star and disk share an inclination of $34^{\circ} \pm 2^{\circ}$ [18], they derive a rotation period of ~ 32 days. As noted in [2], the handful of observed magnetic HAeBe stars are also slow rotators, consistent with V1295 Aql's apparently very slow rotation rate. For the observations spanning multiple years [4], the P Cygni absorption is consistently growing weaker. In 2005 and 2006 dates blue shifted absorption is detectable in $H\alpha$, $H\beta$, $H\gamma$, and $H\delta$, but can only be seen in $H\alpha$ and $H\beta$ thereafter; simultaneously, the emission component's EW is also growing weaker [4]. The Ca II infrared triplet is also dramatically weakening, as are the Na I D lines. The Ca II H and K lines, notable for their complex structure ([22], and references therein), are not seen to vary much on night to-night timescales, or within any given night. In the works [2, 3] were noted spectropolarimetric changes indicating V1295 Aql had a stable, aligned dipole over observations from 2004-2009, but in 2011-2012, variability was observed, indicating a change in the star's magnetic field structure [OI] 6300 Å in particular is of interest, as its driving mechanism remains unclear. Using multi-epoch data in the work [11] noted a relationship between the [OI] emission and the presence of near-IR excess; they suggested the IR excess was indicative of accretion. Line component analysis of [4] time-series data finds that the $H\alpha$ wind absorption component is weakly anticorrelated with the [OI] emission: over the period of observation, the [OI] 6300 Å emission line grew stronger as the wind absorption in $H\alpha$ grew weaker. The [OI] and [Ca II] lines show sharp, violet-shifted features [9, 13]. Additionally, [Fe II] lines appear to be weakly present in emission.

Since in 2015 summary 22 nights of observations carried out during the period June-September, and this is the longest observation season, in first part of the work (article I) we will consider the variability of the star's spectrum for this year separately. In the second part (article II) we will present results of observations for 2016-2023 years and full analysis of the results of investigations.

2. OBSERVATIONS

Observations in 2015 were obtained with the Cassegrain Echelle Spectrograph (CES), which was created on the basis of the UAGS spectrograph [16, 17, 20]. As a detector was used a CCD matrix $530 \times 580\text{px}$, with size of pixels 24 mm devel-

oped at the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences. Observations were made in the λ range 4700-6700 Å. The CES spectrograph obtained a total of 22 pairs of spectrograms suitable for processing with a spectral resolution of 14000. Observations in 2016-2023 carried out using the ShAO Fiber-Echelle Spectrograph (ShAFES), developed jointly by specialists from ShAO and SAO. A detailed description of the technical characteristics of this spectrograph is given in [21]. A CCD STA4150A (USA) with a size of 4096x4096px, with the size of pixel is 15 m, was used. The CCD cooled to a temperature of -120°C using liquid nitrogen. Spectral range $\lambda 3700 - 8000$ Å. Observations were performed with a combination of 2x2 pixels (binning), which allows to obtain a spectral resolution of $R = 28000$.

In just 8 years from 2015 to 2023, for 54 nights high-resolution echelle spectra have been obtained (Table 1). At each observation, spectra of the standard stars HR 7300 (Sp G8II-III) and HR 7734 (Sp F0V) were obtained. In all spectra, the signal to noise level on average reached $S/N = 80 - 100$ in the region of the $H\alpha$ line. The errors in measuring radial velocities for standard stars were 1-1.5 km/s. Positional errors for spectrums with resolution 14000 nearly twice as large. The equivalent widths of the Balmer lines of hydrogen are determined with an precision less than 4 – 5% and in intensities at 0.5%. The equivalent widths of absorption lines less than 0.4 Å was determined with errors at 10%.

Table 1. Obtained spectral material

Period	MJD Range	N	Range (Å)	Spectrograph	R	Mean Exposure (sec)
June 2015 - September 2015	57177.871 - 57275.813	22	4400-6700	CES	14000	900
June 2016 - September 2016	57581.938 - 57640.822	6	3700-8000	ShAFES	28000	1500
June 2017 - August 2017	57951.866 - 57978.781	7	3700-8000	ShAFES	28000	1500
June 2018 - August 2018	58300.871 - 58337.969	5	3700-8000	ShAFES	28000	2500
August 2019	58699.727 - 58719.802	5	3700-8000	ShAFES	28000	2500
June 2020 - August 2020	59034.942 - 59070.8	3	3700-8000	ShAFES	28000	2500
August 2021	59448.809	1	3700-8000	ShAFES	28000	2500
July 2022	59780.881	1	3700-8000	ShAFES	28000	3000
June 2023 - August 2023	60145.789 - 60178.8555	4	3700-8000	ShAFES	28000	3600

3. $H\alpha$ AND $H\beta$ LINES VARIABILITY IN 2015

As can be seen from Table 1, in 2015, 22 nights of observations of the star carried out for June September (MJD 57177.871 - 57275.813). Some of preliminary results of this material published in our works [6, 7].

In the Fig.1, we have presented all profiles of the lines $H\alpha$ and $H\beta$, obtained in 2015. The line $H\alpha$ has one peak emission structure that superimposed a typical absorption profile with good detected absorption component in blue wing-P Cyg profile. For some dates, we can detect weak absorption component in the red wing of $H\alpha$. The emission peak is asymmetric and the peak mainly has positive radial velocity in range $+50 \div 60$ km/s, since bisector radial velocity RVbis (displacement of the line center at the level of the half intensity) shows mainly $\sim +30$ km/s values. As can be seen from Fig.1, emission components in the line $H\beta$ has relatively weak intensity than in the line $H\alpha$. Emission component demonstrated double peak emission with clearly detected central absorption. Both of the line profiles, $H\alpha$ and $H\beta$ is showed variability from night to night.

In the Table 2 have presented some spectral parameters of the $H\alpha$ line: Sp-spectral designation, where each spectra have got as average of two spectra, obtained in the same night in sequence. Next columns are ordinary and modified Julian Date (MJD) dates of observations, EW1a -equivalent

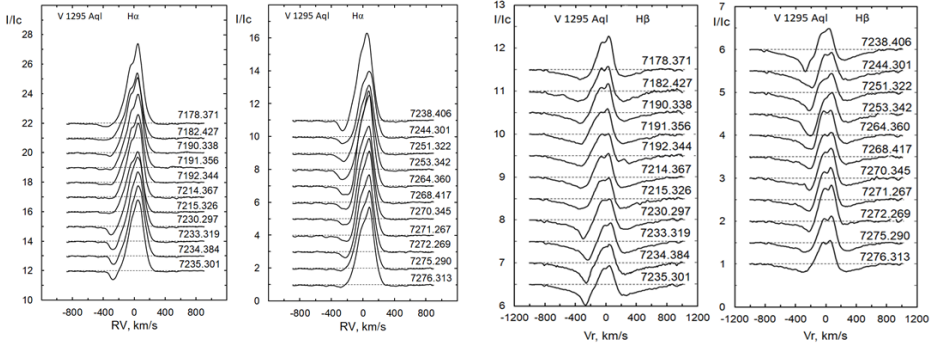


Fig. 1. All obtained profiles of the line $H\alpha$ (left two panels) and $H\beta$ (right two panels) in the spectrum V1295 Aql on the observations for 2015. Dates for each profiles in the figure presented in JD 2450000+

widths of the blue absorption component, EWE- equivalent widths of the emission component, EW2a –equivalent widths of the red absorption component, Ia1, Ia2 relative intensities of the same components, FWHMe - full width at half maximum of intensity of emission component, RVp- the peak radial velocities of the emission component, RVbis –bisector radial velocity of the emission component (the line center displacement at half of the central intensity). In the last two lines of Table 2 have presented mean values and rms (sigma) of these parameters. Spectral parameters of the line $H\beta$ is presented in the Table 3. In this table radial velocities of each components of the line central emission is presented: RV1p and RV2p are the emission component blue and red peaks radial velocities, RVa radial

Table 2. Some measured spectral parameters of the line $H\alpha$ in 2015.

Sp	Date	MJD	EW1a (Å)	Ewe (Å)	EW2a (Å)	Ia1	Ie	Ia2	FWHMe (Å)	RWp (km/s)	RWbis (km/s)
KS 6117-18	15.06 .04	57177.871	1.48	23.89	0.77	0.27	-4.13	0.14	4.66	62.2	27.56
KS 6156-57	15.06 .08	57181.927	1.04	21.15	0.36	0.17	-4.41	0.14	4.36	58.71	24.94
KS 6208-09	15.06 .16	57189.838	1.17	23.69	0.53	0.28	-4.79	0.12	4.96	54.97	24.73
KS 6224-25	15.06 .17	57190.856	1.89	22.7	0.44	0.2	-4.53	0.11	4.44	57.19	28.39
KS 6237-38	15.06 .18	57191.844	1.48	22.33	0.58	0.21	-4.4	0.09	4.53	58.92	29.9
KS 6439-40	15.07 .10	57213.867	1.45	24.17	0.61	0.11	-4.81	0.13	4.66	55.42	23.02
KS 6450-51	15.07 .11	57214.826	1.12	19.64	0.74	0.15	-3.96	0.09	4.5	54.78	18.56
KS 6530-31	15.07 .26	57229.797	2.14	22.35	0.54	0.58	-4.58	0.13	4.65	45.36	23.59
KS 6589-90	15.07 .29	57232.819	2.22	20.91	0.63	0.57	-4.6	0.1	4.42	47.64	30.44
KS 6607-08	15.07 .30	57233.884	2.67	20.81	0.48	0.58	-4.46	0.1	4.31	52.91	36.96
KS 6617-18	15.07 .31	57234.801	1.75	21.63	0.66	0.61	-4.71	0.09	4.6	50.01	28.44
KS 6670-71	15.08 .03	57237.906	1.86	24.02	0.6	0.67	-5.31	0.15	4.31	52.89	28.91
KS 6719-20	15.08 .09	57243.801	2.14	18.08	0.95	0.44	-3.87	0.12	4.64	75.2	49.73
KS 6818-19	15.08 .16	57250.822	2.72	18.75	0.72	0.52	-4.19	0.12	4.34	72.78	43.78
KS 6834-35	15.08 .18	57252.842	2.22	19.72	0.57	0.63	-4.56	0.13	4.27	70.08	40.08
KS 6870-71	15.08 .29	57263.860	2.1	24.6	0.4		-5.67		4.7	61.03	29.51
KS 6903-04	15.09 .02	57267.917	2.39	19.8	0.76	0.43	-4.37	0.14	4.49	58.48	20.4
KS 6937-38	15.09 .04	57269.845	1.21	22.85	0.09	0.33	-5	0.03	4.65	58.04	26.94
KS 6957-58	15.09 .05	57270.767	1.23	24.06	0.29	0.35	-5.3	0.07	4.6	60.23	27.39
KS 6974-75	15.09 .06	57271.767	1.06	21.79	0.17	0.37	-4.71	0.06	4.67	58.66	25.91
KS 7031-32	15.09 .09	57274.790	1.03	27.83	0.29	0.31	-5.87	0.06	4.89	58.64	24.69
KS 7060-61	15.09 .10	57275.813	1.1	22.07	0.6	0.17	-4.7	0.11	5.2	63.02	26.04
Mean			1.70	22.13	0.54	0.38	-4.68	4.59	4.59	58.51	29.09
Sigma			0.56	2.25	0.21	0.18	0.51	1.00	1.00	7.32	7.45

velocity of the central absorption components. Other parameters in Table 3 are the same as in Table 2 for the line $H\beta$.

Figure 2 shows graphs illustrating changes in individual parameters of the $H\alpha$ line. In Fig. 2, individual panels from left to right and from top to bottom shows the time variability in the following parameters: for dates JD 2457230-2455775 we have detected increasing of the parameters EW1a, decreasing of EWe and some red displacement in radial velocities of emission component of the line $H\alpha$. As can be seen from Fig.2, all these parameters are demonstrated variations with characteristic time nearly 45 days. The maximal amplitude of variation of the radial velocity of emission line is about 25 km/s. If we compare the profile variability

Table 3. Spectral parameters of the line $H\beta$ for 2015.

MJD	EW1a (Å)	Ewe (Å)	EW2a (Å)	Ia1	Ie	Ia2	FWHM(Å)	RV1p (km/s)	RV2p (km/s)	RVbis (km/s)	RVa (km/s)
57177.871	1.35	1.98	1.34	0.26	-0.7	0.23	3.07	-27.4	57.1	13.9	3.6
57181.927	1.01	1.96	1.25	0.21	-0.6	0.24	3.3	-32.8	51.0	-3.2	4.2
57189.838	1.21	2.12	1.25	0.26	-0.63	0.22	3.7	-47.3	44.0	-15.4	-6.2
57190.856	1.16	2.03	1.23	0.23	-0.59	0.22	3.81	-39.5	41.4	-23.3	-15.2
57191.844	1.26	1.85	0.9	0.24	-0.51	0.2	3.52	-29.8	52.8	-14.0	5.6
57213.867	1.34	1.79	1.22	0.26	-0.56	0.24	3.43	-61.4	30.9	-29.8	-22.5
57214.826	1.41	1.39	1.66	0.26	-0.43	0.26	3.65	-61.5	38.3	-24.6	-17.2
57229.797	1.7	1.61	1.1	0.44	-0.49	0.21	3.4	-26.3	44.7	-5.0	6.9
57232.819	1.44	1.48	1.28	0.43	-0.49	0.24	3.2	-24.5	43.9	1.6	1.6
57233.884	1.92	1.12	2.06	0.49	-0.39	0.28	2.8	-24.4	37.6	3.8	-7.5
57234.801	2.03	1.35	1.24	0.51	-0.49	0.25	3.2		33.2	-4.4	
57237.906	1.93	1.17	1.52	0.43	-0.43	0.27	2.84	-33.3	36.1	-3.5	-17.4
57243.801	1.92	1.21	1.18	0.39	-0.43	0.21	2.97	-31.0	45.6	8.6	-7.7
57250.822	1.89	1.21	0.94	0.43	-0.42	0.21	3.48		41.6	-4.0	
57252.842	1.93	1.36	1	0.51	-0.5	0.21	2.99	-37.5	48.1	12.1	-4.0
57263.860	1.64	1.63	1.12	0.33	-0.52	0.23	3.4	-61.7	26.4	-19.8	-19.8
57267.917	1.33	1.7	1.21	0.29	-0.5	0.22	3.4	-33.5	52.7	1.8	-2.1
57269.845	1.25	2.25	0.77	0.29	-0.7	0.18	3.6	-14.7	55.0	16.6	11.7
57270.767	1.18	2.42	0.73	0.27	-0.74	0.16	3.44	-55.1	29.0	-16.7	-20.4
57271.767	1.25	2.13	0.89	0.3	-0.64	0.2	3	-32.1	53.5	1.4	8.9
57274.790	0.92	2.13	1.02	0.21	-0.64	0.19	3.38	-39.8	47.4	-0.6	-0.6
57275.813	1.02	1.78	0.96	0.2	-0.53	0.18	3.66	-52.4	33.4	-16.5	-18.4
Mean	1.46	1.71	1.18	0.33	-0.54	0.22	3.33	-38.30	42.89	-5.50	-5.83
Sigma	0.35	0.40	0.31	0.10	0.10	0.03	0.30	14.29	8.53	12.83	11.10

of the $H\alpha$ line with this interval of time variations, demonstrated in the Fig.1, we can make sure that increasing of intensity of blue absorption component and variation of measured spectral parameters occurred simultaneously. In the Fig1 we clear can see that starting from JD 2457230 blue absorption component in $H\alpha$ emission is appeared.

Such structure in emission component is observed up to JD 2457275, total for 45 nights. Interestingly that variability of intensity versus wavelength of the emission component for parameter σ_2 (rms of intensity versus λ) shows double peak structure, which demonstrated that main variability in the structure of

emission, occurred on the both blue and red wings of the line $H\alpha$ (last panel in Fig.2). To make it easier to compare the values of σ_2 with the average intensity for the season, we formally added one to the values of σ_2 . It is indicated that we have observed both ejection and fall of the matter in the circumstellar disc. This argument showed that rather in V1295 Aql we could see some signs of the matter accretion.

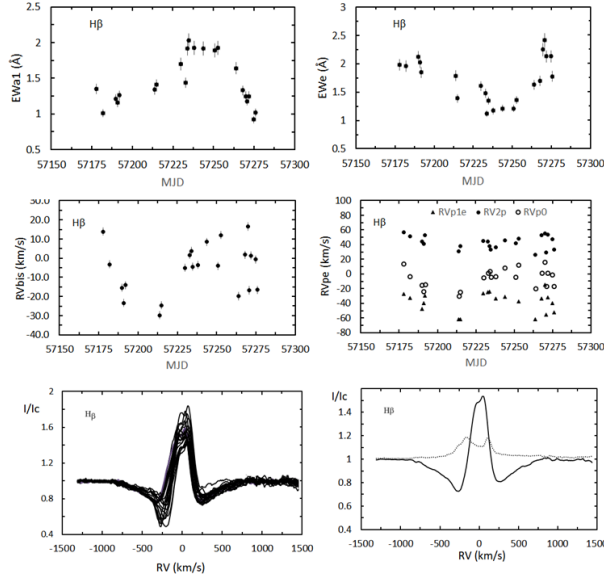


Fig. 2. Variation of spectral parameters (from Table 2) and profiles of the line $H\alpha$. In last panels presented superimposed line profiles (left) and average profile for the 2015. With dotted lines demonstrated rms (σ_λ) of intensity in wavelength. To make it easier to compare the values of σ_λ with the average intensity for the season, we formally added one to the values of σ_λ .

In the Fig. 3 have presented the diagrams, which illustrated time variability of some obtained parameters for the $H\beta$ line. In the panels of Fig. 3 from left to right are presented parameters EW1a, If we look at the profiles of the $H\beta$ lines, which are also shown in the Fig. 1, it is clear that the central emission is superimposed on the normal photospheric profile of the A star with wide Stark wings. Unlike $H\alpha$, the emission intensity in the $H\beta$ line is weaker, so absorption components are clearly distinguished in both the blue and red wings of the emission. As can be seen from Fig.1, the blue and red borders of the emission peak and the entire $H\alpha$ line at the continuum level have a displacement of $\pm 400 - 450$ km/s. If we measure the boundaries of the blue and red wings of the emission component of the $H\beta$ line from the points of intersection with the photospheric wings, then here too the width of the emission component at the continuum level will be about

450 km/s. Of course, as in $H\alpha$, also in the $H\beta$ line, an absorption component with non-photospheric nature can be most likely observed in the blue wing. However, this component cannot be resolved from photospheric absorption in blue wing.

The FWHM of the emission component of the $H\alpha$ line are 225 – 250 km/s, and the line width at the level of 10% of the central intensity was obtained nearly of 350 km/s. The maximum FWHM of the emission component of the $H\beta$ line is ~ 225 km/s, and the full width at the level of 10% of the central intensity, like that of the $H\alpha$ line, is about 350 km/s. As is known, non-accreting objects exhibit narrow ($\Delta V \lesssim 230 - 270$ km/s) and symmetric line profiles of chromospheric origin, while accreting objects have wide ($\Delta V \gtrsim 230 - 270$ km/s) and asymmetric profiles [23, 25]. This is an argument indicating the existence of disk accretion in the star.

A comparison of the profiles of these two lines in the Fig. 1 showed that the absorption structure observed in the blue wing of the $H\alpha$ line shows the outflow of gas from the disk, while the absorption in the blue wing of the $H\beta$ line emission also has a contribution from the photospheric wing.

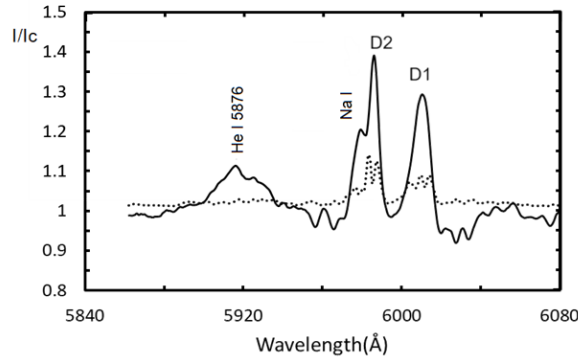


Fig. 3. Variation of spectral parameters (from Table 3) and profiles of the line $H\beta$. In last panels are presented superimposed line profiles (left) and average profile (right) for the 2015. With dotted lines demonstrated rms (σ_λ) of intensity in wavelength.

