MAIN SEQUENCE ABUNDANCES, MASS LOSS AND MERIDIONAL CIRCULATION

Georges Michaud
Département de Physique, Université de Montréal
Montréal, Québec, CANADA H3C 3J7

ABSTRACT Constraints that abundance anomalies observed on main sequence stars put on turbulence, meridional circulation and mass loss are reviewed. The emphasis is on recent observations of Li abundances.

Upper limits to turbulence are obtained from the Be abundance in the Sun and from underabundances of Ca and Sc in FmAm stars. The Li abundance in G type stars suggests the presence of turbulence below convection zones.

The abundance anomalies, both over and underabundances, observed in FmAm and λ Booti stars can be explained by diffusion in the presence of mass loss. A mass loss rate of 10^{-15} $M_{\odot}$ yr^{-1} is required to explain the FmAm stars while a mass loss rate of 10^{-13} $M_{\odot}$ yr^{-1} is required by the λ Booti stars.

The position and width of the Li abundance gap observed in Hyades and other open clusters is explained by diffusion. A detailed reproduction of the Li(T_{eff}) curve seems to require a mass loss rate of slightly more than 10^{-15} $M_{\odot}$ yr^{-1}, of the same order as the mass loss rate required by the FmAm stars. In the presence of such a mass loss only small overabundances of heavy elements are expected. The observed variations in the Li abundance as a function of the age of clusters suggests that the Li abundance observed in old halo stars <u>does not</u> represent the cosmological abundance.

Detailed two dimensional calculations of diffusion in presence of meridional circulation for HgMn and FmAm stars lead to a cut-off of about 100 km s^{-1} for the maximum equatorial rotational velocity at which abundance anomalies are expected in these objects. This agrees with observations. A similar calculation for the F stars of the Hyades where Li underabundances are observed leads to a contradiction, unless meridional circulation patterns are modified by the presence of convection zones once they become as large as in late F stars. There remains a possibility that meridional circulation would be responsible for some of the reduction of the Li abundance as observed in the Hyades and UMa. Further observations are suggested to distinguish the effects of settling and nuclear destruction.

I. Particle Transport Velocities

It is necessary to compare atomic diffusion and mass loss velocities to other possible transport velocities in order to evaluate the relative importance of each. Each process is briefly presented in this section.

The results of Tassoul and Tassoul (1982, 1984) will be used to evaluate meridional

https://doi.org/10.1017/S0252921100093325 Published online by Cambridge University Press

circulation. The two dimensional meridional circulation velocity patterns are well determined by their calculations and will be compared to the other velocity fields. They apply strictly to stars with outer radiative zones only.

Following Schatzman et al. (1981), the turbulent diffusion velocity can be approximated by:

$$v_T = D_T\left(-\frac{\partial \ln c}{\partial r}\right) = R_* D_{11}\left(-\frac{\partial \ln c}{\partial r}\right) \qquad (1)$$

where D_T is the turbulent diffusion coefficient taken to be R_* times larger than the atomic self diffusion coefficient, D_{11}. For a trace element, the quantity c is defined by $c(A) = N(A)/N_P$ where N_P is the particle number density exclusive of electrons. Particle transport by turbulent diffusion is speculative because D_T is only assumed (Michaud 1985).

The mass loss rate, dM/dt, is assumed small enough to have negligible effect on stellar structure. It merely introduces, throughout the static stellar envelope, a global outward velocity of matter, v_W, expressing the conservation of the flux of the main constituent. A trace element diffusing in the presence of mass loss must satisfy the conservation equation, in which both v_W and the diffusion velocity appear (Michaud and Charland 1986, Paquette et al. 1986).

