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λ Bootis stars: Current status and new insights from Spitzer

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Abstract. The group of λ Bootis type stars comprises late B- to early F-type, Population I objects which are basically metal weak, in particular the Fe group elements, but with the clear exception of C, N, O and S. We present a spectroscopical definition for the group membership by using the light element versus metal abundance pattern. One of the current explanations for the λ Bootis peculiarity is the accretion of interstellar material as the star travels through a diffuse interstellar cloud. We will review this hypothesis in the context of ESO high resolution spectra and Spitzer imaging and photometry. The Na I D lines provide simultaneously stellar abundances and physical properties of interstellar material along the line of sight. The new Spitzer results shed light on the presence of dust around these stars, its composition and geometric distribution.

Key words: stars: abundances – stars: chemically peculiar – circumstellar matter – reflection nebulae

1. Introduction

The peculiar nature of λ Bootis itself was first noted by Morgan *et al.* (1943), followed by the identification of two more stars of the same nature, HD 110411 and HD 192640, in the 1950s (Slettebak, 1952; 1954), and the first quantitative abundance analysis by Burbidge and Burbidge (1956). Eventually, Gray (1988) presented the first homogeneous definition for the λ Bootis stars as a group based on classification spectra and photometry. He noted the weak Mg II 4481 line, the general metal weakness and the presence of peculiar hydrogen lines as two of the main features exposed by this group of stars.

Kodaira (1967) had already noted the solar abundance of oxygen in a sample of λ Bootis stars and Venn and Lambert (1990) pointed out the overall solar abundances of the lighter elements C, N, O, S versus the weakness of heavier metals in three studied λ Bootis stars. They noted the striking similarity between the abundance pattern found in the λ Bootis stars and those of several post-AGB stars which reveal substantial amounts of circumstellar dust from their infrared excesses, and of the interstellar medium. They speculated that the peculiar abundance pattern of the λ Bootis stars may be connected to the accretion of circumstellar gas, where the heavy elements are depleted due to their incorporation into grains, while the lighter elements C, N, O and S remain in the gas at the solar abundance level. Paunzen *et al.* (1999) and Kamp *et al.* (2001) established the solar abundances of C, N, O, and S in a sample of 16 λ Bootis stars.

Farragiana and Bonifacio (1999) suggested an alternative hypothesis, namely that the λ Bootis stars are all spectroscopic binary systems, where the combined spectra mimic that of a typical λ Bootis star with solar C, N, O abundances and underabundances of other metals (Farragiana, Bonifacio 2005). However, Stütz and Paunzen (2006) show that such spectroscopic binary systems do not reproduce the observed photometry of λ Bootis stars. Interferometric observations by Ciardi *et al.* (2007) led to the conclusion that the prototype λ Bootis itself is a single star. Even though the binary star hypothesis may explain a few stars originally classified as single λ Bootis stars, it does not present a viable explanation of the group as a whole.

2. Theories for the λ Bootis phenomenon

Several theories were developed over the last decades to explain this abundance pattern (see Paunzen, 2004 for a summary). The commonly accepted one is the accretion/diffusion model first formulated by Venn and Lambert (1990). They noticed the similarity between the abundance pattern of λ Bootis stars and the depletion pattern of the interstellar medium (ISM) suggesting the accretion of interstellar or circumstellar gas. In the ISM metals are underabundant because of their incorporation in dust grains or ice mantles around the dust grains. Waters *et al.* (1992) worked out a scenario, where the λ Bootis star accretes metal-depleted gas from a surrounding disk. In this model, the dust grains are blown away by radiation pressure and coupling between dust and gas is negligible. Considering the spectral type of λ Bootis stars, the gas in the disk remains neutral and hence does not experience significant direct radiation pressure. The authors showed that these conditions hold for mass accretion rates below $10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$, assuming that the gas-to-dust mass ratio in the disk is 100 and that the disk consists of $0.1\,\mu$m carbon grains. Turcotte and Charbonneau (1993) derived a lower limit of $10^{-14}\,M_{\odot}\mathrm{yr}^{-1}$ for the accretion/diffusion model to produce a typical λ Bootis abundance pattern. Moreover their rotating models provide evidence that meridional circulation cannot destroy the established accretion pattern for rotational velocities smaller than $125\,\mathrm{km\,s}^{-1}$. Since diffusion wipes out any accretion pattern within 10^{6} yr, a number of λ Bootis stars should show observational evidence of the presence of circumstellar material. This was indeed found by King (1994) and Paunzen *et al.* (2003).

