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CONSEQUENCES OF A POPULATION II ANALOGY TO THE F STAR LITHIUM DIP *

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Abstract

Observers have found a small number of lithium depleted halo stars in the temperature range of the Spite plateau. Their existence can be undertood as an evolutionary consequence of the "mass loss" hypothesis proposed to explain the lithium dip in Pop I, F stars. On the main sequence, Pop II stars evolve to the blue, entering the narrow temperature region in which mass loss driven by a main sequence "instability strip" is assumed to occur. They then move back through the lower temperature area of the Spite plateau. If 0.05 M_0 or more have been lost, they will show lithium depletion. The effect of this hypothesis on the ratio of high to low lithium stars and on the luminosity function are discussed. Finally, mass loss in this temperature range would operate in stars near the turn-off of metal poor globular clusters, resulting in apparent ages 2 to 3 Gyr older than they actually are.

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Introduction:

The age and density of the universe remain outstanding issues in observational cosmology. As a sensitive indicator of baryonic density during Big Bang nucleosynthesis, the primordial lithium (^7Li) abundance is of extreme interest (Kawano et al. 1988; Walker et al. 1991). Estimating this value from observed stellar features depends on understanding the production and destruction mechanisms causing the abundance to evolve in individual stars, and between stellar populations.

Complicating the determination of the original lithium abundance is a narrow temperature region in which lithium depletion is observed in Pop I stars (Boesgaard and Tippico, 1986, and Hobbs and Pilachowski 1988). Within 1 Gyr of the zero age main-sequence, F type stars in the temperature range (6600 +/- 200) show a substantial lithium depletion. The possible interaction of this "lithium dip", with the mechanism causing a general decrease of the lithium abundance in later type stars must be understood in the metal poor stars of the Spite plateau (Spite and Spite, 1982) from which the primordial value is determined.

The discovery of a lithium deficient main-sequence turn-off star, G186-26 (Hobbs, Welty, and Thorburn 1991), demonstrated that a non-uniform depletion mechanism existed in the halo population. Evidence for this existence was strengthened by Thorburn (1992) who has found two additional low lithium stars in the temperature range 5600 to 6200 K. These objects are either pathologically low in lithium for some unknown reason, or represent subgiants that have evolved from the "F star dip." For a halo age of 9 Gyr, or older, a few post-turn-off, subgiant stars are expected to be visible in this temperature region.

Hypotheses to understand the lithium dip in F type stars include radiative diffusion (Michaud 1989) and localized mass loss on the main sequence (Schramm, Steigman, and Dearborn, 1990) The mass loss explanation was motivated by the coincidence of its location with an extrapolation of the instability strip down to the main sequence (Wilson, Bowen, and Sturck-Marcell 1987). The existence of Delta Scuti stars (early F type variables about a magnitude above the main sequence) supported this extrapolation to the required temperature range. On the main sequence, the detection of variability in an F0 V star, 9 Aur A (Krisciunas et al, 1993) marks the high temperature wing of the proposed instability (and mass losing) strip.

In a preliminary study, Dearborn Schramm and Hobbs (1992) applied the mass loss hypothesis to Pop II models and showed that subgiant stars with low lithium abundance's would be expected to be seen in some stars. While the mass loss rates necessary to produce the lithium dip are far too small for a direct observational signature, there is some hope to detect related phenomena. Mass loss in the presence of even a small magnetic field produces rotational breaking. If a careful comparison of the of rotation rates in F type stars showed a systematic lowering of rotation in those stars with a pronounced lithium deficiency, it would strongly suggest the occurrence of mass loss. Balachandran (1990) saw some evidence that the rotation rates in lower temperature, lithium deficient stars were preferentially lower, but additional investigation (Balachandran 1993) has found little correlation between rotation rate and lithium abundance. Such investigations might be extended to higher temperatures.

In an attempt to test the generalized mass loss hypothesis, Swenson and Faulkner (1992) examined the luminosity function of open cluster stars. They show that the luminosity function provides a powerful tool for testing the existence of mass loss. While available data can be used to exclude mass loss as the origin of the gradual decline observed in later G type stars, the sparcity of open clusters inhibits testing the small amount of mass loss necessary for lithium depletion observed in F type stars.

Globular clusters are much richer objects, and the development of CCD photometry has permitted the extension of luminosity functions down onto the main sequence. Additionally, the temperature of the turn-off in metal poor ([Fe/H] = -2) clusters is in the range of interest. With this, the work of Swenson and Faulkner (1992) suggests that globular cluster observations could provide a definitive test of the mass loss hypothesis.

Here we begin a more specific study examining the effect of mass loss localized in a narrow temperature range (as motivated by the Pop I lithium dip) on the isochrones and luminosity function of pop II models. An immediate consequence of this hypothesis is that stars evolving into the mass losing region "turn" at an earlier stage of evolution. The resulting isochrones have a lower luminosity turn-off, causing clusters to appear "older". Because the temperature range of the lithium dip is narrow, the mechanism that produces it will effect bluer, low metalicity globular clusters, more than those with higher metalicity.

As a result of this attempt to understand the primordial lithium abundance, a mechanism results that affects the ages assigned to globular clusters (see also Wilson et al). These ages are an important constraint on cosmological models, and any plausibly supported mechanism that impacts them must be tested. By causing stars to "turn" earlier in their evolution, an excess of "subgiant"-like objects will occur in clusters whose turn-off is near the mass loss region. While such an excess has been observed in the globular cluster M30 (Bolte 1993), it is small. Following Swenson and Faulkner (1992), the luminosity function may be used to suggest mass loss in the F star region, and to limit its magnitude.

Mass Loss Assumptions and Constraints:

As a star approaches the main sequence, lithium, a fragile nucleus, is destroyed throughout the interior. For a 0.8 M_O Pop II model, this results in a lithium abundance profile in which the abundance drops rapidly, at a depth of about 0.05 M_O below the original surface. Because stars in the temperature range of interest have small convection zones, the surface lithium abundance tracks this profile as mass is removed. In consequence, only about 0.05 M_O must be ejected to produce a lithium depletion of an order of magnitude or more, as observed. Because the lithium profile is established early in the main sequence lifetime, the lithium depletion is nearly independent of the time history of the mass loss, and is primarily dependent on how much mass is lost.

Boron and Beryllium are hardier nuclei requiring slightly higher temperatures to destroy. When lithium has decreased to 20% of its original value, the beryllium abundance has only begun to show some effect, and when the lithium abundance has decreased to 3%, the beryllium abundance has dropped to 60%. Depletion of the beryllium requires nearly 0.1 M_O of mass to be lost. As we discuss below, this much mass loss would strongly affect the luminosity function of a cluster of stars. Boron is hardier still.

The lifetime of Pop II stars with temperatures near 6600K is of order 10 Gyr, so that a steady rate of only $5X10^{-12}$ M_o/yr will have a significant impact on the lithium abundance. As the F star dip defines a narrow temperature range, evolving stars move through it and spend only part of their lifetimes losing mass. As a result, peak mass loss rates of order 10^{-11} M_o/yr are required. This rate is lower than that required in a Pop I star, because the lifetime of a metal poor Pop II star at this temperature is nearly 3 times longer.

The halo appears to be too old (>7Gyr) to have stars defining the high temperature wing of the lithium dip. Therefore, we must use the lithium distribution observed in the Pop I stars to define a temperature dependence for the mass loss rate and apply this to Pop II models. The shape of the lithium dip in Pop I and Pop II stars will differ, even if the same temperature dependence is assumed for the mass loss. Figure 1 shows the evolutionary track of a Pop I (M=1.50 M_o, X=0.70, Z=0.02) model, and a Pop II model (M=0.85 M_o, X=.76, Z=0.0002). While on the main sequence, the temperature of the Pop I model decreases. The relatively small change in the temperature of these objects while on the early main sequence results in a lithium dip that is closely related to the mass loss dependence assumed, though the region of lithium depletion will be shifted to slightly lower temperatures. The temperatures of Pop II models increase considerably over the main sequence lifetime, resulting in a lithium dip that extends to higher temperatures than those observed in Pop I stars.

For the purpose of this paper, we will assume the mass loss has a gaussian dependence on temperature, with a peak loss rate of 10^{-11} M_o/yr. Because Pop I stars evolve to lower temperatures, a central temperature below 6500 K is unlikely to fit the observed location of the lithium dip, and we will consider temperatures of 6500K and 6600K. As discussed in the introduction, evolutionary tracks of stars that "turn" to the red in the mass losing region will do so at a slightly lower luminosity and appear older. The age range affected is very dependent on the temperature of the mass loss region. In figure 2, the turn-off temperature for a set of unperturbed models is plotted versus age. A peak mass loss centered near 6600 K will affect the apparent age of clusters near 11 Gyr old. Reducing the central temperature of the mass loss to 6500 K results in clusters between 12 and 13 Gyr looking 2 to 3 Gyr older.

The Models:

Models were calculated at least every 0.05 $M_\odot$ between 0.6 and 1.0 solar masses, and when necessary every 0.02 $M_\odot$. The initial hydrogen mass fraction was set to 0.76, consistent with the most recent determinations of the primordial helium value (Skillman, 1993), and the metalicity set to 0.01 solar, representative of metal poor globular clusters. The new OPAL opacities (Iglesias and Rogers 1990, 1992) were used at temperatures above 6000K, and Los Alamos opacities including the contribution of molecules were used for lower temperature regions (Heubner et al. 1977).

All models were begun as pre-main sequence objects on the Hayashi track, and evolved to helium flash, and a mixing length was selected to fit the color magnitude data for M30 (Bolte 1993) The code that we used is derived from that of Eggleton (1967, 1968), and is described in Dearborn, Greist and Raffelt (1991). As a benchmark, the code produces a solar model with 7.9 SNU, and matches the p-mode spectrum comparably to the calculations of Bachall and Ulrich (1988).

The nucleosynthesis network used in this calculation included the reactions to track deuterium, ^3He, ^4He, ^6Li, ^7Li, ^9Be, and all stable CNO isotopes. In the mass range that we examined here, pre-main sequence deuterium was fully converted to ^3He. At masses below 0.65 $M_\odot$, pre-main sequence burning completely destroyed the fragile ^6Li and reduced the surface abundance of ^7Li, though not as much as in Pop I models (Proffitt and Michaud, 1989). The ^9Be showed no pre-main sequence evolution. This pre-main sequence depletion is probably substantially responsible for the lithium decrease seen at temperatures below the Spite plateau.

The Results:

We begin by considering an individual case where the mass loss has a peak rate of 10^{-11} $M_\odot$/yr centered at 6500 K,. The FWHM of the gaussian was 200 K. This resulted in a lithium dip that matched the low temperature wing of the Pop I dip, though, for reasons explained above, the high temperature wing was broader. The resulting lithium abundance's for ages between 10 and 13 Gyr are plotted against temperature in figure 3. The limits for the lithium depleted objects observed by Hobbs et al. (1991) and Thorburn (1992) are shown as open triangles Main sequence stars lie along the top of the plot with their original lithium abundances shown as filled triangles (Thorburn 1993). For the assumed values of mass loss, stars in the age range 10 Gyr to 12 Gyr, have turn-offs in the lithium dip region, and subgiant show lithium depletion.

For ages less than 10 Gyr, the subgiant stars originate on the high temperature side of the lithium dip. Their passage through the mass loss region is too quick to produce a significant lithium depletion. Increasing the mass loss rate broadens the age range some, but as we will discuss later, rapidly leads to unacceptable modifications of the luminosity function. Between 10 Gyr and 12 Gyr, stars from the base of the lithium dip are subgiants, and show the maximum amount of lithium depletion for the mass loss that occurs. After 12 Gyr, the low temperature wing of the lithium dip begins to evolve, and again the lithium depletion is negligible.

The stars observed by Thorburn (1992) have temperatures lower than those defined by the Pop I lithium dip. Regardless of mechanism, if the low lithium stars are related to the F star dip seen in Pop I stars (either by mass loss or by diffusion), they must be subgiants. As the evolution rate increases considerably for subgiants, relatively few of the stars observed at any particular temperature are expected to be in this phase. It is simple to calculate the expected ratio of sub-dwarf to subgiant stars. In the temperature range 5600 K to 6300 K, The mass range contributing to this ratio is small (0.65 M_o to 0.90 M_o, or less depending on the age), so the result is insensitive to the assumed initial mass function. However, predicting this ratio for the halo is complicated by the possible age range. For a population with a range of ages and compositions, the subgiant population can evolve from stars both above and below the F star dip. Observations of halo subgiants by Pilachowski (1993) shows many of them to have unperturbed lithium.

As the presence of a mass losing region near the turn-off effects the evolutionary track of a star, the ratio of sub-dwarfs, main sequence stars to subgiant stars is effected. For mass loss rates centered at 6500K and 6600K, the ratio ranges from 60 to 80 sub-dwarf stars for every subgiant at an age of 8 Gyr. By 10 Gyr, the ratio drops to between 25 and 30, and by 15 Gyr the ratio is 10 to 13. An extensive survey by Thorburn (1993) finds 4 lithium depleted stars in a sample of 70 stars. While this ratio is consistent with the mass loss hypothesis, and an old halo, it neglects the fact that subgiants are 1 to 2 magnitudes brighter than dwarfs (depending on temperature) and, in a magnitude limited survey, are observed in a greater volume. This correction require younger ages for the halo, near 10 Gyr. If mass loss in the temperature region of Pop I, F stars is causing the lithium depletion's observed by Thorburn, the ratio of normal to depleted stars will be a sensitive indicator of the age range in the halo, once the volume correction is made.

Before turning to an examination of the effect that mass loss has on apparent cluster ages and luminosity functions, we wish consider the sensitivity of our results to the assumed central temperature of the mass loss region. The observed lithium distribution in Pop I stars constrains the temperature of the peak mass loss rate to a narrow range around 6500K or 6600K. Because more massive stars have a shorter lifetime, increasing the central temperature to 6600 degrees requires an approximately 20% increase in the peak mass loss rate to provide the same levels of lithium depletion, and, in this case, the maximum lithium depletion occurs between 9 and 11 Gyr. Reducing the central temperature to 6400 K requires reducing the peak mass loss rate to obtain the lithium depletion without losing too much mass and concentrating all of the stars in the mass losing region at the low temperature edge. For this temperature, the peak lithium depletion occurs for stars with ages between 12 and 15 Gyr.

The ages determined for globular clusters are fundamentally dependent on the ability to identify the luminosity of the turn-off in an HR diagram. CCD photometry has improved the definition of the this luminosity and reduced the associated uncertainty in globular cluster ages. In figure 4, the luminosity of the turn-off is plotted against age for a cluster without mass loss and one with the standard mass loss assumptions described above. At 12 Gyr, subgiants originate from stars that have lost 0.05 M_o, and show lithium depletion's exceeding an order of magnitude. The turn-off luminosity of the 12 Gyr isochrone is that of a 15 Gyr cluster without mass loss. This is shown more conventionally in the isochrone plots in figure 5. The 12 Gyr mass losing isochrone is slightly bluer than the 15 Gyr standard isochrone because it is younger, and stars with masses below 0.75 M_o have not been affected by the mass loss. A small reduction in the assumed mixing length will make these curves coincident.

If the order of magnitude lithium depletion's observed by Thorburn result from mass loss, they require approximately 0.05 M_o of mass be lost over the main sequence lifetime, and results in a cluster that appears as much as 25% older. A mass loss rate that removes only 0.03 $M_\odot$, reduces the surface lithium by a factor of 3 instead of 10 and results in a cluster that appears approximately 17% older. We also evolved a set of models in which some stars lost 0.1 $M_\odot$. Stars from the base of the lithium dip retained virtually no lithium, and appeared 50% older than they actually were. This much mass loss caused all of the stars in the mass losing region to concentrate at the low temperature edge of the region and significantly impacted the luminosity function. For the models calculated here, age changes of over 3 Gyr appeared to impact the luminosity function dramatically. A comparison to actual data will be made in a later paper to set firm limits on the possible age difference.

The same CCD photometry that is improving the color-magnitude diagrams for globular clusters is permitting the luminosity function to be determined down onto the main sequence. Standard, mass conserving calculations of stellar evolution fit the general characteristics of the observed curves (Bolte 1993, VandenBerg, 1992), but there are some differences. First, a small but significant excess is seen at luminosity's above the turn-off. Second, the drop to the giant branch is not as large in the observed clusters as it is in the calculations.

In figure 6, we assume a Salpeter mass function to plot the luminosity function (dLog(N)/dLog(L) vs Log(L)) of our models. The luminosity of a 15 Gyr cluster with no mass loss is shown as a solid line. Luminosity functions for clusters losing 0.03 (dashed line) to 0.05 (dotted line) solar masses are given for comparison. The ages of the mass losing clusters were selected so that the isochrones would have the same turn-off luminosity as the mass conserving cluster. The mass losing models are seen to have in a small excursion from the unperturbed curve, and an increase in the level of the giant branch. Mass loss of 0.1 $M_\odot$ (not shown) produces a large bump in the luminosity function as all of the stars between 0.8 and 0.9 $M_\odot$ congregate at the lower mass edge of the temperature range where mass loss is assumed to occur.

Conclusions:

The hypothesis that a small amount of mass loss is responsible for the lithium depletion seen in Pop I, F type stars has been extended to calculations of metal poor Pop II models of the same temperature.

Such mass loss affects the isochrones of models that would cause a cluster to appear older than it genuinely was. Small amounts of mass loss should improve the fit of the calculated luminosity function with actual data, but large amounts of mass loss can probably be excluded. It will require additional work to compare our models to globular cluster data, but it is exciting that globular clusters of 12 Gyr can appear as old as 15 Gyr (if the mass loss hypothesis is correct).

Three lithium depleted stars are known in the temperature range 5900 K to 6200 K, (Hobbs et. al., 1991; Thorburn , 1992). Subgiant stars in this temperature range are 1.5 to 2 magnitudes brighter than their main sequence counterparts, and in an apparent magnitude limited sample, they are detected to a distance 2.0 to 2.5 times further out (for an age of 12 Gyr). This must be considered in comparing the expected number of lithium depleted dwarfs in a particular temperature range.

This also leads to a major concern for the hypothesis, requiring that the lithium deficient stars observed by Thorburn are evolved. In this hypothesis, the low temperature lithium deficient stars must all be subgiant stars. Thorburn considered this problem, and, using a luminosity for subgiants that is consistent with our models, found that the proper motions of her lithium deficient stars corresponded to velocities of 725 and 910 Km/s These are much higher than the observed radial velocities of halo stars, and would require an extended dark halo to be bound. If astrometry or surface gravity indicators prove these stars to be dwarfs, it will be necessary to abandon the hypothesis that they are related to the Pop I, F star dip.

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Figure Captions:

Figure 1. Evolutionary tracks are shown for models that cross the temperature region of the lithium dip. While on the main sequence Pop I models (1.50 M_o X=0.70, z=0.02) decrease in temperature. The Pop II (0.8 M_o X=0.76 Z=0.0002) model increases significantly in temperature and luminosity over its main sequence lifetime, then decreases as a subgiant.

Figure 2. The temperature of the turn-off is plotted versus age for the non-mass losing Pop II models (X=0.76 Z=0.0002). Mass loss in a narrow temperature range will effect the apparent age of clusters whose turn-off is near that age, making them look older.

Figure 3. The predicted lithium abundance for various ages is plotted against temperature for a mass loss rate of 10^{-11} M_o/yr centered at 6500K. Between 10 and 12 Gyr, the subgiants originate from lithium depleted stars. Observed Lithium abundance's (Hobbs et al, 1991; Thorburn, 1992; and Thorburn, 1993) are included for comparison.

Figure 4. Mass loss in a narrow temperature region lowers the luminosity of a clusters turn-off, making it look older. The effect of a mass loss rate of 10^{-11} M_o/yr centered at 6500 K is compared to non-mass losing models. The 12 Gyr isochrone of a mass losing model has the same luminosity as a 15 Gyr standard model.