II. The Sun

While the Li solar photospheric abundance is some 100 to 200 times smaller than the interstellar value, the Be abundance is about normal (Boesgaard, 1976). This observation can be coupled with Li abundance observations in field stars and in clusters (Cayrel et al. 1984). Since no element separation is expected in the convection zone itself (Schatzman 1969), those observations show that, in solar type stars, Li has probably been carried below the convection zone by some mild turbulence (Schatzman 1977; Vauclair et al. 1978b; Baglin et al. 1985) to the region where it can burn ($T=2.5\ 10^6$ K). Turbulence must be weak enough not to carry Be to the slightly deeper region where it can burn ($T=3.5\ 10^6$ K). The Li abundance then gives a value for the turbulence below the convection zone ($R_*=50$; see Michaud 1985) and an upper limit to the turbulence ($R_*<90$) a little deeper in (between 2.5 and 3.5 10^6 K). While the value of $R_*=50$ depends on the exact depth of the convection zone and so is model dependent, the upper limit is well established since it depends only on the temperatures at which Li and Be burn.

III. The F Stars

Boesgaard an Tripicco (1986a) have recently obtained striking observations showing a clear hole in the Li abundance of the Hyades F stars at T_{eff} =6700 K. It is perhaps two orders of magnitude deep but only 300 K wide in T_{eff} (see their Fig. 2). The low Li abundance stars at T_{eff} =6700 K are clearly separated from the stars showing a progressive decrease of the Li abundance with T_{eff} as observed below 6000 K. The separation of the

https://doi.org/10.1017/S0252921100093325 Published online by Cambridge University Press

gap from the cooler stars seems to imply that 2 processes are involved. The nuclear burning of Li transported by turbulence is probably involved below 6000 K (see the preceding section), but a different process seems required around 6700 K.

The gravitational settling of Li explains without arbitrary parameters the presence and width of the hole in the Li abundance at this T_{eff}. As can be seen from Fig. 2 of Michaud (1986), the depth of the superficial convection zone increases by more than two orders of magnitude as one goes from 7000 to 6500 K. While Li has one electron left at the T of the bottom of the convection zone in the model for T_{eff} =7000 K, it has none in the model for 6500 K. The radiative acceleration on Li at the bottom of the convection zone decreases from being about 5 times larger than gravity in the model with T_{eff} = 7000 K to being negligible in models with T_{eff} = 6800 K or less (see also Vauclair, this conference). If the T_{eff} is slightly smaller than 7000 K, Li settles gravitationally while it is supported by radiative acceleration at higher T_{eff}. At T_{eff} =6800 K, the Li abundance is reduced by gravitational settling by a factor of 20 according to Michaud (1986). In still cooler stars, the effect is smaller as convection zones become progressively deeper and the diffusion time scale increases: the bigger the reservoir, the longer it takes to empty. At the age of the Hyades, diffusion has had little effect in stars with T_{eff} < 6500 K. The diffusion time scale varies approximately as $\Delta M^{0.5}$ (see Michaud 1977). It varies from 2.8 10^8 yr at T_{eff} = 6900 K to 4 10^9 yr at 6300 K and 10^{10} yr at 6000 K (assuming α=1.4).

Observations of other clusters can lead to a better understanding of the evolution of the Li abundance. In the Pleiades, Pilachowski and Hobbs (1987) have observed less than a factor of 1.5 decrease of the Li abundance in the gap (see also Duncan and Jones 1983, Duncan 1981). Since the Pleiades are about ten times younger than the Hyades, a scaling of the exponential dependence of the abundance reduction leads to exp(3.4/10)=1.4; this is reasonable agreement.

Other clusters have now been observed: Coma by Boesgaard and Tripicco (1987) and NGC 752 and M 67 by Hobbs and Pilachowski (1986a, 1986b). In Coma and NGC 752 a dip occurs at the same T_{eff} as in the Hyades, though not as well defined. In the older clusters, NGC 752 and M 67 the Li abundance around T_{eff} =6200 K appears to have been lowered by diffusion and/or burning. Within the error bars, the interstellar matter Li abundance is consistent with the original Li abundance in young clusters (Hobbs 1984).

