Mass Loss on the Main Sequence

The hypothesis is advanced that stars on the main sequence in the pulsation instability strip lose mass at rates in excess of 10^{-9} $M_{\odot}$/yr and thus evolve down the main sequence. The mass loss rate is expected to diminish steeply when the convective surface layers become substantial. As a result, a significant fraction of early G stars in populations more than 10^{9} yrs old were A stars when they commenced core hydrogen burning. Among other consequences, such mass loss will cause some clusters to appear much older than they are, suggesting a resolution to the apparent conflict between current estimates for the ages of globular clusters and other recent determinations of the age of the galaxy and the universe. This hypothesis leads to an explanation for blue stragglers, has implications for the chemical evolution of our galaxy, and alters the mass function of stars on the main sequence. We also suggest that the sun was such a star, arriving on the main sequence with $M = 2$ $M_{\odot}$ and losing the excess over $\sim 10^{9}$ yrs.

Key Words: *stellar evolution, mass loss*

Mass loss from stars to the interstellar medium is ubiquitous. In some cases the mass loss can be very large and have major effects on the stars' evolution. However, for stars with $M < 15$ $M_{\odot}$ which are on the main sequence—in other words, for most of the lifetime of most stars—the typical mass loss rate appears to be very small. (For the present solar wind, $\dot{M} \sim 10^{-14}$ $M_{\odot}$/yr.) It is universally assumed that mass loss for such stars can therefore be neglected in evolutionary calculations.

We suggest that in fact significant mass loss does occur from stars of $\sim$1–2.5 $M_{\odot}$ during at least the early part of their lives on the main sequence. As we shall argue below, plausible mass loss

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rates are in the range 10^{-9} to 10^{-8} $M_{\odot}$/yr; for stars below about 3 $M_{\odot}$, this is sufficient to remove a substantial fraction of the star's mass before the star evolves off the main sequence.

PLAUSIBILITY AND MECHANISMS FOR THE PROPOSED MASS LOSS

Observational constraints (discussed below), together with the substantial mechanical energy flux requirements of the winds, are consistent with the assumption that the mass loss occurs in the region where the "Cepheid instability strip" intersects the main sequence, from early A to mid F spectral types. Main sequence stars in this range include the obviously pulsating δ Scuti stars. Also the average rotation velocities of A and early F stars are several hundred km/s, i.e., a substantial fraction of the critical velocity at which rotation alone can drive destructive rates of mass loss. We propose that the main sequence mass loss is driven by a combination of pulsation and rapid rotation; the pulsation provides the necessary mechanical energy flux, and the rapid rotation facilitates mass loss. While our experience with atmospheric models for pulsating stars suggests that pulsation will be effective in driving mass loss under these conditions,[1,2] the details of the mechanism—oscillation modes, effects of rotation, role of magnetic fields—will require considerable theoretical investigation. Here, we present simple arguments justifying our assumed mass loss rates, based on the observed properties of pre-main sequence and young main sequence stars.

Energy Requirements

To drive a wind with a mass loss rate $\dot{M}$ from a star with an escape velocity v_e requires a minimum energy flux into the wind of

$$\phi_{\min}(\dot{M}) = (GM_*\dot{M}/R_*)/4\pi R_*^2 = (\dot{M}/4\pi R_*^2)v_e^2/2 \qquad (1)$$

where v_e is the escape velocity at the stellar radius R_*. This minimum energy flux provides the gravitational potential energy that is needed to lift the material to $r = \infty$; to give $v_\infty > 0$ and to allow for radiative losses will require more energy. However, typical terminal wind velocities are $<\sim v_e$, increasing the necessary energy flux by only a factor $<\sim 2$; and radiative losses can be constrained by direct observation.

