Astron. Astrophys. 325, 1083–1087 (1997)

ASTRONOMY
AND
ASTROPHYSICS

The luminosity of the H_α-emission envelopes of variable Is(A)-type stars

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Received 30 April 1996 / Accepted 20 November 1996

Abstract. We present the results of the analysis of the emission spectra of variable Is(A)-type stars. Sixteen stars have been observed in 1988–1992 at the 6-m telescope of Special Astrophysical Observaroty, Russian Academy of Sciences (SAO RAS) with the middle-resolution (R≈3000) echelle spectrograph "Zebra". Equivalent widths of the H_α and H_β (if available) emission components were obtained, the underlying profile of the corresponding absorption lines were taken into account. The luminosities of the emission envelopes in the H_α and H_β lines were then calculated. The main result of the investigation is that the luminosity of the emission envelope appears to depend on the effective temperature of the star.

Key words: stars: early type – stars: emission line – stars: variables: other – stars: pre main-sequence

1. Introduction

In the last decades there are growing evidences that the structure of the Herbig Ae/Be (HAeBes) group is not so homogenuous as it was previously thought. Because of lack of adequate definitions, many emission A-stars having different morphological, physical and evolutional characteristics, were prematurely included in the HAeBes group. HAeBes show a vast variety of emission features which makes a strict classification of the HAeBes in a frame of unified conception a very problematic task. In spite of the fact that more and more complex system and criteria of classification have appeared during the last decade (Bastian et al. 1983; Hamann & Person 1992; Thé et al. 1994) a strict universal criterion is not yet elaborated and an ambiguety still remains.

There is a small subgroup of HAeBes showing significant photometric variations. The light variability of these stars is governed by drastic non-periodic light fadings, of which the amplitude ranges up to 3 magnitudes in several days or weeks (Kolotilov et al. 1977; Pugach 1981; Kardopolov & Philipjev 1985; Bibo & Thé 1991). The stars are indicated as Is(A)-type stars (rapid irregular variables with Algol-like minima) in the General Catalogue of Variable Stars (Kholopov et al. 1985). Owing to the specific form of their light curves the stars are sometimes called *"antiflare stars"*. We shall conventionally call them ALIVARS – Alpha Line (or Algol Like) Irregular VARiable Stars.

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The ALIVARS, being members of a larger sample of the HAeBes group, differ from *"classic"* HAeBes by photometrically as well as spectral characteristics. The emission spectrum of ALIVARS is poorer than that of HAeBes. There are numerous emission lines of CaII, FeI, [FeII], OI and others elements, which are clearly seen in the near infrared spectrum of HAeBes. However these lines are absent in the ALIVARS (see for example spectra of XY Per, HK Ori, VV Ser to be presented in paper of Hamann & Persson 1992).

Spectral differences between ALIVARS and classic T Tau-stars are more pronounced owing to noticeable differences in their temperatures. However, an intermediate temperature interval 6000 K $< T_{eff} <$7000 K exists where these two group of stars intersect each other. Such stars with the intermediate temperatures as CO Ori, CQ Tau, EZ Ori and others may often be considered as HAeBes (Herbig & Bell 1988) and T Tau-stars simultaneously (Herbst et al. 1994). The spectra of HAeBes, ALIVARS and T Tau-stars are different, however, they have in common a special feature, namely the emission line H_α. For this reason, the examination of this line would provide significant informations for diverse types of emission stars in order to be classified more strictly. However, ALIVARS being mostly of spectral class A, have in their spectra a strong absorption H_α-line ($EWH_{abs} \sim 10 - 20$Å) which distorts the real form and the equivalent width of the emission profiles. The influence of the underlaying absorption line should be accurately taken into account before the correct value of the emission line equivalent width can be determined.

In the present article the true parameters of the H_α-emission luminosity of a representative group (16 objects) of ALIVARS are obtained after the contribution of the absorption profile was accounted for.