In the UMa moving group and in a new study of the Hyades, Boesgaard, Budge and Burck (1988) and Boesgaard (1987) obtain upper limits of 10^{-3} the original Li abundance in some stars. Since there is a measurement error of $\pm$2 mA (Boesgaard, Budge and Burck, 1988 §II), and since an underabundance by a factor of 30 leads to a line of about 2 mA in the middle of the gap (see Fig. 4 of Boesgaard and Tripicco 1986a), it appears to me that no underabundance by a factor of more than 30 can be determined from these spectra. The presence of a blend can only make the determination of the upper limit more difficult. It cannot be used to reduce the upper limit, as was apparently done here.

Spite and Spite (1982) and Spite et al. (1984) have determined the Li abundance in Halo stars (see also Hobbs and Duncan 1987). It is about 8 times smaller than the current value in young stars before it is affected by diffusion or burning. But if one uses the diffusion time scale at T_{eff} = 6300 K (τ= 4 10^9 yr as seen above) at an age of 8 10^9 yr, which is a minimum for halo stars, one obtains a factor of exp(-2)=7.4 reduction in the Li abundance at T_{eff} = 6300 K by diffusion alone. This suggests that the original Li abundance in halo stars may well have been about the same as the original Li abundance in young clusters today. In the cooler of the halo stars nuclear burning would have reduced the Li abundance. There would be a large T_{eff} interval over which the Li abundance would be about constant because these two effects would combine to form a plateau.

That the Li abundance observed by Spite and Spite (1982) could not be the cosmological abundance but had been reduced by a factor of at least 4 by either diffusion or burning was first noted by Michaud, Fontaine and Beaudet (1984). These authors also emphasized that this plateau is constant over a surprisingly large T_{eff} interval. This remains a problem requiring further study.

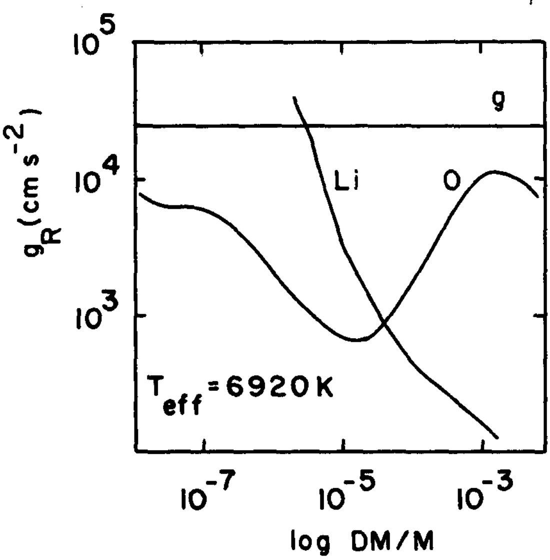
That the plateau should be shifted to lower T_{eff} in halo stars can be understood rather easily as due to a Z dependence of the depth of the convection zone at a given T_{eff} (Michaud, Fontaine and Beaudet 1984).

The interpretation of the Li abundance gap using a diffusion model has been questioned because of the observed absence of abundance anomalies of heavy elements in F stars (Boesgaard and Lavery 1986; Thévenin, Vauclair and Vauclair 1986; Tomkin, Lambert and Balachandran 1985) where Be has been observed to be underabundant. Such anomalies had been predicted on account of the diffusion calculations in the absence of any mass loss (Michaud et al. 1976, Vauclair et al. 1978b). It has recently been shown that even a very small mass loss was sufficient to reduce considerably any expected overabundance in F stars. On Fig. 2c of Michaud and Charland (1986), it is shown that a mass loss rate of 10^{-15} $M_\odot$ yr^{-1} is sufficient to keep the Sr overabundance below a factor of 1.5 while Sr would be expected to be more than 100 times overabundant in the absence of mass loss (Michaud et al. 1976). The presence of even a very small mass loss rate considerably limits any overabundance when the radiative acceleration and gravity are close to each other as is the case for heavy elements in stars cooler than T_{eff} = 7000 K. The same small mass loss rate reduces the Li overabundance in stars of T_{eff} = 7000 K or more where Li is supported. As shown in Fig. 4 of Michaud (1986), the same mass loss rate of 10^{-15} $M_\odot$ yr^{-1} eliminates the Li overabundance of a factor of 10 expected in the absence of mass loss at T_{eff} = 7000 K. It has now been verified that the presence of mass loss cannot increase the Li underabundance that diffusion leads to beyond a total factor of 30 underabundance.