Figure 5. 12 and 15 Gyr isochrones (dotted lines) of models without mass loss are shown around the 12 Gyr isochrone (solid line) formed from models with a mass loss rate of 10-11 M_o/yr centered at 6500 K. The "mass loss" isochrone has the same luminosity as the 15 Gyr isochrone, but is bluer. A small reduction in the assumed mixing length would make these isochrones nearly identical.

Figure 6. The calculated luminosity function of a mass conserving cluster at an age of 15 Gyr, is shown as a solid line. Luminosity functions predicted for models loseing 0.03 M_o (dotted line) and 0.05 Mo (dashed line) are shown for ages that have the same turn-off luminosity. Mass loss in a narrow temperature region enhances the number of stars at the lower edge of that temperature range, resulting in a "bump" on the luminosity function.

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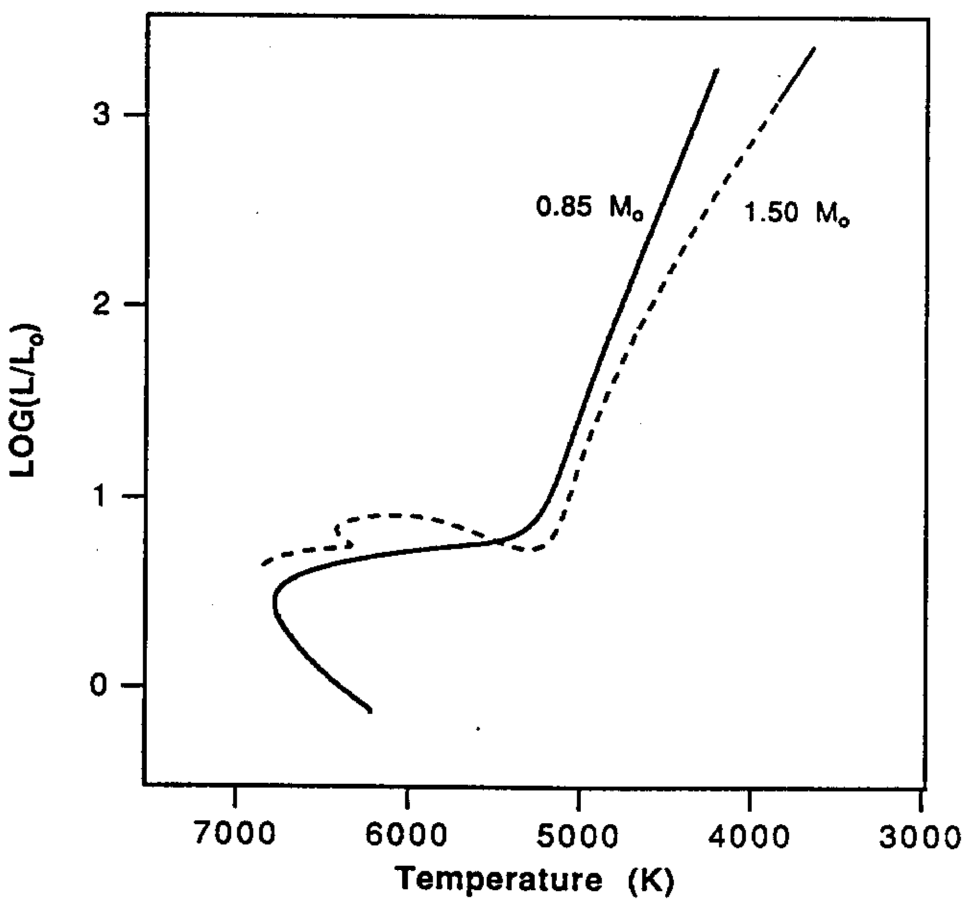
Figure 1



LOG(L/L$_o$)
3
2
1
0
0.85 M$_o$
1.50 M$_o$
7000
6000
5000
4000
3000
Temperature (K)