2. Observations and results

The observations have been made in 1988–1992 with the middle resolution (R≈3000) echelle spectrograph "Zebra" (Gazhur et al. 1990; Klochkova & Panchuk 1991) mounted at the Nasmyth focus of the 6-m telescope (SAO RAS). The names of the objects and the data of the observations are listed in Table 1. According to our visual estimations neither of the stars were at a deep light minimum at the moment of the observations.

The reduction of the numerical spectra from the images was achieved with a set of programmes elaborated in SAO RAS (Galazutdinov 1992). The final treatment of the spectra was performed using a software of the Main Astronomical Observatory of Ukraine. Scattered light and the spectral responce function of the detecting system were taken into account and a procedure of spectrum linearization was carried out. More details concerning the full treatment prosedure can be found in the preceding paper (Kovalchuk & Pugach, 1997, hereafter KP1). To obtain the correct equivalent widths of the observed H_α-emission lines, theoretical profiles of the H_α-absorption line were calculated in advance. We have used the effective temperatures, T_{eff}, and the gravity parameter lg g previously determined (KP1). The atmospheric model method of Kurucz (1979) was applied and the corresponding theoretical absorption profiles for hydrogen lines of each star were calculated. Then all theoretical profiles were convolved with the instrumental profile function as to make them comparable with the observations. The rotation effect of the star is considered to be negligible, because moderate rotation seems hardly effect broad hydrogen lines. Finally, profiles obtained in this way were shifted by $\Delta\lambda$ defined as follows,

$$\Delta\lambda/\lambda = 0.5[(\lambda_\gamma/4340.47 - 1) + (\lambda_\delta/4101.74 - 1)] \qquad (1)$$

where: λ_γ and λ_δ are the observed wavelenghts of the hydrogen lines of each star.

The equivalent widths were expressed as a difference between the observed emission profiles and the corresponding calculated absorption ones. The same procedure was applied for the determination of the equivalent widths of $H_\beta e$ and $H_\gamma e$ if available.

The conversion of the equivalent widths EW_e into luminosities L_e is allowed by virtue of the coefficient $J_\lambda(T_{eff})$. The coefficient J_λ gives a fraction of the total energy of the star which is radiated within a spectral interval of 1 Å at the centre of H_α or the H_β lines. The J_λ is roughly considered to be a function of T_{eff} and corresponding values of J_λ may be calculated using Planck's formulae. Then the total luminosities L_e for the given emission line was determined by means of:

$$L_e = J_\lambda EW_e L^* \qquad (2)$$

where: $L^*=L(T_{eff}$, lg g) are luminosities of the stars depending on the effective temperature T_{eff} and the parameter of gravity lg g. The values of L(T_{eff}, lg g) were taken from the paper by de Jager & Nieuwenhuijzen (1987) and all the stars studied were considered to be giants.

Table 1 summarizes the results obtained. The following data are listed in this table:

1. Designation of the star
2. Date of observations
3. Effective temperature (mean from KP1)
4. Parameter of gravity (mean from KP1)
5. Adopted luminosity of the stars L^* (from de Jager & Nieuwenhuijzen, 1987)
6. Measured equivalent widths of H_α
7. Measured equivalent widths of H_β
8. Measured equivalent widths of H_γ if possible
9. $L_{e\alpha}$-emission envelope luminosities in erg s^{-1}
10. $L_{e\beta}$-emission envelope luminosities in erg s^{-1}
11. Emission decrement $L_{e\alpha}/L_{e\beta}$
12. Form of the emission line profile

The values of EWH_γ however should not be taken too seriously since their uncertainty is very great.