4. VARIABILITY OF SOME OTHER LINES

The He I 5876 line is observed as a weak and wide emission, whose width at the continuum level reaches 850 – 900 km/s. However, the FWHM of the line is the same as that of the $H\alpha$ and $H\beta$ hydrogen lines (~ 350 km/s). On certain dates, this line exhibits two peaks and a central dip, although more probable a profile with one peak is observed. Figure 4 shows the average line profile for the

lines He I 5876 and Na I D1, D2 averaged over the entire 2015 season. In the same place, the dotted line shows the intensity variation level (rms) in each wavelength, -92 . As can be seen, the central intensity of the He I 5876 line does not show any definite variability.

In the Table 4 is presented the measured parameters of the He I 5876 line. In the columns of Table 4 from left to right have shown the dates of observations in MJD, equivalent widths EW($\text{\AA}$), central intensities I_e , full width at half maximum FWHM ($\text{\AA}$), radial velocities of the largest emission peak RVp(km/s), bisector radial velocity RVbis (km/s). To add the provided data to a 'longtable' with a caption and label in LaTeX, you can use the following code:

Table 4: Some measured parameters of the He I 5876 line.

MJD	EW ($\text{\AA}$)	I_e	FWHM ($\text{\AA}$)	RVp (km/s)	RVbis (km/s)
57177.871	1.05	-0.13		-44.46	-36.51
57181.927	0.48	-0.10	5.35	-39.74	-33.76
57189.838	0.49	-0.11	5.03	-43.84	-23.01
57190.856	0.59	-0.12	5.80	-40.80	-24.28
57191.844	0.84	-0.13	7.30	-41.00	-5.56
57213.867	0.50	-0.10	4.79	-45.69	-20.50
57214.826	0.45	-0.08	6.33	5.76	-25.43
57229.797	0.50	-0.10	6.99	-42.38	-10.12
57232.819	0.67	-0.10	6.90	-50.34	-19.00
57233.884	0.89	-0.14	6.90	-41.78	-5.31
57234.801	1.01	-0.15	5.96	-38.48	4.43
57237.906	0.55	-0.13	4.93	-47.48	-28.49
57243.801	0.43	-0.14	4.32	-49.79	-20.86
57250.822	0.62	-0.14	6.00	-53.14	-24.37
57252.842	0.55	-0.12	5.28	-52.22	-18.52
57263.860	0.82	-0.18	6.47	-62.33	-24.56
57267.917	0.83	-0.13	6.82	-33.93	-15.69
57269.845	1.17	-0.14	6.62	-43.03	-30.77
57270.767	0.64	-0.09	6.40	-16.01	-10.25
57271.767	0.80	-0.10	6.53	-11.52	-34.61
57274.790	0.62	-0.11	6.48	-64.86	-26.52
57275.813	1.01	-0.14	7.50	-10.43	-24.80
Mean	0.71	-0.12	6.13	-39.43	-20.84
Sigma	0.22	0.02	0.88	17.14	10.34

The sodium doublet lines NaI D1, D2 are exhibit double peak emission with central absorption. In the Figure 4 next to the He I 5876 line we show the average D Na I line profiles for 2015. The dotted line there also shows variation in the parameter σ_2 along the wavelength. As can be seen, the maximal variations in both D1 and D2 lines is detected in the strongest red component, which also as a hydrogen emission lines exhibits double peaks in the σ_2 distribution.

In the Figure 5 is shown a graphs of time variations in the equivalent widths and bisector radial velocity of the He I 5876 line. As can be seen in Figure 4, in some nights there is a certain scatter around

the average value, while in whole observation season 2015 the average value does not show significant variations in time. As can be seen in Fig.5, the He I and [OI] emission lines parameters show a weak scatter, in which the wave-like variability is not as clearly expressed as in the hydrogen and other lines.

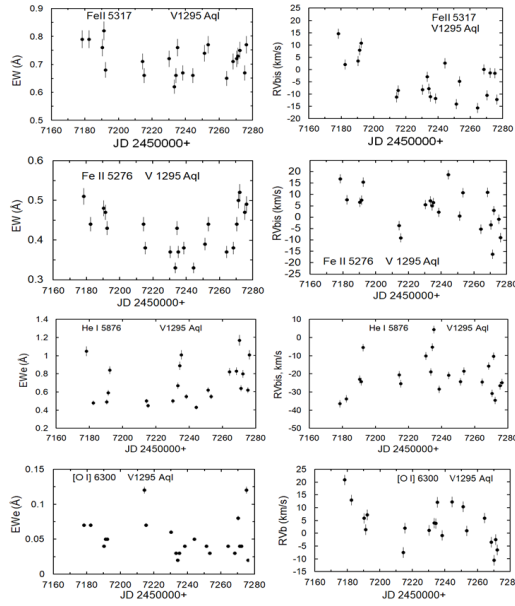


Fig. 4. From top to bottom time variations of the equivalent width and bisector radial velocity of lines Fe I 5317, 5276, He I 5876 and [O I] 6300.

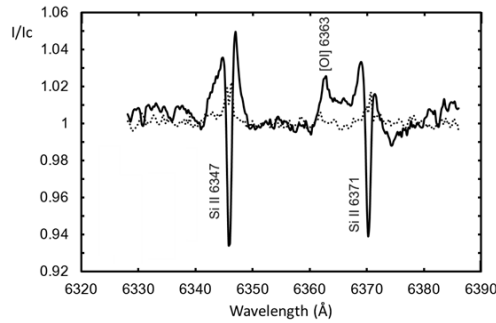


Fig. 5. Mean seasonal profiles of the He I 5876 and Na I D1, D2 emission lines for 2015. Dotted lines indicated variation level of intensity σ_λ along the spectral lines.

5. SI II DOUBLET LINES 6347 AND 6371.

The Si II 6347 and 6371 lines are one of the most intensive and, in terms of their profile, typical spectral lines in the spectrum of the star. In the Figure 6 is shown the Si II doublet lines averaged over

the 2015 season, as well as the forbidden line [OI] 6363. As can be seen, the line has a double emission peak with a deep and narrow central absorption. The dotted line shows variation in intensity along the spectral line. It can be seen that the greatest variations in intensity is observed in the central part of the line. As can be seen from Table 5, the blue and red components, respectively, have negative and positive velocities, and the central absorption shows RVbis close to the radial velocities of the stellar photosphere. At the continuum level, both emission components together are expanded up to 350 km/s, and the FWHM of the central absorption corresponds to a vsini at ~ 30 -35 km/s. In the Figure 7

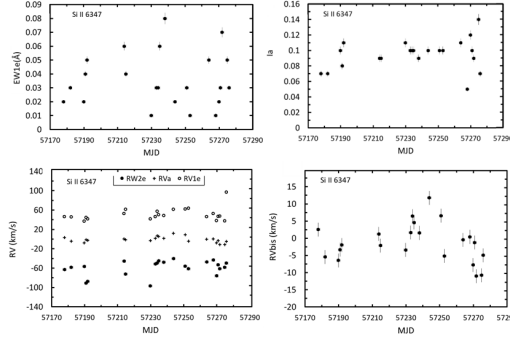


Fig. 6. Average line profiles of Si II 6347, 6371, as well as their standard deviation from the average σ_λ (dashed line).

is shown time variations diagrams in some parameters used from Table 5. As can be seen from this figure, the largest variability have observed for the parameters of the blue emission component. Radial velocities for individual components also shows a variation in range from 5 (for absorption component) to 40 km/s (for blue emission component) for various components.

From Fig. 7 it is clearly seen that the variations in the parameters EW1e and RVbis in the range of dates MJD 57230-57270 exhibit a wave-like smooth variation with characteristic time scale of about 40 days. Note that a similar variation is clearly visible in the hydrogen emission lines $H\alpha$ and $H\beta$. The data in the line Si II 6371 shows the same results as the Si II 6347 line. In the Figure 4 have shown graphs

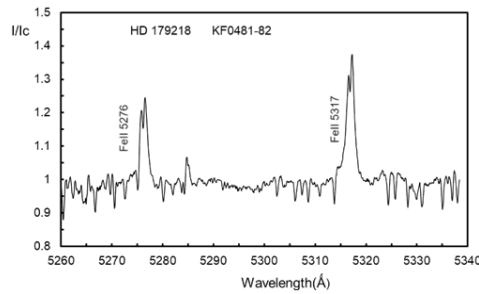


Fig. 7. Time variability of parameters of spectral line SiII 6347: from left to right and from top to bottom – EW1e, I_a , RV2e (open circles), RVa (crosses), RV1e (dark circles). In right panel RVbis for central absorption component for the line SiII 6347.

of time variations of equivalent widths (left panels) and radial velocities (right panels) for individual emission spectral lines FeII 5317, 5276, HeI 5876 and [OI] 6300. The FeII lines exhibit smooth variations in the observed parameters. For lines, He I 5876 and [OI] 6300 obtained some level scatter of measured

Table 5. Some spectral parameters of the line Si II 6347

MJD	EW1e Å	EWa Å	EW2e Å	Ie1	Ia	Ie2	RV1e km/s	RVa km/s	RV2e km/s	RVbis km/s	FWHM Å
57177.871	0.02	0.05	0.03	-0.02	0.07	-0.03	-62.82	3.21	46.29	2.54	0.69
57181.927	0.03	0.05	0.01	-0.02	0.07	-0.02	-58.43	-4.26	45.95	-5.44	0.84
57189.838	0.02	0.07	0.03	-0.03	0.1	-0.04	-56.36	-7.91	36.9	-6.46	0.78
57190.856	0.04	0.06	0.04	-0.02	0.08	-0.05	-90.85	-1.71	44.78	-3.33	0.8
57191.844	0.05	0.1	0.03	-0.04	0.11	-0.03	-87.56	-2.47	41.44	-1.96	0.89
57213.867	0.06	0.05	0.05	-0.06	0.09	-0.05	-45.33	0.32	52.44	1.24	0.68
57214.826	0.04	0.08	0.01	-0.03	0.09	-0.01	-72.13	-1.28	61.11	-2.11	0.96
57229.797	0.01	0.09	0.03	-0.02	0.11	-0.03	-96.58	-3.39	41.73	-3.39	0.89
57232.819	0.03	0.08	0.01	-0.04	0.1	-0.02	-51.43	1.66	45.97	1.66	0.8
57233.884	0.03	0.06	0.06	-0.03	0.1	-0.05	-49.57	6.45	57.4	6.45	0.64
57234.801	0.06	0.06	0.03	-0.04	0.1	-0.04	-44.84	5.69	50.62	4.58	0.74
57237.906	0.08	0.06	0.02	-0.06	0.09	-0.02	-47.54	1.56	48.42	1.56	0.73
57243.801	0.02	0.08	0.03	-0.02	0.1	-0.04	-40.18	11.78	61.55	11.78	0.94
57250.822	0.03	0.09	0.03	-0.04	0.1	-0.03	-56.01	8.71	62.15	6.56	0.9
57252.842	0.01	0.08	0.01	-0.04	0.1	-0.02	-61.4	-4.48	63.76	-5.15	0.87
57263.86	0.05	0.08	0.02	-0.03	0.11	-0.03	-47.29	-0.45	46.32	-0.45	0.8
57267.917	0.01	0.03	0.03	-0.02	0.05	-0.03	-43.35	0.4	52.43	0.4	0.7
57269.845	0.02	0.08	0.04	-0.02	0.12	-0.04	-75.9	-7.76	38.12	-7.76	0.76
57270.767	0.03	0.07	0.08	-0.03	0.1	-0.07	-52.92	-3.01	46.83	-1.23	0.8
57271.767	0.07	0.05	0.09	-0.01	0.09	-0.05	-61	-11.45	47.34	-11.01	0.78
57274.79	0.05	0.11	0.01	-0.01	0.14	-0.02	-58.47	-11.59	37.48	-10.76	0.87
57275.813	0.03	0.04	0.07	-0.03	0.07	-0.06	-49.76	-4.93	96.89	-4.93	0.7
Mean	0.04	0.07	0.03	-0.03	0.10	-0.04	-59.53	-1.13	51.18	-1.24	0.80
Sigma	0.02	0.02	0.02	0.01	0.02	0.02	15.82	6.01	13.00	5.67	0.09

parameters around mean values.

The star's spectrum exhibit numerous lines of single ionized and neutral iron, most of which has double-peak profiles with weak central absorption. These are lines Fe II 5317, 5276, 4924, 4957, 5018, 5169, 5197 and others. A typical profile for a pair of lines FeII 5317, 5276 is shown in Fig. 7.

As can be seen, the line profile is mainly demonstrated an double peak emission with central absorption, and on some dates, weak narrow absorption components are detected on the blue wing. It is well known that similar profiles of emission lines of Fe II ions in the spectrum of a star has been observed in the flare spectrum of the solar chromosphere. Some measured parameters of the line Fe II 5317 presented in the Table 6. In the Fig.4 time variations of equivalent widths (left panels) and radial velocities (right panels) of the emission lines Fe II 5317, 5276 are presented. Both lines demonstrated large scatter of parameters from average value and smooth variation in time.

FWHM of these lines is nearly 1.8-2 Å (Table 6), so this equivalent to width 110-120 km/s. On the stellar continuum level these emission lines has maximal width at 200 km/s.

Table 6. Some spectral parameters of the line Fe II 5317.

MJD	EW(Å)	Ie2	FWHM(Å)	RV2e (km/s)	RVbis (km/s)
57177.871	0.79	-0.42	1.66	16.6	14.5
57181.927	0.79	-0.40	1.71	12.0	2.1
57189.838	0.76	-0.39	1.80	10.9	3.5
57190.856	0.82	-0.42	1.60	17.2	7.9
57191.844	0.68	-0.36	1.63	19.2	10.7
57213.867	0.71	-0.31	2.03	6.3	-11.3
57214.826	0.66	-0.29	1.95	1.1	-8.5
57229.797	0.72	-0.29	1.85	0.1	-8.2
57232.819	0.62	-0.27	2.06	11.9	-2.9
57233.884	0.66	-0.29	2.07	12.9	-7.8
57234.801	0.76	-0.30	2.30	8.9	-11.0
57237.906	0.67	-0.27	2.31	-13.4	-11.7
57243.801	0.66	-0.29	2.12	22.0	2.6
57250.822	0.74	-0.30	2.10	-8.7	-14.0
57252.842	0.77	-0.32	2.10	8.9	-4.7
57263.860	0.65	-0.30	1.85	-7.1	-15.6
57267.917	0.71	-0.30	2.20	13.2	0.1
57269.845	0.72	-0.30	1.96	4.5	-10.5
57270.767	0.73	-0.30	1.80	-10.9	-24.2
57271.767	0.75	-0.33	2.00	3.8	-1.4
57274.790	0.67	-0.31	1.94	2.2	-1.5
57275.813	0.77	-0.30	2.10	-9.8	-12.2
Mean	0.72	-0.32	1.96	5.54	-4.73
Sigma	0.05	0.05	0.20	10.35	9.32

6. DISCUSSION AND CONCLUSIONS

Our long-term spectral observations of the star in 2015 made it possible to identify a number of new characteristics of the star's spectrum and features of spectral variability in the unusual Herbig Ae star V1295 Aql. Below we briefly list the main results that were obtained in our work using these data.

1. We were able to trace the progress of variations in the profiles and spectrophotometric parameters of the emission components of the $H\alpha$ and $H\beta$ hydrogen lines. It is shown that with an increase in the blue absorption component in the profiles of hydrogen lines, the variability of the star's spectrum increases, which indicates the existence at this moment of an increase in mass ejection from the star. In a time interval of 98 days of observations in 2015, synchronous variability was discovered in these lines with a characteristic time of about 40 days.
2. All other spectral lines showed a synchronous smooth variation in spectrophotometric parameters with the lines of hydrogen $H\alpha$ and $H\beta$. For different lines, the magnitude of the amplitude of variations in different parameters differs.
3. Monitoring variations over time in the profiles of the emission components of the $H\alpha$ and $H\beta$ lines

showed that the main variability in the lines occurs on the wings of individual components. The half-width (250 km/s) and full width (350 km/s) at the continuum level of the hydrogen emission lines probably indicate the existence of outflow and accretion of matter from the circumstellar disk.

4. It has been shown that the intensities of the lines He I 5876 and [O I] 6300, 6363 do not show significant variations versus time. Apparently, the He I 5876 line is formed in the stationary part of the disk, and the [OI] lines are formed in the outer rarefied part of the circumstellar disk. However, the weak synchronous variability of the [O] lines with the hydrogen lines indicates their sensitivity to the main mechanism of variability of the star's spectrum.

5. Lines D1, D2 NaI show double peak emission, with a dominant red component in intensity. The main variability in these lines is found only in the red wing. Since on some dates it is impossible to resolve the blue component in the D1 line, and the red component shows significant variability, this indicates the formation of these lines mainly in the zone of accretion of matter to the star.

6. Si II lines 6347, 6371 show a double emission peak with a deep central absorption, which has a width of 32 km/s, which significantly exceeds the rotation speed $v_{\text{ini}} \sim 3.2$ km/s obtained in the work of [3]. Perhaps this line component has an additional contribution from Boltzman expansion in a higher temperature environment (self-absorption).

7. FeII lines have a two-component emission peak with weak central absorption. This structure applies to most emission spectral lines. Perhaps the star has a powerful chromosphere, where similar spectral lines can form.

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ABOUT REGIONAL COSMIC MONITORING OF SNOW COVER IN THE SOUTH-EASTERN REGION OF THE GREATER CAUCASUS

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A methodological approach to space monitoring of snow cover in the south-eastern region of the Greater Caucasus is considered. Based on the Landsat 9 image data, an index image was constructed for the winter season and a classification of snow cover was carried out.

Keywords: space monitoring – south-eastern region of the Greater Caucasus
–snow cover

1. INTRODUCTION

The current stage of development of space research is characterized by the regular use of satellite data to obtain prompt and accurate information about the state of the environment both at the local and global levels. These studies are based on Earth remote sensing (ERS) methods. These methods are based on spectrophotometric measurements of the energy characteristics of the reflection of sunlight from the “atmosphere – earth’s surface” system [1, 6]. Remote sensing data are indispensable sources when studying natural phenomena in remote mountainous areas. Current problems of remote sensing include issues of cartographic modeling of snow cover using geoinformation systems technologies. Modeling the snow cover of mountain peaks is one of the stages of modeling the hydrological cycle as a whole [2, 6]. In this work, a comprehensive study of snow cover is carried out using data from the Landsat 9 satellite for the South-Eastern region of the Greater Caucasus. This region is famous for its Shollar water (spring water pro-

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duced in the village of Shollar, Khachmaz region of the Republic of Azerbaijan) [7].

2. METHOD OF CALCULATION

Data obtained from satellites is initially considered an unprocessed or “raw” product [6]. Processing of spatial images is divided into several stages. (fig. 1) [1–3]: - obtaining unprocessed (raw) images;

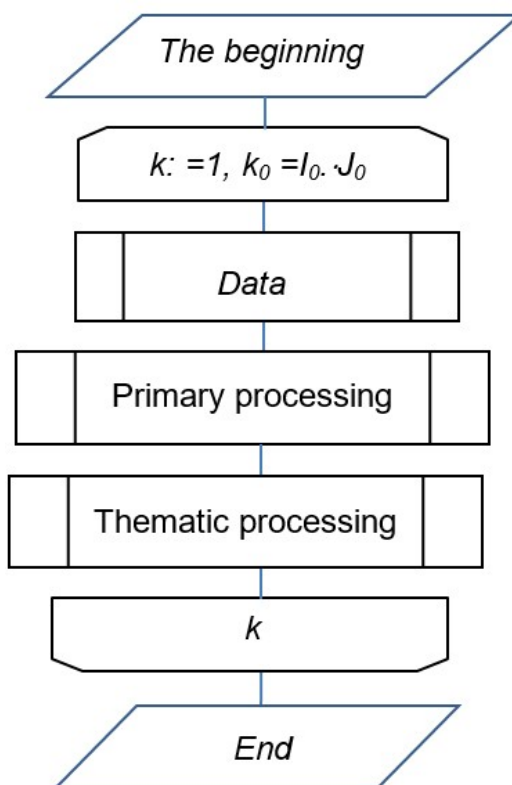


Fig. 1. Block diagram of spatial image processing.

- pre-processing (level 0): image restoration of fuzzy areas, sorting data in chronological order with full resolution and saving all auxiliary data;
- pre-processing (level 1): geometric, radiometric and atmospheric correction;
- secondary processing (level 2): determination of spectral characteristics, spatial structure and temporal changes of observed objects (for example, classification and decoding of an object or area);

– detailed integrated processing (level 3): data generation, thematic processing of aerospace data.

As can be seen from fig. 1, processing of remote sensing data is reduced to thematic processing of images of the earth's surface. This procedure includes image indexing and classification of the earth's surface. The main purpose of this procedure is to map the soil cover.

Indexing of images is based on the calculation of special indices - indicators calculated as a result of arithmetic operations (addition, subtraction, division, multiplication) over different spectral ranges (channels) of remote sensing data, characterizing the reflective and absorption features of the soil cover in a given pixel of the image [2–4] or indexing images are derived mainly empirically [1].

Snow typically has very high visible reflectivity (VIS) and very low short-wave infrared (SWIR) reflectivity. This feature is used for snow detection by distinguishing between snow and most types of clouds [2, 3]. We believe that the reflective properties of the earth's surface are most fully described by the spectral brightness coefficient (SBC) [1]:

$$\rho_{\lambda}(\mu_0, \mu) = L_{\lambda}(\mu_0, \mu) / S_{\lambda 0} \cdot \mu_0 \quad (1)$$

where $\rho_{\lambda}(\mu, \mu_0)$ is the SBC of the underlying surface of the Earth, $L_{\lambda}(\mu, \mu_0)$ [W/(m² · μm · sr)] is the spectral brightness of direct solar radiation at the upper boundary of the atmosphere at radiation wavelength λ , $S_{\lambda 0}$ is the spectral solar constant, μ_0 and μ are direction cosines, respectively, the zenith angle of the Sun and the zenith angle of the observation direction.

To probe snow cover, the NDSI index (Normalized Differential Snow Index) is used [6]. Instead of the characteristic $L_2(\mu, \mu_0)$ we use SBC, then we can write:

$$NDSI = \frac{\rho_{\text{Green}} - \rho_{\text{STIR}}}{\rho_{\text{Green}} + \rho_{\text{SWIR}}} \quad (2)$$

where Green is the amount of green light with a wavelength of 0.525 - 6 mkm reflected from the area; SWIR is the amount of short-wave light with a wavelength of 1.56 - 1.66 mkm reflected from the same area. Classification (decoding) of the earth's surface as a method of environmental research is based on the relationship between the physical characteristics of natural objects and phenomena and the way they are reproduced in photographs [1, 2]. Classification of objects is carried out according to certain classes of objects to which they belong. To do this, the so-called decision function $i = f(x)$ is introduced, where i is the number of the class to which the feature vector x of the recognized object belongs. This function

is constructed based on partitioning the feature space U into i_0 disjoint classes $U_i, i = 1, \dots, i_0$:

$$\bigcup_i^{i_0} U_i = U, U_i \cap U_j = \emptyset \text{ at } i \neq j \quad (3)$$

The decision function $f(x)$ is used to determine the number i of the region U_i to which the argument x belongs. The criterion for choosing this function can be the minimum identification error. To carry out procedure (3) we use GIS programs.

We consider the use of a regional model of the optical atmosphere as an important condition for the use of formulas (2) and (3), since, as is known, the atmosphere is a significantly distorting factor in the deciphering characteristics of the earth's surface. We solve this problem by using a regional model of the atmosphere of the Caucasus-Caspian region given in [1, 5].

3. CALCULATION RESULTS

First of all, we will take into account the influence of the atmosphere on the rising solar radiation perceived by the sensor on board the satellite. Fig. 2 defines a two-dimensional space of spectral features of the territory of the south eastern region of the Greater Caucasus on the Green and SWIR axes. Due to the disproportionality of the readings in fig. 2, it follows that the effect of the atmosphere of the Green and SWIR channels is significant. Fig. 3 shows the vertical structure of the optical thickness of the atmosphere for the effective wavelength of solar radiation (green light) using an optical model of the atmosphere [1, 5]. The cases of reflection from the water surface and land are considered. The first case corresponds to the case of atmospheric correction of satellite images using the DOS (Dark Object Subtraction) method [6]. We use this case to reconstruct the vertical structure of the atmosphere over land.

In accordance with the scheme of fig. 1, further, indexing (fig. 4) and classification fig. 5 of the satellite image were carried out. Fig. 4 shows the calculated snow areas. The case we are considering corresponds to the case of heavy winter snow (01/31/2024).

Fig. 5 shows the classification of soil cover using a false-color image (table). As can be seen from this figure, the soil cover depends on the terrain. This dependence gives a complete picture of the regional climatic conditions characteristic of the area in question (shown by color characteristics). In accordance with the figure, snowfall on the date in question covers mountainous and foothill areas.

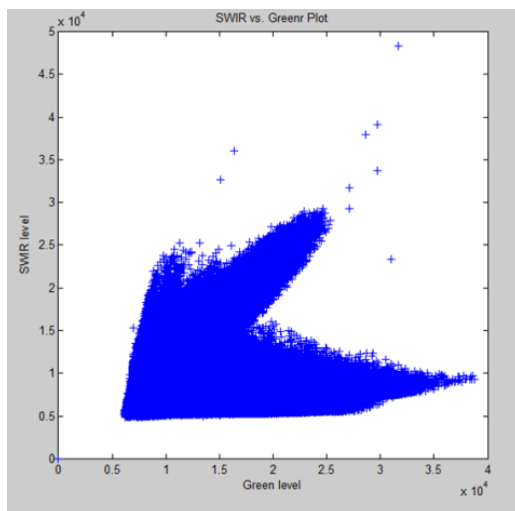


Fig. 2. Two-dimensional space of spectral features of images *LC09_L1TP_167032_20240131_20240131_02_T1_B3*, and *LC09_L1TP_167032_20240131_20240131_02_T1_B6*.

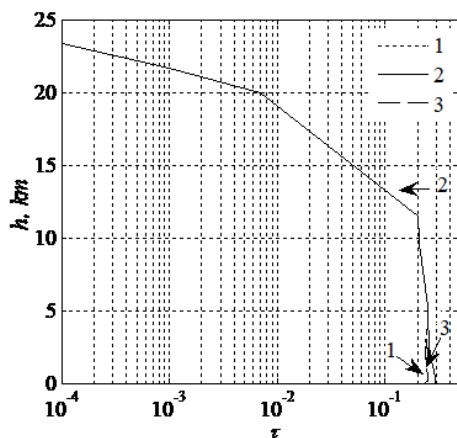


Fig. 3. Vertical profiles of the optical thickness of the atmosphere according to satellite imagery for: 1- the middle part of the Caucasus (the region of the Greater Caucasus), 2- Eastern part of the Caspian Sea, 3- southeastern part of the Caspian Sea (*LC09_L1TP_167032_20240131_20240131_02_T1_refl*).

4. CONCLUSION

1. A step-by-step method for space monitoring of the southeastern slopes of the Greater Caucasus is given. in winter .

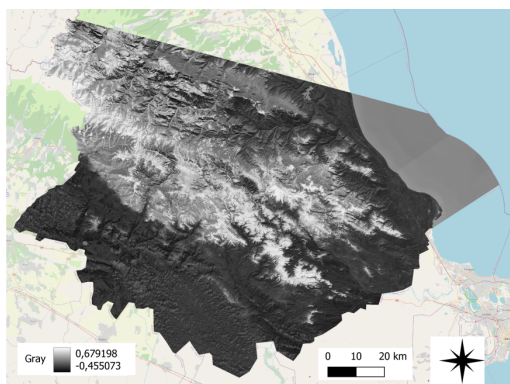


Fig. 4. NDSI for the southeastern Greater Caucasus region
LC09_L1TP_167032_20240131_20240131_02_T1_B3,B6: Thick snow cover
 $-770 km^2$, Thin snow cover $-1533 km^2$

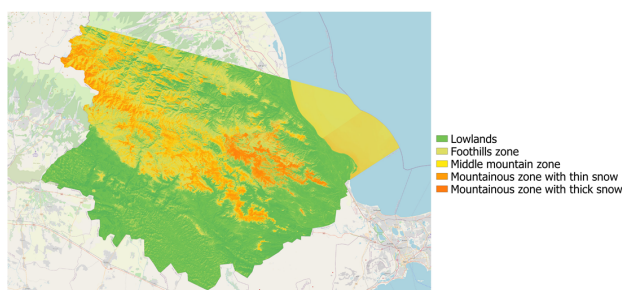


Fig. 5. The south-eastern region of the Greater Caucasus: Earth surface classification
(LC09_L1TP_167032_20240131_20240131_02_T1_refl).

Table 1. Image color conversion [1]

Image bands	Water color	Snow color	Soil color
Near IR, R, G	Black	Red	Gray blue

2. Indexing and classification of the Landsat 9 satellite image in the winter period (01/31/2024) was carried out.

3. Thematic maps were compiled and the areas of snow cover distribution were calculated.

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DETERMINING THE PROJECTION OF THE ROTATIONAL VELOCITY OF STARS BY THE SPECTRA OBTAINED AT THE SHAO ECHELLE SPECTROGRAPH

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In this study, methodological work has been developed and applied to determine the projection of the rotation velocity of stars from echelle spectra with a resolution of $R = 28000$, obtained at the Cassegrain focus of the 2 m ShAO telescope. To determine the instrumental contour, blend-free lines from the comparison spectrum of the calibration lamp were used. The instrumental contour was obtained with a FWHM of lines as $\Delta\lambda = 0.15 \pm 0.02 \text{ \AA}$. Test measurements for 11 stars with different spectral types showed satisfactory agreement with previously measured data except for the HAe star HD179218. A formula has been obtained for determining the projection of the rotation velocity for a given spectrograph, which allows one quite accurately to determine this parameter for different stars.

Keywords: stars–stellar rotation rates–spectroscopy–peculiarity

1. INTRODUCTION

As is known, one of the most important physical parameters of stars is the projection of the rotation velocity in the direction to the line of sight $v \sin i$, where v is the rotation velocity at the equator, and i is the inclination angle of the rotation axis to the line of sight. Since the angle i is not always known, the measurement result always shows the minimum value of the star's rotation velocity. The rotation velocity is most accurately determined by comparing the profiles of

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lines observed in the spectrum with synthetic profiles. However, for most of the objects on our list there are no accurate estimates of the atmospheric parameters (Teff, log g) necessary to build an adequate model. A way out of this situation can be the use of Fourier analysis of profiles. However, this method can produce very different errors for different rotation rates (line profile widths) and is best suited for measuring $v \sin i$ in rapidly rotating stars. Therefore, to obtain rotation rates, we used the classical method based on measurements of the half-width of spectral profiles (Full width at half maximum - FWHM) [1]. We applied the classical method, which is based on measuring the exact half-width of the narrowest photospheric lines in the spectrum of the star.

2. OBSERVATION AND RESULTS

Spectral observations of a group of standard stars, as well as some stars with emission lines in the spectrum, were carried out on the 2 m telescope of the Shamakhy Astrophysical Observatory named after Nasiraddin Tusi. An echelle spectrograph ShAFES was used as a light detector, operating in combination with a STA4150A CCD camera with $4K \times 4K$ elements [2,3]. The CCD matrix is cooled with liquid nitrogen to a temperature of -120°C . Observations were performed in the range $\lambda 3700 - 9000$. The spectral resolution is $R = 28000$. Reduction and calibration of the spectrograms is performed in the DECH programs. The observational devices, processing programs and method of observations were described in more detail in the work [2,3].

To determine the half-width of the instrumental contour $\delta\lambda$, unblended lines of the spectrum of the ThAr lamp were used. From the available 70 echelle orders suitable for processing, 10-12 ThAr spectral lines were selected every 5 orders, from which the half-widths of the lines were determined. Then, for each order, the mean and standard deviation from the mean were determined. Thus, across the entire spectrum in steps of 5 orders of the ThAr spectrum, the parameter $\delta\lambda$ was determined. Figure 1 shows a graph of the dependence of the instrumental profile for different echelle orders of the spectrum. As can be seen, there is a tendency for the instrumental profile to slightly increase with increasing order number.

If we average the half-widths over orders, then for the half-width of the instrumental contour we obtain $\delta\lambda = 0.15 \pm 0.02$. In the future, we will take this value into account when determining the half-widths of individual spectral lines from stellar spectra.

For each star, two pairs of spectra were obtained, which, after calibration, were averaged for each night of observations. Next, the half-widths of selected

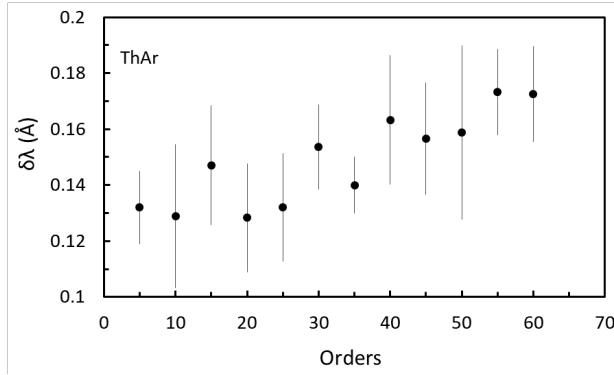


Fig. 1. . Graph of distribution of instrumental profile for echelle orders. Vertical bars show the standard deviation from the mean in orders.

spectral lines were measured for all stars. When calculating the rotation velocity, a formula was applied taking into account the instrumental contour in the line:

$$v \sin i = c(\text{FWHM} - \delta\lambda)/\lambda_0 \quad (1)$$

where c , is the velocity of light, FWHM is the half-width of this line in angstroms, $\delta\lambda$ is the instrumental contour, and λ_0 is the laboratory wavelength of the line. The results of our measurements are given in Table 1 for each star.

Table 1 provides a list of test standard stars and some stars with emission lines in the spectrum. The list also includes two Herbig Ae (HAe) stars HD 179218 and HD 190073, for which clarification or redefinition of the rotation velocity projection is of particular importance. The fact is that it is very important to know the angle of inclination of the rotation axis i of stars AeBe Herbig in order to correctly interpret the observed cyclic variability in the spectrum and brightness of these stars.

The columns of Table 1 from left to right show the serial number, the name of the star according to HD, another name of the star, spectral type, $v \sin i$ values taken from the literature and obtained in this work, and a link to the literary source for the $v \sin i$ parameter. The remaining data for each star is collected from the SIMBAD astronomical database. To measure the half-widths in the spectrum of each star, from 15 to 40 of the narrowest absorption lines of metals were selected. Table 2 shows, as an example, the results of half-width measurements in the spectra of the stars α Lyr and HR 8474. From left to right in the columns of Table 2, the list of elements, wavelength of spectral lines, FWHM, projection of rotation velocity and results for the selected smallest values of the parameter $v \sin i$, and further, the same parameters for the star HR 8474 are given. The last row of Table 2 shows the average values $v \sin i$ and the standard deviation from the average $\pm \sigma$. Despite the large number of measured lines, we selected the results for those lines for which the FWHM value is the smallest. Obviously,

Table 1. List of observed test stars.

No	Stars	Other Name	Sp	vsini (liter)	vsini (in this work)	Literature
1	HD172167	alpha a Lyr a	A0V	25	26	4
2	HD 1280	tet And	A2V	125	102	5
3	HD210884	HR8474	F2V	43	33	6
4	HD208501	13 Sep	B8Ib	40	28	7
5	HD187982	-	A3Ia	45	33	8
6	HD198478	55 Cyg	B2IIa	38	16	8
7	HD141513	mu Ser	B9.5III	96	80	7
8	HD14489	iPer	A1Ia	33	31	7
9	HD163506	89 Her	F2Ibp	25	25	9
10	HD179218	HWC 614	A0Ve	69	101 :	10
11	HD190073	V1295 Aql	A2III-IVe	3	8	10

the lower limit of the half-width values should be free from additional expansion, for example, by blending with other lines, or expansion due to surface activity such as pulsation. Here's the updated and complete table using the 'longtable' environment, including the new entries:

Table 2: Results of measurements of FWHM of spectral lines for α Lyr and HR 8474.

		Vega			HR 8474		
Atoms	Wavelength (Å)	FWHM(Å)	vsini (km/s)	Selected	FWHM(Å)	vsini (km/s)	Selected
MgII	4481.13	0.59	29.32		0.79	43.11	
FeI	4045.82	0.48	24.47	24.47	0.88	54.28	
TiII	4053.83	0.68	39.44		0.79	46.99	
MgI	4057.51	0.61	33.94		0.90	55.08	
FeI	4063.60	0.54	28.50		0.69	40.16	
FeI	4071.75	0.50	25.86	25.86	0.61	33.74	33.75
SrII	4077.72	0.49	25.16	25.16	0.65	36.56	36.57
FeI	4118.55	0.69	39.55		0.83	49.31	
FeI	4122.52	0.52	26.85	26.85	0.60	32.38	32.38
VI	4128.08	0.48	24.20	24.20	0.82	48.55	
SiI	4130.86	0.48	23.82	23.82	0.65	36.17	

Atoms	Wavelength (Å)	FWHM(Å)	vsini (km/s)	Selected	FWHM(Å)	vsini (km/s)	Selected
FeI	4143.87	0.70	39.89		0.97	59.65	
TiII	4163.65	0.57	29.90		0.64	35.38	35.38
MgI	4167.28	0.66	36.64		0.66	37.00	
FeI	4171.91	0.57	30.49		0.59	31.78	31.78
FeII	4173.47	0.53	27.39	27.39	0.83	48.59	
FeII	4178.86	0.55	28.64				
FeI	4202.04	0.63	34.27		0.72	40.69	
SrII	4215.53	0.57	29.53		0.95	56.72	
CaI	4226.73	0.63	34.28		0.85	49.97	
FeII	4233.17	0.55	27.99	27.99	0.91	53.72	
CrII	4242.38	0.55	27.93	27.93	0.75	42.43	
ScII	4246.84	0.57	29.53		0.85	49.24	
CrII	4254.34	0.61	32.16		0.64	34.62	34.62
FeI	4260.48	0.73	40.56		0.81	46.33	
FeI	4271.77	0.57	29.43		1.10	66.93	
TiII	4290.22	0.57	29.44		0.72	39.65	
FeI	4294.12	0.55	28.08		0.63	33.32	33.32
FeII	4296.58	0.52	25.90	25.90	0.66	35.68	35.68
TiII	4300.05	0.57	29.37		0.98	57.63	
TiII	4301.93	0.81	45.68		1.15	69.81	
FeII	4303.17	0.63	33.53		0.56	28.37	28.37
TiII	4312.87	0.58	29.77		0.61	31.93	31.93
ScII	4314.09	0.61	31.78		0.80	45.34	
TiII	4314.98	0.59	30.59		0.85	48.39	
FeI	4383.56	0.54	26.90	26.90	0.71	38.60	
TiII	4395.04	0.62	31.74		0.75	40.89	
Average				26.04			33.38
$\pm\sigma$				1.49			2.40

Figure 2 shows the distribution of the values of vsini obtained from different lines for the star α Lyr and HR 8474 according to the data in Table 2. As you can see from here, most of the points on the graph are located below 30% of the maximum level. Therefore, when averaging the vsini values, we used the values of these points.

