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The sodium abundance in λ Bootis stars (*Research Note*)

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ABSTRACT

Context. Numerous observational studies have shown that the atmospheres of λ Boo type stars are strongly deficient in such elements as Ti, Cr, Fe, while some of the light elements (e.g. carbon, oxygen and sulphur) do not show any remarkable abundance anomalies. Such a specific abundance pattern is regarded to be the direct consequence of the selective accretion of stellar envelope material after its depletion of refractory elements. At the same time, sodium with its rather high condensation temperature shows almost normal content in λ Boo star atmospheres in apparent contradiction to a prediction of the accretion hypothesis.
Aims. We aim to show that the normal sodium abundance seen in some λ Boo type stars is connected with the specific ionization regime of the sodium atoms which is formed in the circumstellar envelope.
Methods. The analytical expression connecting the fraction of ionized atoms and circumstellar envelope characteristics (electron temperature, optical depth, etc.) is used.
Results. Under the special assumptions about the circumstellar envelope characteristics, the sodium remains essentially ionized over the whole envelope volume, while elements such as iron are ionized only in the vicinity of the central star. This favours iron dust grain formation in the envelope, and prevents effective adhesion of the sodium charged particles. Thus, the sodium remains in the gaseous medium which is accreted by the star, while such elements as Ti, Fe and some other refractory elements, which are locked in the dust grains, are effectively swept out of the envelope. This results in a specific abundance pattern which is seen in some λ Boo stars whose atmospheres appear to be deficient in Ti, Fe, Ni, but possess almost normal sodium content.

Key words. stars: chemically peculiar

1. Introduction

In Andrievsky et al. (2002) and Heiter (2002) it was reported that in some λ Boo stars sodium shows an almost normal (solar) or even enhanced abundance. The NLTE sodium abundance derived using the sodium resonance doublet appeared to be significantly higher in these stars than abundances of some other elements like Ti, Cr, Fe (hereafter, the elemental abundances relative to solar are considered). A similar result was also obtained earlier by Stürenburg (1993) and Paunzen et al. (1999). Following the accretion based hypothesis, which seems to be the most credible hypothesis to explain the λ Boo phenomenon, one would expect that sodium with its rather high condensation temperature should be much less abundant than, say, carbon and oxygen ($T_c \approx 150$ K), and its abundance should be as small as that of the elements like Ca, Ti, Cr, Fe, Ni and some others ($T_c > 1250$ K). However, all observational results indicate that sodium is more abundant than the iron-group elements, and its abundance is comparable to that of C and O. This fact cannot be explained by theory which is based only on mass-loss and accretion. Below a possible solution for this problem is given.

2. Solution of the problem

Although sodium has a condensation temperature similar to that of titanium, chromium, iron or nickel, its ionization potential is much lower than for those elements. Therefore, under the same physical conditions in the plasma of a circumstellar envelope, the sodium should have a larger fraction of ionized atoms. If an appreciable fraction of Na in the circumstellar envelope exists in the form of Na^+, then sodium will not be able to condense easily in the dust grains, because of the electrostatic force that prevents atomic coagulation. Thus, a significant ionization of the sodium atoms can effectively inhibit dust grain formation, and sodium may remain in the gaseous phase. The latter is supposed to be accreted by the central star, and results in the normal atmospheric sodium abundance.

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To estimate the fraction of ionized atoms in the circumstellar envelope, we use an expression (similar to the Saha equation):

$$n_{\rm e}\frac{n^+}{n^0} = \frac{2g^+}{g^0}pW\left(\frac{T_{\rm e}}{T_*}\right)^{1/2}\left(\frac{2\pi m_{\rm e}kT_*}{h^2}\right)^{3/2}\exp\left(-\frac{\chi}{kT_*}\right) \times\exp\left(-\tau\right), \quad (1)$$

where $n_{\rm e}$ is the electronic concentration, g^+ and g^0 are statistical weights of the ground level of the ion and atom respectively, p is the fraction of recombinations on the ground level, W is the dilution factor, $T_{\rm e}$ the characteristic value of the envelope electronic temperature, T_* the effective temperature of the central star, χ the first ionization potential of the considered atom, τ the optical depth at the wavelength of ionization threshold.