3. Discussion of the results

Before discussing the results we would like to say some words concerning the validity of the approach used. An operation of an absorption profile subtraction from an observed one seems to be allowed provided that the emission and absorption lines have independent origin. It is well known that the H_α-line intensity of ALIVARS increases while the brightness of the star become lower (Kolotilov 1977). The observations appear to favour the hypothesis that the emission is formed in a region above the dust clouds, which in its turn may lay far away above the photosphere. Unlike chromospheric lines the emission observed is formed in envelopes with radius R_e, which in Herbig Ae/Be stars is estimated to be ranging from

$2.5R^* < R_e < 100R^*$

(Baschek et al. 1982; Garrison 1978). More recent kinematic evaluations of a dust cloud, distant from the star, gives a value R_e near 1000R^* (Herbst et al. 1994). Therefore it is obvious that the process of the formation of emission and absorption lines cannot be comparable for both geometrical and physical conditions. Hence, we may state their independence. This allows the absorption and emission intensivities to be arithmatically added. Such a procedure is widely used for the calculation of the intensity of emission component in Be stars (Dachs et al. 1990; Köppen et al. 1982). Therefore, the values of L_e obtained were plotted against the temperature T_{eff}. There seems to exist a positive regression relation between L_e and T_{eff} in the temperature interval 7000 K $< T_{eff} <$11000 K (Fig. 1).

However two stars, namely CO Ori and EZ Ori, are lying outside this relationship, showing much more intense emission than required for the corresponding temperature. Perhaps these stars were erroneously assigned as giants, whilst they might probably be dwarfs or subgiants at least. CO Ori and EZ Ori have some years ago been included in our observing programme to make a check as marginal stars, both being HAeBes (Herbig & Bell 1988) but never ALIVARS. Moreover, CO Ori is sometimes classified as an object of the T Tau group (Herbst et al. 1994). Both CO Ori and EZ Ori are probably main (or pre-main) sequence objects, whilst all ALIVARS are giants having an average group parameter of gravity lg g≈3.0 (KP1). Thus, the

Table 1. Main hydrogen emission characteristics of ALIVARS

Star	Date	T_{eff}, K	lg g	L^*, 10^{34}erg s^{-1}	W_e(Å), emission			Luminosity 10^{31}erg s^{-1}		D_{34}	fp
		(^{a}	(^{a}		H_α	H_β	H_γ	H_α	H_β		
VX Cas	01.25.89	9800	3.25	47.1	14.2	1.8	< 0.5	48.5	11.3	4.29	d^+
SV Cep	01.24.89	9800	3.50	47.1	9.7	1.1	< 0.5	33.2	7.2	4.58	s^0
BH Cep	01.24.89	6450	3.5:	8.6	5.4	-	-	4.9	-	-	$d:^+$
BO Cep	01.24.89	6590	3.5:	8.6	6.2	-	-	5.6		-	s^+
-"-	02.23.92	6590	3.0:	8.6	5.1	-	-	4.7		-	s^0
V517 Cyg	01.23.91	8200	2.55	15.9	10.6	1.4	-	15.1	3.8	3.90	s^0
BN Ori	01.22.91	6950	3.5:	9.0	4.3	-	-	3.9	-	-	$d:^-$
CO Ori^b	02.23.92	6220	?	8.8	10.8	-	-	10.4	-	-	s^0
-"-	as a dwarf			0.81				0.9			
EZ Ori^b	01.21.91	5850	?	9.4	14.2	1.8	-	15.0	2.4	6.12	s^0
-"-	as a dwarf			0.44				0.7			
UX Ori	02.24.92	9000	2.90	27.6	13.2	(^{c}		31.1	-		s^0
V346 Ori	01.23.89	8200	2.10	16.0	6.3	-	-	9.1	-	-	$d:^+$
V351 Ori	01.27.89	7900	1.40	13.0	4.1	-	-	5.0	-	-	s^0
-"-	02.23.92	7900	1.40	13.0	3.4	-	-	4.2	-	-	$d:^+$
V451 Ori	01.21.91	10750	3.45	84.4	16.8	2.8	1.6	85.6	29.4	2.91	s^0
V586 Ori	01.25.89	9000	3.10	27.6	17.8	1.3	0.5	39.5	5.0	7.79	s^0
-"-	02.22.91	9000	3.10	27.6	14.3	(^{c}	-	31.7	-	-	$d:^+$
-"-	02.23.92	9000	3.10	27.6	16.9	3.1	-	37.5	12.3	3.03	s^0
IP Per	11.24.89	8800	2.00	21.6	12.5	2.2	1.8	21.9	6.6	3.32	s^0
-"-	02.23.91	8800	2.00	21.6	12.0	1.1	-	21.0	3.2	6.46	s^0
XY Per^e	01.27.89	9100	3.00	30.0	10.1	-	-	18.5	-	-	s^0
DD Ser	02.23.91	8600	2.40	20.8	7.2	1.8:	0.9:	12.8	5.5	2.32	d^0
CQ Tau	01.25.89	6860	3.5:	8.8	6.3	-	-	5.7	-	-	s^-
RR Tau	02.22.91	8800	2.05	24.0	19.6	2.2	0.8:	37.4	7.4	5.03	d^+
-"-	02.23.91	8800	2.05	24.0	17.3	1.6	(^{c}	33.0	5.2	6.32	d^+

