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Research Note

On the possible origin of λ Boo stars

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Abstract. We discuss a new approach to the problem of the origin of λ Boo stars. It is proposed that at least some of these stars may arise from contact binary systems of W UMa type. Simple estimations based on this supposition can account for the present-day number of λ Boo stars in the solar neighbourhood, their masses and spectral classes. It is also important that the proposed scenario does not exclude circumstellar shell formation, which is responsible for the chemical peculiarities of λ Boo stars.

Key words: stars: binaries; close – stars: chemically peculiar – stars: evolution

1. Introduction

λ Boo stars are known to be Population I objects mainly of A spectral classes having the following main properties: 1) observed $v\ sin\ i$ values achieve 100 - 200 km s^{-1}; 2) they show slight overabundance (or normal abundance) of CNO-elements and moderate or strong underabundance of the heavier elements; 3) some stars have an infrared excess that indicates an existence of a circumstellar shell.

A comprehensive review on the λ Boo phenomenon was recently provided by Stürenburg (1993).

For the explanation of λ Boo stars' peculiar chemical composition, Venn and Lambert (1990) proposed an accretion hypothesis. It consists of the supposition that depleted gas from the circumstellar envelope is accreted by the star, while dust grains are swept from the shell due to radiative pressure. The dust grains accumulate metals with high condensation temperature (e.g. Si, Fe), but elements with lower temperature of condensation (C, N) remain in the gaseous phase and then can be accreted by the stars. Further consideration of the proposed accretion scenario was given by Charbonneau (1991,1993), who combined it with theory of diffusion.

Despite some difficulties of the accretion/diffusion model, it is generally adopted at the present time. The main feature of this model is the existence of a circumstellar shell. Such a shell is regarded to be usual remnant of the protostar evolution. However, the λ Boo phenomenon is not prevalent among A stars and the specific mechanism forcing only certain protostars to evolve toward the λ Boo phenomenon is not clear. Any hypothesis, proposed for these stars has to explain three observed properties: 1) these stars are found *only* among A stars and they constitute a small stellar group, 2) on average, these stars are fast rotators, and 3) they possess circumstellar shells.

Here we propose an addition scenario of λ Boo star formation, based on the supposition that there could be a possible connection between these stars and contact binary systems. We emphasize that the proposed scenario is not alternative to the currently-adopted protostar hypothesis, but can be considered as a complementary one.

2. λ Boo stars and W UMa systems. Simple estimations

Supposing that λ Boo stars can be created as a result of close binary evolution, one can account for their main properties in a natural way. An existence of the possible connection between λ Boo stars and close binary systems can be argued from different facts.

2.1. The relative numbers of the stars

The most appropriate progenitors for λ Boo stars are contact binaries of W UMa type. Interacting components of close binaries can merge, forming a more massive single star. The ability of contact binary components to coalesce is widely discussed in the literature, particularly in connection with the blue straggler phenomenon (e.g., Stryker, 1993) and FK Com-like stars.

W UMa systems consist of the main-sequence components of approximately equal spectral classes. Both components can effectively approach one another, due to the angular momentum loss through the magnetic stellar wind and gravitational radiation (Iben and Tutukov, 1984). The necessary time for such systems to be completely merged is difficult to estimate. For example, Van't Veer (1984) adopts a contact lifetime of about 100-200 Myr, while Leonard and Linnell (1992) use the widely adopted value of 500 Myr. We adopt the latter value as a merger timescale $\tau_m \approx 500\ Myr$. A similar estimate was adopted by Mateo et al. (1990), who investigated stellar mergers just in W UMa binaries.

After the successful merger, the λ Boo star is evolving with the nuclear timescale τ_n. For spectral class A3 ($M \approx 2.5\ M_\odot$), which is appropriate for λ Boo stars, we get the lifetime:

$$\tau_n \approx 10^{10}(\frac{M}{M_\odot})^{-2.5} \approx 1 Gyr \quad (1)$$

Note that Iliev and Barzova (1994) give the following ages of the λ Boo stars: 0.2-1 Gyr (some stars from their list have ages up to 2 Gyr).

Using τ_m and τ_n values, one can estimate a relative number of the observed λ Boo stars and W UMa systems:

$$\frac{N_W}{N_\lambda} \sim q^{-1}\frac{\tau_m}{\tau_n}, \quad (2)$$

where q takes into account the probability of the components' coalescence. If we adopt that near to 100% of contact binaries undergo coalescence, then in the right part of (2) we get ≈ 0.5.

On the other hand, one can derive the N_W/N_λ ratio from the observations. Using all necessary information from the *General Catalogue of Variable Stars* (GCVS), we find that there are about 30-40 systems of EW/KW type (contact or near-contact binaries) within 150 pc of the solar neighbourhood. The number of known λ Boo stars is ≈ 55 (Iliev and Barzova, 1994). These stars were carefully selected by the authors from the more extensive list by Renson et al. (1990) and Gray and Corbally (1993).