In table 3 and table 4 provide a list of lines from which the value of vsini was measured in HAe type stars HD 179218 and HD 190073. Since some absorption lines of HAe stars

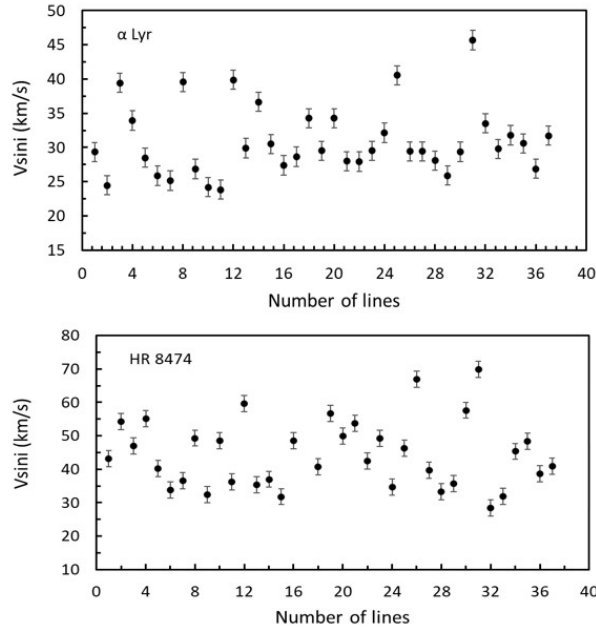


Fig. 2. Distribution of vsini values obtained from different lines from Table 2 for α Lyr and HR 8474. Vertical bars show the mean standard deviation.

may have a contribution from emission and other peculiarities, it is necessary to select the purest photospheric lines for measurements. Figure 3 shows the distribution of the vsini parameter for each of the indicated stars. Despite the preliminary careful selection of spectral lines, as can be clearly seen from Fig. 3, in the star HD 190073 some lines show a significant deviation from the average value obtained from most points. Therefore, the average vsini value for the star HD 190073 was calculated from points that are located in the lower part of the distribution. This star showed the value $v_{\text{ sini}} = 8.1 \pm 3.4$ km/s.

Unlike the star HD 190073, it is more difficult to find confidently identified pure photospheric lines in the spectrum of the H Ae star HD 179218. We measured a total of 13 absorption lines, a list of which is given in Table 4. The distribution of the vsini value along different lines is also shown in the bottom panel of Fig.3. The half-widths of absorption lines for this star show little variability and therefore the value of vsini was determined with approximately an order of magnitude worse accuracy than for other stars. For this star we obtained the value $v_{\text{ sini}} = 101.2 \pm 10.6$ km/s. As can be seen from Table 4, the error in determinations for individual lines for this star reaches up to 20 km/s. We found for HD 179218 only 3 values of the parameter vsini in the literature –60 km/s [9], 69 km/s [11] and 72 km/s [12], which is significantly less than the value we obtained. This suggests that the results of our measurements on this star require additional clarification.

Figure 4 shows a comparison graph of the obtained results of measuring the velocity projection to the line of sight for selected stars. The open circle in the figure shows how the parameter vsini, according to our measurements, differs significantly from the data of

Table 3. List of measured lines in the spectrum of HD 190073

Atoms	Wavelength (Å)	FWHM (Å)	$\pm\sigma$ (Å)	$V \sin i$ (km/s)	$\pm\sigma$ (km/s)
TiII	4028.34	0.29	0.04	10.36	2.83
Fel	4030.49	0.58	0.08	31.87	6.16
FelI	4032.94	0.42	0.12	20.33	9.06
SilI	4035.28	0.33	0.07	13.74	5.02
ZnII	4048.67	0.44	0.12	21.21	8.68
TiII	4053.82	0.38	0.08	17.33	5.70
Fel	4045.81	0.24	0.03	6.43	2.29
Fel	4063.59	0.26	0.04	8.33	2.63
Fel	4071.74	0.25	0.04	7.70	3.03
SilI	4077.71	0.24	0.07	6.85	4.84
TiII	4163.65	0.27	0.04	8.99	2.76
Fel	4173.46	0.27	0.03	8.69	2.01
MgII	4481.33	0.54	0.02	26.34	1.24
Fel	4515.34	0.22	0.06	4.39	3.74
Fel	4491.41	0.27	0.04	7.84	2.54
FelI	4541.52	0.31	0.04	10.28	2.72
CrII	4558.65	0.28	0.05	8.50	3.25
CrII	4618.8	0.31	0.04	10.28	2.55
FelI	4629.34	0.22	0.04	4.21	2.30
CrII	4634.07	0.31	0.04	10.51	2.68
FelI	4731.45	0.29	0.04	8.97	2.46
TiII	5172.37	0.32	0.13	9.71	7.74
MgII	5183.6	0.27	0.09	7.00	5.11
FelI	5362.87	0.27	0.13	6.51	7.06
Fel	5383.37	0.40	0.05	13.74	3.02

[10] (69 km/s) and [11] [12] (72 km/s). For the remaining stars, satisfactory agreement with the data from the literature was obtained. Approximation of the dependence in Fig. 4 by a linear polynomial gives a formula for linking our data with literature data.

$$v \sin i (ShAO) = 0.8159 v \sin i + 0.7959 \quad (2)$$

Thus, formula (2) allows us to determine the projections of the rotation velocity in the international system from measurements of the FWHM of lines in the spectra of stars obtained in this spectrograph.

Table 4. List of measured lines in the spectrum of HD 179218.

Atoms	Wavelength (Å)	FWHM (Å)	$\pm\sigma$ (Å)	Vsini (km/s)	$\pm\sigma$ (km/s)
FeII	4233.16	1.58	0.39	101.14	16.94
MgII	4481.33	1.60	0.13	97.16	-1.07
TiII	4501.27	1.72	0.32	104.37	11.50
TiII	4563.76	1.52	0.38	90.31	14.91
FeII	4555.89	1.72	0.42	103.17	17.46
MgII	4534.28	1.73	0.56	104.80	26.93
FeII	4549.47	1.67	0.16	100.21	0.41
CrII	4558.65	1.73	0.43	103.92	18.10
TiII	4571.97	1.68	0.33	100.16	11.74
FeII	4583.83	1.76	0.35	105.65	12.86
FeII	4923.93	1.81	0.15	101.18	0.04
MgII	5172.68	1.88	0.23	100.58	4.79
MgI	5183.60	1.93	0.21	102.83	3.52

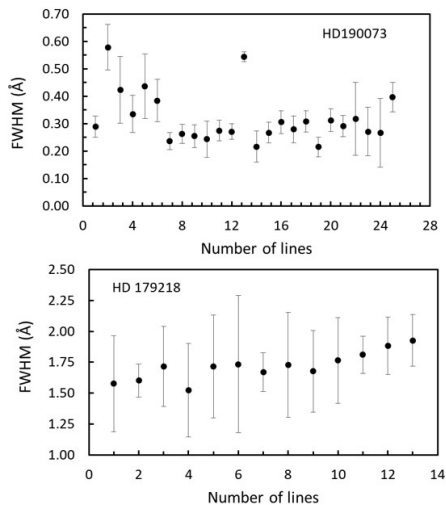


Fig. 3. Rice. 3. Distribution of measured FWHM values along different lines for the H Ae stars HD 190073 (top) and HD 179218 (bottom). Vertical bars show the standard deviation from the average for individual lines.

3. CONCLUSIONS

Thus, in this work, we carried out a methodological study to determine the projection of the rotation velocity of stars from the spectrum, obtained in the ShAFES spectrograph

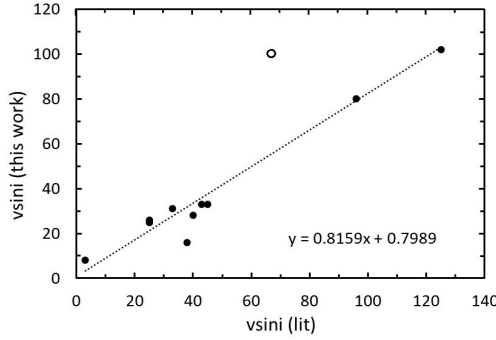


Fig. 4. Graph comparing the results of our measurements with literature data. The dotted line is drawn by approximation by a linear polynomial. The open circle refers to the star HD179218.

on the 2 m ShAO telescope with a resolution of $R = 28000$. A formula has been obtained relates the values of v_{sini} obtained in the ShAO system and in the international system. The method used is based on measuring the half-widths of photospheric absorption lines. The technique was tested using the spectra of 11 stars, for which, except for the star HD 179218, satisfactory agreement with the literature data was obtained. This difference in the spectrum of the H Ae star HD 179218 is apparently associated with the existence of short-term variability of photospheric lines.

To calculate the projection of the rotation velocity of stars along the half-width of spectral lines, it is also necessary to take into account the expansion of lines due to the instrumental profile of a given spectrograph. To do this, we measured the half-widths of selected spectral lines of the ThAr lamp comparison spectrum. Our measurements showed that there is a tendency for the instrumental profile to increase across the spectrum during the transition from the blue to the red part. The average value of the instrumental profile over all echelle orders for binning 2×2 was $\delta\lambda = 0.15 \pm 0.02 \text{ \AA}$.

This work has shown that the classical method of determining the projection of the rotation velocity from high-resolution spectra allows one to obtain a satisfactory estimate of the value of v_{sini} . At the same time, the results of measurements on active variable stars must also be checked and confirmed by alternative methods.

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MHD INSTABILITIES IN SHEAR FLOWS OF ANISOTROPIC COSMIC PLASMAS. I. FIRE HOSE MODES

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The stability of the anisotropic collisionless plasma layer to small disturbances in the MHD description is studied based on moment equations obtained from the Vlasov kinetic equation taking into account the heat flow along the spatially shearing flow. To find the complex spectral parameter that determines the growth rate of instability, on the base of the obtained wave equation, the boundary value problem is solved using WKB approximation for the case of a smooth hyperbolic velocity profile. A general integral dispersion equation, based on these solutions is obtained. This equation describes all types of body and interface instabilities in the presence of heat flow along the magnetic field, well studied for infinite stationary and homogeneous anisotropic plasma. It is shown that reducing the layer width greatly enhances the mirror instability, and strongly suppresses the oblique fire-hose instability. We limited ourselves here to study how the spatial gradient of the plasma flow affects the properties of an aperiodical oblique fire-hose instability in a limited layer. It was found that the spatial gradient in flow velocity greatly enhances this instability. With a narrowing of the shearing layer width and an increasing of the velocity gradient, the body hose modes transform into surface Kelvin-Helmholtz modes existing on the interface between the two parts of the flow with the different velocities.

Keywords: Solar wind – anisotropic plasma instability – MHD shearing flows

1. INTRODUCTION

In collisionless plasmas, the mechanism of dissipation of the energy contained in macroscopic scales is still a matter of considerable debate (Cranmer et al. 2015)

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[9]. The primary mechanism is considered to be the turbulent transfer of energy from macroscales to microscales (to scales such as the ion gyro-radius and ion inertial length), resulting in the conversion of energy into heat through kinetic processes (e.g. Marsch 2006) [42]. The transition between the scales occurs in a cascade (e.g. Loureiro & Boldyreva 2017) [37], and on kinetic scales processes such as wave-particle resonances (e.g. Gary et al. 2016) [20] and various plasma processes in coherent structures come into play (e.g. Chasapis et al. 2017; Jain et al. 2021) [10, 33]. The turbulent cascade mechanism is often used to explain plasma heating under cosmic conditions, such as coronal heating and solar wind generation (e.g. Kiyani et al. 2015; Verdini et al. 2019) [33, 34]. Turbulence scales can be conditionally divided into cascade stages: energy-containing macroscales, inertial acceleration scales, and resonant dissipative scales. We are interested in the onset of turbulence formation (instability of the ground state of the plasma) at macroscopic scales, which contain the bulk of the energy. In the case of low-collision plasmas, the theory is complicated by the fact that rarefied hot plasmas in the presence of a magnetic field become highly anisotropic relative to the direction of the external magnetic field, such as in the solar wind. Pressure anisotropy can cause additional instabilities, both in micro and macro scales (e.g. Vedenov & Sagdeev 1958) [56], which tend to bring the plasma into a thermodynamic equilibrium state. Micro-instabilities play an important role for macroscale energy redistribution (e.g. Verscharen et al. 2019) [58]. However, the observed anisotropies, for example, in the solar wind (e.g. Hellinger et al. 2006) [25], are remarkably stable and long-lived (Bale et al. 2009, Matteini et al. 2013) [2, 38] making them difficult to explain.

The main reason for the development of turbulence is plasma instabilities, i.e., instability can be thought of as the onset of turbulence. The generation and growth of instability are driven by free energy contained in the spatial gradient of the physical parameters of the medium or the non-Maxwellian distribution of plasma particles. The most common source of free energy in nature, including in space, is flows with a velocity gradient. Shear flows of fluid or plasma are usually characterized by a flow velocity gradient across the direction of flow. The simplest example is when plasma slips over a more static environment (e.g. Kivelson & Chen 1995) [36]. Examples include interaction regions that arise between fast and slow flows in the solar wind (Bale et al. 2009, Bruno & Carbone 2013) [1, 2], the interface between the solar wind and a planetary magnetosphere (Hasegawa et al. 2004) [23], the surface of coronal mass ejections (CME) (Foullon et al. 2011) [16], and the surfaces of various astrophysical jets (Hamlin & Newman 2013) [29]. Under such conditions, Kelvin-Helmholtz instability (KHI) can be easily excited by free energy flows with a velocity gradient. If fluid or plasma is considered an incompressible medium, then any value of transverse shear (velocity jump) causes

KHI instability (e.g., Chandrasekhar 1961) [6]. The magnetic field is known to stabilize this instability. However, when the shear becomes larger (usually the threshold is determined by the Alfvén speed in the direction of the flow), instability occurs again. KHI can cause some phenomena that are directly observed. For example, under certain magnetic field configurations, solar flux can penetrate the magnetosphere of planets due to the magnetic reconnection effect (e.g. Sisti et al. 2019) [51] transferring momentum, mass, magnetic flux, and energy. (e.g. Delamare M. et al. 2024) [11]. Interestingly, there are possible situations where newly born KHI vortices, before transitioning to a nonlinear regime and decaying, can transfer energy into the magnetic field and, through the reconnection mechanism, heat the plasma of the corona. (Telloni et al 2022) [52].

Many studies are devoted to the theory of KHI development, both in the MHD approximation (e.g. Walker 1981; Faganello et al. 2008) [17, 59] and in the kinetic description (e.g. Pritchett & Coroniti 1984; Henri et al. 2013) [28, 48]. If the plasma is collisionless and the width of the shear layer is comparable to the ion scales (in the solar wind at a distance of 1 AU, proton inertial length = 140 km, proton gyration radius = 160 km), then the kinetic description is preferable, as seen in Earth's magnetopause. (e.g. Faganello & Califano 2017) [18]. Shear flows are studied mainly in two aspects. If the KHI threshold is not yet reached, then the flow is stable to small perturbations, and various types of MHD waves can propagate in such flows. However, stable waves are strongly affected by shear. For example, the phase mixing mechanism can generate small scales in the direction of the flow velocity gradient (e.g., Pucci & Malara 2014) [46], which can transform ordinary Alfvén waves into kinetic Alfvén waves (Hollweg and Kaghshvili 2012) [31], the dissipation of which can become one of the main heating mechanisms in collisionless plasma. The shear can cause interactions and energy transformation between different types of waves (Pucci et al. 2016) [45]. The fluctuations on smaller scales lead to wave dissipation (e.g., Mok & Einaudi 1985; Hollweg 1987; Kaghshvili 2007; Pucci et al. 2014) [31, 35, 39, 46] which may also contribute to the appearance of anisotropy in the distribution function (e.g., Pezzi et al. . 2017) [47]. In the MHD description at such small scales, taking into account Hall effects becomes important (Vàsconez et al. 2015, Maiorano et al. 2020) [41, 57]. If the instability threshold is met, then Kelvin-Helmholtz instability (KHI) occurs. This means that vortex mixing of the shear layer is generated, which in a nonlinear stage, turns into turbulence (Blasl et al. 2022; Hasegawa et al. 2020) [3, 30]. When the shear layer width is on the order of the ionic inertial scale, dispersion effects can strongly modify the KHI. (Chac'on et al. 2003) [5].

In the kinetic description, both for wave propagation and KHI, the construction of the initial stable state of shear flows is a separate, rather complex task (e.g. Guzzi et al. 2021) [21]. For the MHD description, this difficulty does not

exist. Therefore, the averaged fluid description of a collisionless plasma, despite its disadvantages (the inability to describe in detail important kinetic effects such as resonant interactions of particles and waves, Landau damping, and others), also has advantages for the case of large-scale and low-frequency phenomena. For example, in the (Wang & Hau 2003) [60] it has been shown that the basic properties of fire hose instabilities (incompressible parallel and compressible inclined) obtained from the kinetic theory are not lost in the fluid approach. The introduction of sufficient viscosity and resistivity into the MHD model also leads to results consistent with the kinetic description for the nonlinear decay stage of the process under consideration.

In a homogeneous anisotropic plasma, classical MHD (shear) Alfvén waves become unstable if the condition $p_{\parallel} > p_{\perp} + B^2/4\pi$ or $\beta_{\parallel} - \beta_{\perp} > 2$ (hose instability) is met. These incompressible modes have the maximum instability growth rate when is propagating in parallel. The second type of hose mode is compressible and has maximum instability when is propagating obliquely (Hellinger & Matsumoto 2000) [26]. This instability has a higher growth rate than the classic hose modes.

In another limit of pressure anisotropy $p_{\parallel} < p_{\perp}$ another type of plasma instability arises - obliquely mirror instability. In this limit, kinetic resonance ion cyclotron instabilities are also possible, which do not arise in the MHD description. However, for mirror modes, the instability threshold in the MHD description, taking into account heat flow, exactly coincides with the low-frequency kinetic results, $\beta_{\parallel} < \beta_{\perp}^2/(1 + \beta_{\perp})$. Our results (Dzhalilov et al. 2011) [14] are identical to the one based on the linear Vlasov theory (Hau and Sonnerup.1993) [24]. Note that the CGL MHD model (Chew et al. 1956) [4], which admits double-adiabatic laws, does not correspond to the results of the linear Vlasov kinetic theory (e.g., Hasegawa 1975) [22].

In the case of a tangential discontinuity between flows with different velocities, only surface modes arise, including KHI. If the transition from one flow to another has a finite width and a smooth velocity profile (more consistent with real situations), then in this transition layer, in addition to surface modes, body waves are also possible, and they can interact with each other. Issues of the effect of finite width of the transition layer with different velocity profiles in isotropic MHD have been studied, (Ray & Ershkoyich (1983); Miura (1982); Choudhury (1986) ; Uberoi (1986), and in Choudhury & Patel (1985)) [7,8,40,49,54] and the plasma anisotropy were considered within the framework of the CGL MHD model. However, if we consider a layer of anisotropic plasma with a finite width, shear flow, and heat flux, then the following questions arise: 1) If the KHI threshold is not reached, how are MHD waves and associated classical instabilities (fire hose, mirror, and others) modified? 2) If KHI occurs, how is it modified by shear and how do other instabilities and waves change? Our work is devoted to studying

these issues. In this work, we focused on how the second type of fire hose instability (compressible oblique modes) is modified by the shear flow (finite width) of an anisotropic plasma, taking into account heat flux along the magnetic field. Similar questions for classical fire hose modes (incompressible parallel modes) in an infinite medium with a linear velocity gradient were studied using the asymptotic method in (Uchava et al. 2020) [53].

Section 2 presents MHD equations that describe the fluid behavior of a collisionless plasma taking into account the heat flux along the magnetic field. Based on these equations, a general wave equation is obtained for linear disturbances in a plasma layer with shearing in the flow velocity. In section 3, for a smooth hyperbolic flow velocity profile, a boundary value problem is solved based on the WKB approximation. The resulting integral dispersion equation describes the growing rates of all types of instabilities that arise in a shear layer with a finite arbitrary width and with the arbitrary transverse flow velocity gradient. In section 4, the limiting transition to the homogeneous flow, but in a spatially limited plasma layer, is separately studied. Changes in instability grows rates depending on the layer width have been studied. In section 5, oblique compressible aperiodic hose modes in a spatially limited shear layer are studied. Modification of instability depending on the width of the transition layer and the velocity gradient are the main subjects of research. Concluding remarks are provided in section 6.