Notes: fp - Form of an emission profile:
s - singe; d: - probably double but unresolved; d - double;
"+" - positive asymmetry; "0" - symmetrical;
"−" - negative asymmetry.
(^{a} - Mean values are taken from (KP1);
(^{b} - as a giant (see text);
(^{c} - there is an emission component but the measurement is impossible;
(^{e} - double star, the component with coordinates (1989.0) $03^h48^m53.09^s$ and $+38°57'39.1''$ was observed

relationship "L_e-T_{eff}" may be employed as a sensitive tool for the classification of ALIVARS and T Tau-type stars to separate them in those cases when photometric data are insufficient.

Now we would like to discuss the fact that the luminosity-temperature relation is not a quite trivial one. One would not expect at all an existence of the relatioship *a priori* at least for two reasons. First, neither classic T Tau stars (Cohen & Kuhi 1979; Strom et al. 1989), nor weak emission stars in the Orion Belt (Kogure et al. 1992), nor HAeBes when considered as a whole, show such a dependence. It is obvious that the HAeBes, being non-homogenious in the sense of their structure, include stars of different types with diverse physical and environmental conditions. Second, the previous result of Pugach & Kovalchuk (1993) indicates that the Balmer emission decrements of ALIVARS do not agree with the supposition that the emitting atoms are excited by radiation. The decrements appear to favour the hypothesis that the electron collisions are the preferential mechanism to excite hydrogen atoms. Since the radiative mechanism does not play a dominant part in the formation process of emission lines one hardly can suppose by anticipation that the emission line intensities would correlate with the temperature of the star.

Theoretical calculations (Boyarchuk 1966; Brocklehurst 1971) have shown that the decrement for radiative mechanism cannot exceed a certain value, i.e. $D_{34}(rad) \leq 2.8$. The previous conclusion of Pugach & Kovalchuk (1993) regarding the prevalence of collisional mechanism over the radiative one was based on the fact that decrements for the three stars VX Cas, V586 Ori and SV Cep were

$D_{34} = L_{e\alpha}/L_{e\beta} \geq 3.22$.

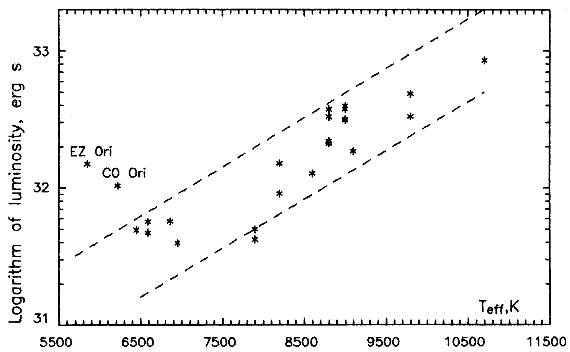

Fig. 1. H_α-emission envelope luminosity $L_{e\alpha}$ of observed ALIVARS versus effective temperature T_{eff}. The higher the temperatures the more luminous the envelopes are. Two stars, EZ Ori and CO Ori, are lying ouside this relationship, because probably they are not ALIVARS and not giants at all