Detailed calculations of radiative accelerations for a few selected elements are currently underway at Montréal to define a test of this model. Nitrogen and oxygen seem specially promising (see Fig. 1): they are in the He configuration when Li is not supported. This is based on calculations carried out as described by Michaud et al. (1976) but needs to be confirmed by more detailed calculations.

The introduction of a mass loss rate may seem arbitrary. However in this case the position and depth of the observed Li abundance gap is explained without arbitrary para-

https://doi.org/10.1017/S0252921100093325 Published online by Cambridge University Press



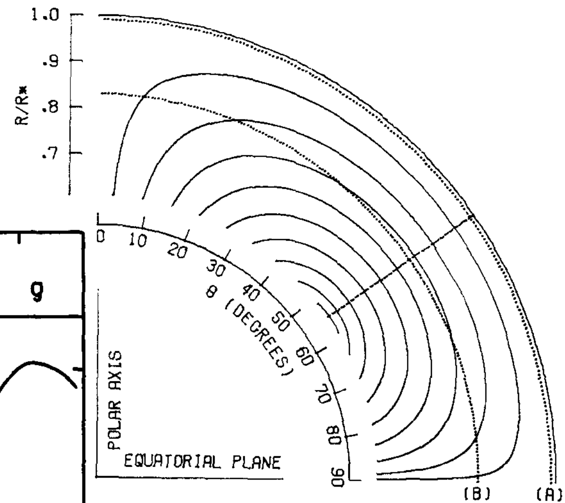


Fig. 1 Radiative accelerations of Li and oxygen as a function of the mass above the point of interest. When the radiative acceleration on Li is smaller than gravity, so is that on O. According to these calculations oxygen should sink if Li sinks.

Fig. 2 Meridional circulation stream lines (full lines) as a function of the angle from the polar axis. The position of convection zones is indicated by dotted lines. That identified by A is for a 12000 K main sequence star while that indicated by B is for a 6400 K star.

meters, other than the uncertainty on α, and the introduction of the mass loss is only necessary to improve the fit of the shape of the Li abundance curve with T_{eff}. Furthermore, as I will now show, such mass loss rates are also required to explain the observed abundance anomalies in FmAm stars which are probably the hot continuation of the F stars of the Hyades with Li underabundances.

IV. The FmAm and λ Booti stars.

If one assumes that the outer region of an Am star is perfectly stable and calculates the abundance anomalies produced, one obtains values that exceed the observed overabundances by more than a factor of 10 (Michaud et al.1976). Some perturbing process appears to be important.

It is possible to get an upper limit to the turbulence below the H convection zone in FmAm stars by its effect on the abundance of Sc and Ca. As mentioned by Jugaku (this conference) these 2 elements are generally observed to be underabundant in these objects and it was obtained by Vauclair et al. (1978a) that to explain the observed underabundance implied $R_* \lesssim 3$ even if the uncertainty on the radiative acceleration of Sc was used to maximise this value. This is then a rather strict upper limit for turbulence in the outer regions of FmAm stars. This may be related to the presence of a μ gradient caused by the progressive increase of the He abundance inward. Once turbulence is so small, however, it can have essentially no effect on the abundance of heavy elements. Turbulence cannot be the hydrodynamical process reducing overabundances in FmAm stars.

Mass loss appears to reduce sufficiently the observed overabundances (Fig. 3 of Michaud et al. 1983 and Fig. 2d of Michaud and Charland 1986) while maintaining the observed underabundances (Fig. 4 of Michaud et al. 1983). A mass loss rate of about 10^{-15} $M_\odot$ yr^{-1} is needed.