Figure 2

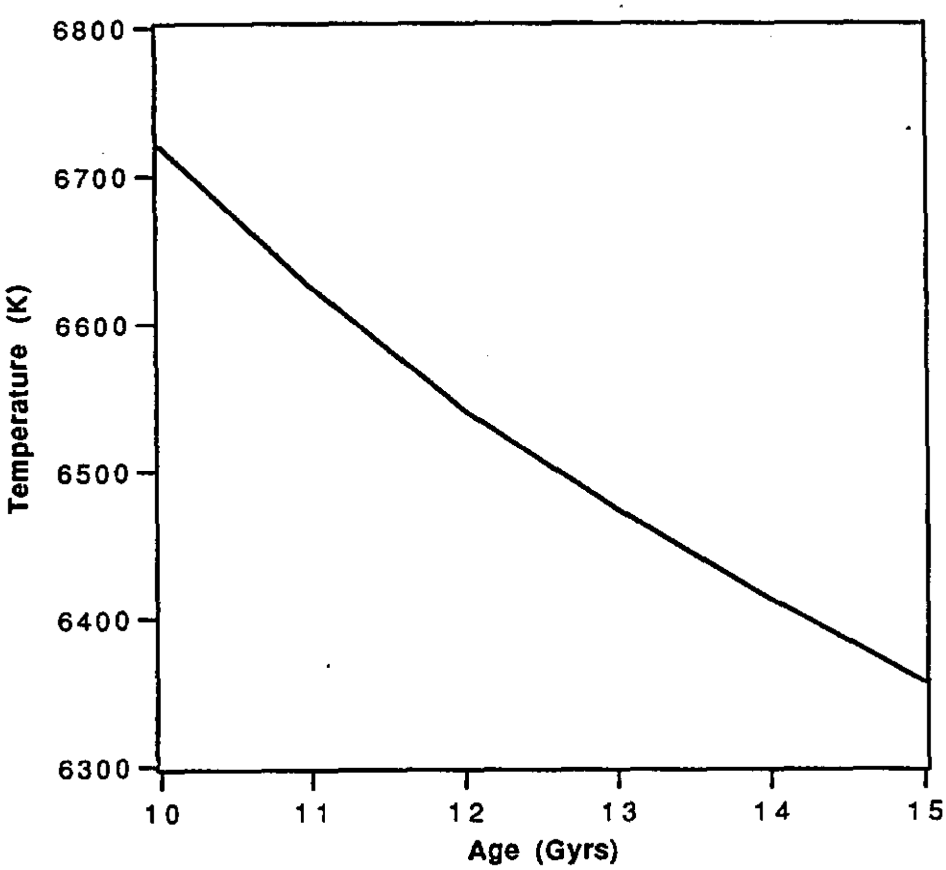
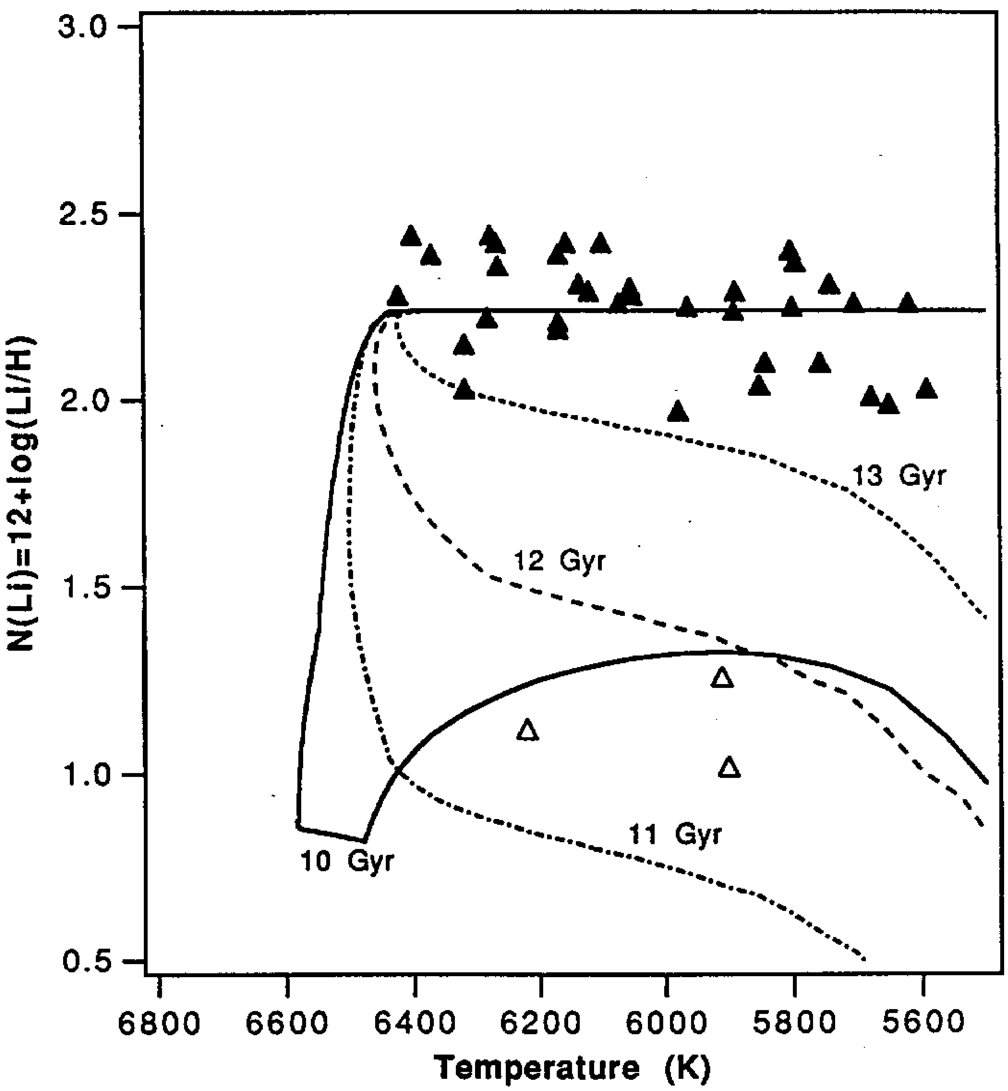