The above expression is usually used for the investigation of ionization balance in nebulae, but it could be applied to estimate the photoionization degree caused by the central star radiation in an optically thick envelope. In this formula the exponential factor $\exp\left(-\tau\right)$ contains the optical thickness at the ionization threshold of a given element. The greater the thickness, the smaller the volume where this element is ionized. This is the principal idea of the present paper – to show that under some assumtions made the sodium atoms are ionized over the whole envelope volume, while, for example, the iron atoms are ionized only in the vicinity of the central star. This situation can occur because of a significant difference in the optical thickness at the wavelength of the sodium ionization threshold and that of iron.

The formula that gives the ratio between the coefficient of recombination on the ground level and the total recombination coefficient (valid for H-like atoms, e.g. sodium) can be written as follows (Allen 1973):

$$p = \frac{C_1}{C_{\rm tot}} \approx \frac{3.3\times10^{-6}T_{\rm e}^{-3/2}\exp\left(\frac{\chi}{kT_{\rm e}}\right)E_1\left(\frac{\chi}{kT_{\rm e}}\right)}{2.1\times10^{-11}T_{\rm e}^{-1/2}\phi}, \quad (2)$$

where ϕ for the envelope temperature equals approximately 4.0.

This formula can be simplified using the following expression:

$$\exp\left(\frac{\chi}{kT_{\rm e}}\right)E_1\left(\frac{\chi}{kT_{\rm e}}\right) \approx \frac{kT_{\rm e}}{\chi}. \quad (3)$$

For those atoms that cannot be considered as H-like ones, one can use the following expression for the p coefficient (Allen 1973):

$$p \approx 8.3\times10^{-3}T_{\rm e}^{1/4}. \quad (4)$$

Adopting some envelope model parameters following Andrievsky & Paunzen (2000): $W \approx 10^{-4}$, $T_{\rm e} \approx 10^3$ K, $T_* \approx 8500$ K, one can get for sodium ($\chi_{\rm Na} = 5.14$ eV) $p \approx 0.8$, while for the non-H-like atoms Eq. (4) gives $p \approx 0.05$.

For the practical use of Eq. (1) one needs to know the electron concentration in the envelope and the optical depth at the wavelength of the ionization threshold. To estimate both these values one should know at least the total atom concentration in the λ Boo envelope. Since we do not know the detailed structure of a circumstellar envelope of a presently seen λ Boo star when it was just formed, either as a result of close binary star evolution (Andrievsky 1997), or at the earlier stages of protostar evolution (Paunzen 1997), one can consider the total concentration as an arbitrary parameter. Let us use for the following estimates $n_{\rm tot} \approx n_{\rm H} = 10^{13}$ cm^{-3}, that seems to be a not unusual value for the stellar envelopes. The number density was considered as an initial value in the circumstellar envelope at the time of its formation. The present day density seen in the λ Boo type star envelopes (Andrievsky & Paunzen 2000) is smaller than this adopted value, since the larger fraction of the envelope material has already been accreted by the central star, and this resulted in the λ Boo phenomenon.

One can also assume that the primordial chemical composition of the λ Boo progenitor star was similar to the solar one.

Let us consider together with sodium elements such as titanium and iron. They have a rather high condensation temperature, and in contrast to sodium they are remarkably deficient in λ Boo atmospheres. Table 1 contains information concerning the atomic parameters of these elements (see Allen 1973).

Using the threshold photoionization cross-sections and relative-to-hydrogen abundances of the considered elements listed in Table 1 together with $n_{\rm H} = 10^{13}$ cm^{-3} and envelope radius 5×10^{12} cm (Andrievsky & Paunzen 2000), one can calculate the corresponding optical depths (see Table 1). Optical depth at the ionization threshold should include all the opacity sources. Among them there is, of course, additional absorption in the Balmer continuum. However, with the adopted parameters of the circumstellar envelope (low electron temperature and not very high temperature of the central star) the number of excited hydrogen atoms is small and can be neglected in the subsequent estimates.

As was shown by Andrievsky & Paunzen (2000), the main contributor to the star's envelope electron concentration is sodium itself. Its abundance is rather high, while its ionization potential is low. Moreover, the optical depth in the envelope for sodium is significantly lower than for other species (including, of course, the most abundant hydrogen and helium), and this makes it possible for sodium atoms to undergo an effective ionization over the whole envelope. Thus, one can roughly adopt $n_{\rm e} \approx n_{\rm Na} = 2.14\times10^{-6}\cdot n_{\rm H}$.