Most of the stars listed by Iliev and Barzova (1994) are within the same distance of 150 pc. Therefore, we obtain $N_W/N_\lambda \approx 0.7$, which accords with the previous estimate. Nevertheless, it should be noted that the observed N_W/N_λ ratio can be somewhat overestimated, because there are more favourable conditions for eclipsing variable detections than for λ Boo stars, whose identification requires more subtle (in particular, spectroscopic) analysis. Note that list of Renson et al. (1990) contains nearly one hundred possible λ Boo candidates, whereas Gray and Corbally (1993) give only 20 unambiguously identified stars.

One can also estimate the total number of the W UMa stars that were born during the timescale τ_n and compare it to the present-day number of λ Boo stars. For this we use a well-known expression of the stellar production rate (Salpeter, 1955):

$$R = 2 \times 10^{-12}(\frac{M}{M_\odot})^{-2.35} d(\frac{M}{M_\odot}) \quad (3)$$

For the mass interval of 1-2 $M_\odot$, we get the rate of about 10^{-12} stars $pc^{-3}\ yr^{-1}$. For the mean lifetime of λ Boo stars ($\tau_n \approx 1\ Gyr$) in the volume $4/3\pi\ (150pc)^3$, approximately 10^4 stars are expected to be produced. Assuming the W UMa star frequency among F-G-K dwarfs to be $f_W = 10^{-3}$ (Rucinski 1993), we find that there must be ≈ 10 λ Boo stars within the considered volume. Of course, this estimate is uncertain, but the order of magnitude is consistent with the observed number of λ Boo stars (at least with the Gray and Corbally 1993 estimate).

2.2. Masses and circumstellar envelopes

The typical spectral class of the components of W UMa type stars is F8 (varying from K0 to F0). A corresponding mass interval is 0.7-1.7 $M_\odot$. Thus, the merger product must be an A or early F star with mass in the interval 1.5-3.5 $M_\odot$ (conservative case). Note that Iliev and Barzova (1994) also give the range 1.5-3.0 $M_\odot$ for λ Boo stars.

During the merger phase, some mass fraction can be lost by the system. Such material thrown out from the system can form a circumstellar shell. The *initial* mass of the shell can be very roughly estimated using the following simple formulae for kinetic energy:

$$T_W \sim T_\lambda + T_{sh} \quad (4)$$

$$J_W\omega_W \sim J_\lambda\omega_\lambda + J_{sh}\omega_{sh} \quad (5)$$

where J_W, ω_W, J_λ, ω_λ, J_{sh} and ω_{sh} define the angular momentum and angular velocity of the W UMa system, the λ Boo star and the circumstellar shell, respectively. An initial value of angular momentum of binary system having the masses of components M_1 and M_2 and semi-major axis a is:

$$J_W = M_1 M_2(\frac{Ga}{M_1 + M_2})^{0.5} \quad (6)$$

For example, if $M_1 \approx M_2 \approx 1.3\ M_\odot$ and $a \approx 1.5\ R_\odot$, we get $J_W \approx 8 \times 10^{51}\ g\ cm^2\ s^{-1}$. The angular velocity of the W UMa system is $\omega_W \sim 10^{-4}\ s^{-1}$ (i.e. period $P < 1^d$).

Final configuration is presented by the single star rotating with $v\ sin\ i \approx 150\ km\ s^{-1}$ (equatorial velocity $\approx 200\ km\ s^{-1}$). Its angular momentum is $J_\lambda = M_3(k_sR)^2\omega$. If the gyroradius of the resulting A star (having the radius $\approx 2R_\odot$) is $k_sR \approx 0.7 \times 2\ R_\odot$, the mass $M_3 \approx 2.5\ M_\odot$ and angular velocity $\omega_\lambda \approx 2 \times 10^{-4}\ s^{-1}$, then $J_\lambda \approx 7 \times 10^{51}\ g\ cm^2\ s^{-1}$.

The angular momentum of the shell is $J_{sh} = \Delta M\ (k_{sh}R)^2\ \omega$. Adopting for the gyroradius of the shell k_{sh}R ≈ 10 stellar radii and $\omega_{sh} \approx 0.1\omega_\lambda$, i.e. $10^{-5}\ s^{-1}$, we obtain from (5) the mass of the primordial shell: $\Delta M \approx 10^{-2}\ M_\odot$.

3. Conclusion

Simple estimations show that the basic properties of some λ Boo stars can be explained supposing that they are the descendants of contact binary systems. The coalescence of W UMa components results in a single star of 2-3 $M_\odot$ of A spectral class, having rapid rotation and a circumstellar shell. Further evolution of such a star with shell can produce the observed chemical peculiarity.

