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Main Sequence Mass Loss and The Lithium Dip

David N. Schramm

University of Chicago
5640 S., Ellis Avenue
Chicago, Illinois 60637
and
NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
Box 500
Batavia, Illinois 60510

Gary Steigman

Departments of Physics and Astronomy
The Ohio State University
174 West 18th Avenue
Columbus, Ohio 43210-1106

and

David S. P. Dearborn

Lawrence Livermore National Laboratory
MS L387, P.O. Box 808
Livermore, California 94550

ABSTRACT

The significant dip in observed lithium abundances for Pop I stars near $M \sim 1.3M_\odot$ is discussed. It is noted that this dip occurs where the instability strip crosses the main sequence and may be associated with δ - Scuti stars and, that stellar pulsations are expected to give rise to mass loss. A total mass loss of $\sim 0.05M_\odot$ over the main sequence lifetime of these stars would be sufficient to explain the observations of lithium depletion. The absence of a dip in the Pleiades and of depletion of beryllium in the Hyades places tight constraints on the rate of mass loss. These constraints make unlikely the high main sequence mass loss rates which would effect globular cluster ages.

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Introduction

The observation by Boesgaard (1976) of a significant dip in the lithium abundance for Pop I stars near $\sim 1.3 M_\odot$ (log $T_{eff} \sim 3.82$) has been a significant problem for stellar evolution (see Figure 1). The fact that the dip is seen in a cluster as young as the Hyades as well as in the older cluster NGC752, but is not seen in the very young Pleiades cluster, clearly tells us something about the timescale for the process generating this dip. Recently the critical role of lithium as a cosmological constraint (c.f. Kurki-Suonio *et al.*, 1989; Kawano, Steigman and Schramm, 1988) has given a great deal of importance to understanding all aspects of lithium observations and evolution.

Previous attempts to explain the *Li* dip have focused on diffusion processes (Michaud, 1989). Such processes are plausible but not mandatory due to their large number of adjustable parameters. Here we focus our efforts on showing that another mechanism exists which might also explain the lithium dip. This new mechanism is main sequence mass loss resulting from pulsations of main sequence stars in the variable strip. We find very suggestive the fact that the variable strip intersects the main sequence at the lithium dip.

The possibility of significant main sequence mass loss due to pulsations in the variable strip and the relation to δ - Scuti stars has received much recent attention in the work of Wilson, Bowen and Struck-Marcell, 1987 (see also Guzik, 1989). Wilson *et al.* have argued that main sequence mass loss could be large enough to effect globular cluster dating by causing low mass stars to leave the main sequence sooner. We will argue here that, independent of whether or not the lithium dip is due to mass loss, lithium and beryllium abundances do place severe constraints on main sequence mass loss. Wilson *et al.* have recognized the potential of lithium as a constraint but have tried to avoid it by proposing a mechanism for self-enrichment of lithium in stars. We will also discuss why self-generation seems unlikely.

Hobbs, Iben and Pilachowski (1989) have also recently discussed a relationship between lithium and main sequence mass loss. However, their work focuses on lower mass main sequence stars ($0.8 \lesssim M \lesssim 1.1 M_\odot$) with extensive convective zones and large lithium depletions. Our work here concentrates on lithium and beryllium and mass loss near the Boesgaard dip, $1.2 \lesssim M \lesssim 1.4 M_\odot$. Our mechanism is pulsation driven mass loss (Wilson *et al.*), rather than convection driven mass loss (Hobbs *et al.*). However, it is interesting that the overall rates we obtain are quite comparable to those used by Hobbs *et al.* for the lower main sequence.