At the same T_{eff} as the FmAm stars showing overabundances of most heavy elements (see e. g., Van't Veer-Menneret et al. 1985, Burkhart et al. 1987), there are also the λ Booti stars that have underabundances of most heavy elements (Baschek and Searle 1969). Diffusion in presence of a mass loss rate of 10^{-13} $M_\odot$ yr^{-1} leads to generalized underabundances by factors of ~ 3. Such a different mass loss rate may be caused by the higher rotation rate of the λ Booti stars as compared to the FmAm stars.

V. Meridional Circulation

Following the derivation by Tassoul and Tassoul (1982) of a physically consistent meridional circulation velocity field, it became possible to do detailed calculations of gravitational settling in presence of circulation. The first comparison (Michaud 1982, Michaud et al. 1983) was encouraging, though based on a very rough approximation of the meridional circulation velocity fields (Figure 2) and justified the effort of a detailed two dimensional calculation of diffusion in presence of meridional circulation. The aim becomes to test a well defined hydrodynamic model as precisely as possible using observed abundance anomalies. We test whether the meridional circulation patterns obtained by Tassoul and Tassoul (1982) for radiative models explain the disappearance of abundance anomalies at about 100 km s^{-1} for HgMn and FmAm stars. We then test for the Li abundance gap observed in young stellar clusters. As the external convection zone becomes deeper, the model of Tassoul and Tassoul assuming a purely radiative outer region should break down at some point.

The calculations turned out to require a grid of 20 (horizontal)x 100 (vertical). Details of the calculations may be found in Charbonneau and Michaud (1987a).

For the HgMn stars, Wolff and Preston (1978) obtain an upper limit of 100 km s^{-1} for the V sin i at which they are observed. The meridional circulation is slow enough to allow the disappearance of the He convection zone by He settling for rotational velocities up to 75 km s^{-1} (Charbonneau and Michaud 1987a). Once the He convection zone has

https://doi.org/10.1017/S0252921100093325 Published online by Cambridge University Press

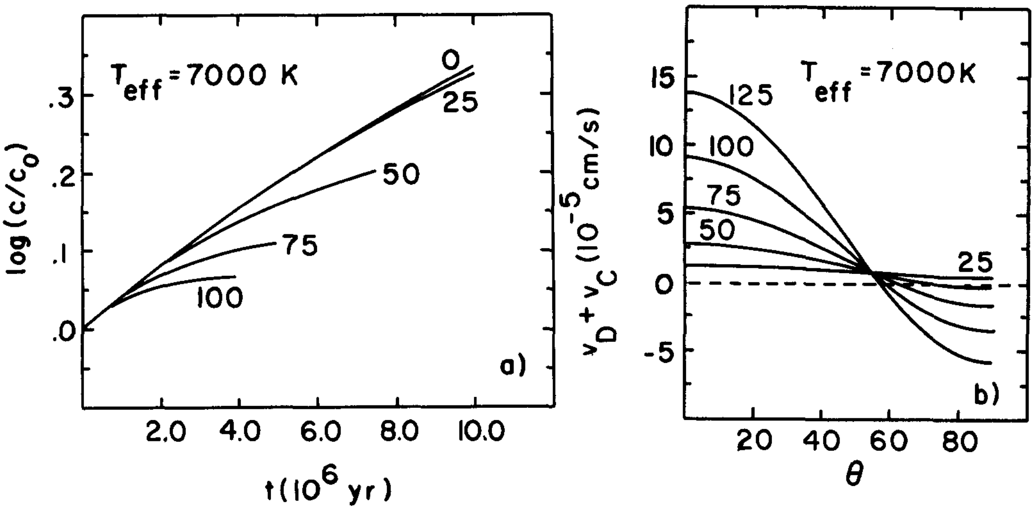


Fig. 3 On part a) is shown the Li abundance as a function of time in a T_{eff} = 7000 K star. The curves are identified by the equatorial rotational velocity in km s^{-1}. The effect of meridional circulation on the Li abundance starts to be felt for rotational velocities of 50 km s^{-1}. This can be understood from part b) of the figure where the total vertical transport velocity is shown as a function of the angle from the rotation axis. For rotational velocities of up to some 40 km s^{-1}, the transport velocity is everywhere positive.