2. THE BASIC WAVE EQUATIONS IN THE FLUID DESCRIPTION

For the fluid description of a collisionless anisotropic plasma regarding to the direction of the external magnetic field, the 16-moment set of equations may be used which is complete (in comparison of CGL approximation) in the sense that these equations include the evolution of heat fluxes along the magnetic field. [43,50] For the one component (ion) plasma, these equations are given as follows:

$$\frac{d\rho}{dt} + \rho \operatorname{div} \mathbf{v} = 0, \quad (1)$$

$$\begin{aligned} \rho \frac{d\mathbf{v}}{dt} + \nabla \left(p_{\perp} + \frac{B^2}{8\pi} \right) - \frac{1}{4\pi} (\mathbf{B} \cdot \nabla) \mathbf{B} = \\ = \rho \mathbf{g} + (p_{\perp} - p_{\parallel}) [\mathbf{h}_B \operatorname{div} \mathbf{h}_B + (\mathbf{h}_B \cdot \nabla) \mathbf{h}_B] + \\ + \mathbf{h}_B (\mathbf{h}_B \cdot \nabla) (p_{\perp} - p_{\parallel}), \end{aligned} \quad (2)$$

$$\frac{d}{dt} \frac{p_{\parallel} B^2}{\rho^3} = -\frac{B^2}{\rho^3} \left[B (\mathbf{h}_B \cdot \nabla) \left(\frac{S_{\parallel}}{B} \right) + \frac{2S_{\perp}}{B} (\mathbf{h}_B \cdot \nabla) B \right], \quad (3)$$

$$\frac{d}{dt} \frac{p_{\perp}}{\rho B} = -\frac{B}{\rho} (\mathbf{h}_B \cdot \nabla) \left(\frac{S_{\perp}}{B^2} \right), \quad (4)$$

$$\frac{d}{dt} \frac{S_{\parallel} B^3}{\rho^4} = -\frac{3p_{\parallel} B^3}{\rho^4} (\mathbf{h}_B \cdot \nabla) \left(\frac{p_{\parallel}}{\rho} \right), \quad (5)$$

$$\frac{d}{dt} \frac{S_{\perp}}{\rho^2} = -\frac{p_{\parallel}}{\rho^2} \left[(\mathbf{h}_B \cdot \nabla) \left(\frac{p_{\perp}}{\rho} \right) + \frac{p_{\perp}}{\rho} \frac{p_{\perp} - p_{\parallel}}{p_{\parallel} B} (\mathbf{h}_B \cdot \nabla) B \right], \quad (6)$$

$$\frac{d\mathbf{B}}{dt} + \mathbf{B} \operatorname{div} \mathbf{v} - (\mathbf{B} \cdot \nabla) \mathbf{v} = 0, \quad (7)$$

$$\operatorname{div} \mathbf{B} = 0, \quad (8)$$

where ρ denotes the density, $p_{\parallel}$ and $p_{\perp}$ the parallel and perpendicular gas pressure, $\mathbf{B}$ the magnetic field, $\mathbf{v}$ the bulk velocity of the plasma, $\mathbf{g}$ the gravitational acceleration, $\mathbf{h}_B = \mathbf{B}/B$ is a unit vector of magnetic field, and $d/dt = \partial/\partial t + (\mathbf{v} \cdot \nabla)$ denotes the convective derivative. Here $S_{\parallel}$ and $S_{\perp}$ are the heat fluxes along the magnetic field due to parallel and perpendicular thermal kinetic motions of ions, respectively. If the heat fluxes are neglected, i.e., when $S_{\parallel} = 0$ and $S_{\perp} = 0$, we obtain with Eqs. (1)-(4), (7) and (8) a closed system of equations that is called the CGL (Chew-Goldberger-Low) equations, see the pioneering work by Chew et al. [4]. Given the 16 -moments set of Eqs. (1)-(8), one can consider including the heat fluxes to obtained a more complete form compared to the CGL equations.

In our calculations, Eqs. (1)-(6) are simplified versions of 16-moment equations, including both the ionic and electronic components of the plasma (Ramos 2003) [50]. Since the plasma is collisionless, electron and ion fluids are weakly coupled. In conditions $m_e/m_i \ll 1$, the hydrodynamic behavior of the plasma is essentially determined by the ionic component. Equations (1)-(6), as in the case of the CGL MHD model, describe the dynamics of the ion plasma, while the role of electrons is reduced only to the implementation of the plasma quasi-neutrality condition.

We consider plane-parallel geometry of the $\mathbf{z}$ -directed MHD plasma flow with shearing in $\mathbf{x}$ -direction, i.e. the equilibrium velocity $\mathbf{v}_0$ has a component only in the $\mathbf{z}$ -direction, which varies on the $\mathbf{x}$ -axis, $\mathbf{v}_0 = (0, 0, V_0(x))$. Let the background magnetic field $\mathbf{B}_0 = \text{const}$ is directed along the $\mathbf{z}$ -axis. We assume also that the background state with non-zero heat fluxes is homogeneous (the gravitational acceleration, $g = 0$, and the quantities $\rho_0, p_{\perp 0}, p_{\parallel 0}, B_0, S_{\perp 0}, S_{\parallel 0}$ are constant).

We consider the stability of the such system with respect to linear perturbations of all the physical variables, according to the form $f = f_0 + f'(x, y, z, t)$, where the perturbation $f'(x, y, z, t) \sim F(x) \exp[i(k_y y + k_z z - \omega t)]$. So we Fourier

decompose the perturbation with respect to y, z , and t , as all the coefficients in the differential equations are only depending on x . Here, ω is the wave frequency and k_y, k_z are the wave numbers which means that the wave vector $\mathbf{k}$ lies in the (y, z) plane. After linearization of the set of Eqs. (1)-(8), we obtain

$$\frac{\rho'}{\rho_0} = \frac{k_y}{\omega_z} v_y + \frac{k_z}{\omega_z} v_z - \frac{i}{\omega_z} \frac{\partial v_x}{\partial x}, \quad (9)$$

$$\rho_0 \omega_z v_x + i \frac{\partial p'_\perp}{\partial x} + i \frac{B_0}{4\pi} \frac{\partial B_z}{\partial x} + \frac{B_0}{4\pi} k_z B_x - p_\Delta k_z \frac{B_x}{B_0} = 0, \quad (10)$$

$$\rho_0 \omega_z v_y - k_y \left(p'_\perp + \frac{B_0}{4\pi} B_z \right) + \frac{B_0}{4\pi} k_z B_y - p_\Delta k_z \frac{B_y}{B_0} = 0, \quad (11)$$

$$\rho_0 \omega_z v_z + i \rho_0 V'_0(x) v_x + i \frac{p_\Delta}{B_0} \frac{\partial B_x}{\partial x} - \frac{p_\Delta}{B_0} k_y B_y - k_z p'_\parallel = 0, \quad (12)$$

$$p'_\perp = \frac{k_z}{\omega_z} \left(S'_\perp - 2S_{\perp 0} \frac{B'}{B_0} \right) + p_{\perp 0} \left(\frac{B'}{B_0} - \frac{\rho'}{\rho_0} \right), \quad (13)$$

$$p'_\parallel = \frac{k_z}{\omega_z} \left(S'_\parallel - S_{\parallel 0} \frac{B'}{B_0} + 2S_{\perp 0} \frac{B'}{B_0} \right) - p_{\parallel 0} \left(2 \frac{B'}{B_0} + 3 \frac{\rho'}{\rho_0} \right), \quad (14)$$

$$S'_\perp = \frac{p_{\parallel 0} p_{\perp 0} k_z}{\rho_0 \omega_z} \left(\frac{p'_\perp}{p_{\perp 0}} - \frac{\rho'}{\rho_0} + \frac{p_\Delta B'}{p_{\parallel 0} B_0} \right) + 2S_{\perp 0} \frac{\rho'}{\rho_0}, \quad (15)$$

$$S'_\parallel = 3 \frac{p_{\parallel 0}^2 k_z}{\rho_0 \omega_z} \left(\frac{p'_\parallel}{p_{\parallel 0}} - \frac{\rho'}{\rho_0} \right) - S_{\parallel 0} \left(3 \frac{B'}{B_0} - 4 \frac{\rho'}{\rho_0} \right), \quad (16)$$

$$\omega_z B_x + B_0 k_z v_x = 0, \quad (17)$$

$$\omega_z B_y + B_0 k_z v_y = 0, \quad (18)$$

$$\frac{\partial B_x}{\partial x} + i k_y B_y + i k_z B_z = 0. \quad (19)$$

Inserting (15) and (16) into (13) and (14), we can write

$$p'_\perp = p_{\perp 0} \frac{a_1(x)}{a_0(x)} \frac{B_z}{B_0} + p_{\perp 0} \frac{a_2(x)}{a_0(x)} \frac{\rho'}{\rho_0}, \quad (20)$$

$$p'_\parallel = p_{\parallel 0} \frac{b_1(x)}{b_0(x)} \frac{B_z}{B_0} + p_{\parallel 0} \frac{b_2(x)}{b_0(x)} \frac{\rho'}{\rho_0}. \quad (21)$$

Here $p_\Delta = p_{\parallel 0} - p_{\perp 0}$, $V'_0(x) = \partial V_0 / \partial x$, and $\omega_z = \omega - k_z V_0(x)$ is the Doppler shifted frequency. We can reduce the system of Eqs. (9)-(19) to one

single second-order differential equation by using the obvious relations between the physical variables

$$v_x = -\frac{\omega_z}{B_0 k_z} B_x, \quad (22)$$

$$v_y = -\frac{\omega_z}{B_0 k_z} \frac{ik_y A}{\beta_A} \frac{\partial B_x}{\partial x}, \quad (23)$$

$$v_z = -\frac{\omega_z}{B_0} \frac{iA\beta_1}{\beta_\star} \frac{\partial B_x}{\partial x}, \quad (24)$$

$$B_y = \frac{ik_y A}{\beta_A} \frac{\partial B_x}{\partial x}, \quad (25)$$

$$B_z = \frac{ik_z A}{\beta_\star} \frac{\partial B_x}{\partial x}, \quad (26)$$

$$\rho' = \frac{\rho_0}{B_0} \frac{ik_z A (1 - \beta_1)}{\beta_\star} \frac{\partial B_x}{\partial x}, \quad (27)$$

$$p'_\perp = \frac{a_1 + (1 - \beta_1) a_2}{a_0} \frac{p_{\perp 0}}{B_0} \frac{ik_z A}{\beta_\star} \frac{\partial B_x}{\partial x}, \quad (28)$$

$$p'_\parallel = \frac{b_1 + (1 - \beta_1) b_2}{b_0} \frac{p_{\parallel 0}}{B_0} \frac{ik_z A}{\beta_\star} \frac{\partial B_x}{\partial x}. \quad (29)$$

Substituting all these relationships and thus eliminating variables, we obtain

$$\frac{\partial}{\partial x} \left(A(x) \frac{\partial B_x}{\partial x} \right) - \beta_A(x) B_x = 0, \quad (30)$$

where

$$A(x) = \frac{\beta_A \beta_\star}{k_y^2 \beta_\star + k_z^2 \beta_A}, \quad (31)$$

and

$$\begin{aligned} \beta_A &= \beta - \bar{\alpha} - \frac{1}{\eta^2}, & \beta_\star &= \beta_0 - \alpha \frac{a_2}{a_0} \beta_1, \\ \beta_0 &= \alpha \frac{a_1 + a_2}{a_0} + \beta, & \beta_1 &= \frac{b_0 \bar{\alpha} - b_1 - b_2}{b_0 / \eta^2 - b_2}, \end{aligned} \quad (32)$$

while the coefficients $a_{0,1,2}$ and $b_{0,1,2}$ are determined as

$$\begin{aligned} a_0 &= 1 - \eta^2, & b_0 &= 1 - 3\eta^2, \\ a_1 &= 1 - 2\gamma\eta - \bar{\alpha}\eta^2, & b_1 &= 2\gamma\eta(\alpha - 2) - 2, \\ a_2 &= 1 + 2\gamma\eta - \eta^2, & b_2 &= 3 + 4\gamma\eta - 3\eta^2. \end{aligned} \quad (33)$$

In the above equations, the following dimensionless parameters were used for the basic unperturbed physical quantities and the indexes zero are dropped for simplification of the notation:

$$\begin{aligned} \alpha &= \frac{p_{\perp}}{p_{\parallel}}, \quad \bar{\alpha} = 1 - \alpha, \quad \beta = \frac{B^2}{4\pi p_{\parallel}} = \frac{v_A^2}{c_{\parallel}^2}, \quad c_{\parallel}^2 = \frac{p_{\parallel}}{\rho}, \\ \eta &= \frac{c_{\parallel} k_z}{\omega_z}, \quad \gamma_{\parallel} = \frac{S_{\parallel}}{p_{\parallel} c_{\parallel}}, \quad \gamma_{\perp} = \frac{S_{\perp}}{p_{\perp} c_{\parallel}}, \quad \gamma = \gamma_{\parallel} = \gamma_{\perp}. \end{aligned} \quad (34)$$

The case where $\gamma = \gamma_{\parallel} = \gamma_{\perp}$ is a simplified approach. Here, $c_{\parallel}$ denotes parallel sound speed, v_A is the Alfvén velocity, α the anisotropy parameter, γ the background heat fluxes parameter, and β is inversely proportional to the plasma beta ($\beta = 2/\beta_{pl}$). We also denote θ for the wave propagation angle relative to the magnetic field, i.e., $k_z = k \cos \theta$, $k_y = k \sin \theta$, and after denoting $\cos^2 \theta \equiv \ell$, we can write $k_z = k\sqrt{\ell}$ and $k_y = k\sqrt{1-\ell}$, and let $k > 0$.

3. EIGEN OSCILLATIONS OF THE LAYER WITH SHEARING FLOW

The coefficients of obtained second order ordinary differential wave equation Eqs.(30) are variable, and they are complex functions of $V_0(x)$. Furthermore, the velocity profile $V_0(x)$ is still an arbitrary function of the x -coordinate. In the case when two plasma flows adjoin, there arises a transition layer with a finite thickness between them. The thickness of the transition layer is determined by the flow velocities and physical parameters in each flow. In the simplest case, to mimic this situation we consider an analytical velocity profile given by the hyperbolic function of

$$V_0(x) = \frac{V_{02}e^{\sigma x} + V_{01}e^{-\sigma x}}{e^{\sigma x} + e^{-\sigma x}}, \quad \sigma \geq 0. \quad (35)$$

Here $V_0(-\infty) = V_{01}$ and $V_0(+\infty) = V_{02}$ are the limit velocities and let $h = V_{01}/V_{02} \geq 1$, $V_0(0) = (V_{01} + V_{02})/2 = \bar{V}_0$ is the average of the two velocities. In the Eqs.(35) the σ parameter characterizes the thicknesses of the transition layer L . Figure 1 shows schematically the various profiles of $V_0(x)$ for different values of σ . As the parameter $\sigma L > 0$ increases, the width of the transition layer between the two flows sharply decreases and becomes a discontinuity ($\sigma L \gg 1$) between the velocities V_{01} and V_{02} . For the small $\sigma L \ll 1$ the width of the transition layer becomes very large.

Let's introduce the next notations

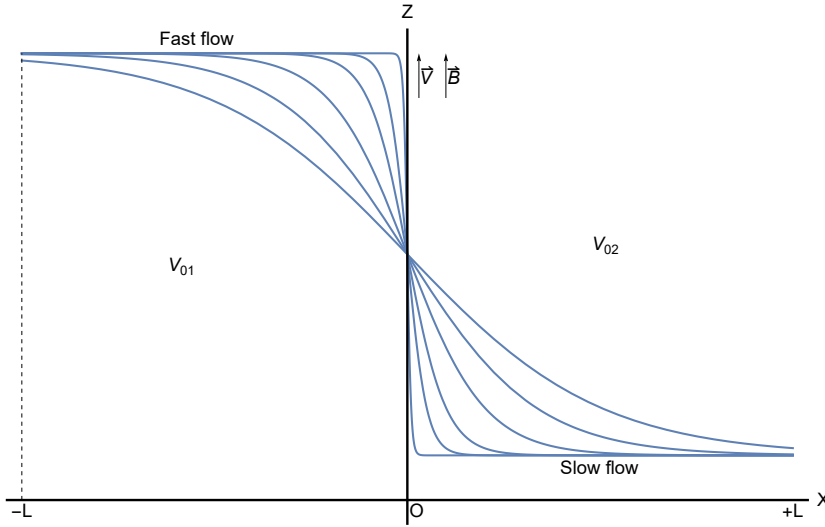


Fig. 1. Schematic representation of MHD plasma shearing flow. Different line profiles correspond to different values of $\sigma_L = \sigma L$ in (35).

$$\begin{aligned}
 y(x) &= \frac{B_x}{B_0}, \quad \xi(x) = \frac{\omega - k_z V_0(x)}{c_{\parallel} k_z}, \quad \beta_A(x) = \alpha + \beta - 1 - \xi^2, \\
 \beta_*(x) &= \beta + 2\alpha + 2\alpha^2 \cdot \frac{\xi^4 + 2\gamma\xi^3 + 2\gamma^2\xi^2 - 5\xi^2 - 6\gamma\xi + 3}{(\xi^2 - 1)(\xi^4 - 6\xi^2 - 4\gamma\xi + 3)}.
 \end{aligned} \tag{36}$$

Then we can write the Eqs.(30) as

$$\frac{d}{dx} \left(\frac{\beta_A \beta_*}{k_y^2 \beta_* + k_z^2 \beta_A} \frac{dy(x)}{dx} \right) - \beta_A y(x) = 0. \tag{37}$$

As noted in the Introduction, we will be interested in the excitation of waves and instabilities due to the free energy of a flow with a gradient. As we showed earlier in (Ismailli et al.2018) [32], waves can grow due to the energy of the flow if these waves are in resonance with the flow, i.e. when the phase velocity along the flow is close to the average flow speed, $\omega \sim k_z \bar{V}_0$. Therefore, let $\omega = k_z \bar{V}_0(1 + \Omega)$, where Ω is the spectral parameter to be determined. Then $\xi(x) = M[\Omega + \Delta \tanh(\sigma x)]$, where $M = \bar{V}_0/c_{\parallel}$ is the Mach number, $\Delta = (h - 1)/(h + 1)$ is the shear rate. Note that $0 \leq \Delta \leq 1$ and hence, $\Delta = 0$ corresponds to a uniform flow ($V_{01} = V_{02}$) and $\Delta = 1$, if the plasma slips over a more static environment ($V_{02} = 0$).

Now let's move on to the dimensionless independent variable $\tau = x/L$ in Eq.(37). Designating $\sigma_L = \sigma L$, $\bar{k} = kL$ and so $\xi(\tau) = M[\Omega + \Delta \tanh(\sigma_L \tau)]$ we have

$$(\mathcal{P}y')' - Qy = 0, \tag{38}$$

where $y' = y'(\tau)$ and

$$\mathcal{P}(\tau) = \frac{\beta_A \beta_*}{(1-l)\beta_* + l\beta_A}, \quad Q(\tau) = \bar{k}^2 \beta_A. \quad (39)$$

Our main goal in the next step is solving the boundary value problem based on the Eq. (38), to find the complex spectral parameter Ω with $\Omega_i = \text{Im}(\Omega) \neq 0$. For such a problem, we can use the fact that in the real integration axis τ for the coefficients (39) it is possible to satisfy the conditions $\mathcal{P}(\tau) \neq 0$ and $Q(\tau) \neq 0$. This situation makes it possible to find WKB (Wentzel-Kramers-Brillouin) approximate analytical solutions of the second-order equation (38). So, for the complex $\mathcal{P}(\tau), Q(\tau) \Rightarrow C^2(I)$ functions assuming $\text{Re}(QP) \geq 0$ we can write the leading expansion term of WKB solutions, e.g. in (Fedoryuk M.1983) [19] as

$$\tilde{y}_{1,2} = \frac{e^{\pm iS(\tau)}}{\sqrt{w}}, \quad w = \sqrt{\mathcal{P}Q}, \quad S = \int_{\tau_0}^{\tau} \sqrt{-\frac{Q}{\mathcal{P}}} d\tau. \quad (40)$$

The deviation of exact solutions $y_{1,2}$ from WKB ones $\tilde{y}_{1,2}$ is determined by the right-hand side of the following expression

$$\left| \frac{y_{1,2}}{\tilde{y}_{1,2}} - 1 \right| \leq T_{WKB} = 2 \left(e^{2\mu_I(\tau)} - 1 \right) < 1, \quad (41)$$

where

$$\mu_I(\tau) = \left| \int_{\tau_0}^{\tau} |\mu| d\tau \right|, \quad \mu(\tau) = \frac{1}{8w^5} \left[(\mathcal{P}w')' w - \frac{5}{4} \mathcal{P} (w')^2 \right]. \quad (42)$$

Two independent solutions of the Eqs. (38) with accuracy of (41) can be represented in the form

$$y(\tau) = \frac{1}{\sqrt{w}} (C_1 e^{iS} + C_2 e^{-iS}), \quad (43)$$

where $C_{1,2} = \text{const}$ to be determined from the boundary conditions. Let's limit the region of integration along the x axis within $-L \leq x \leq +L$. This means that the shearing layer is located in this area (see in the Fig.1). Let's limit the layer on the left $\tau = -1$ and right side $\tau = +1$ with hard boundaries, which corresponds to natural conditions of $y(\pm 1) = 0$.