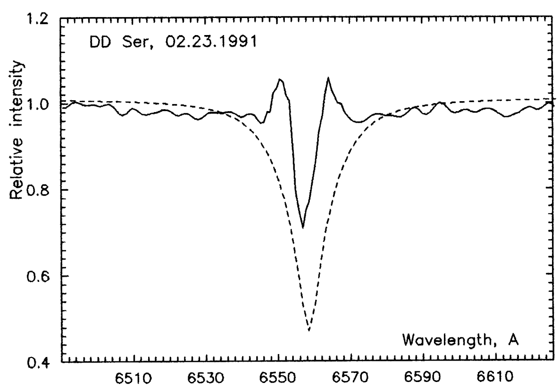

Fig. 2. Observed H_α-line profile of DD Ser (solid line). Strong absorption reversal is overlapping the main body of the emission line. The theoretical profile for T_{eff}=8600 K and lg g=2.4 (dashed line) is also shown for comparison

The new data presented in Table 1 seem to confirm the former conclusion. So far as the decrements D_{34} for all but one ALIVARS range in the interval

$2.89 \leq D_{34} \leq 7.79$

one may insist upon collisional rather than radiative mechanism of excitation.

DD Ser having the smallest value of the decrement (D_{34}=2.32) at the same time has the most interesting profile of the H_α-line. The point is that the sharp absorption reversal laying over the H_α-emission profile is very strong and that the core of the sharp absorption line is lower than the continuum level (see Fig. 2).

One would can interpret such a form of a line profile as being due to the presence of an additional mass of hydrogen in the line of sight (cloud, disk, shell?). However, no traces of a shell line are visible on the H_γ and H_δ profiles. Several other stars resembling DD Ser, RR Tau and BO Cep, have a sharp absorption line component which splits the top of the emission line, but less intensive. These observations indicate that a certain portion of the H_α-radiation emitted by the envelope is extinguished by masses of neutral hydrogen. Thus our determinations of the luminosities L_e, listed in the Table 1, give the lower level of the possible values. In some cases the presented values of $L_{e\alpha}$ slightly differ from those published in our previous articles because new and more exact luminosities L^* of the stars are now employed.

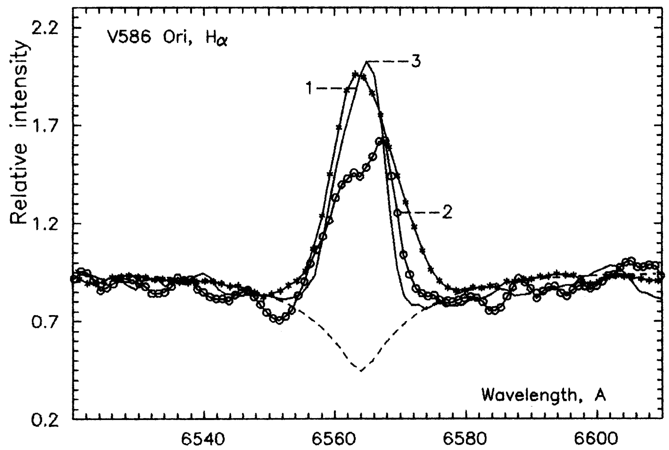

Fig. 3. Three H_α-line profiles of V586 Ori show variations of form and equivalent widths of the emission line. Dates of observations are as follows: 1 – 05.25.1989; 2 – 02.22.1991; 3 – 02.23.1992