Assuming that the energy which drives the wind comes directly or indirectly from the stellar luminous energy flux, $L_{\rm tot} = L_{\rm rad} + L_{\dot{M}} \geq L_{\dot{M}}$. Thus the maximum mass loss rate which can be driven—independent of the mechanism—is given by Eq. (1) with $\phi_L = L_*/4\pi R_*^2 = \phi_{\rm min}(\dot{M})$. This translates to $\dot{M} \leq 3 \times 10^{-8}\,(LR/M)$ $M_\odot$/yr, where L, R, and M are the stellar luminosity, radius, and mass in units of the solar $L_\odot$, $R_\odot$, and $M_\odot$. For a 2 $M_\odot$ zero-age main sequence star, $L \sim 15$ and $R \sim 1.5$, giving possible mass loss rates up to $\sim 3 \times 10^{-7}$ $M_\odot$/year—more than 50 times larger than the mass loss rates which we propose actually occur. Young F and G main sequence stars have observed (coronal) x-ray fluxes $\sim 10^{-2}$ to 10^{-3} L_*. Assuming $L_X < \sim 0.1\ L_{\rm corona} \leq 4\pi r^2 \phi_{\rm mech}$, the observed fluxes may be interpreted as implying mechanical energy fluxes that are 1% to 10% of the luminous flux, confirming that the transport of this fraction of the stellar luminosity into the atmosphere in the form of mechanical energy does occur along the relevant portion of the main sequence.

The fact that the late A and early F stars show significantly smaller L_X/L_* than the young G stars may then be interpreted in two ways: (a) they have much smaller mechanical energy fluxes $\phi_{\rm mech}$; or (b) $\phi_{\rm mech}$ is being channeled into mass loss rather than heating and radiative losses for these stars. While the first alternative has been commonly assumed, the second alternative is more likely to apply for the A and F stars which fall in the instability strip. Large mechanical energy fluxes—~ 0.1–$1\ \phi_L$—are expected for stars in the instability strip. Nonlinear models of pulsating main sequence late A stars show an excess of driving over damping for reasonable amplitudes; Stellingwerf[3] suggested that damping in the atmosphere and wind might be required to avert a "main sequence catastrophe" for these stars. This is also consistent with the observation that at least some δ Scuti stars have shock waves in their lower atmospheres[4]; derived mechanical energy fluxes are $\sim\phi_L$. It is now commonly supposed (following Dziembowski[5]) that the reason that the mid A to late F stars on the main sequence are not all pulsating with enormous amplitude is that the energy is partitioned among a number of modes, radial and nonradial. This does not necessarily reduce by much the total energy flux which will propagate into the atmosphere, however, and the simultaneous presence of a number of modes may actually increase the efficiency with which the mechanical energy is channeled into mass loss.

The mass loss rates needed to alter the evolution of stars with initial masses ~2 $M_\odot$ can be provided by the conversion of a few percent of the stellar luminous energy flux into mass loss. That the conversion of at least a few percent of the luminous flux into mechanical energy occurs is proven by the observed x-ray fluxes of young F and G stars. Pulsation is expected to give rise to mechanical energy fluxes in the A and F stars which are quite large enough, and pulsation also makes the efficient conversion of this energy flux into the gravitational potential and kinetic energy of mass loss more likely.

On the Feasibility of Observing the Proposed Mass Loss

There are very few A stars for which winds with $\dot{M} > 10^{-9}$ $M_\odot$/yr have been detected, and those which have such winds have typically been classified as pre-main sequence objects. If most stars which reach the main sequence in this mass range typically lose up to one solar mass, should not this mass loss have been detected? There are three reasons why these winds would be difficult to detect: (1) the expected wind temperature is ~10^6 K, where x-ray fluxes are moderate but also line signatures in the accessible visible and UV spectral regions are scarce; (2) the expected wind velocity is high; and (3) the rapid mass loss phase is short-lived, and the stars with the largest mass loss rates will be found embedded in young clusters with HIT regions and other nebulosity to complicate the observations.

The commonly used methods for detecting mass loss depend on (a) the optical depth, i.e., the column density, of the wind, $\propto \dot{M}/v$; or (b) the emission measure, $\int N_e^2 dV \propto (\dot{M}/v)^2$. