MIXING AND ACCRETION IN $\lambda$ Bootis Stars

S. Turcotte

Lawrence Livermore National Laboratory, L-413, P.O. Box 808, Livermore, CA 94551; sturcotte@igpp.ucllnl.org

Received 2002 April 8; accepted 2002 May 31; published 2002 June 12

ABSTRACT

Strong evidence for deep mixing has been uncovered for slowly rotating F and A stars of the main sequence. As the accretion/diffusion model for the formation of $\lambda$ Bootis stars is heavily dependent on mixing in superficial regions, such deep mixing may have important repercussions on our understanding of these stars. It is shown that deep mixing at a level similar to that of FmAm stars increases the amount of matter that needs to be accreted by the stars with respect to the standard models by some 3 orders of magnitude. It is also shown that significantly larger accretion rates have to be maintained, as high as $10^{-11} \, M_\odot \, yr^{-1}$, to prevent meridional circulation from canceling the effect of accretion. The existence of old ($\approx 1$ Gyr) stars is not a likely outcome of the present models for accretion/diffusion with or without deep mixing. It is argued that $\lambda$ Bootis stars are potentially very good diagnostics of mixing mechanisms in moderately fast rotators.

Subject headings: stars: abundances — stars: evolution — stars: interiors

1. INTRODUCTION

The defining characteristic of $\lambda$ Bootis stars is their peculiar surface composition in which only four elements are roughly solar (C, N, O, and S) and all others show a definite trend toward depletion by a factor of up to 10 typically (Heiter 2002; Solano et al. 2001). Yet, despite their apparent metal-poor composition, these are Population I stars in which the peculiar chemical composition is only superficial. There are concerns that the class, as it is now defined based on their chemical composition, does not represent a homogeneous population resulting from a common physical process. For example, it is now clear that there is a wide scatter in the abundances of individual elements from star to star, larger than in chemically normal A-type stars (Heiter 2002). Other potentially conflicting observations and the failure of models to reproduce all the characteristics of $\lambda$ Bootis stars, which will be discussed briefly in this Letter, caution us to keep that possibility in mind.

In addition to their chemical signature, this class of stars is also characterized by a limited range in spectral types (early F- and A-type stars; Solano et al. 2001). For a long time, they were also thought to be strictly limited to young stars (zero-age main sequence [ZAMS] or pre–main sequence), but the evidence now points to ages ranging from the ZAMS to the terminal-age main sequence (Iliev & Barzova 1995; Iliev et al. 2002). A majority of $\lambda$ Bootis stars are pulsating stars in the general class of $\delta$ Scuti–type variable stars (Bohlender, Gonzalez, & Matthews 1999). Such pulsations indicate that the superficial helium abundance is roughly solar or higher. As a much larger fraction of $\lambda$ Bootis stars than other A-type stars are $\delta$ Scuti variables (Paunzen et al. 1998), it suggests that the $\lambda$ Bootis phenomenon itself has an effect in their pulsational behavior. Finally, many $\lambda$ Bootis stars show signs of circumstellar matter (Holwege, Hempel, & Kamp 1999).

Several ideas have been put forward to account for the $\lambda$ Bootis phenomenon. The very peculiar abundances of $\lambda$ Bootis stars cannot be reconciled with the diffusion models that have been so successful for other chemically peculiar A stars such as the FmAm stars (Richer, Michaud, & Turcotte 2000). Nevertheless, as diffusion is an important process in A stars, it is an important feature of two leading models proposed for $\lambda$ Bootis stars: the diffusion/mass loss model (Charbonneau 1993) and the accretion/diffusion model (Venn & Lambert 1990; Charbonneau 1991, hereafter C91). A third hypothesis calls for a binary merging to account for some fraction of $\lambda$ Bootis stars (Andrievsky 1997). It also has been shown that a small number of $\lambda$ Bootis stars were in fact unidentified binaries for which the combined spectra were mistakenly interpreted as metal-poor (Faraggiana et al. 2001). It is doubtful, however, that a significant fraction of $\lambda$ Bootis stars suffer from this problem. The pros and cons of these hypotheses have been nicely summarized in Solano et al. (2001). It is clear that at this moment no model can adequately reproduce all the observed properties of $\lambda$ Bootis stars.

The first challenge facing the models is their inability to produce both young and old $\lambda$ Bootis stars. The diffusion/mass loss and binary merging models can only yield old $\lambda$ Bootis stars. On the other hand, the accretion/diffusion model as it stands now can only occur in young stars before the circumstellar disk associated with star formation is dissipated.

Currently, the most favored model is the accretion/diffusion model, but new observational data have raised questions about it. Heiter, Weiss, & Paunzen (2002) have shown that the composition of $\lambda$ Bootis stars might not be as consistent with circumstellar gas as previously thought. They have also raised the question as to why some stars that have circumstellar disks with ongoing accretion and are similar to $\lambda$ Bootis stars do not have peculiar compositions.

This Letter concentrates on if and how new insight in the depth of mixing in slowly rotating F- and A-type stars (Richer et al. 2000; Richard, Michaud, & Richer 2001) might affect the accretion model. Those models, which will be discussed further in § 2, have shown that the mixing in slowly rotating stars extends substantially deeper than the base of the H-He convection zone in A and B stars. The depth of mixing is of crucial importance in determining the timescales for the formation and persistence of superficial abundance peculiarities in stars such as the $\lambda$ Bootis stars. Therefore, as a first step in the computation of more complete models for $\lambda$ Bootis stars including as much of the physics of chemical evolution in stars as possible, the possible effect of deep mixing on timescales and accretion rates in models of accreting $\lambda$ Bootis stars will be discussed here. A brief overview of the accretion/diffusion model in the context of deeper mixing will be presented first. Simple models will then be used to estimate timescales for chemical evolution.
2. ACCRETION, DIFFUSION, AND MIXING

The model that has had the most success in reproducing most observed properties of λ Bootis stars is based on the idea of accretion of dust-depleted matter first suggested by Venn & Lambert (1990). A model featuring accretion and diffusion was developed by C91, and a full numerical simulation in one and two dimensions in a static model was performed by Turcotte & Charbonneau (1993, hereafter TC93). In this scenario, circumstellar matter would be depleted of most heavy elements as the result of dust formation. The gas would thereafter fall back on the star, whereas the dust would be pushed out, presumably by radiation pressure. While there exists no complete model of the accretion process itself including the dust-gas separation needed by the accretion scenario, Andrievsky & Paunzen (2000) have calculated a simple model for this, which shows that the process is possible under favorable circumstances. The accreted matter would form a superficial layer on the star reflecting the composition of the circumstellar gas. As the circumstellar matter (supposedly in a disk) would dissipate with time, the accretion would stop and diffusion and meridional circulation would destroy the λ Bootis signature within 1 or 2 Myr, the implications being that all λ Bootis stars are young and currently undergoing accretion. Circumstellar matter has been found around many but not all λ Bootis stars. This was not thought to be a problem, as King (1994) has argued that the amount of circumstellar gas needed to permit the formation of abundance anomalies is so small that the lack of observed circumstellar dust does not necessarily mean that there is none available for accretion. The results that follow may challenge this estimation.

As we proceed, we assume that accretion in the spirit of the idea advanced by Venn & Lambert (1990) is a formative process in at least some λ Bootis stars. Many of the challenges facing the accretion scenario, such as why some stars with ongoing accretion are not λ Bootis stars, will not be tackled. The evolution of circumstellar media is fundamental to the accretion model but is outside the scope of this Letter.

As the matter falls on the stellar surface, it is being mixed (diluted) in a superficial region in which mixing is strong enough to ensure chemical homogeneity. The time necessary to establish and destroy the λ Bootis signature is inversely proportional to the mass of this mixed region and directly proportional to the flux of matter in and out of that region. The net flux, in turn, is determined by the accretion rate and the rate of diffusion (adding mixing, meridional circulation, and any other relevant particle transport process) in or out of the bottom of the mixed region.

The depth to which superficial mixing extends is a critical parameter in the evolution of the superficial composition of these stars. In standard models, only the superficial convection zone (SCZ) determined by the ionization of H and He is fully mixed. There is growing evidence that there is mixing at greater depths in A stars. It has been shown by Richer et al. (2000) that the composition of slowly rotating A stars can only be reproduced by models in which the superficial mixed zone (SMZ) is much deeper than the SCZ. Richer et al. (2000) and Richard et al. (2001) have both shown that in such slowly rotating stars, diffusion strongly enhances the composition of iron peak elements where they dominate the opacity, which can result in convection. This convection defines a minimum depth of the mixing well below the H/He SCZ, but it does not explain the even deeper mixing that is found to be required for the models to fit the observations. In more rapidly rotating stars such as the λ Bootis stars, the mixing is more efficient, as evidenced by the fact that the effect of diffusion is not seen in rapidly rotating A stars. The mixing found in slowly rotating A stars is expected to be present as well in fast rotators. We therefore expect that mixing in (faster rotating) λ Bootis stars will be at least as deep as in slowly rotating A stars. From Richer et al. (2000), the mass of the SMZ is assumed to be greater than 10⁻⁶ times the stellar mass for the range of stars relevant to λ Bootis stars.

Following equations (3)–(5) of C91, one can write the timescale for the evolution of the surface composition for a given accretion rate, a given mass of the SMZ, and a given chemical species as

\[ \tau = \frac{\rho^4 \pi r^2}{M_{\text{SMZ}}} (v_{\text{acc}} - v), \]

as long as \( v_{\text{acc}} > v \), where all radius-dependent variables are evaluated at the base of the SMZ. The right-hand term describes the net flux of particles at the base of the SMZ in which the flux created by the accretion (4πr²v_{\text{acc}}) is opposed by the flux of matter from diffusion and other processes (4πr²v). Each chemical species has a different timescale owing to the specifics of diffusion (i.e., a different \( v \)) for individual elements.

A large-scale velocity field due to accretion occurs to preserve hydrostatic equilibrium. We assume that the accretion rate is small enough that the mass of the star can be considered constant for the timescales that concern us here. The velocity field is defined by

\[ v_{\text{acc}}(r) = \frac{\dot{M}}{4\pi r^2 \rho(r)}, \]

where \( \dot{M} \) is the accretion rate in units of \( M_\odot \, \text{yr}^{-1} \). The inverse density dependence of \( v_{\text{acc}} \) implies that it decreases at the base of the SMZ as its depth increases.

The transport velocity of particles \( v \) in eq. [1]) is the sum of the contributions of diffusion and of advection, such as meridional circulation. The diffusion velocity is defined as in Turcotte et al. (1998), where the effects of abundance gradients, radiation pressure, gravity, and temperature gradients are taken into account. Radiation pressure is included as discussed in Richer et al. (1998). The only advection term included here is rotationally induced meridional circulation. The only component of the meridional flow included here is the polar flow, which determines the maximum opposing effect of meridional circulation to accretion. A very rough estimate of the polar circulation velocity can be found by using equation (117) of Tassoul & Tassoul (1982), with \( \mu = 1 \) and \( u(r) \) from their Tables 5–9 and scaling the model to the right mass, radius, and luminosity. This has been shown to be a reasonable approximation by Charbonneau, Michaud, & Proffitt (1989).

The diffusion velocity depends on the net force exerted on a unit mass of a specific element, which is mainly the difference between gravitation and radiative pressure. The gravitational part is essentially constant with depth near the surface, but the radiative pressure is very sensitive to pressure and temperature. The magnitude of the diffusion velocity will generally decrease with increasing depth but is subject to changing signs as the radiation pressure dominates the gravity in sections of the star. The meridional circulation velocity varies less rapidly with depth, and its effect increases relative to diffusion and accretion with increasing depth. Thus, increasing the depth of the SMZ...
will change the flux term of the timescale (eq. [1]), and the timescales themselves, in a variety of ways. The timescales will generally increase monotonically and proportionally to the mass of the SMZ.

3. TIMESCALES IN MODELS WITH DEEP MIXING

Figure 1 compares the timescales (eq. [1]) for Ti and Fe for a model of a 1.8 $M_\odot$ star at 100 Myr ($T_{\text{eff}} = 8290$ K, $L = 10.7 L_\odot$) with a homogeneous (solar) chemical composition. The figure also compares the net velocity with and without meridional circulation velocities. The diffusion velocities are taken from another model of the same mass and similar age in which diffusion is computed and in which composition is not homogeneous (as in Richer et al. 2000). Both the timescales and the velocities are shown as a function of depth in the model to illustrate the effect of increasing the depth of the SMZ. The standard depth determined by the second ionization of helium occurs at around $10^{-3}$ in fractional mass, whereas the depth of the SMZ if it reaches the depth of the “metal opacity bump” at 200,000 K is shown at a little above $10^{-7}$ in fractional mass. The simple fact of this deep mixing increases the mass of the SMZ by a factor of at least 50. In fact, Richer et al. (2000) show that the range of mixed mass necessary to account for SMZ by a factor of at least 50. In fact, Richer et al. (2000) show that the range of mixed mass necessary to account for SmA and stars pushes the mixing to a typical depth of $-6$ to $-5$. The timescale is then multiplied by a factor of more than 1000.

In addition, the radiation pressure for some elements (Ti, shown here, and Ca, among others) overwhims gravity in a large section of the star centered roughly at the base of the iron convection zone. This means that there is a flux of matter opposing the accretion in the SMZ. When the meridional circulation is added, the upward particle flux at the base of the SMZ is even higher and can dominate accretion even for elements for which radiation pressure is not significant. The depth at which meridional circulation dominates over accretion depends on the accretion rate and on the rotational velocity of the star. Diffusion plays only a minor role in sufficiently rapidly rotating stars. However, whatever the rotational and diffusion velocities, it is possible to ensure that the “right” abundances are established in the SMZ in a short enough time by increasing the accretion rate sufficiently.

In all the cases shown in Figure 1, the net flux in the SMZ is still dominated by accretion because the flux at the surface is larger than the flux at the base of the SMZ ($M > 4\pi[\rho v^2(v_{\text{acc}} - v)]_{\text{SMZ}}$), even when diffusion and circulations overwhelm the accretion flow at the base of the SMZ. In those cases, however, the timescales become too long to expect the necessary abundance anomalies to form remarkably early in the star’s life.

In the cases of C, N, O, and S, it is generally assumed, as we do here, that their abundance is normal in the accreted matter. As these elements are not significantly supported by radiative pressure, their abundance will remain normal in $\lambda$ Bootis stars provided that the accretion rate is large enough to compensate the gravitational settling at the base of the SMZ. This is easily satisfied in the models, and so they do not provide significant additional constraints.

4. DISCUSSION

It has been shown that indications of deep mixing in F, A, and B stars (Richer et al. 2000) can have a significant effect on the accretion/diffusion model for $\lambda$ Bootis stars, leading to larger predicted accretion rates or longer timescales for the formation of the requisite surface composition. This assumes that the mixing found in slowly rotating stars is similarly active in faster rotators. Such an extrapolation is still founded on circumstantial evidence and is subject to confirmation.

Nevertheless, deep mixing in $\lambda$ Bootis stars raises intriguing possibilities regarding the important points of contention between the standard accretion/diffusion model (TC93) and the observations (Solano et al. 2001; Heiter et al. 2002). One of the most difficult problems facing the accretion model is the existence of old $\lambda$ Bootis stars. In A-type stars, circumstellar disks are not expected to persist more than a couple of hundred megayears (Meyer & Beckwith 2000), which is far less than the oldest $\lambda$ Bootis star. If one assumes that $\lambda$ Bootis stars are mixed to a depth of $10^{-6}$ in fractional mass, as argued here, and that the accretion rate was high enough early on to ensure the observed abundances reflect those of the accreted matter, then the larger timescale for the evolution of the surface abundance might provide a way to explain older $\lambda$ Bootis stars.

With a standard SMZ only as deep as the SCZ, the time needed to erase the $\lambda$ Bootis signature is of the order of 1 Myr (TC93). The timescale in the case of deep mixing will be increased by a factor of a few hundred because of the increase in the mass of the SMZ, but this is mitigated by an increase in the flux due to meridional circulation. The net effect for a mixed mass of $10^{-5}M_\odot$ is an increase of the timescale by a factor of 5 only.

A complicating factor for the accretion scenario is that not only is it necessary to dramatically increase the amount of gas accreted on the star in order to impart the composition of dust-depleted circumstellar gas to the SMZ, which may be accounted...
for by much larger accretion rates on the pre–main sequence, but much larger ongoing accretion rates are necessary to sustain the abundance peculiarities if the SMZ is as deep as suggested here. Figure 2 shows that an accretion rate of $10^{-12}$ to $10^{-11} \, M_\odot \, \text{yr}^{-1}$ is necessary to just balance the flux of particles entering or leaving the SMZ at its base from diffusion and meridional circulation. Such large rates may not be problematic, as they have been claimed in β Pictoris (Beust et al. 1996). It might, however, raise questions as to whether the amount of circumstellar matter required to provide such large rates could remain unseen, as is the case in many λ Bootis stars. Still, if one assumes that the necessary accretion has occurred and is ongoing as long as the circumstellar disk is present, one would still not expect λ Bootis stars as old as 1 Gyr.

We have restricted ourselves to rotational velocities of 100 km s$^{-1}$ or lower because of the limitations of the formalism for meridional circulation used here. λ Bootis stars can rotate at a much faster rate, as much as 250 km s$^{-1}$ (Paunzen 2001). In such stars, the meridional circulation would dominate a given accretion rate for much shallower SMZs. The accretion rates required to establish the λ Bootis signature could then be an order of magnitude larger, or more, than those found for the models discussed here.

Finally, as λ Bootis stars often are pulsating stars, it is tantalizing to imagine that there might be a seismic signature of the depth of the mixing considering that the abundance of most metals would be severely reduced in the metal opacity bump. The role that metals play in determining the structure and pulsations in these stars suggests that accretion and deep mixing might yield an observable signature, either by changing which modes become overstable or by shifting the frequencies of predicted pulsations with respect to standard models for δ Scuti stars. Preliminary models have shown shifts in frequencies by as much as 10%–30% (Turcotte 2000), but a seismic test for mixing in λ Bootis stars, possible only with reliable mode identification, remains out of our reach at this point in time.

λ Bootis stars are perhaps the best candidates to provide constraints on mixing mechanisms in moderately rapidly rotating early-type stars for which more standard diagnostics, such as lithium abundances, are not available. The major observational effort spent on these stars in recent years and their inclusion as main targets for planned asteroseismology experiments make a parallel theoretical effort necessary.

I gratefully acknowledge the comments of Georges Michaud and an anonymous referee from which this Letter has benefited greatly. This work was performed under the auspices of the US Department of Energy, National Nuclear Security Administration, by the University of California, Lawrence Livermore National Laboratory, under contract W-7405-Eng-48.

REFERENCES

Andrievsky, S. M., 1997, A&A, 321, 838
Andrievsky, S. M., & Paunzen, E. 2000, MNRAS, 313, 547
Beust, H., Lagrange, A.-M., Plazy, F., & Mouillet, D. 1996, A&A, 310, 181
Bolhender, D. A., Gonzalez, J.-F., & Matthews, J. M. 1999, A&A, 350, 553
Charbonneau, P. 1991, ApJ, 372, L33 (C91)
———. 1993, ApJ, 405, 720
Charbonneau, P., Michaud, G., & Proffitt, C. R. 1989, ApJ, 347, 821
Faraggiana, R., Gerbaldi, M., Bonifacio, P., & François, P. 2001, A&A, 376, 586
Heiter, U. 2002, A&A, 381, 959
Heiter, U., Weiss, W. W., & Paunzen, E. 2002, A&A, 381, 971
Holweger, H., Hempel, M., & Kamp, I. 1999, A&A, 350, 603
Iliev, I. Kh., & Barzova, I. S. 1995, A&A, 302, 735
Iliev, I. Kh., Paunzen, E., Barzova, I. S., Griffin, R. F., Kamp, I., Claret, A., & Koen, C. 2002, A&A, 381, 914
King, J. R. 1994, MNRAS, 269, 209
Meyer, M. R., & Beckwith, S. V. W. 2000, in Lect. Notes Phys. 548, ISO Survey of a Dusty Universe, ed. D. Lemke, M. Stickel, & K. Wilke (Berlin: Springer), 341
Paunzen, E. 2001, A&A, 373, 633
Paunzen, E., et al. 1998, A&A, 335, 533
Richard, O., Michaud, G., & Richer, J. 2001, ApJ, 558, 377
Richer, J., Michaud, G., Rogers, F. J., Iglesias, C. A., Turcotte, S., & LeBlanc, F. 1998, ApJ, 492, 833
Richer, J., Michaud, G., & Turcotte, S. 2000, ApJ, 529, 338
Solano, E., Paunzen, E., Pintado, O. I., & Varela, J. 2001, A&A, 374, 957
Tassoul, J.-L., & Tassoul, M. 1982, ApJS, 49, 317
Turcotte, S. 2000, in ASP Conf. Ser. 210, Delta Scuti and Related Stars, ed. M. Breger & M. H. Montgomery (San Francisco: ASP), 468
Turcotte, S., & Charbonneau, P. 1993, ApJ, 413, 376 (TC93)
Turcotte, S., Richer, J., Michaud, G., Iglesias, C. A., & Rogers, F. J. 1998, ApJ, 504, 539
Venn, K. A., & Lambert, D. L. 1990, ApJ, 363, 234

Fig. 2.—Minimum accretion rate needed to balance the diffusion + meridional circulation velocity of Ti at the base of the SMZ for an equatorial rotation velocity of 50 km s$^{-1}$ (solid line) and 100 km s$^{-1}$ (dotted line). Vertical lines are as in Fig. 1.