Let $\tau_0 = 0$, $u(\tau) = \sqrt{-Q/\mathcal{P}}$ and

$$S_+ = \int_0^1 u d\tau, \quad S_- = \int_{-1}^0 u d\tau, \quad I = S_- + S_+ = \int_{-1}^1 u d\tau. \quad (44)$$

From the boundary conditions of $y(\pm 1) = 0$ we get that $\exp(2iS_-) = \exp(-2iS_+)$ or

$$\sin(I) = 0; \quad I = n\pi, n = 0, \pm 1, \pm 2, \dots \quad (45)$$

This is the desired dispersion equation for the eigen oscillations of an anisotropic plasma layer with shear flow. Introducing the notation $z = \tanh(\sigma_L \tau)$, $\xi_{\pm} = M(\Omega \pm \Delta z)$ and $b = \tanh(\sigma_L)$ let us present this equation in the form

$$\int_0^1 \left(\sqrt{f(\xi_+)} + \sqrt{f(\xi_-)} \right) d\tau = \lambda_n, \quad (46)$$

or

$$\int_0^b \frac{\sqrt{f(\xi_+)} + \sqrt{f(\xi_-)}}{1 - z^2} dz = \sigma_L \lambda_n, \quad (47)$$

where

$$f(\xi) = -\frac{(1-l)\beta_*(\xi) + l\beta_A(\xi)}{\beta_*(\xi)}, \quad \lambda_n = \frac{n\pi}{kL}, = \frac{\lambda_{\perp} n}{2L}. \quad (48)$$

The λ_n parameter is the ratio of the wavelength $\lambda_{\perp}$ in the $(y-z)$ plane ($k^2 = k_y^2 + k_z^2$ and $k = 2\pi/\lambda_{\perp}$) to the geometric width ($2L$) of the plasma layer with a flow that is a multiple of the number of unevenly located nodes n of the eigenfunctions along the x axis. If we denote the scale of fluctuation structures caused by shear flow along the x -axis as $\lambda_x = 2L/n$, then $\lambda_n = \lambda_{\perp}/\lambda_x$.

The eigenfunctions taking into account (44) and (45) can be represented in the form

$$y(\tau) = (-1)^{n+1} \frac{C}{w} \sin \left(\int_{-1}^0 u(\tau) d\tau - \int_{\tau}^0 u(\tau) d\tau \right), \quad -1 \leq \tau \leq 0 \quad (49)$$

$$y(\tau) = \frac{C}{w} \sin \left(\int_0^1 u(\tau) d\tau - \int_0^{\tau} u(\tau) d\tau \right), \quad 0 \leq \tau \leq 1 \quad (50)$$

where $C = \text{const}$.

4. INSTABILITIES IN HOMOGENEOUS FLOW

Let us briefly consider the well-known fire-hose and mirror instabilities of an anisotropic plasma (in the domains of $\alpha < 1$ and $\alpha > 1$, correspondingly) with a uniform flow, so that we can compare them with modified instabilities due to shearing of the flow. For a homogeneous flow $\Delta = 0$, and therefore $\xi_+ = \xi_- = M\Omega = \Omega_*$, $f(\xi_+) = f(\xi_-) = f(\Omega_*)$. Then dispersion equation (47) reduces to $f(\Omega_*) - \bar{\lambda}_n^2 = 0$, where $\bar{\lambda}_n = \lambda_n/2$. This is an 8th order polynomial on the spectral parameter Ω_* :

$$c_8 \Omega_*^8 + c_7 \Omega_*^7 + c_6 \Omega_*^6 + c_5 \Omega_*^5 + c_4 \Omega_*^4 + c_3 \Omega_*^3 + c_2 \Omega_*^2 + c_1 \Omega_* + c_0 = 0. \quad (51)$$

Here

$$\begin{aligned}
c_0 &= 6(\bar{\lambda}_n^2 - l + 1)\alpha^2 - 6(\bar{\lambda}_n^2 - l/2 + 1)\alpha - 3(\beta\bar{\lambda}_n^2 - l + \beta), \\
c_1 &= -12\gamma(\bar{\lambda}_n^2 - l + 1)\alpha^2 + 8\gamma(\bar{\lambda}_n^2 - l/2 + 1)\alpha + 4\gamma(\beta\bar{\lambda}_n^2 + \beta - l), \\
c_2 &= 2(\bar{\lambda}_n^2 - l + 1)(2\gamma^2 - 5)\alpha^2 + 18(\bar{\lambda}_n^2 - l/2 + 1)\alpha + 9(\beta\bar{\lambda}_n^2 - 2l/3 + \beta), \\
c_3 &= 4\gamma[(\bar{\lambda}_n^2 - l + 1)\alpha^2 - 2(\bar{\lambda}_n^2 - l/2 + 1)\alpha - \beta(\bar{\lambda}_n^2 + 1)], \\
c_4 &= 2(\bar{\lambda}_n^2 - l + 1)\alpha^2 - 14(\bar{\lambda}_n^2 - l/2 + 1)\alpha - 7(\beta\bar{\lambda}_n^2 + 2l/7 + \beta), \\
c_5 &= 4\gamma l, \quad c_6 = (2\bar{\lambda}_n^2 - l + 2)\alpha + \beta\bar{\lambda}_n^2 + 6l + \beta, \quad c_7 = 0, \quad c_8 = -l.
\end{aligned}$$

Note that this dispersion equation for an infinite medium $L = \infty$, therefore $\bar{\lambda}_n = 0$, was studied in detail in (Dzhililov and Kuznetsov, 2013) [12] and the obtained results were compared with the results of low-frequency kinetics. The good agreement between the thresholds and growth rates of low-frequency instabilities obtained in the kinetic and MHD approaches indicates that the MHD model based on the 16-moment fluid equations is quite applicable for the hydrodynamic description of collisionless plasma.

Here first of all we want to show how the spatial limitation of the plasma layer ($-\infty < L < +\infty$) along the x -axis can influence to the known instabilities growing. Note that in this case the classical incompressible fire-hose modes are separated (see in the Eq. (30): the term $\beta_A = 0$ describes the frequency of Alfvén oscillations). Other modes are described by the Eq. (51), coefficients of which depend on the parameters α , β , γ , l and λ_n . We will simplify the problem, eliminating the influence of heat flux, $\gamma = 0$ and fix the magnetic parameter, let $\beta = 0.1$ (weak magnetic field). For an infinite layer width, $\lambda_n = 0$, the dependence of the instability growing rates of aperiodic in the moving fluid frame modes ($\Omega_r = \text{Re}(\Omega) = 0$) - oblique fire hose and mirror instabilities on the wave propagation angle l and on the anisotropy parameter of α is shown in Fig. 2. These parameter dependence growing rate results are well known.

To clarify the role of flow layer width limitation, let us take two typical cases from the figure 2: $\alpha = 0.5$ for the fire-hose mode and $\alpha = 1.4$ for mirror modes. As it follows from Figure 3, with increasing parameter λ_n , the region of existence of fire-hose modes sharply narrows and it disappears if $\lambda_n > 1$. The opposite situation arises for mirror modes: with increasing parameter λ_n , the region of occurrence of mirror instability on parameter l expands and covers all possible propagation angles, $0 \leq l \leq 1$. With increasing λ_n , the growth rate of mirror modes increases to the maximum asymptotic value (in the case under consideration, $(M\Omega_i)_{max} = 0.53$), i.e. the instability of mirror modes becomes stronger than fire-hose modes.

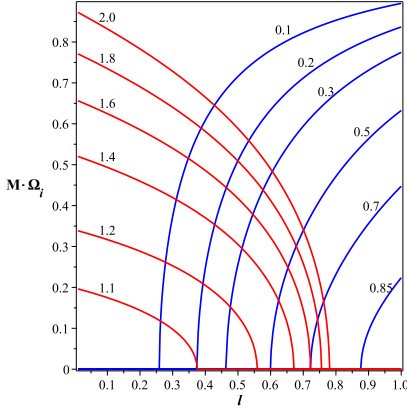


Fig. 2. Dependence of the growing rates of quasi-parallel fire hose (blue lines) and quasi-perpendicular mirror (red lines) instabilities from $l = \cos^2(\theta)$ in different α (numbers at curves) for $\bar{\lambda}_n = 0$. With decreasing of anisotropy $\alpha \rightarrow 1$ both instabilities fade out

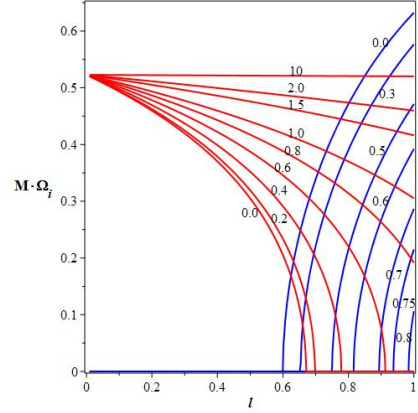


Fig. 3. Dependence of the growing rates of fire hose (blue lines) and mirror (red lines) instabilities from $l = \cos^2(\theta)$ in different $\bar{\lambda}_n \neq 0$ (numbers at curves). For the mirror modes $\alpha = 1.4$ and fire-hose modes $\alpha = 0.5$ are chosen as the typical examples.

5. OBLIQUE FIRE-HOSE MODE INSTABILITY IN SHEARING FLOW

Now let us consider how the instabilities change when the flow is sheared. In this case, two additional parameters, Δ and σ_L , are added to the problem for which the rather difficult integral dispersion Eq. (47) must be solved. In this work we will restrict ourselves to oblique fire-hose modes only. We fix the plasma anisotropy parameter $\alpha = 0.5$, the magnetic parameter $\beta = 0.1$, the propagation angle parameter $l = 0.9$, heat flux parameter $\gamma = 0$ and the Mach number $M = 5$ (supersonic flow). The dependence of the fire-hose instability growing rate on Δ for various values of λ_n and σ_L is shown in figures 4 and 5.

It is characteristic that with the appearance of the slightest shifting in velocity, the instability intensifies sharply and reaches a maximum. For the small λ_n a minor shift is sufficient to enhance the instability. A similar picture is obtained when changing the σ_L parameter. At small scales of the velocity gradient ($\sigma_L \rightarrow 0$), the flow is almost uniform and the instability is weak. As the gradient increases, instability sharply increases.

In the figures 6 and 7 we show the results of the dependence of instability growth rate of fire-hose modes Ω_i on the parameter λ_n for the different given Δ and σ_L parameters values. These examples cover both a very wide plasma layer ($kL \gg 1$) and a narrow layer ($kL \ll 1$). We see that the hose modes that arise in a wide layer as body waves disappear as the layer width decreases and goes to

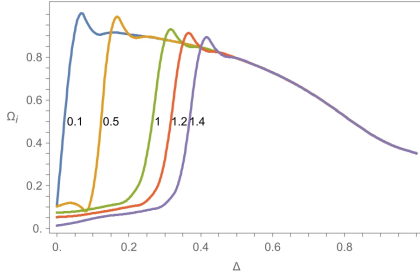


Fig. 4. The dependence of instability growing rate Ω_i of fire-hose modes on the shearing rate of plasma supersonic flows Δ at different values of λ_n (numbers at curves) when $\sigma_L = 1$.

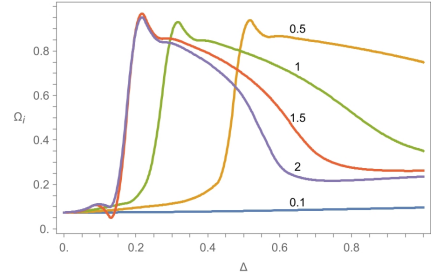


Fig. 5. The dependence of instability growing rate Ω_i of fire-hose modes on the shearing rate of plasma supersonic flows Δ at different values of σ_L (numbers at curves) when $\lambda_n = 1$.

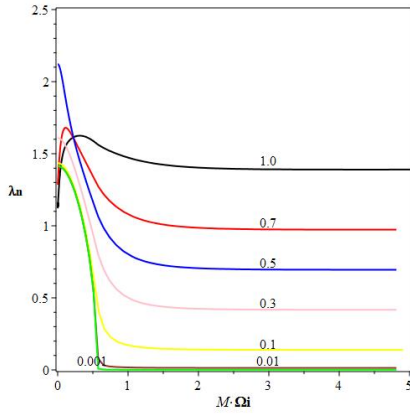


Fig. 6. The dependence $\lambda_n = n\pi/kL$ from the instability growing rate $M\Omega_i$ of fire-hose modes at the different values of the shearing rate of $M\Delta$ (numbers at curves) for the case of $\sigma_L = 3$ and $\gamma = 0$.

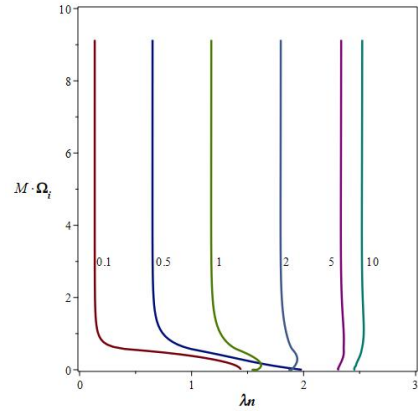


Fig. 7. The dependence of instability growing rate $M\Omega_i$ of fire hose modes on the λ_n at different values of σ_L (numbers at the curves) when $M\Delta = 1.5$

zero. Note that the discontinuous case corresponds to $L \rightarrow 0$ and $\sigma_L \gg 1$.

5.1. On the validity of the WKB solutions

In this work, we solved the boundary value problem based on the WKB solutions (40). Taking into account that the coefficients of the equation (37) are the ratio of polynomials, and the eigenfunctions are expressed by complex irrational expressions, it is important to show the smoothness of the eigenfunctions and the domain of definition of the obtained results. In this issue, the main is that the

sought and found eigenvalues (oscillation frequencies) are complex, and are found such values at which the divergence of terms in the WKB expansion is excluded. Proof of this is Figure 8, where for the found eigenvalues (for four cases), the dependence of the T_{WKB} deviation of the WKB solutions from the exact one (41) is calculated as a function of $n = 0, 1, 2, \dots$ numbers. As can be seen, the curves are smooth, and the region of validity $T_{WKB} < 1$ of the illustrated results is located in the region of larger n . These cases in the Fig.8 are:

- 1) $\gamma = 0, \sigma_L = 3, \Omega_r = 0, M\Omega_i = 1.0604, \lambda_n = 2.1203$;
- 2) $\gamma = 0, \sigma_L = 3, M[\Omega_r, \Omega_i] = [0.9007, 0.1], \lambda_n = 2.7724$;
- 3) $\gamma = 0.7, \sigma_L = 3, M[\Omega_r, \Omega_i] = [0.5, 0.3419], \lambda_n = 2.2291$;
- 4) $\gamma = 0.7, \sigma_L = 0.55, M[\Omega_r, \Omega_i] = [0.10201, 0.3248], \lambda_n = 1.4473$.

These eigenvalues have been found in the parameter values of: $M = 5, \Delta = 0.3, \alpha = 0.5, \beta = 0.1$ and $l = 0.9$.

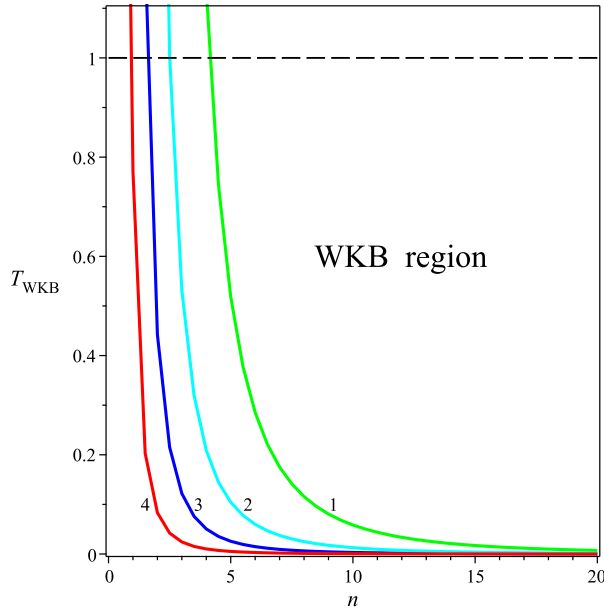


Fig. 8. The range of applicability of the obtained results based on the WKB solutions, $T_{WKB} < 1$, for four cases of eigenvalues (see the text).

6. CONCLUSIONS

In this work, we considered a layer of anisotropic collisionless plasma with a finite width. It was assumed that a homogeneous plasma flows along the magnetic field has a transverse velocity gradient. The stability of the plasma layer

to small disturbances in the MHD description was studied on the basis of moment equations obtained from the Vlasov kinetic equation taking into account the heat flux along the flow. A wave equation is derived, which is a second-order ordinary differential equation with complex variable coefficients. To solve the boundary value problem and find the complex spectral parameter that determines the growth rate of instability, the WKB approximation was used to find asymptotic solutions for the case of a hyperbolic velocity profile. A general integral dispersion equation, based on these solutions is obtained. This equation describes all types of instabilities in the presence of heat flux along the magnetic field, well studied for infinite stationary anisotropic plasma (Dzhililov, Kuznetsov, 2008, 2011, 2013; Dzhililov, Ismaili 2023). [12–15] These instabilities, such as parallel and oblique firehose modes, mirror modes, KHI modes, and others in an infinite medium and velocity discontinuities, arise under certain conditions determined by the plasma parameters.

Note that the case considered here, the spatially limited plasma layer with a transverse gradient in flow velocity, is a more realistic case that occurs in various cosmic situations. Therefore, studying the effect of plasma confinement on known properties of instabilities, modification of them, and the interaction of various modes due to a shearing of flow velocity in the presence of a heat flux are poorly studied problems. The resulting general dispersion equations allow us to move to known limiting cases - into an infinite medium without a shearing in velocity and an extremely narrow layer with a jump in the velocity (discontinuity limit). The first important result is that the spatial limitation of the plasma greatly affects the instabilities of the mirror and oblique fire-hose mode instabilities. Namely, reducing the layer width greatly enhances the mirror instability, and strongly suppresses the hose instability. Further, we limited ourselves here to study how the spatial gradient of the plasma flow, characterized by two σ_L and Δ parameters, affects the properties of oblique hose instability in a limited layer. It was found that the spatial gradient in flow velocity greatly enhances this instability. With a narrowing of the layer width ($L \rightarrow 0$) and an increase of the velocity gradient ($\sigma_L \gg 1$), the body hose modes transform into surface KH modes existing on the discontinuity surface between the two parts of flow. Note that the results presented here are only for aperiodic modes ($Re(\Omega) = 0$) without taking into account the influence of heat flux. For the same fixed anisotropic plasma and magnetic parameters (α and β) and propagation angle relative to the magnetic field (l), in addition to aperiodic instabilities, periodic instabilities also arise ($Re(\Omega) \neq 0$, $Im(\Omega) \neq 0$), as a result of interaction with other modes (most likely with KH modes, see (Dzhililov, Ismaili, 2023) [15]. These results are not included here.

In future works, the mirror and other shear instabilities will be considered. It is especially interesting how the KHI is modified as a result of interaction with

other modes, and what happens during the transition from a jump in velocity (discontinuity) to a plasma layer with a finite width and with a transverse gradient. In conclusion, we note that the facts of increase of hose instability due to the velocity shearing are important for the general theory of turbulence generation in anisotropic space plasmas.

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THE FUNDAMENTAL PARAMETERS OF THE STAR HR 6725(F2 III)

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The atmosphere of HR 6725 (F2 III) giant star of F spectral class was studied using the model and parallax methods. The effective temperature (T_{eff}) and surface of gravity g on the surface of the star were determined based on a comparison of the observed and theoretically calculated values of the photometric quantities $[c_1]$, Q , and the equivalent widths of the spectral lines of the hydrogen Balmer series and the using of parallax. Based on the FeI lines the microturbulence (ξt) and the metallicity $[Fe/H]$ were determined. In the atmosphere of the star, the metallicity is close to the metallicity of the Sun. This shows that the star we are studying and the Sun are formed from the same metallicity matter.