disappeared, the atmospheric region becomes stable and diffusion can cause the abundance anomalies observed on HgMn stars (Michaud 1982). For FmAm stars, Abt and Levy (1985) obtain an upper limit of 0.9 day for the orbital period of the binary systems in which there are FmAm stars while the limit obtained by Charbonneau and Michaud (1987a) is 0.7 day or V_e=100 km s^{-1} assuming synchronous rotation. In my opinion this constitutes excellent agreement and suggests that the meridional circulation patterns of Tassoul and Tassoul (1982) constitute the main velocity field opposing chemical separation. In particular it appears that turbulence does not play a major role. Note that in obtaining their solution Tassoul and Tassoul had to assume a non negligible turbulent viscosity though the solution did not depend on the value chosen (the dependence was only as $\mu^{1/11}$).

One can similarly use the meridional circulation fields to test its effect on the diffusion of Li in the F stars of clusters (Charbonneau and Michaud (1987). It turns out however that the upper limit of the equatorial rotation velocity is much smaller. This can be traced to the increase in the depth of the convection zone. The diffusion velocity decreases considerably due to the ρ^{-1} dependence of the diffusion coefficient while the meridional circulation velocity is nearly constant as one goes deeper in the star. While the critical velocity in the middle of the gap is about 15 km s^{-1}, there are stars in the middle of the gap of the Hyades with a V sin i of 50 km s^{-1} (Boesgaard 1987). These stars have very low Li abundance and if the low Li abundance in the gap is to be explained by diffusion it is clear that the calculations of Tassoul and Tassoul (1982) do not apply to F stars.

It is however interesting to consider the alternate possibility that in those stars

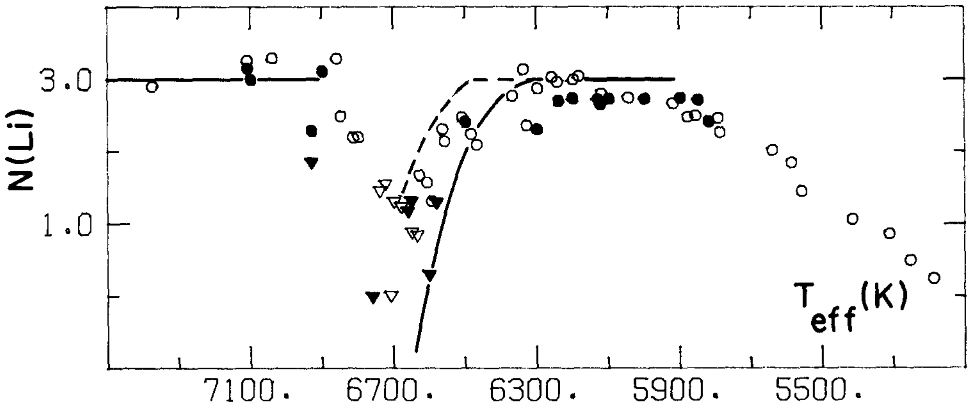


Fig. 4 The Li underabundance caused by the matter brought, to the convection zone, by meridional circulation from the region where Li burns, is shown as a function of T_{eff} for the Hyades (8 10^8 yr) and UMa (4 10^8 yr). It is compared to observations for these two clusters (Boesgaard, Budge and Burck 1988).

rotating fast enough to stop diffusion, meridional circulation brings to the surface matter from which Li has been burned. Calculations for this model were carried out using the same circulation velocity fields as previously. The burning of Li was assumed to be complete at T=2.5 10^6 K so that matter arriving from that depth has no Li. When after a time t_0, matter that was originally deeper than T= 2.5 10^6 K arrives in the convection zone, the Li abundance starts decreasing in the convection zone. It then decreases with a time constant Θ, obtained from the time it takes to replace the mass of the convection zone by new material. The time evolution of the abundance is then:

$$c = c_0 \exp((t-t_0)/\theta) \qquad \text{for } t>t_0 .$$

The effect of diffusion was completely neglected in this calculation. Where the radiative acceleration on Li is negligible, the settling would increase the effect of the burning and so taking it into account could only strengthen the argument. When however the radiative acceleration is larger than gravity, the situation is a little more complex. Figure 3 shows the effect of meridional circulation on the superficial Li abundance in a case when Li is supported. The meridional circulation starts reducing the Li overabundance only for equatorial rotational velocities larger than about 50 km s^{-1}. On part b of Figure 3 meridional circulation and diffusion velocities are compared as a function of the angle from the rotation axis. For V> 35 km s^{-1}, the upward diffusion velocity is everywhere larger than the downward circulation velocity, so shielding the surface Li by keeping it in the convection zone. For stars with T_{eff} >6900 K and V<50 km s^{-1}, the surface Li is shielded from the burning zone.

On Fig. 4 is shown the Li abundances to be expected from such a model at the age of the Hyades and of Uma. They are compared to the observations of Boesgaard, Budge and Burck (1988). To do these calculations the equatorial rotation velocity is needed. I used V= 50 km s^{-1} at T_{eff}=6700 K and V=25 km s^{-1} at T_{eff} =6350 K, from an average of the observed rotational velocities in the appropriate T_{eff} range taking the effect of sin i

Table 1
Stars that are a Problem for Meridional Circulation

Star	Cluster	T_{eff} (K)	v sin i	v_e(crit)	log(N(Li))
TR111R	Coma	6400	35	21	2.67
HD2377B	Pleiades	6400	75	68	2.9
HD23584	Pleiades	6500	85	68	2.8
HD23351	Pleiades	6700	80	70	2.9
HD23608	Pleiades	6650	110	70	2.8

into account. The rotational velocities were interpolated linearly in between those 2 T_{eff}. Above T_{eff} =6900 K, Li is shielded by g_R(Li). One could argue that the agreement is quite satisfactory at least for the Hyades. A somewhat larger rotational velocity would be needed to explain the results for UMa.

In Table 1 are shown a number of stars that have large Li abundances and rotational velocities. Are indicated both the measured rotational velocities and the limiting rotational velocity beyond which Li should be strongly depleted by the mechanism just described. These contradict the model just described. They require that the penetration of the convection zone by meridional circulation be at most partial.

VI. CONCLUSIONS

While gravitational settling explains the presence of a Li abundance gap in F stars, it cannot explain underabundances by more than a factor of about 30 in the Hyades. If larger underabundance factors were confirmed, it may imply that Li has been destroyed by nuclear reactions in at least some of the F stars. It was shown how meridional circulation may then be implied. The blue side of the abundance gap would still be explained by the drop of g_R(Li) between T_{eff} =7000 and 6700 K. Observations of N and O may allow to distinguish between the effect of settling and of nuclear burning of Li though more calculations of radiative accelerations are needed to confirm this test. While the meridional circulation model of Tassoul and Tassoul appears to pass the test of abundance anomalies in HgMn and FmAm stars, it may not pass that of the F stars. The difference may come from the deeper convective zones of the F stars which may modify the solutions obtained by Tassoul and Tassoul for purely radiative envelopes. Note that given the observed solar rotational velocity, meridional circulation should have no effect on the Li abundance before the Sun is 2 10^{10} yr old.

Abundance anomalies imply mass loss rates smaller than 10^{-13} $M_\odot$ yr^{-1}. The Li abundance implies mass loss rates smaller than 10^{-14} $M_\odot$ yr^{-1}. This contradicts the assumption of Guzik, Willson, and Brunish (1987) that stars with $1 < M < 3$ $M_\odot$ lose mass at the rate of 10^{-9} to 10^{-8} $M_\odot$ yr^{-1}.

I thank Paul Charbonneau and Yves Charland for carrying out most of the calculations reported in this paper.