This scenario implies a constraint on the evolutionary status of the star, because the existence of a disk or a shell has to be explained in the context of stellar evolution. Circumstellar disks are thought to exist during the pre-main-sequence phase of stellar evolution, while a shell can either occur in a very early phase of pre-main-sequence evolution or after a stellar merger. Kamp and Paunzen (2002) proposed a slightly different accretion scenario for the λ Bootis stars, namely the accretion from a diffuse interstellar cloud. This scenario works at any stage of stellar evolution as soon as the star passes a diffuse interstellar cloud. The interstellar dust grains are blown away by the stellar radiation pressure, while the depleted interstellar gas is accreted onto the star. Typical gas accretion rates are between $10^{-14}\,M_{\odot}\mathrm{yr}^{-1}$ and $10^{-11}\,M_{\odot}\mathrm{yr}^{-1}$ depending on the density of the diffuse cloud and the relative velocity between star and cloud. The hot limit for this model is due to strong stellar winds for stars with $T_{\mathrm{eff}} > 12\,000\,\mathrm{K}$, whereas the cool limit is defined by convection which prevents the accreted material being manifest at the stellar surface.

The underlying mechanism of all these scenarios is the accretion of material onto the star. Hence, the peculiar abundance pattern of λ Bootis stars is explained to first order by external processes rather than internal ones as in the case of the Am/Fm phenomenon or Ap stars. Especially the last suggested hypothesis of a star-diffuse cloud interaction also suggests a temporary nature of the λ Bootis phenomenon: *any* star in the spectral range late F to early A-type could experience a period of a few million years, where it appears to be a λ Bootis star.

3. Sodium: a clue to the origin of the λ Bootis phenomenon

Based on LTE abundance determinations and literature collections by Heiter (2002), Paunzen *et al.* (2002) noted the wide spread of Na abundances in λ Bootis stars: –1.3 to 1.2 dex with respect to the Sun. A first comparison with nearby interstellar (IS) sightlines revealed a correlation between the IS Na column density and the stellar Na abundance. However, some of these sightlines are to stars significantly further away than the respective λ Bootis star itself. Mashonkina *et al.* (2000) show that typical NLTE effects for the Na D lines are of the order of -0.3 to -0.6 dex. Hence, we decided to obtain a homogeneous set of sightlines towards the λ Bootis stars themselves at sufficiently high resolution and signal-to-noise ratio to determine the stellar NLTE Na abundance and the IS Na column density from the same spectrum.

Fig. 1 shows that most of our target λ Bootis stars are actually within the local Bubble and will probe a so far unexplored region that is thought to be largely devoid of IS clouds.