With the adopted electron concentration $n_{\rm e}$ and the calculated ratios p and optical depths, one can find from Eq. (1) the fraction of ionized atoms of Na, Ti and Fe. Results are given in Table 1. As one can see, under the assumptions made above sodium is remarkably ionized, while Ti and Fe stay essentially neutral in the envelope.

For the choice of $T_{\rm e}$ and $n_{\rm H}$ values, we have adopted $T_{\rm e} = 10^3$ K, but the value of the envelope electron temperature has no significant impact on the estimates made above, because of the rather weak dependence of the parameter p on $T_{\rm e}$.

On the contrary, the obtained results are very sensitive to the adopted $n_{\rm tot}$ value. We take $n_{\rm tot} = 10^{13}$ cm^{-3}. If even slightly increased, this value causes a significant opacity increase in the envelope, thus even for sodium the exponential factor $\exp\left(-\tau\right)$ in Eq. (1) becomes very small (see Table 1). This means that in such a dense envelope all considered elements (including sodium) stay essentially in the atomic form. This favours dust grain formation. Thus, if the λ Boo progenitor

Table 1. Some characteristics of the considered elements and results for three values of n_{tot}.

Atom	g^0	g^+	χ, eV	α, 10^{-18} cm^2	f	
Na	2	1	5.14	0.08	2.14×10^{-6}	
Ti	21	28	6.82	5	1.05×10^{-7}	
Fe	25	30	7.87	5	3.16×10^{-5}	
	$n_{tot} = 10^{10}$ cm^{-3}		$n_{tot} = 10^{13}$ cm^{-3}		$n_{tot} = 2 \times 10^{13}$ cm^{-3}	
Atom	τ	n^+/n^0	τ	n^+/n^0	τ	n^+/n^0
Na	8.6×10^{-3}	2.1×10^9	8.6	4.1×10^2	17.2	0.2
Ti	2.6×10^{-2}	3.3×10^7	26	0	52	0
Fe	7.9	2.7×10^3	7.9×10^3	0	1.6×10^4	0

Remarks: α is a cross-section at the ionization threshold (for sodium and iron this characteristic value was taken from Butler & Mendoza (1983); Lombardi et al. (1978); Hansen et al. (1977); for Ti the same value as for iron was adopted). Fractions f of atomic concentrations (relative-to-hydrogen) are from Grevesse et al. (1996).

star possessed a primordial envelope with a characteristic concentration larger than the critical one (in our very simple model – roughly 10^{13} cm^{-3}), then the atmosphere of the (presently seen) λ Boo star may become deficient in sodium and other refractory elements. If the total atomic concentration in the circumstellar shell is lower than the critical value, then the optical depth can, in principle, be small enough for elements such as Ti and Fe, and they should be ionized in the envelope similarly to sodium (see Table 1). In this case, dust grain formation is prevented by electrostatic forces and the star will not develop the λ Boo peculiar properties at all.

3. Discussion and conclusion

Another explanation of the λ Boo phenomenon, and, in particular, the normal sodium abundnace in these stars was proposed by Kamp & Paunzen (2002). In that scenario the star passes through an interstellar cloud where the refractory elements are already locked up in grains. If this is true, then the appearance in some λ Boo type stars of such a specific feature as a normal sodium and decreased iron abundance should be attributed to some processes in the interstellar cloud. Nevertheless, this scenario seems to be not effective because of the low probablity of the direct encounter between the star and a cloud with sufficiently high gas density. Moreover, such an encounter at the relative velocity of a few tens km s^{-1} should cause local heating in the cloud (the shock wave, for example) that can evaporate any dust grains within the captured circumstellar envelope.

Thus, from our estimates one can conclude that there exists a certain value of the envelope density that is favourable for the ionization of sodium atoms over the whole circumstellar envelope. Being essentially ionized, sodium does not form dust particles, and hence remains in the gaseous medium which is accreted by the star, while elements such as Ti, Fe and some other refractory elements, being essentially neutral, are locked into the dust grains and effectively swept out of the envelope. This results in a specific abundance pattern seen in some λ Boo stars whose atmospheres are deficient in Ti, Fe, Ni, but possess an almost normal sodium content.

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