REFERENCES

Abt, H. A., and Levy, S. G. 1985, Ap. J. Suppl., 59, 229.
Baglin, A., Morel, P., and Schatzman, E. 1985, Astr. Ap., 149, 309.
Baschek, B., and Searle, L. 1969, Ap. J., 155, 537.
Boesgaard, A. M. 1976, Ap. J., 210, 466.
Boesgaard, A. M. 1987, Pub. A. S. P., in press.
Boesgaard, A. M., Budge, K. G., and Burck, E. E. 1988, Ap. J., February.
Boesgaard, A. M., and Lavery, R. J. 1986, Ap. J., 309, 762.
Boesgaard, A. M., and Tripicco, M. J. 1986a, Ap. J. (Letters), 302, L49.
Boesgaard, A. M., and Tripicco, M. J. 1986b, Ap. J., 303, 724.
Boesgaard, A. M., and Tripicco, M. J. 1987, preprint.
Burkhart, C., Coupry, M. F., Lunel, M., and Van't Veer, C. 1987, Astr. Ap., in press.
Cayrel, R., Cayrel de Strobel, G., Campbell, B., and Dappen, W. 1984, Ap. J., 283, 205.
Charbonneau, P., and Michaud, G. 1987a, submitted for publication.
Charbonneau, P., and Michaud, G. 1987b, in preparation.
Duncan, D. K. 1981, Ap. J., 248, 651.
Duncan, D. K., and Jones, B. F. 1983, Ap. J., 271, 663.
Guzik, J. A., Willson, L. A., and Brunish, W. M. 1987, Ap. J., 319, 957.
Hobbs, L. M. 1984, Ap. J., 286, 252.
Hobbs, L. M., and Duncan, D. K. 1987, Ap. J., 317, 796.
Hobbs, L. M., and Pilachowski, C. 1986a, Ap. J. (Letters), 309, L17.
Hobbs, L. M., and Pilachowski, C. 1986b, Ap. J. (Letters), 311, L37.
Michaud, G. 1977, Nature, 266, 433.
Michaud, G. 1982, Ap. J., 258, 349.
Michaud, G. 1985, in Solar Neutrinos and Neutrino Astronomy, Ed. M.L Cherry, K. Lande and W. A. Fowler (New York: American Institute of Physics), p. 75.
Michaud, G, 1986, Ap. J., 302, 650.
Michaud, G., Charland, Y. 1986, Ap. J., 311, 326.
Michaud, G., Charland, Y., Vauclair, S., and Vauclair, G. 1976, Ap. J., 210, 447.
Michaud, G., Fontaine, G., and Beaudet, G. 1984, Ap. J., 282, 206.
Michaud, G., Tarasick, D., Charland, Y., and Pelletier, C. 1983, Ap. J., 269, 239.
Paquette, C., Pelletier, C., Fontaine, G., and Michaud, G. 1986, Ap. J. Suppl., 61, 177.
Pilachowski, C. A., and Hobbs, L. M. 1987, preprint.
Schatzman, E. 1969, Astr. Ap., 3, 331.
Schatzman, E. 1977, Astr. Ap., 56, 211.
Schatzman, E., Maeder, A., Angrand, F., and Glowinski, R. 1981, Astr. Ap., 96, 1.
Spite, F., and Spite, M. 1982, Astr. Ap., 115, 357.
Spite, M., Maillard, J.-P., and Spite, F. 1984, Astr. Ap., 141, 56.
Tassoul, J.-L., and Tassoul, M. 1982, Ap. J. Suppl., 49, 317.
Tassoul, M., and Tassoul, J.-L. 1983, Ap. J., 271, 315.
Tassoul, M., and Tassoul, J.-L. 1984, Ap. J., 279, 384.
Thévenin, F., Vauclair, S., and Vauclair, G. 1986, Astr. Ap., 166, 216.
Tomkin, J., Lambert, D. L., and Balachandran, S. 1985, Ap. J., 290, 289.
Van't Veer-Menneret, C., Coupry, M. F., and Burkhart, C. 1985, Astr. Ap., 146, 139.
Vauclair, G., Vauclair, S., and Michaud, G. 1978a, Ap. J., 223, 920.
Vauclair, S., Vauclair, G., Schatzman, E., and Michaud, G. 1978b, Ap. J., 223, 567.
Wolff, S. C., and Preston, G. W. 1978, Ap. J. (Suppl.), 37, 371.