The Lithium Dip

Boesgaard and Tripicco (1986) and Hobbs and Pilachowski (1988) have examined lithium abundances in Pop I clusters of different ages. These observations are schematically summarized in Figure 1. They have found that, for the Pleiades, with an age of $\sim 8 \cdot 10^7 yr$, there is no significant variation of the upper envelope of Li/H as a function of surface temperature (stellar mass). In contrast, the older Hyades ($t \sim 7 \cdot 10^8 yr$) and NGC 752 ($t \sim 1.7 \cdot 10^9 yr$) clusters clearly do show a distinct dip in Li/H near $\log T_{eff} \sim 3.82$ which would correspond to main sequence stars near $M \sim 1.3 M_\odot$. [These latter clusters also show depletions in stars at very low temperatures, presumably due to burning associated with deep convective zones (Demarque *et al.*, 1989) and possible mass loss (Hobbs *et al.*).] Although the clusters M67 ($t \sim 5 \cdot 10^9 yr$) and NGC 188 ($t \sim 5 - 10 \cdot 10^9 yr$) do have lithium determinations, the stars with $M \sim 1.3 M_\odot$ are no longer on the main sequence in clusters of these ages. The dip, when present, is sufficiently deep that, at its center, no Li is seen to limits a factor of 100 below similar mass (temperature) Pop I stars. Recently Boesgaard (1989) has also observed beryllium in the Hyades and found no depletion in those stars where the Li dip was present. The range in masses of the dip for the Hyades, when converted to zero age main sequence masses from the Dearborn and Hawkins (1990) models, is $1.2 \leq M \leq 1.4 M_\odot$. The dip mass range for NGC 752 includes this range but may extend to slightly lower masses, although the statistical significance of the differences is marginal.

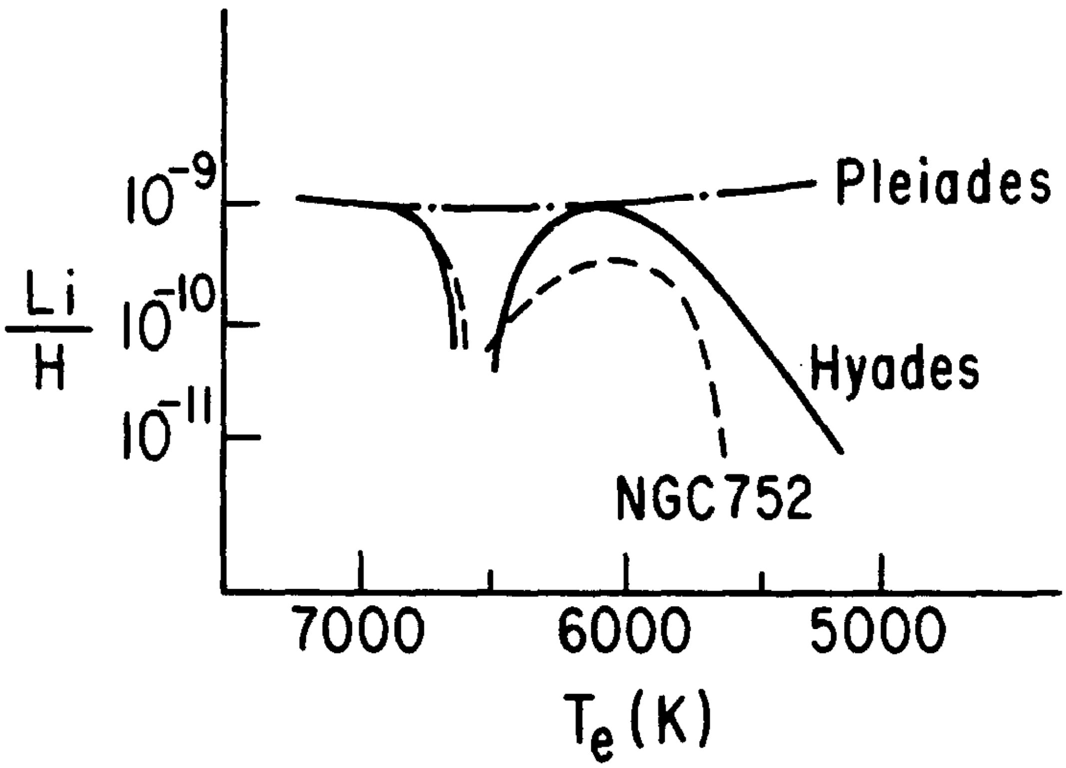

Figure 1. Pop I Lithium abundances for open clusters (based on Hobbs and Pilachowski, 1988)