Keywords: F spectral class–giant stars–fundamental parameters of stars

1. INTRODUCTION

In this work, the fundamental parameters of the star–effective temperatures (T_{eff}), surface of gravity (g), microturbulent velocity (ξt) and metallicity $[Fe/H]$ were determined.

Knowing the effective temperature and surface gravity the models of stellar atmospheres are calculated and on the basis of these models the chemical composition of stars is determined, also the evolutionary parameters of star – mass, radii, luminosity, age are calculated.

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In astrophysics, microturbulence is considered as a mechanism broadening of the spectral line. The equivalent width of the spectral line depends on microturbulence, therefore, to determine the chemical composition, it is necessary to know the microturbulent velocity.

Metallicity is one of the main fundamental parameters of stars. According to the definition of this parameter, it is determined that the star and the Sun are formed the same or different metallicity matter, the problem of the correctness of the provisions of the modern theory of chemical evolution of stars is solved.

It should be noted that from the considered star, only the metallicities of the star HR 6725 (F2 III) are determined by other authors [1]. The surface of gravity (g) on the surface of the star, the microturbulence (ξt), and the metallicity $[\text{Fe}/\text{H}]$ were determined by us.

2. OBSERVATION MATERIAL

The spectra of the star were obtained with the spectrograph of the CCD-matrix of the 2-meter telescope of the Shamakhy Astrophysical Observatory ($R=56000$, $S/N=150-400$). The spectra were processed by the DECH program. The equivalent widths of spectral lines were measured. The equivalent widths of the lines of FeII atoms used are given in Table 1.

3. EFFECTIVE TEMPERATURE AND SURFACE OF GRAVITY

The effective temperature (T_{eff}) and the surface gravity (g) of the star were determined by the model and the parallax method. This method is described in detail in [2]. We have studied the atmospheres of several A, F, G-spectral class giants and supergiant stars using the model method [3–7]. The effective temperature and surface of gravity were determined based on a comparison of the observed and theoretically calculated values of the photometric quantities $[c_1]$, Q , and the equivalent widths of the spectral lines of the hydrogen Balmer series and the use of the parallax method. The parallax method is a completely new method and does not depend on models.

The index $[c_1]$ is defined as $[c_1]=c_1-0.2(b-y)$, in the uvby photometric system, and the Q index is defined as $Q=(U-B)-0.72(B-V)$ in the UBV system.

These indices are released from the absorption effect in interstellar space. The observation values of the quantities $[c_1]$, Q are determined from the catalog [8]. The theoretically calculated values of the equivalent widths of the Balmer series are given in [9], theoretically calculated values of quantities $[c_1]$, Q in [10]. The parallax of the star was measured in [11]. The diagram defining T_{eff} and $\log g$

Table 1. List of the used Fell lines

λ (Å)	E_{low} (eV)	$\log gf$	$W(\text{mÅ})$	$\log \epsilon$
4122.64	2.57	-3.67	103	7.25
4233.16	2.57	-1.88	237	7.40
4258.15	2.69	-3.93	103	7.60
4296.57	2.69	-3.32	148	7.60
4416.82	2.77	-2.57	168	7.28
4446.25	5.93	-2.12	27	7.34
4508.29	2.84	-2.33	183	7.30
4515.33	2.83	-2.50	215	7.26
4520.22	2.79	-3.17	206	7.56
4541.52	2.84	-2.83	87	7.26
4663.70	2.88	-4.42	54	7.60
5100.66	2.79	-4.22	63	7.46
5234.62	3.21	-2.14	177	7.22
5256.93	2.88	-4.33	36	7.27
5276.00	3.19	-2.06	184	7.20
5337.72	3.22	-3.99	58	7.52
5362.86	3.19	-2.84	149	7.47
5425.27	3.19	-3.35	85	7.20
5534.84	3.23	-2.92	86	7.25
6113.32	3.21	-4.20	29	7.25
6147.73	3.87	-2.73	110	7.37
6238.38	3.87	-2.64	117	7.36
6239.95	3.87	-3.44	35	7.20
6247.56	3.87	-2.34	132	7.25
6416.91	3.87	-2.75	106	7.33
6432.67	2.88	-1.11	87	7.26
6456.38	3.89	-2.09	165	7.44
6482.19	6.19	-1.84	41	7.54

is shown in Figure 1. Based on this diagram, HR 6725 (F2 III) is assigned to the star: $T_{\text{eff}} = 6800\text{K}$, $\log g = 2.6$. Other authors have obtained the value: $T_{\text{eff}}=6874\text{K}$ [1] for star HR 6725 (F2 III). As can be seen, the value determined in [1] corresponds to the value determined by us.

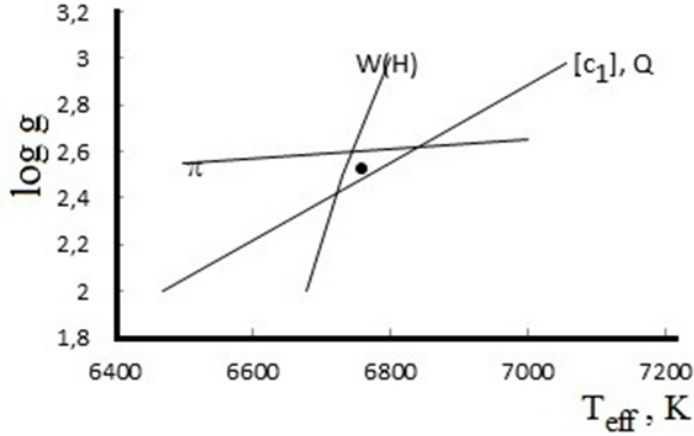


Fig. 1. $\lg g - T_{eff}$ diagram

4. THE MICROTURBULENT VELOCITY

The determination of the microturbulent velocity by the model method is based on the study of equivalent widths in a wide range of spectral lines of a neutral atom or ion of any element. Several values are given to the microturbulent velocity (ξ_t), the equivalent widths (W_λ) of the spectral lines of the considered element are calculated and compared with the equivalent widths measured from observation. Based on each spectral line, the abundance of the element $\log \varepsilon$ is calculated for different values of the microturbulent velocity (ξ_t), the abundance of the element ($\log \varepsilon$) determines the microturbulent velocity (ξ_t) in the atmosphere of the studied star according to the graph does not depend on the equivalent widths (W_λ) of its spectral lines. Note that the deviation from LTT does not affect the FeII line. Therefore, the microturbulent velocity (ξ_t) and the iron abundance are determined by FeII lines in the stellar atmosphere. Only the fairly weak lines are used when determining the microturbulent velocity (ξ_t). These lines are formed in deep layers of the atmosphere, these layers are plane-parallel and in the LTT form.

The main parameters-effective temperature $T_{eff}=6800\text{K}$ and surface of gravity $\log g=2.6$. Knowing the effective temperature and surface of gravity of the star, we calculate its model using Kurucz ATLAS 9 program.

Based on these models, the iron abundance $\log \varepsilon(\text{FeII})$ is calculated by giving different values to the microturbulent velocity ξ_t in the atmosphere of each star. The iron abundance is determined on comparison of the measured from observation and theoretically calculated values of the equivalent width of lines FeII. The atomic data of spectral lines are taken from the VALD 3 [12].

In Fig.2 is shown the dependence graph of the abundance $\log\varepsilon(\text{Fe})$ determined based on the different equivalent widths of FeII on the equivalent widths W_λ - in the atmospheres of HR 6725 star.

As can be seen from Fig.2 there is no correlation between $\log\varepsilon(\text{Fe})$ and W_λ for the star HR 6725 (F2 III) at $\xi_t=3$ km/sec. When analyzing the microturbulence

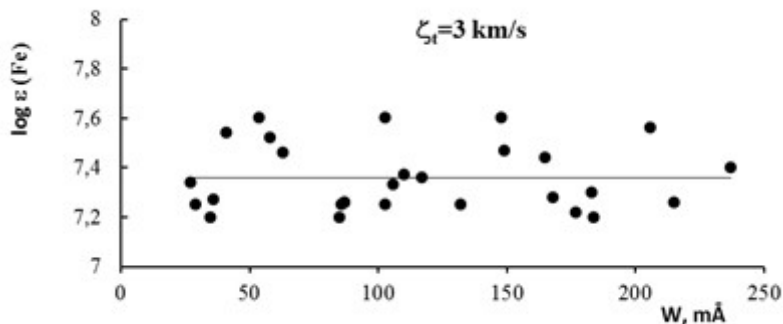


Fig. 2. Determination of microturbulent velocity. When $\xi_t=3$ km/sec is no correlation between the iron abundance $\log\varepsilon(\text{Fe})$ and the observed equivalent width (W_λ) of Fe II lines

on the basis of FeII lines, the abundance of the iron element $\log\varepsilon(\text{Fe})$ is simultaneously determined: $\log\varepsilon(\text{Fe})=7.36\pm0.12$. The abundance of iron in the sun is $\log\varepsilon(\text{Fe})=7.47$ [13]. As is shown the metallicity of the studied star and the Sun is practically the same. This shows that the star is studied and the Sun is formed from the same metallicity matter .

Main results:

1. The effective temperatures and the surface of gravity of F spectral class HR 6725 (F2 III) star have been determined by model and parallax methods.
2. The microturbulent velocity has been determined in the atmospheres of the star: $\xi_t = 3$ km/sec.
3. The metallicity was calculated in the atmosphere of the HR 6725 (F2 III) star. It has been found that the iron abundance is close to the abundance in the Sun. This shows that the star is studied and the Sun is formed from the same metallicity matter.

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DYNAMICAL EVOLUTION AND STATISTICS OF DAMOCLOIDS. 1

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The orbital evolution of 144 Damocloids and their clones (12 for each real object, a total of 1872 test particles) is modeled for 100 million years in the future. It is shown that the population of Damocloids retains high orbital inclinations during the integration time of 100 million years. By their dynamic life time, Damocloids can be divided into two subpopulations, with a short and long time of life. The first includes 85.75% of the objects and has an average life span of 2.68 ± 0.04 million years. The subsistence population with a long life span is 14.25%, with an average lifetime of 126 ± 6 million years. The main parameter by which the division can be made without prior simulations is perihelion distance: We found 5 interesting objects that have a long time of life, but in parameter space they occupy positions among objects with a short life span. Taking into account the bimodal distribution of Damocloids in a dynamic life span, it is proposed to clarify the definition of Damocloids by perihelion distance q (more or less than 9 AU). We propose to name these long-lived and short-lived subpopulations as trans-Saturnian and pre-Saturnian Damocloids.

Keywords: damocloids – comets – evolution – statistics

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1. INTRODUCTION

Damocloids are selected among minor bodies as objects satisfying the two criteria: they show no cometary activity (and thus are classified as asteroids), and they have the Tisserand parameter $T_J \leq 2$ [1]. 144 Damocloids have been discovered by the time our simulation began according to JPL HORIZONS [2]. The Damocloids orbits are mostly high inclined to the ecliptic plane (from 1.7° to 175.2°). 84 from 144 Damocloids move on retrograde orbits. Their orbital eccentricities are in a range from 0.2523 to 0.9983. Damocloids' perihelia are from 0.205AU up to 23.797AU. Damocloids' aphelia are from 4.57 AU up to 3176.53 AU.

Damocloids are believed to be Halley-type cometary nuclei originating in the Oort cloud that have lost their volatiles [1]. Some assigned Damocloids later showed cometary activity. The first Damocloid, (5335) Damocles, was discovered in 1991, and the first retrograde Damocloid, discovered in 1999, was named Dioretsa (20461) - the name is "asteroid" spelled vice versa. Damocloids' retrograde orbits provide one argument more in favor of their relationship with the Oort cloud and Halley-type comets. In the present study we focused on several objectives of the work: What is the dynamic lifetime of Damocloids' population and its dynamic link to the hypothetical Oort cloud and Halley-type comets [3]? For how long can their inclined orbits be preserved? How often the transitions from direct to retrograde motion or vice versa happens? What is the mechanism of such transitions? Can distant Damocloids move closer to the sun thus replenishing the population of Halley-type comets [4,5]? Can Damocloids replenish the near-Earth region?

2. CALCULATION METHOD

To simulate the dynamical evolution of Damocloids we applied the RMVS integration technique (Regularized Mixed Variable Symplectic method [6, 7]) from the SWIFTER package. We considered the presence of Lidov-Kozai mechanism in transition of Damocloids from prograde to retrograde motion. In celestial mechanics, the Lidov-Kozai mechanism, effect, or resonance is the periodic change in the ratio of the eccentricity and inclination of the orbit under the action of a massive body or bodies. The second manifestation of this effect is libration (oscillations around a stable value) of the argument of the pericenter. This effect was described in 1961 by M. L. Lidov when he studied the orbits of artificial and natural satellites of the planets [8], and in 1962 by the Japanese astronomer Kozai when he analyzed the orbits of asteroids [9]. For the orbit of a celestial body with

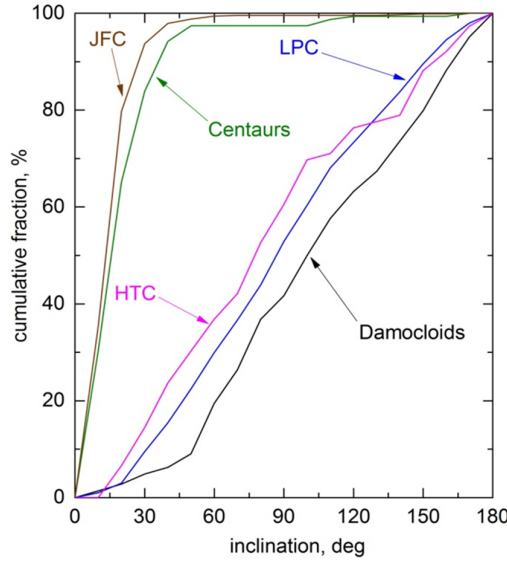


Fig. 1. The cumulative distribution of orbital inclinations for 144 Damocloids (black curve), 155 Centaurs (green curve), compared with 667 Jupiter family comets (brown curve) ($P \leq 20$ years and inclinations $20^\circ - 30^\circ$ or less), 401 LPCs (blue curve), and 76 Halley-type comets (magenta curve) ($20 < P < 200$ yrs, and inclination from 0° to 90° or more), according to the JPL Horizons service, on 21st of February, 2018. The similarity between Damocloids, LPCs, and HFCs is seen, with even greater similarity between Centaurs and JFCs populations.

eccentricity e and inclination i , which revolves around a larger body, the following constant ratio is preserved:

$$\sqrt{(1 - e^2)} \times \cos i = \text{const}$$

That is, periodic oscillation can lead to resonance between two celestial bodies. Thus, nearly circular, extremely inclined orbits can gain a very large eccentricity in exchange for a smaller inclination. Thus, for example, increasing eccentricity, with a constant semimajor axis, decreases the distance between objects at perihelion, and this mechanism can force comets to become nearsolar.

As a rule, for objects in orbits with a small inclination, such fluctuations lead to precession of the pericenter argument. Starting from a certain minimum value of the angle - the Kozai angle, which is 39.2° for bodies in direct orbits and 140.8° for retrograde bodies - precession goes into libration around one of two values of the angle: 90° or 270° , that is, the pericenter (point of maximum convergence). will fluctuate around this value. Physically, the effect is related to the transfer of momentum and the preservation of its total amount in a connected system.

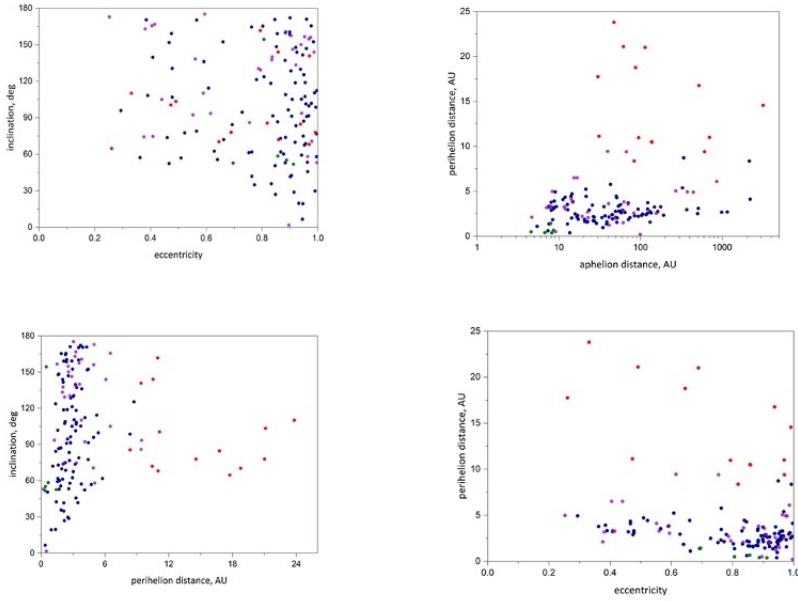


Fig. 2. The Damocloids' orbital parameters distributions with respect to the particles lifetime. Here red dots correspond to the particles from the long-lived subpopulation, the blue dots correspond to the particles from the short-lived subpopulation, and the violet dots are those particles for which less then a half of clones appeared in the long-lived subpopulation. The green dots are particles that broke the general rules, revealed by the plots analysis.

1. It was checked to what extent the distributions of inclined Damocloids, Centaurs and comets of individual families really differ [10]. For comparison, families with similar distributions were selected: Centaurs and JFC, as well as Damocloids, HTC and LPC. The Kolmogorov-Smirnov criterion was used [11].

2. Comparison of cumulative inclination-distributed and centaur comets of the known family (JFC). The distributions are based on 155 known centaurs and 667 JFCs for 18 inclination intervals with a step of 10° in the range $0 - 180^\circ$. The null hypothesis that their distributions are the same was tested. The maximum difference in values distributed for Centaurs - JFC is 0.146. Application of the Kolmogorov-Smirnov criterion shows that the probability of the same distribution is $\alpha = 0.0094$. That is, with a probability of more than 99%, these families differ.

3. Comparison of cumulative slope-distributed i Damocloids and known comets (NTC) and (LPC). The distributions are based on 144 known Damocloids, 76 NTCs, and 401 LPCs for 18 slope intervals with a step of 10° in the range $0 - 180^\circ$. The null hypothesis that their distributions are the same was tested.

The maximum difference between Damocloids and HTC is 0.212 . This gives the probability of the same distribution according to the Kolmogorov-Smirnov criterion $\alpha = 0.023$. That is, more than 97% of these Damocloids of the HTC family are different. The maximum difference in values distributed for Damocloids is LPC 0.134 . The application of the Kolmogorov-Smirnov criterion shows that the probability of the same distribution $\alpha = 0.044$. That is, the null hypothesis is rejected at the level of statistical significance above 95%. The maximum difference for LPC - HTC is 0.094. This gives the probability of the same distribution according to the Kolmogorov-Smirnov criterion $\alpha = 0.65$. In this case, there is an ambiguity when it is impossible to say definitely that LPCs and HTCs have the same or different distributions on the slope. Perhaps, with the further accumulation of data on new comets, this question will be clarified.

Thus, there are statistically reliable differences in the slope distributions between Damocloids, Centaurs, and comets with similar orbits on the other hand. Apparently, this indicates a different origin of these families.

