The \( \lambda \) Bootis phenomenon: interaction between a star and a diffuse interstellar cloud

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ABSTRACT

The \( \lambda \) Bootis stars, a group of late B to early F-type population I stars, have surface abundances that resemble the general metal depletion pattern found in the interstellar medium. Inspired by the recent result that the fundamental parameters of these peculiar stars differ in no respect from a comparison sample of normal stars, the hypothesis of an interaction between a star and a diffuse interstellar cloud is considered as a possible explanation of the peculiar abundance pattern. It is found that such a scenario is able to explain the selective accretion of interstellar gas depleted in condensable elements as well as the spectral range of the \( \lambda \) Bootis phenomenon.

Key words: Stars: abundances – Stars: chemically peculiar – Accretion

1 INTRODUCTION

The \( \lambda \) Bootis stars are late B to early F-type population I stars, which show a peculiar surface abundance pattern: while the light elements (C, N, O and S) are roughly solar, the Fe-peak elements show underabundances of up to a factor of 100. Venn & Lambert (1990) are the first who noticed the similarity between this abundance pattern and the depletion pattern of the interstellar medium (ISM) and suggested the accretion of interstellar or circumstellar gas to explain the \( \lambda \) Bootis stars. In this respect they differ from the rest of the peculiar A-type stars where the abundance pattern is caused by separation processes in the stellar atmosphere itself. The abundances are ascribed to diffusion in the presence of slow rotation (Am stars) or strong magnetic fields (Ap stars).

Paunzen et al. (2002) scrutinized the available observational data to put constraints on any model trying to explain the \( \lambda \) Bootis phenomenon. A comparison between the \( \lambda \) Bootis stars and a reference sample of normal stars showed that both groups share the same fundamental parameters, like effective temperature, gravity, mass, rotational velocity and age. But most surprisingly, the Na abundance of the \( \lambda \) Bootis stars revealed a correlation with nearby local interstellar column densities of Na\(\text{I}\).

This discovery, although so far tentative, because of the inhomogeneity of the stellar Na abundances, motivated a detailed analysis of the interaction between a star and a diffuse ISM cloud as an explanation for the \( \lambda \) Bootis phenomenon.

2 INTERACTION BETWEEN ISM AND STAR

Vergely et al. (2001) reconstructed the density distribution of the ISM in the solar neighbourhood from Na\(\text{I}\) and H\(\text{I}\) observations. They found density fluctuations of a factor of 100 for Na\(\text{I}\) and about 250 for H\(\text{I}\). Typical number densities for diffuse clouds in the ISM range from 0.1 to 100 cm\(^{-3}\).

Fig. 1 shows what is supposed to happen, if a \( \lambda \) Bootis star travels through a diffuse ISM cloud: the star creates a cavity in the ISM cloud. There are two questions arising: What happens to the ISM dust? What are the typical gas accretion rates? We assume in the following a moderate density of \( n = 10 \text{ cm}^{-3} \); using a mean molecular weight \( \mu = 1.4 \), appropriate for atomic gas, this leads to a lower limit of the ISM mass density, \( \rho = 2.34 \times 10^{-23} \text{ g cm}^{-3} \).

The dust grains of the diffuse ISM cloud will be charged in the vicinity of the star. Hydrogen will be mostly neutral and the dominant charged gas species is C\(^+\). Assuming 50 Å dust particles and a density of \( n(\text{C}^+) = 10^{-3} \text{ cm}^{-3} \), we
and

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The ISM consists mainly of particles much smaller than in the two following sections. Hence, we deal with dust and gas separately via collisions. Hence, we deal with dust and gas separately at distances out to about 10,000 AU from the star. At these low densities dust and gas are also not effectively coupled via collisions. Hence, we deal with dust and gas separately in the two following sections.