Main Sequence Mass Loss and Lithium

Wilson *et al.* noted that the variable star instability strip will cross the main sequence where the δ - Scuti variables are observed ($1 \lesssim M \lesssim 2M_\odot$), with the edges somewhat poorly defined. Wilson *et al.* argue that the radial pulsations associated with these variations will lead to significant mass loss; they suggest mass loss rates $\dot{M} \gtrsim 10^{-9} M_\odot/yr$. (For comparison, note that the solar wind has $\dot{M} \sim 10^{-14} M_\odot/yr$.) Here we note that the center of this main sequence instability strip is also at the center of the lithium dip $M \sim 1.3 M_\odot$ and that the lithium and beryllium observations constrain mass loss rates to lie well below those suggested by Wilson *et al.*. Our constraint results from the facts that since mass loss will expose the inner zones of the star which were at higher temperature, and since lithium and beryllium are quite fragile, these nuclei would no longer present in the newly uncovered layers. Conversely, if the center of the pulsation range ($1.3 \pm 0.1 M_\odot$) does indeed have some mass loss (though much less than Wilson *et al.* propose), then the Li dip can be explained.

To quantify these arguments and put limits on the integrated mass loss, we will calculate how deep lithium and beryllium can survive within a $1.3 M_\odot$ star. However, before doing so, we note that the production of lithium following such mass loss, but prior to present observations, is unlikely. Wilson *et al.* have attempted to avoid these constraints from light element destruction by invoking the self-generation of lithium in these stars via spallation processes à la Fowler, Greenstein and Hoyle (1961). The problem with spallation production is two-fold. First, ordinary spallation, as in the cosmic rays, makes $^7Li/^6Li$ in a ratio of ~ 2; not the $^7Li/^6Li \sim 12$ observed in meteorites or $^7Li/^6Li > 10$ observed in some stars and the interstellar gas (Hobbs and Pilachowski, 1988; Spite and Spite, 1982). Spallation also makes $^6Li/^9Be$ in the solar ratio, which means that ^7Li will be underproduced relative to its Pop I value if ^9Be is made at the Pop I value. Subsequent destruction of ^6Li does not alleviate the $^7Li/^9Be$ problem. Second, Ryter, Audouze and Reeves (1970) successfully argued against the original Fowler *et al.* model on the basis of gross energetics.

Spallation is a very energy inefficient process. Ryter *et al.* showed that significant light element production by spallation would require energies exceeding the binding energy of a star. While their main argument concentrated on deuterium, which is $\sim 10^4$ times as abundant as Li, the energy available for spallation in flares, is $<< 10^{-4}$ the total stellar binding energy, so the energetics problem remains.

A further problem for any self-generation model is the uniformity of the lithium "plateau" on either side of the lithium dip and the consistency of this plateau from cluster to cluster, including the Pleiades which shows no dip nor any lower main sequence depletion either. Spallation models (as well as other plausible schemes) would, presumably, have some dependence on surface temperature or stellar mass. For example, the intensity of flaring varies inversely with the mass of the star. Thus, the uniformity of the Pop I lithium plateau argues for it being representative of the abundance out of which the stars formed, rather than a self-generative process.

In the absence of self-generation, it is clear that the observations of lithium in Pop I stars with $M \gtrsim 1M_\odot$ indicates that, for those stars, mass loss has not uncovered zones where Li is depleted. (Stars with $M \lesssim 1M_\odot$ have outer connective zones which may change the argument as per Hobbs *et al.*, 1989).