3. FOURIER-ANALYSIS

For some Damocloids, the dependence of the inclination i on time shows quasi-periodic changes. This is characteristic of the presence of resonances with giant planets. The presence of such resonances should manifest itself in the frequency spectrum of changes in the elements of the orbits over time. To detect such frequencies, we used the discrete Fourier transform method, which is widely used for digital signal processing. In this method, the signal (in our case, one of the elements of the orbit) is represented as a series $x_n = \frac{1}{N} \cdot \sum_{k=0}^{N-1} A_k \cdot \exp\left(\frac{2\pi i}{N} kn\right)$, where x_n is the value of the element of the orbit at the n th time, N is the total number of values of the element of the orbit, A_k is the complex amplitude for the k -th harmonic. Period P_k and frequency v_k for the k -th harmonic

$$P_k = \frac{k}{N} \cdot \Delta t, \quad v_k = \frac{1}{P_k} = \frac{N}{k \cdot \Delta t},$$

where Δt is the time step in Julian years for the calculated values of the orbit elements. The fast Fourier transform program from the Matlab mathematical package was used to study the frequency spectrum in the dependence of the elements of the orbits on time. Based on the values of the complex amplitudes, a power spectrum was constructed, which is the dependence of the modulus of the complex amplitude A_k on the frequency v_k . At the same time, the value of A_0 was not taken into account, since we were interested in the change of orbital elements. As a rule, the spectrum shows frequencies that correspond to the rotation periods

of the giant planets 0.08431 h^{-1} (Jupiter), 0.03393 h^{-1} (Saturn) and less often with smaller amplitudes 0.01190 h^{-1} (Uranus), 0.00607 h^{-1} (Neptune).

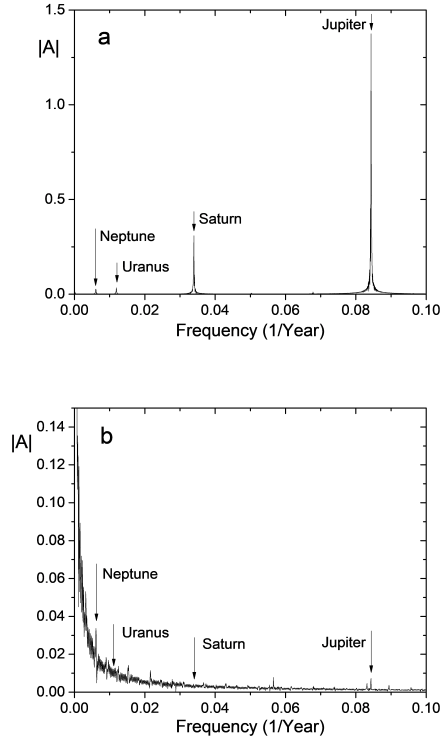


Fig. 3. Examples of spectra of changes in the inclination of the orbit i for Damocloids: a) with strong resonances with Jupiter and Saturn of Damocloid #418; b) in the absence of resonances with the giant planets of Damocloid #421.

4. METHODS AND RESULTS

To perform the objectives of this work we accomplished the following steps:

1. We integrated the 1872 test particles (of 144 Damocloids and 12 clones for each of them, created by rounding up back and forth the last decimal number in the values of their state vector parameters) for 100 Myr forward in time, with the integration step 29.22 days and step of data output 80 years. The four giant planets and the Sun (with added mass of terrestrial planets) were taken into account. Each particle was followed till it reached 5000 AU distance from the Sun. RMVS integration technique [7] from SWIFTER software package [6] was used. Integration allowed us to get the particles' distribution on their lifetime

(Fig.4), and also distribution of particles' lifetimes as a function of their initial inclinations (Fig. 5). Also, in the course of calculations we analyzed all possible close encounters of Damocloids with planets in order to better understand the evolution of this family [12,13]. The decay half-life for the population is given by

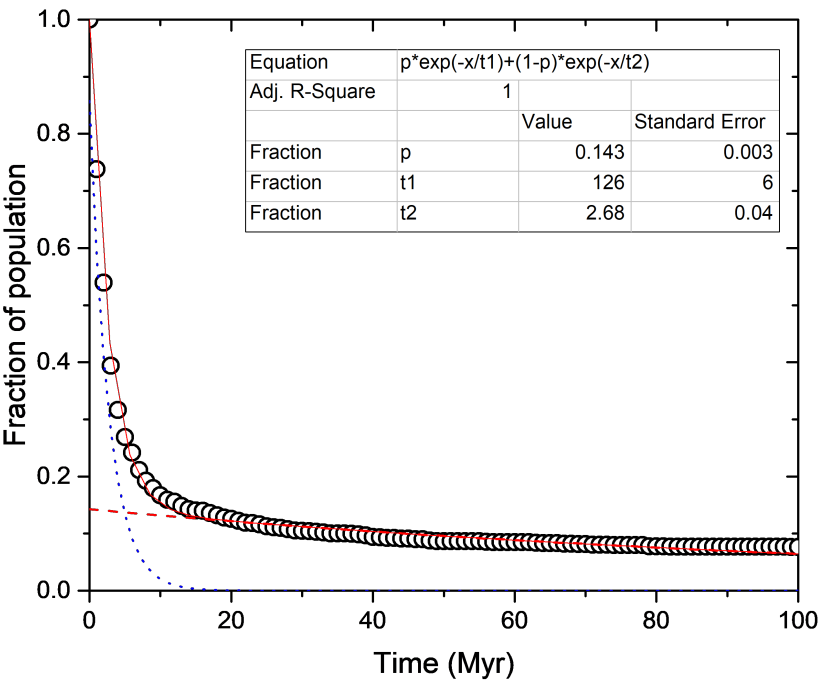


Fig. 4. The fraction of surviving in the simulation Damocloids as a function of simulation length, up to 100 Myr forward in time (circles). The exponential law approximation was applied to the curve. Dotted line is the best fit for the short-lived subpopulation, while dashed line is the best fit for the long-lived subpopulation. Parameters of exponential equation and value errors are presented in a table within the plot.

$N = N_0 e^{-\lambda t}$, where N_0 is initial number of particles, and $\lambda = \frac{0.611}{T_{1/2}}$, where $T_{1/2}$ is the half life time.

2. To reveal which orbital parameter is responsible for the length of particle's lifetime and the division of Damocloids in two subpopulations - long-lived and short-lived - we plotted the initial orbital parameters' distributions for 144 Damocloids, partially shown on Fig. 2. The orbital parameters distributions on the plots $i(e)$, $i(a)$, and $i(Q)$ don't reveal the division of Damocloids in two subpopulations by their lifetime. The orbital parameters distributions on the plots $e(a)$, $q(a)$, $q(Q)$, $i(q)$, $q(e)$ do reveal the division of Damocloids in two subpopulations by their lifetime. Thus, by location of the Damocloids' particle in

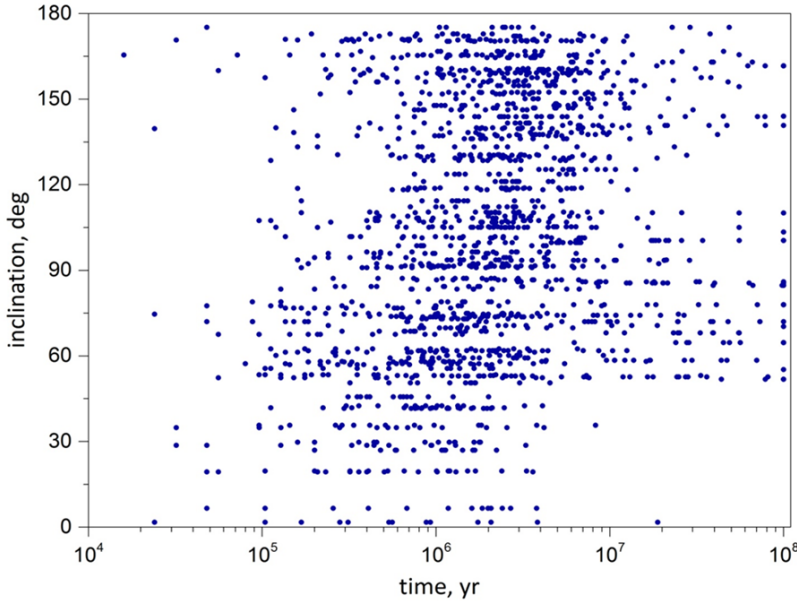


Fig. 5. The particles' lifetimes distribution as a function of initial inclinations. Particles and clones on less inclined orbits live shorter, while particles on more inclined orbits live longer.

parameter spaces $e(a), q(a), q(Q), i(q), q(e)$ it is possible to predict whether the particle belongs to the short-term or the long-term subpopulation. The long-lived subpopulation particles may have an arbitrary eccentricity, but they have q in the vicinity of Saturn's orbit or beyond, aphelia above 30AU (in the vicinity of Neptune's orbit and beyond), and semi-major axis a above 20 AU. Their inclinations are above 60 degrees, but not all particles with such inclinations are long-lived. The stricter division of subpopulations is by perihelion distance q . If q is about 9AU or above - we may predict without simulations that the particle most likely will be long-lived.

Five strange particles (green dots on Fig. 2); that broke the rules of division in two subpopulations, have something in common. These particles (343158 (2009 HC82), 2005 MW9, 2012 US136, 2010 CA55, and 2016 EB157) all have inclinations above 50 degrees, high eccentricities (0.696-0.912), and small perihelia, mostly inside Earth's orbit (0.377 AU, 0.402 AU, 0.489AU, 0.668AU, and 1.428 AU). But the sample is not big enough to make any profound conclusion.

3. As a next step we applied K-S statistical test to these groups of particles (marked in red, blue, violet, and green on Fig. 2) and revealed that by i and e they are identical, but the statistically significant difference appeared for q (the highest), Q , and a .

4. The K-S test applied to the curves on Fig. 1 revealed that the closest to each other are populations of HTC's and LPC's, then Centaurs and JFC's, and then Damocloids and HTC's.

5. The dynamical evolution integration of Damocloids performed as a step 1 allowed to plot the orbital changes and to see their character. Some Damocloids revealed quasiperiodic behavior, others experienced transitions from direct to retrograde motion or vice versa, others got stuck in resonances.

6. The transiting particles follow the Lidov-Kozai mechanism. Below are the respective plots for $i(t)$ (left) and $e(t)$ (right) for same sets of particles (Fig. 6).

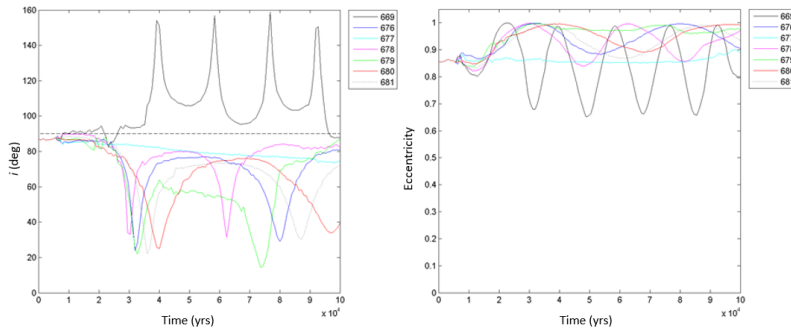


Fig. 6. The comparison of respective plots for $i(t)$ (left) and $e(t)$ (right) for same sets of particles. This figure is an attempt to show the Lidov-Kozai mechanism on the example of 7 individual particles.

7. The long-lived survivals are captured in resonances with giant planets.

8. The Fourier analysis of the power spectrum of i shows which giant planet is responsible for Damocloids' resonances or dramatic changes in their orbits. Below are examples for strong resonances with Jupiter and Saturn (left, Fig. 7a, particle #418), and without resonances (right, Fig. 7b, particle #42).

5. RESULTS

1. The Damocloid population maintains large orbital inclinations over an integration time of 100 million years.

2. Damocloids can be divided into two subpopulations, with a short and a long life, according to the dynamic life span. The first includes 85.75% of objects and has an average lifetime of 2.68 ± 0.04 million years. The long-lived subpopulation accounts for 14.25% of objects, with an average dynamic lifetime of 126 ± 6 million years (Fig. 8).

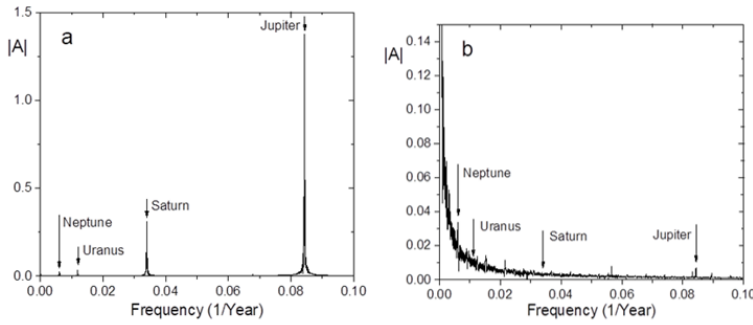


Fig. 7. The power spectrum of i in case of strong resonances with Jupiter and Saturn (left, Fig. 7a, particle #418), and without resonances (right, Fig. 7b, particle #421).

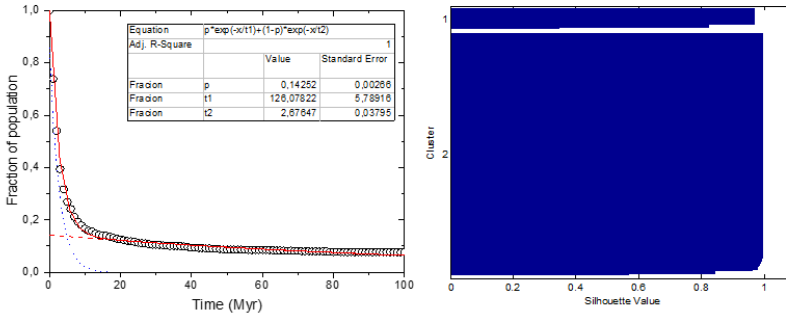


Fig. 8. Bimodal distribution of Damocloids according to dynamic during life, based on the results of approximation by exponential curves (left), and according to the results of cluster analysis (right)

3. It was analyzed which orbital parameter is responsible for the separation of Damocloids into two subpopulations. The separation between them is clearly visible on the graphs $e(a)$, $q(a)$, $q(Q)$, $i(q)$, $q(e)$. The main parameter by which it is possible to determine whether Damocloid belongs to a subpopulation with a longer or shorter life time without prior integration is the perihelion distance, less or more than 9 AU. (Fig. 9).

4. Found 5 objects that violate the rule of point 3, because they have a long-life time, and on the graphs they occupy a position among objects with a short life time. It is shown that the transition of the orbital inclination through a value of 90 degrees, i.e., from forward motion to reverse motion or vice versa, sometimes occurs according to the Lidoy-Kozai mechanism, when the inclination is "exchanged" for the eccentricity, i.e., a change in the inclination leads to a

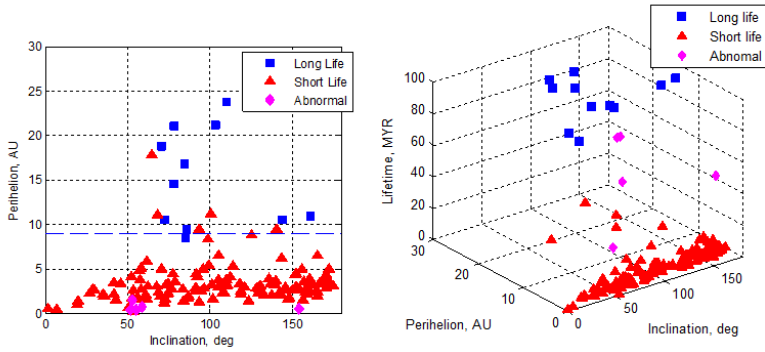


Fig. 9. Two-dimensional (left, $q(i)$) and three-dimensional (right, + particle lifetime) graphs showing the distribution of Damocloids into two subpopulations by lifetime. Blue squares – particles with a long lifetime, red triangles – with a short lifetime, purple rhombuses – anomalous particles (with a long lifetime, but in parametric space they occupy positions among particles with a short lifetime).

sharp change in the value of the eccentricity of the orbit.

5. During the integration time of 20 million years forward, out of 144 sets of orbits (for each known body and its 12 clones), only 17 sets did not have a single body or clone crossing the 90° orbital inclination mark. Some objects undergo repeated inclination changes and transitions through 90 degrees (Fig. 10, left), while others leave the integration zone (from the Sun to 5000 AU) after the inclination change (Fig. 10, middle). Among the Damocloid population are objects that undergo libration around an angle of 90° (Fig. 10, right).

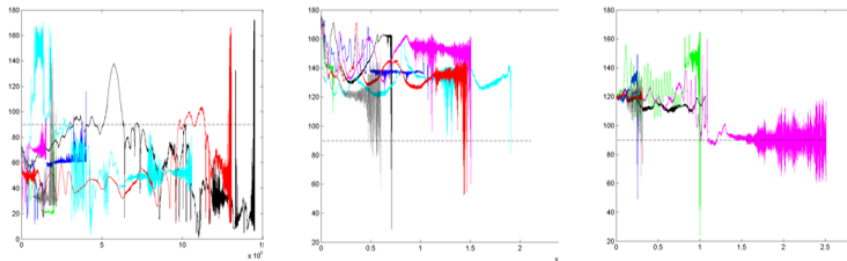


Fig. 10. An example of the orbital evolution of bodies that: repeatedly switched from direct motion to retrograde or vice versa (left); after changing the inclination, they leave the integration zone (from the Sun to 5000 AU) (middle); undergo libration around an angle of 90 degrees (right).

6. Over time, Damocloids can replenish the space near the Earth's orbit. A preliminary analysis gave an estimate of the rate of transition of objects from the Damocloid population to NEO orbits – 0.11% of the population in 10 million years. Integration with a smaller step of 100,000 years showed that every 10,000 years, at least temporarily, from 7.64% to 14.05% of the population has a low perihelion in the region less than or equal to 1.3 AU. 7. Taking into account the bimodal

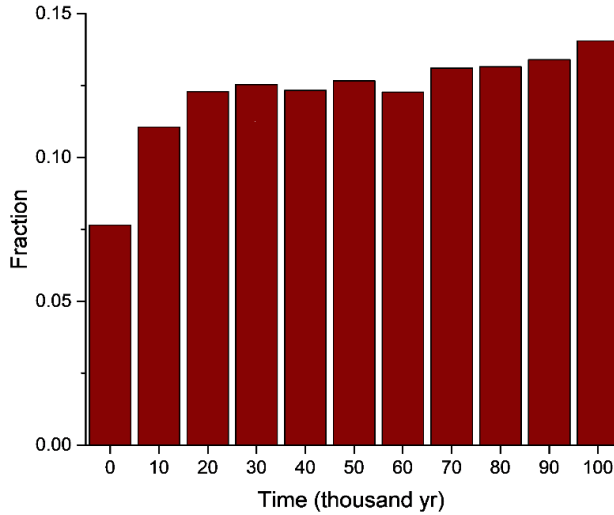


Fig. 11. The portion of the Damocloids that during the integration time of 100,000 years had a perihelion in the region of $q \leq 1.3$ AU. (data for every 10 thousand years).

distribution of Damocloids according to their lifetime, it is proposed to refine the definitions of Damocloids according to their perihelion distance q (more or less than 9 AU). It has been proposed to call these subpopulations with longer and shorter life spans trans-Saturnian and pre-Saturnian Damocloids, respectively.

6. CONCLUSIONS

1. The simulation revealed the existence of two subpopulations of Damocloids: 85.75% are short-lived with the median dynamic lifetime of $2.68\text{Myr} \pm 0.04\text{Myr}$, and 14.25% of the population is long-lived with dynamic lifetime $126 \pm 6\text{Myr}$. The main parameter by which the division can be made without prior simulations is perihelion distance: Damocloids with q from 9AU and above will most likely belong to the long-lived subpopulation. The longlived survivals are captured in resonances with giant planets.

2. Taking into consideration the bimodality of Damocloids lifetime distribution we propose to add to the definition of Damocloids by two criteria (asteroids, and $T_J \leq 2$) the indication to which subpopulation the object belongs - long-lived or short-lived - by perihelion distance q (more or less than 9AU). We propose to name these long-lived and short-lived subpopulations as trans-Saturnian and pre-Saturnian Damocloids.

3. Five strange particles were revealed. They are long-lived, but occupy the parameter space region typical for the short-lived particles. These strange particles all have inclinations above 50 degrees, high eccentricities (0.696-0.912), and small perihelia, mostly inside Earth's orbit (0.377 AU, 0.402 AU, 0.489 AU, 0.668 AU, and 1.428 AU).

4. Some of the evolutionary tracks allow transitions from retrograde motion to direct and vice versa. The Damocloids population retains members on retrograde orbits over the course of integration.

5. Some of Damocloids reached smaller perihelia over the course of integration, allowing them to become nuclei of Halley-type comets.

6. Statistically the closest to each other are populations of HTC's and LPC's, then Centaurs and JFC's, and then Damocloids and HTC's.

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