2 Interstellar dust

The ISM consists mainly of particles much smaller than 1 μm. The following calculations are performed for 0.01 μm grains. Artymowicz & Clampin (1997) showed that the ISM dust particles undergo Rutherford scattering off the star and hence never approach the star closer than its avoidance radius, which resembles the radiation field of a black body, A-type stars have strong line blanketing in the UV. Hence, to calculate the number of Lyman α continuum photons, $N_\alpha$, and the density of the ISM, $n_\text{H}$,

$$r_s = 8.66 \times 10^{-13} \left( \frac{R_s}{R_\odot} \right)^{2/3} n_\text{H}^{1/3} n_\alpha^{-2/3} \text{ AU}.$$  

while the radiation field of an O star can be reasonably approximated by a black body, A-type stars have strong line blanketing in the UV. Hence, to calculate the number of Lyman α continuum photons for A and F-type stars, we used Kurucz (1992) model atmospheres and the appropriate stellar radii taken from Cox (2000).

$$N_\alpha = \int_0^{912\lambda} F_\nu d\nu \text{ photons cm}^{-2} \text{ s}^{-1}.$$  

The resulting Str"omgren radii are summarized in Table 2 for various A and F-type stars. Assuming a density of 10 cm$^{-3}$ for the ISM cloud, the Str"omgren radii lie between 3.1 and 0.8 AU. Assuming a relative velocity of 17 km s$^{-1}$, a gas particle takes about 1 yr to reach the stellar surface from this radius. The time which a neutral hydrogen atom spends before it is ionized can be calculated from the photoionization rate of H$^+$

$$t = R^{-1} = \left( \int_{912\lambda}^{\infty} a_E F_\nu \left( \frac{r}{R_s} \right)^{2} d\nu \right)^{-1} \text{ s},$$  

using the parameterized photoionisation rate $a_E$ from Cox (2000). The timescales at the Str"omgren radius are then between 3.2 × 10$^7$ and 10$^{10}$ yr depending on the spectral type of the star. A comparison with the dynamical timescale shows that the accreted interstellar gas will be mostly neutral.

2.2 Interstellar gas

Interstellar gas around O and B-type stars is known to be ionized (HII regions). In a first approximation, the Str"omgren radius around the star can be calculated from the number of Lyman α continuum photons, $N_\alpha$, and the density of the ISM, $n_\text{H}$,

$$r_s = 8.66 \times 10^{-13} \left( \frac{R_s}{R_\odot} \right)^{2/3} n_\text{H}^{1/3} n_\alpha^{-2/3} \text{ AU}.$$  

The grain potential $U$ is related to strength of the stellar and interstellar ultraviolet radiation field, the potential for dust grains at 500 AU around an A0 V star being $U \sim 4 - 8$ V and $U \sim 2 - 4$ V for a F5 V star depending on the grain material. From this comparison we conclude that radiation pressure clearly dominates the grain potential $U$ grains at 500 AU around an A0 V star being $U \sim 4 - 8$ V and $U \sim 2 - 4$ V for a F5 V star depending on the grain material. From this comparison we conclude that radiation pressure clearly dominates the grain potential $U$

$$d = 9.47 \times 10^3 \left( \frac{L_*}{L_\odot} \right)^{1/2} \left( \frac{U}{V} \right)^{-1/2} \text{ AU}. \tag{1}$$

Derive the distance at which coulomb forces and radiation pressure are equal

$$r_{av} = 2(\beta - 1)GM_\odot v_{\infty}^{-2} \text{ cm}, \tag{2}$$

where $\beta$ is the ratio of radiation pressure to gravity. For a spectral type of A5 V (2 $R_\odot$, 2 $M_\odot$) which resembles β Pictoris and 0.01 μm grains, their fig. 4 gives an avoidance radius of approximately 500 AU. Therefore, the dust grains will not be accreted by the star.

Following their approach, we derived $r_{av}$ for other stars using the radiation pressure efficiencies (mixture of 50 per cent astronomical silicates and 50 per cent graphite) tabulated for various black body radiation fields by Draine & Lee (1984). Our result for β Pictoris, $r_{av} = 340$ AU, using an 8000 K black body radiation field, and that of Artymowicz & Clampin (1997), who used a Kurucz (1992) model atmosphere, agree within a factor of 2, which is more than satisfactory.