Figure 2 shows the abundances of the lithium isotopes and beryllium near the surface of a $1.3M_\odot$ star as a function of the interior mass. The model is from the Dearborn variant of the Eggleton code (see discussion in Dearborn, Eggleton and Schramm, 1976, and in Dearborn and Hawkins, 1990), using reaction rates for all two body light element reactions from Caughlan and Fowler (1988) and fine zoning in the outer regions to map out abundance details. Being the most fragile, ^6Li is present only in the outer $0.03M_\odot$. Being nuclearly the most tightly bound, ^9Be is found throughout the top $0.07M_\odot$ and ^7Li is intermediate, with its depth going to $\sim 0.05M_\odot$. We have carried out similar calculations for stars with $1.1 \lesssim M \lesssim 1.4M_\odot$.

We have also made model calculations with mass loss rates ranging from $10^{-11} \lesssim$

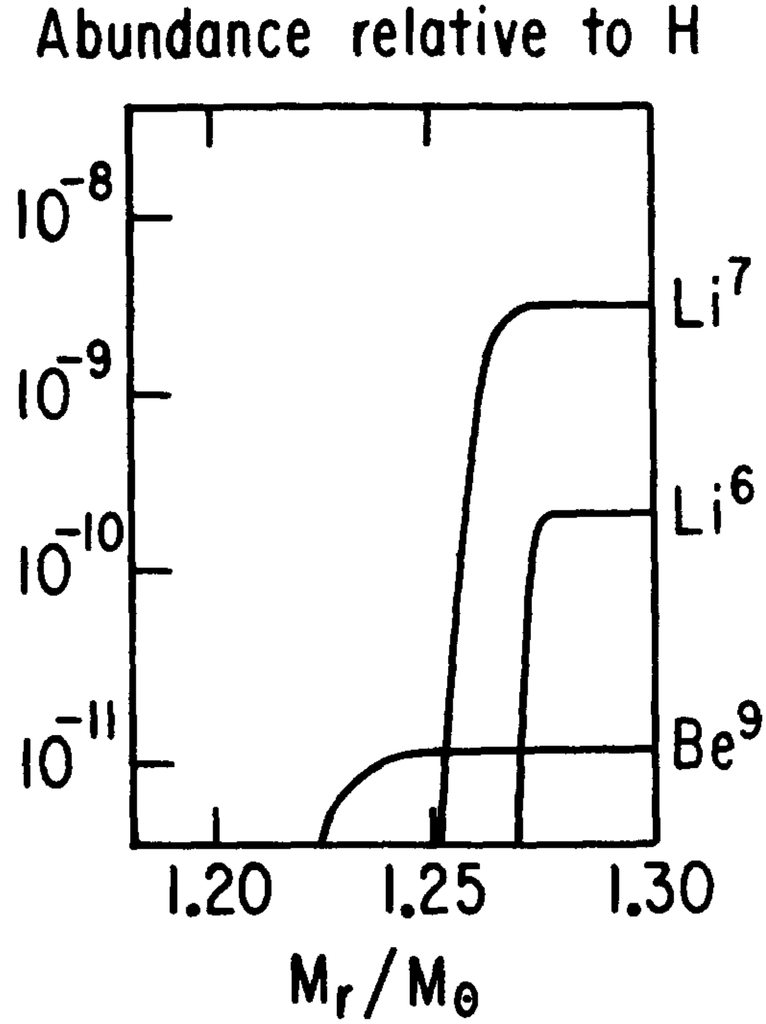

Figure 2. Lithium and Beryllium as a function of interior mass near the surface of a $1.3 M_\odot$ star.

$\dot{M} \lesssim 10^{-9} M_\odot/yr$; the Dearborn code is able to accomodate mass loss routinely due to its rezoning algorithm (Dearborn, Blake, Hainebach and Schramm, 1978). The results of these mass loss calculations can be understood with reference to Figure 2. Figure 2 shows the abundances of Li and Be near the surface of a $1.3 M_\odot$ star with no mass loss. Notice that if more than $0.05 M_\odot$ are shed from the surface, no surface lithium will remain. Thus, in order to account for the lithium dip, $1.3 M_\odot$ stars must lose at least $0.05 M_\odot$ by the age of the Hyades ($t \sim 7 \cdot 10^8 yr$) and NGC 752 ($t \sim 1.7 \cdot 10^9 yr$). In other words, if mass loss is the mechanism for the Li dip, then for the Hyades