6800
6700
6600
6500
6400
6300
Temperature (K)
10
11
12
13
14
15
Age (Gyrs)

Figure 3



3.0
2.5
2.0
1.5
1.0
0.5
N(Li)=12+log(Li/H)
13 Gyr
12 Gyr
11 Gyr
10 Gyr
6800
6600
6400
6200
6000
5800
5600
Temperature (K)

Figure 4

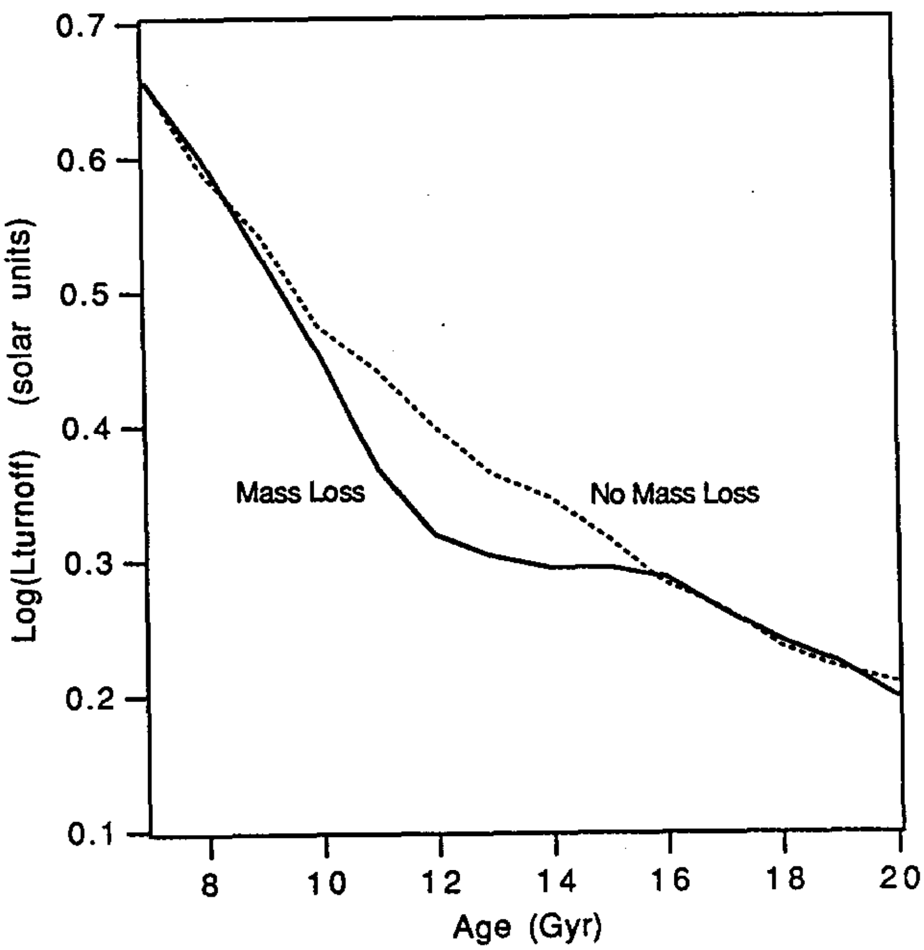
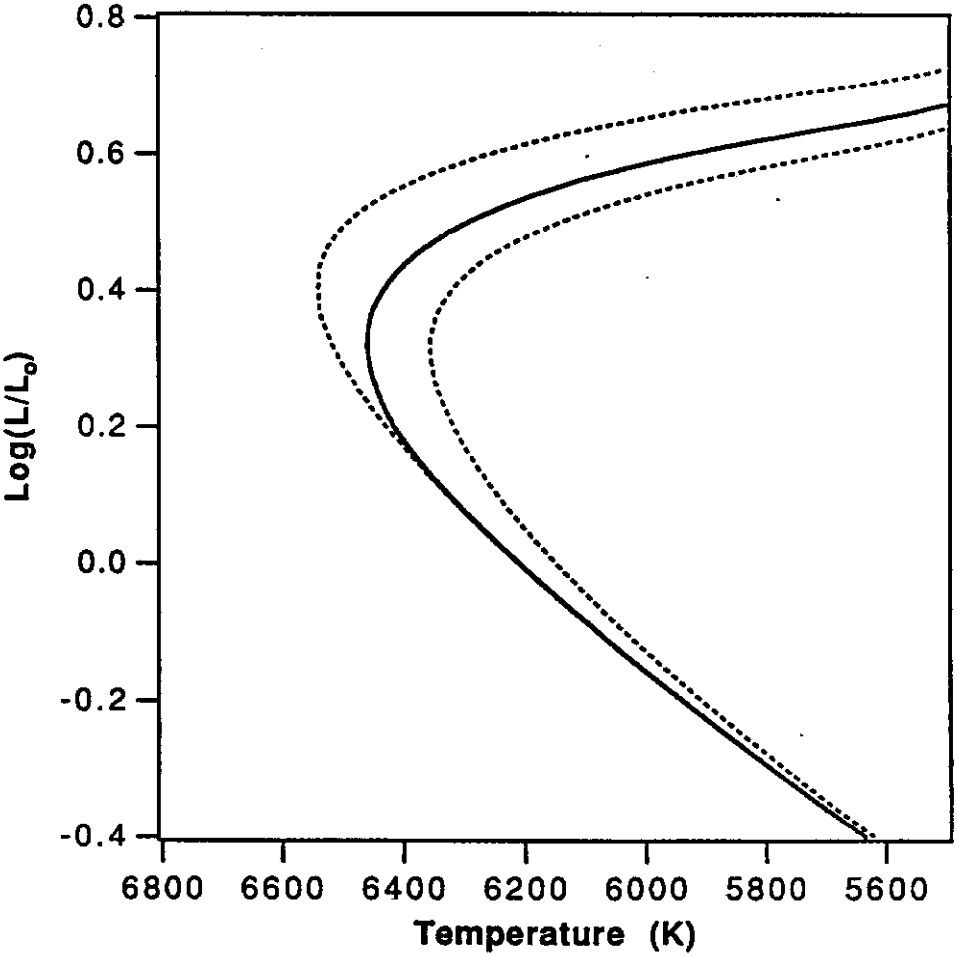
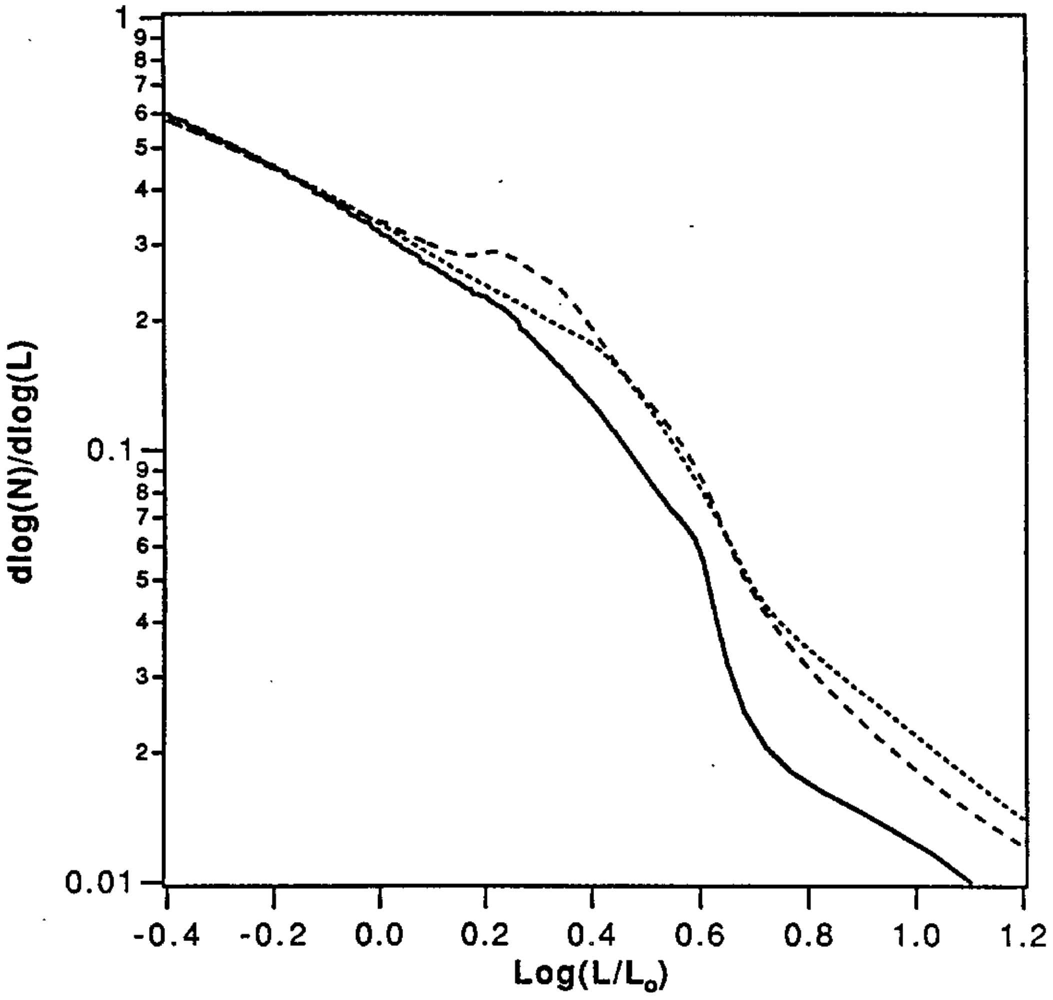

0.7
0.6
0.5
0.4
0.3
0.2
0.1
Log(Lturnoff) (solar units)
Mass Loss
No Mass Loss
8
10
12
14
16
18
20
Age (Gyr)

Figure 5



0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Log(L/L$_o$)
6800
6600
6400
6200
6000
5800
5600
Temperature (K)

Figure 6



1
9
8
7
6
5
4
3
2
0.1
9
8
7
6
5
4
3
2
0.01
dlog(N)/dlog(L)
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Log(L/L$_o$)