Table 1. Stellar parameters used for the calculation of the avoidance radii.

| Star          | A2 V | β Pic (A5 V) | F2 V | F5 V |
|---------------|------|--------------|------|------|
| $T_{\text{eff}}$ [K] | 9000 | 8000 | 6750 | 6550 |
| $M$ [$M_\odot$]     | 1.9  | 1.75 | 1.4  | 1.2  |
| $L$ [$L_\odot$]     | 14.1 | 8.7  | 3.5  | 1.7  |
| $L/M$               | 7.4  | 5    | 2.5  | 1.4  |
| $v_\infty$          | 10.7 | 8.6  | 6.7  | 5.9  |

Figure 2 shows the ratio of radiation pressure to gravity $\beta$ as a function of dust grain size $a$ for a mixture of 50 per cent astronomical silicates and 50 per cent graphite. $\beta$ is shown for 4 different stars: A2 V star (solid line) β Pic (dashed line), F2 V star (dash-dotted line) and F5 V star (dash-dot-dotted line). (b) Radii of avoidance for different ISM dust grain sizes for the 4 different stars.
The second point can be checked by calculating the critical radius up to where gas pressure effects can be neglected (Bondi & Hoyle 1944)

\[ r_{\text{crit}} = \frac{GM}{u^2} \text{ cm} \]  

Here \( u \) is the thermal velocity of the interstellar material. Assuming \( u = 0.1 \text{ km s}^{-1} \) leads to a critical radius of 8.9 × 10^4 AU for a solar-mass star. This is well outside the regime we consider in this study.

Bondi & Hoyle (1944) derive the radius for which ISM particles are accreted onto the star

\[ r_{\text{acc}} = \sqrt{\frac{5}{2}} GM \frac{1}{u_{\text{rel}}} \text{ cm} \]  

Different prefactors can be found in the literature, but Bondi & Hoyle (1944) showed that \( \sqrt{5} \) holds for steady state. This radius leads to an accretion rate of

\[ \dot{M} = \pi r_{\text{acc}}^2 \rho_{\text{rel}} \text{ g s}^{-1} \]  

An A-type star of 2 M_☉ passing the diffuse ISM cloud at a relative velocity of 17 km s\(^{-1}\) has an accretion radius of 9.7 AU and an accretion rate of 4.2 × 10\(^{-14}\) M_☉ yr\(^{-1}\). Since no evidence is found for emission lines in the ultraviolet spectral range and accretion must overcome diffusion, the accretion rate must lie between 10\(^{-9}\) (Bertout 1981) and 10\(^{-14}\) M_☉ yr\(^{-1}\) (Furcotte & Charbonneau 1993). Hence the range of relative velocities between star and diffuse ISM cloud is 1 to 20 km s\(^{-1}\) (Fig. 3).

This estimate assumes that collisions occur frequently enough to reduce the angular momentum of the particles streaming around the star. In order to verify this, one can calculate the number of collisions of a particle on a circular orbit with a radius \( r_{\text{acc}} \) around the star. We assume that collisions are effective in removing angular momentum over a path length of \( \pi r_{\text{acc}} \) and that the cross section of the gas particle is \( 6.3 \times 10^{-16} \text{ cm}^2 \) (corresponding to a radius of 10\(^{-8}\) cm)

\[ N_{\text{coll}} = 6.3 \times 10^{-16} \frac{n \sqrt{5 \pi GM}}{u_{\text{rel}}} \]  

where \( n \) denotes the density of the ISM cloud. Inserting a 2 M_☉ star and assuming a relative velocity of 17 km s\(^{-1}\), we obtain 3 collisions for the orbiting particle. The accretion scenario will certainly work for ISM clouds with densities \( \gtrsim 10 \text{ cm}^{-3} \).

Typical sizes \( d \) for ISM clouds are of the order of 0.1 to 10 pc (Dring et al. 1996). The duration of accretion is determined by the relative velocity between cloud and star and the dimension of the cloud

\[ t_{\text{acc}} = 9.8 \times 10^5 \left( \frac{d}{\text{pc}} \right) \left( \frac{u_{\text{rel}}}{\text{km/s}} \right)^{-1} \text{ yr} \]  

In the above scenario with a relative velocity of 17 km s\(^{-1}\), the star passing a diffuse ISM cloud of 1 pc accretes for 5.8 × 10^7 yr.