$$\dot{M} \gtrsim 7 \cdot 10^{-11} M_\odot/yr. \tag{1}$$

However, the absence of a dip in the Pleiades ($t \sim 8 \cdot 10^7 yr$) tells us that not more than $0.04 M_\odot$ has been shed in $8 \cdot 10^7 yr$. This provides a strong upper bound to the mass loss rate,

$$\dot{M} < 5 \cdot 10^{-10} M_\odot/yr \tag{2}$$

The limit in equation (2) severely constrains the Wilson *et al.* model which requires $\dot{M} \gtrsim 10^{-9} M_\odot/yr$. However, we can obtain an even stronger bound by noting that beryllium is not depleted in the Hyades (Boesgaard 1989). From Figure 2 we see that the mass lost in $7 \cdot 10^8 yr$ must be $< 0.07 M_\odot$ which limits the mass loss rate to,

$$\dot{M} < 1 \cdot 10^{-10} M_\odot/yr. \tag{3}$$

We also note that for stars outside of the lithium dip region, the total mass shed is constrained to be $\Delta M < 0.04 M_\odot$ to avoid lithium depletion. For NGC 752, this corresponds to

$$\dot{M} < 2 \cdot 10^{-11} M_\odot \tag{4}$$

for stars with $M \sim 1.1 M_\odot$ where little depletion is observed. These basic conclusions have been confirmed in more detailed evolutionary calculations with mass loss included consistently.

From the limit in (3), it is clear that mass loss on the main sequence, for stars in the variable strip, is constrained to be an order of magnitude smaller than the rate preferred by Wilson *et al.* This constraint is independent of whether or not the Li dip is actually due to mass loss.

For such a low mass loss rate and its narrow range of applicability (as defined by the dip), globular cluster ages cannot be altered significantly. Furthermore, if mass loss is, indeed, the mechanism for the lithium dip, then

$$0.7 \lesssim \dot{M}/10^{-10} M_\odot yr^{-1} \lesssim 1, \tag{5}$$

such an explanation then places a very tight constraint on the magnitude of main sequence mass loss.

Observational Tests

If viewed naively, mass loss predicts a beryllium depletion for NGC 752 if $\dot{M}$ is $\sim 7 \cdot 10^{-11}$ for $1.7 \cdot 10^9 yr$, since the mass shed would be $\sim 0.12 M_\odot$ and no Be would remain in a $1.3 M_\odot$ star. However, the simple mass-loss process is likely suppressed as the star evolves out of the pulsation zone. Thus, it is conceivable that a full beryllium dip may not develop. But, even a small decrease would be evidence for the process since the alternative of diffusion would not simultaneously remove beryllium with lithium from the surface.

Another prediction is that for older clusters, the Li dip should extend to slightly cooler stars than for the younger clusters, since mass loss will move stars down the main sequence until they leave the pulsation zone. Indeed, the data on NGC 752 does appear to show just such a shift. It will be interesting to see if more detailed studies continue to show evidence in support of such a trend.

Conclusions

To summarize, we use the observed lithium and berylium abundances in clusters to constrain mass loss rates in main sequence stars with $1.1 \lesssim M \lesssim 2M_\odot$. We note that the total mass loss is too small to affect globular cluster ages significantly. However, we do note that the Wilson *et al.* mass loss mechanism can provide a new explanation for the lithium dip near $T_{eff} \sim 6600K$ if eq. (5) is satisfied. We also note that tests for this mechanism are a shift of the dip, in T_{eff}, to slightly lower values in older clusters and a depletion of Be in older clusters (unless $\dot{M}$ goes to zero after $\sim 10^9 yr$).

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Figure Captions

Figure 1. Pop I Lithium abundances for open clusters (based on Hobbs and Pilachowski, 1988)

Figure 2. Lithium and Berylium as a function of interior mass near the surface of a $1.3M_{\odot}$ star.