Although the explanation of the chemical peculiarities of λ Boo stars is not the direct aim of the present work, we would like to stress some points relevant to that problem. As is known, normal C, N and O abundances and heavier elements' deficiency are considered to be a firm feature of λ Boo stars, but none of the existing hypotheses can explain the unusual accretion mechanism following successful separation between the gaseous material (enriched in CNO elements) and grains, having confined the Na-Fe elements in the circumstellar envelope (Charbonneau, 1991). Such a separation is absolutely necessary to reproduce the observed depletion of Mg, Ca, Fe etc., and the solar-like abundance of C, N, O and S.

It is clear that great theoretical efforts have to be undertaken to find the likely mechanism of separation in case there is no doubt that CNO abundances in λ Boo stars are really close to the solar values. Therefore, it is reasonable to estimate the reliability of available results on CNO abundances.

The widely-adopted opinion that λ Boo stars have normal abundances of CNO elements in their atmospheres is based on results of only a few works: Baschek and Searle (1969) analysed strong triplet OI 7770 Å, Lambert et al.(1986) used strong lines of CI 9100 Å, Baschek and Slettebak (1986) applied IUE spectra to derive CNO abundances, Venn and Lambert (1990) used a strong CI feature (multiplet near to 7115 Å, individual lines are not resolved in the spectra of their program stars). Stürenburg (1993) also determined carbon abundances for several stars, but the reader has no idea what carbon lines the author used in the analysis (probably they are CI 4932Å and 5052 Å, but both are dramatically blended for almost all program stars).

Thus, we can conclude that as a rule only strong lines were usually used to derive the abundances of light elements in λ Boo stars. There is no necessity to remind that lines with a great equivalent width are very sensitive to the NLTE effects. An attempt to analyse such lines in the LTE approach leads inevitably to abundance overestimation. Stürenburg (1993) has tried to take into account NLTE corrections to the carbon LTE abundance. Nevertheless, LTE [C/H] values obtained by Stürenburg can hardly be considered as reliable: first, because of the lack of reliable unblended carbon lines in observed spectral regions; secondly, mediocre quality of spectra obtained (see reproduction of the observed spectra from the mentioned work) prevents the determination of the correct continuum place and in some cases does not allow to adjust the synthetic spectrum to observed one.

These two circumstances make it impossible to measure with the required accuracy the carbon lines in the spectra of rapidly rotating stars having broad, shallow and blended spectral features. Despite the author's conclusion that the NLTE correction for carbon is negligible (0.05-0.1 dex) and its abundance remains "solar", it seems that this abundance could be overestimated in LTE analysis, simply due to overestimation of the equivalent widths.

This problem is also severe in the analysis of other elements. For example, accordingly to Baschek and Searle (1969) and Stürenburg (1993), the relative iron content (with respect to the Sun) for 29 Cyg is -1.2 dex, whereas Venn and Lambert (1990) give for this star value [Fe/H] = -1.8 dex and provide arguments that results reported by Baschek and Searle reflect the equivalent width overestimation.

The situation with Vega is more promising. This star was classified by Venn and Lambert as a mild λ Boo star (e.g. [C/H] = -0.14 dex, [N/H] = -0.05 dex, [O/H] = -0.19 dex and [Fe/H] = - 0.8 dex). It has a small projectional velocity and sharp-lined spectrum that enables one to measure the equivalent widths with high accuracy. From this point of view, abundance results by Venn and Lambert are quite reliable for Vega. Nevertheless, further investigations have shown that the NLTE corrections are of paramount importance for light element abundances. Takeda (1992a, 1992b) found NLTE carbon abundance for Vega [C/H] $\approx$ -0.3 dex, nitrogen [N/H] $\approx$ -0.8 dex, oxygen [O/H] $\approx$ -0.3 dex. A recent result of Lemke and Venn is [N/H] $\approx$ - 0.5 dex.

Thus, one can conclude that the reported remarkable differences in CNO and Na-Fe abundances found for λ Boo stars must be taken with some caution. Additional subtle studies of elemental abundances are needed before searching for the mechanism responsible for specific chemical anomality in λ Boo stars.

At the present time, only two characteristics of the stars from this stellar group are undoubted: 1) common metal deficiency, and 2) circumstellar shell presence.

To distinguish between λ Boo stars formed via merger processes and protostar evolution, one can propose a possible observational test: a careful investigation of CNO elements in λ Boo objects. If the stars formed as result of a merger process, we should expect to detect slightly CNO-processed material in their atmospheres that might be anticipated of merged W UMa systems. Further work could consist in a search for some evidence that some λ Boo stars have a higher N/C ratio than solar.

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