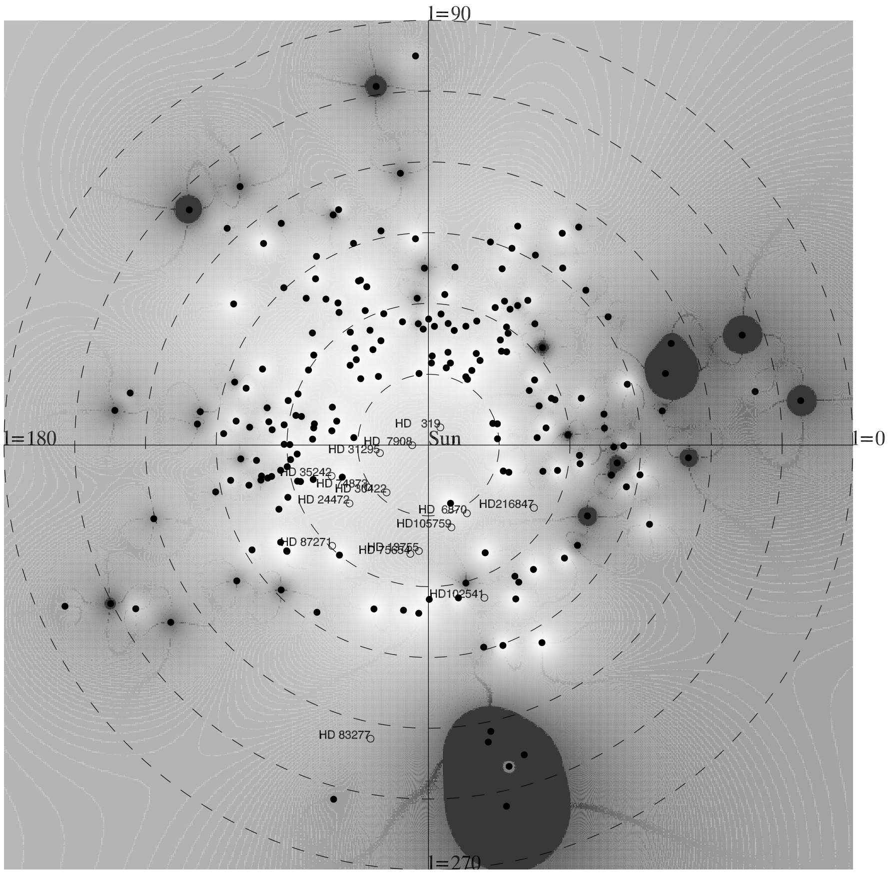

Figure 1. Structure of the ISM within 300 pc of the Sun projected into the galactic plane. Open circles are λ Bootis stars, filled circles are stars from the Sfeir *et al.* (1999) catalogs. The different grey shades denote the equivalent width of the IS Na D2 line towards the sightline. White areas have equivalent width below 5 mÅ, the darkest areas denote 150 mÅ. The dashed circles correspond to heliocentric distances in steps of 50 AU.

3.1. Observations

Observations were carried out in two epochs (January 2003 and April 2005) at the ESO 3.6 m telescope at La Silla, Chile. We used the Coudé Echelle Spectrograph at a resolution of $\lambda/\Delta\lambda = 100\,000$. At the same time, a set of standard stars, typically hot O or B stars, was observed to correct for telluric absorption lines in the Na D spectral range.

We also add observations of 12 additional λ Bootis stars taken by Bohlender *et al.* (1999) with the Coudé spectrograph at the CFHT (Canada-France-Hawaii Telescope) in 1995 and 1996. Those spectra were kindly provided in reduced form by Dr. Bohlender and have a spectral resolution between 92 000 and 97 000, except for the star HD 111604, which has a resolution of only 29 000.

The ESO spectra were reduced with MIDAS using the typical calibration steps including removal of cosmic rays, stray light correction and removal of telluric lines. A more complete description of the data reduction process and the observed data is the subject of a forthcoming paper (Kamp *et al.*, in preparation).