In the light of the above described scenario, the \( \lambda \) Bootis phenomenon is a transient phenomenon. The abundance pattern imprinted by the diffuse ISM cloud will disappear very rapidly, within 10^5 yr, after the star has passed the cloud (Furcotte & Charbonneau 1993). This is due to diffusion taking over again and to effective mixing by convection and meridional circulation. Since the time, which a star actually spends crossing a diffuse ISM cloud, is very short, we do not expect circumstellar/interstellar lines towards every \( \lambda \) Bootis star. In fact Holweger & Rentzsch-Holm (1993) and Holweger et al. (1999) have shown that about 30 per cent of the \( \lambda \) Bootis stars reveal narrow absorption features in Ca II K. On the other hand Bohlender et al. (1998) have found narrow Na I D absorption features in 3 out of 8 \( \lambda \) Bootis stars.

### Table 2. Strömgren radii for various A and F-type stars, assuming a recombination rate appropriate for H\( ii \) regions (\( T = 10^4 \text{ K} \)). The photoionisation rate \( R \) is calculated at the Strömgren radius \( r_s \).

| Star | \( T_{\text{eff}} \) [K] | \( R_s \) [R_☉] | \( r_s \) [\( n_\text{H}^{2/3} \text{ AU} \)] | \( R \) [10\(^{-17}\) s\(^{-1}\)] |
|------|----------------|--------------|----------------|----------------|
| A2   | 9000           | 1.56         | 103.83         | 77.77          |
| A4   | 8500           | 1.51         | 32.32          | 23.92          |
| A6   | 8000           | 1.48         | 13.23          | 9.84           |
| A8   | 7750           | 1.45         | 8.54           | 6.37           |
| A9   | 7500           | 1.43         | 5.45           | 4.07           |
| F0   | 7250           | 1.40         | 3.77           | 2.83           |

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3 THE BORDERS OF THE \( \lambda \) BOOTIS PHENOMENON

The spectral range of \( \lambda \) Bootis stars extends from B9.5 V to F3 V with a peak around F1 V. 60 per cent of the \( \lambda \) Bootis stars are cooler than 8000 K and the stellar masses range between 1.56(8) and 2.50(12) M_☉ (Paunzen et al. 2002). The distribution of rotational velocities of \( \lambda \) Bootis A-type stars is indistinguishable from normal A-type stars (Paunzen 2001), the maximum so far being 250 km s\(^{-1}\). We first consider the hot end of the phenomenon, where stellar winds stop the accretion of interstellar matter and then the cool end, where convection zones become too massive to be contaminated by the above derived accretion rates.
3.1 The hot and cool end

B-type stars possess radiatively driven winds and typical values derived for the mass loss rates from radiative acceleration calculations by Abbott (1982) can be found in Cohen et al. (1997). They range from $3 \times 10^{-8} \, M_\odot \, yr^{-1}$ for a B0 V star to $3 \times 10^{-12} \, M_\odot \, yr^{-1}$ for a B7 Vle star. Babel (1996) has shown that these calculations tend to overestimate the mass loss rate by typically a factor of 4, because they do not take into account the dependence of the radiative acceleration on the outwards velocity in the wind and the detailed shadowing by photospheric lines. So the range of mass loss rates for B-type stars will then become roughly $8 \times 10^{-9} \ldots 8 \times 10^{-13} \, M_\odot \, yr^{-1}$.

For the A-type stars, Babel (1996) has found mass loss rates below $10^{-16} \, M_\odot \, yr^{-1}$. This mass loss is due to selective winds that act only on the metals and the terminal velocity of mass loss rates for B-type stars will then become roughly $3 \times 10^{-7} \, M_\odot \, yr^{-1}$.

The hot and cool end of the mass loss rates is rather high, about 6000 km s$^{-1}$. Comparing the momenta of the wind and the accretion flow, we find that a typical accretion rate of $10^{-13} \, M_\odot \, yr^{-1}$ at velocities of 10 km s$^{-1}$ wins over the selective wind. Such selective mass loss will therefore not affect the formation of a $\lambda$ Bootis abundance pattern. Since we do not know exact mass loss rates for late B-type stars, we can only conclude that the hot end of the $\lambda$ Bootis phenomenon lies at the transition between A and B-type stars.