The "$L_{e\alpha}$-T_{eff}" relationship found is reliable, provided that no deep light fadings of the stars have taken place during the observations. The probability for ALIVARS to be at a deep light minimum does not exceed 3-5%. Our visual estimates during the spectral observations show that the stars were at their normal brightness level excluding deep light minima. Moreover, it is known that the equivalent widths $EW_{e\alpha}$ of VX Cas, UX Ori and WW Vul at deep light minima grow up to values of 28.5 Å, 36.0 Å and 42.8 Å (Kolotilov 1977). Our observations have registered no such large values. This fact unambiguously evidences that no deep light fadings occured at the times of our spectral observations and that our visual estimations agree with this. Therefore, we are certain that our observations do not coincide with deep light minima. However, it is beyond doubt that small amplitude light variations near the point of normal brightness do occure. They may well account for the scatter of the points in the "$L_{e\alpha}$-T_{eff}" diagram. Unfortunately, we have no photometric data and cannot give account of the influence of small photometric variation on the equivalent widths observed.

Table 1 contains no data on the radial velocities of the emission envelopes, because in our case such data are utterly formal. First, considerable variations of widths and forms of the emission lines do take place. Fig. 3 shows the H_α-emission component variation of V586 Ori.

Second, the presence and the displacement of the variable sharp absorption reversal may noticeably affect the position and the form of the emission profile, and would lead to incorrect values of the radial velocity of the envelope.

It is worth to note that there is an undecisive problem concerning the luminosity classes of ALIVARS. We used class III of luminosity for all stars of the group, assuming them to be giants. However, the values of lg g for some stars (V351 Ori, V346 Ori, RR Tau) indicate that the stars should be regarded as supergiants of luminosity class II and even class I. At the same time the distance modulus (m-M_v-A_v) shows that the stars are not very luminous. A similar ambiguity exists for BF Ori and UX Ori. The first has narrow hydrogen lines (Shevchenko 1989) and the latter shows some UV absorption features of supergiants (Tjin A Djie et al. 1984). But both stars in fact can't be very luminous because they are not so distant.

4. Conclusions

1. The investigation of a small subgroup of HAeBes, namely Ae variable stars of Is(A)-type with algol-like light fadings – ALIVARS – shows that the H_α-luminosity of the emission envelopes correlates with the effective temperature of the stars. This finding gives a possibility to distinguish intrinsic ALIVARS from non-ALIVARS-type stars, both being the HAeBes, as well as from marginal T Tau-type stars and emission stars of the Orion Belt.
2. The so-called marginal stars, i.e. the ones with intermediate temperatures, which have a partial resemblance with both ALIVARS and T Tau-type objects, can be tested by mean of the relationship found for the classification, in order to define them more precisely.
3. Two more ALIVARS namely V351 Ori[1] and DD Ser were found to be emission-line objests. They were not known before as emission-line stars and now they will probably be included in the list of HAeBes. After that the validity of the conclusion that all ALIVARS must have an emission envelope has greatly increased.

Acknowledgements. The authors like to thank the staff of the Special Astrophysical Observatory of the Russian Academy of Sciences for the granted observing time at the 6-m telescope, Dr. Panchuk V.E. and Dr. Klochkova V.G. for their time spent in organizing the observations, Dr. Galazutdinov G.A. for his assistance in the treatment of the images. We thank our unknown referee for his useful comments and suggestions and careful English checking. All calculations were done with the computer presented by ESO's C&EE Programme (grant A-01-004). One of the authors (GUK) wishes to express his sincere thanks to the American Astronomical Society for financial support of this work.

[1] While this paper was under preparation, the article by van den Ancker et al. (1996) appears, in which it was shown that V351 Ori is an emission-line star.

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Note added in proof: 5 Middle-resolution spectra of DD Ser (3 of them are available through the courtesy of A.E. Tarasov), which have been obtained at the 2.6-m telescope using SPEM spectrometer in 1984–1986 give true parameters of the star at the normal state:

$$EW_{e\alpha} = 13.8\,\text{Å};\quad L_{e\alpha} = 24.5 \times 10^{31}\ \text{erg/s};\quad D_{34} = 4.46$$

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