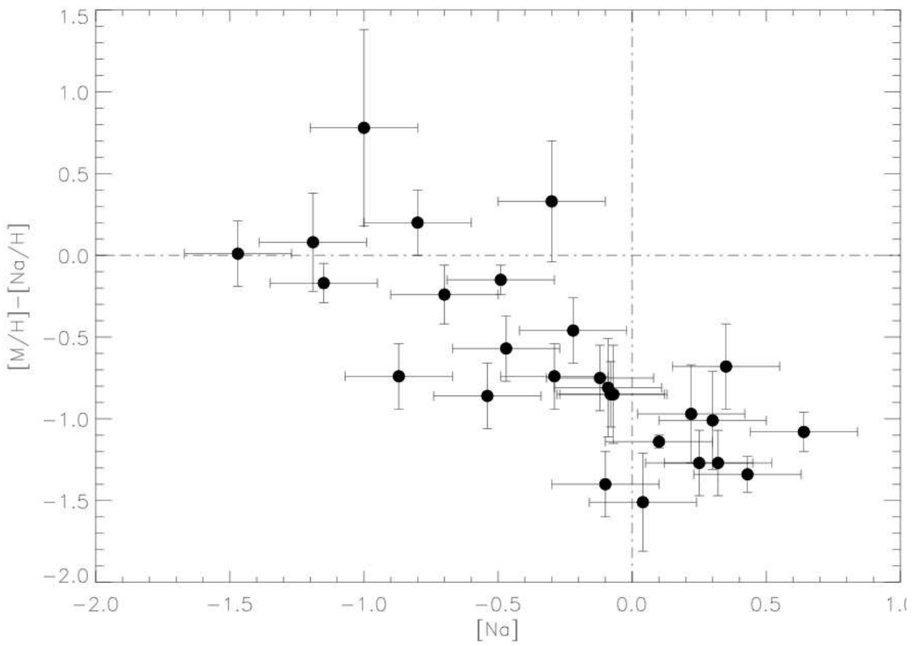

Figure 2. [M/Na] versus [Na] abundances in our sample of λ Bootis stars.

3.2. Stellar abundances

Stellar Na abundance are derived from the two Na D lines at 5889.95 and 5895.92 Å. The atmospheric parameters are taken from the master list by Paunzen *et al.* (2002) and used to compute ATLAS9 model atmospheres. Synthetic spectra (Linfor) are then compared to the observed spectra to derive LTE abundances of sodium and the rotational velocity of the star. The LTE abundances were then modified by using a grid of NLTE abundance differences as published by Mashonkina *et al.* (2000). Fig. 2 shows the metal to sodium abundance ratio, [M/Na], plotted as a function of the resulting Na NLTE abundances. We use here the iron abundances from Heiter (2002) as representative for the metals. It is interesting to note that the NLTE corrections do not remove the large spread in Na abundances. This spread appears to be real and seems unique to the group of λ Bootis stars.

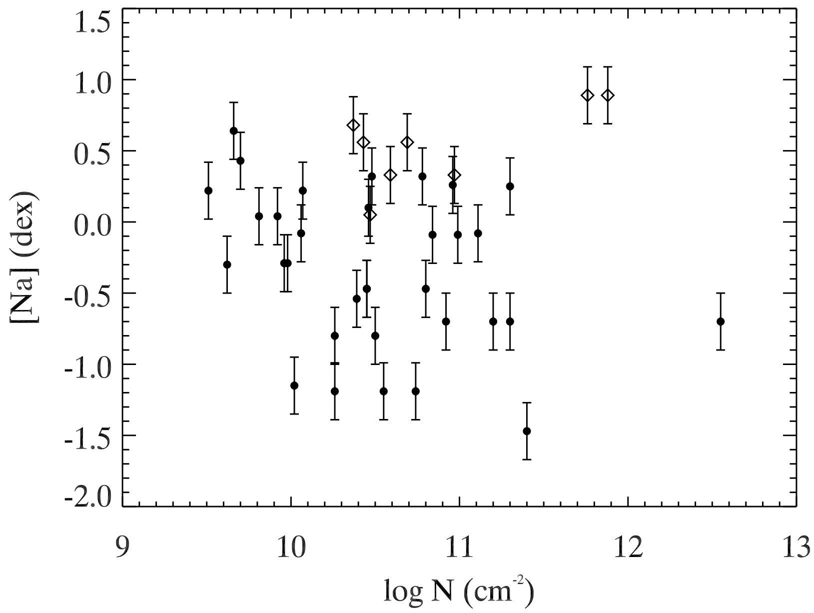

Figure 3. [Na/H] abundances versus IS Na column densities in our sample of λ Boo stars (filled dots). Open circles are data for our comparison stars.

3.3. Interstellar column densities

We use the MIDAS fit/lyman task to determine the column densities for the IS sodium lines. We only use those spectra, where we have a clear IS line detection ($> 3\,\sigma$).

3.4. The Na puzzle

Fig. 3 shows the stellar Na abundances versus the IS Na column densities for all our program stars. The error bars denote here the systematic uncertainty of ± 0.2 dex attributed to the uncertainties in the stellar atmosphere parameters and the fit to the observed line profile. There seems to be no clear correlation between the two quantities. However, we note that there are no stars with low Na column densities that exhibit strong stellar Na underabundances.