Stellar evolutionary models show that the mass of the convection zone at $10^7$ yr (that is on the main-sequence) is $10^{-8}$, $10^{-10}$, and $10^{-11} \, M_\odot$ for a 1.5, 1.7, and 2.5 $M_\odot$ star respectively (Richard et al. 2003). Overshoot is supposed to enlarge this mass by less than a factor of 10 (Freytag et al. 1996 and Freytag & Charbonneau 1999). Given the accretion timescales and rates derived in Sect. 3.1, the photospheres of stars more massive than 1.5 $M_\odot$ can be contaminated by the diffuse ISM cloud.

3.2 The rotational velocity

Charbonneau & Michaud (1991) have shown that meridional circulation does not completely wipe out the chemical abundance pattern established under the influence of diffusion in fast rotating stars. The timescale for mixing by meridional circulation is a fraction of the Eddington-Sweet time (Turrillote & Charbonneau 1993)

$$t_m = \frac{G^2 M_*^4}{L_* R_*^2 v_e^2} \, s,$$  \hspace{1cm} (11)

where $v_e$ denotes the equatorial rotational velocity. For the A5 and F5 star we obtain a mixing time of $8.4 \times 10^6$ and $2.1 \times 10^7$ yr for an equatorial velocity of 200 km s$^{-1}$. This is much longer than we expect the accretion signature to last after the accretion process has ceased.

4 STATISTICS

In order to test our proposed scenario with the observed number of $\lambda$ Bootis type objects within a given space volume, we have made the following analysis. Paunzen (2003) has estimated that the current spectral classification resolution surveys in the relevant spectral domain are complete up to 60 pc. Within this space volume we know of 8 well established $\lambda$ Bootis type stars: HD 30422, HD 31295, HD 74873, HD 110411, HD 125162, HD 142703, HD 183234 and HD 192640.

Within a space volume of 60 pc, there are about 1100 “normal” type stars in the relevant spectral domain. Since most of the spectral classification surveys are mainly devoted to single objects, we discard all apparent spectroscopic binary systems. Taking an average binary frequency of 30 per cent, we are left with 330 apparent single objects.

As next step, we derive a rough estimate of the space volume for which the densities of the ISM are high enough so that accretion of interstellar matter on to the stellar surface occurs. For the space volume considered here, we are confronted with the “Local Bubble” which surrounds the Sun. It stretches out with a radius between 30 and 300 pc. Its characteristics, distribution and kinematic are still not well understood (Génova et al. 1997, Snowden et al. 1998). From the maps of the Local Bubble from Welsh et al. (1998) and Steier et al. (1999), we determine an average value of 3 per cent for which the densities of the ISM are high enough. Notice that the published maps reflect the characteristics on rather large scales only (about 10 to 20 pc). The kinematical and chemically structure varies on scales which are 10 times smaller than that (Génova et al. 1997).

So we are left with 10 stars within a space volume of 60 pc which can be accounted as $\lambda$ Bootis type objects. This is very well in the range of the actual observed number (8). However, this does, by no means, prove our scenario, but naturally explains the low number of detected members.

Let us also make a remark about the (non-) detection of $\lambda$ Bootis type objects in open clusters (Gray & Corbally 1993, 2002). Up to now only few members in the Orion OB1 association and NGC 2264 (ages about $10^7$ yr) are known although an extensive survey by the group of R.O. Gray in about two dozen open clusters has been performed. We believe that the lack of members in open clusters is due to a lack of gas to accrete. Palla & Stahler (2000) have shown that the remnant gas from the stellar formation dissipates in less than $10^7$ yr. This even holds for aggregates containing no massive stars.

5 OBSERVATIONAL TESTS

Some $\lambda$ Bootis stars are members of binary systems. In all cases, where a detailed abundance analysis has been done so far, both stars turned in fact out to be $\lambda$ Bootis stars (Stüreenburg 1993, Iiev et al. 2002, Heiter 2003; HD 84948 A+B, HD 171948 A+B, HD 193281/HD 193256, HD 198160/HD 198161). This is naturally explained by the above described scenario, because both stars pass through the same diffuse cloud and accrete interstellar gas. If both stars have a spectral type between late B and early F, they both appear afterwards as $\lambda$ Bootis stars. But, if one component has an earlier or later spectral type, it will not show the typical $\lambda$ Bootis abundance pattern.

To test the above described scenario, it is crucial to analyze more $\lambda$ Bootis binary systems and to find systems consisting of an A-type star and a companion which is beyond the hot or cool end as described in Sect. 3.1.
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