Even though our data are not yet conclusive and further work, especially on the second observing epoch needs to be done, we add a few interesting comments on the possibility of an anticorrelation between the stellar Na abundance and the IS Na column density. Venn and Lambert (1990) and also Andrievsky *et al.* (2006) point out the low ionisation potential as a possible explanation for the sodium abundances in λ Bootis stars. If the circumstellar/interstellar material is very diffuse, Na is expected to be fully ionized and will thus not be incorporated into dust grains. If the material is, however, much denser and becomes optically thick to Na ionizing radiation ($\chi = 5.14$ eV), Na will be predominantly neutral and thus condense into grains. In the latter case, we expect the gas phase to be depleted in Na. If we would, as a first crude approximation, take the Na column density as a proxy for the total particle density, we would expect the stellar Na abundance to be anti-correlated with the Na column densities of the ISM. The assumption that the Na column density and total particle density of the ISM are correlated may be justified by the fact that most of the λ Bootis stars are in the local Bubble and hence we do expect most of the IS material to be in fact associated or close to the star.

4. λ Bootis stars with Spitzer

Spitzer/IRS observations by Jura *et al.* (2004) show that the spectral shape of debris disk stars and two λ Bootis stars differs fundamentally. The debris disk stars are generally described by a single temperature black body, which may be explained by dust confined to a narrow ring around the star close to its birthplace (collisional destruction of larger parent bodies). The spectral energy distribution (SED) of the λ Bootis stars follows a ν^{-1} power law, indicative of Poynting Robertson drag. However, the authors did not consider the possibility of IS grains as a source of the IR excess around λ Bootis stars.

We subsequently developed a model for ISM grains in a reflection nebulosity around a star to clarify the origin of the IR excess around λ Bootis stars. The model is described in detail in Martínez Galarza *et al.* (2008), and we will only repeat the more salient features here. For a typical ISM grain size distribution, the avoidance radius (parabolic cavity) of each grain size component is derived from the stellar input radiation field (ATLAS9 models) and the relative velocity between star and diffuse cloud. Subsequently, the grain temperatures are derived from radiative equilibrium and the total emission is obtained from a volume integration over all grain components. The parameters obtained from fitting the SED are generally the density of the diffuse ISM cloud and its outer radius. The relative velocity between the star and the ISM is estimated from Hipparcos distances, radial velocities and proper motions.

The comparison of these reflection nebula models and debris disk models shows that they can equally well fit the ISO and Spitzer photometry. However, the detailed spectral shape is very different and thus we expect IRS spectroscopy to be able to break the model degeneracy and help us decide whether the circumstellar environment of λ Bootis stars contains large grains in a disk or small IS grains in a reflection nebula.

In a recent paper, Gáspár *et al.* (2007) have applied the reflection nebula model to the star δ Vel which is located at a distance of 24 pc from the Sun. δ Vel is a system with at least five members, the primary being a binary composed of an A1V and A5V star. The 24 μm MIPS images show a prominent bow shock in the direction of motion of the star. The position of the shock front is consistent with IS material being ~ 15 times denser than the average local Bubble ISM and a relative velocity between star and ISM of 35.8 ± 4.0 km s^{-1}. The star itself does not exhibit a pronounced λ Bootis abundance pattern. This does not violate per se the hypothesis that the peculiar abundance pattern originates from interaction of the star with the ISM, as the star travels at very high speed and is a binary system. Both facts actually lead to a very low mass accretion rate of 6.15×10^{-15} $M_\odot$ yr^{-1} in the analytical Kamp and Paunzen (2002) model. Such accretion rates would not be large enough to significantly alter the photospheric composition.

5. Outlook

We have obtained Spitzer IRS spectra and IRAC images for a sample of 35 bona fide λ Bootis stars taken from the Master list of Paunzen *et al.* (2002). The IRS spectra have been obtained in mapping mode at the stellar position as well as two reference positions offset by the avoidance radius of ISM dust.

The IRS spectra will determine the onset of the IR excess in these stars as well as add important constraints to the spectral shape of the SED in the near- and mid-IR. This data should break the degeneracy between the debris disk and reflection nebulosity models and give us important results on the grain sizes and composition (possible presence of PAH features). The images will be explored for bow shocks similar to that found around δ Vel and/or presence of circumstellar material. Even if no emission is detected, the IRAC images give us good stellar photometry at short IR wavelength complementing the current MIPS photometry obtained for a subset of stars during GO and GTO time.

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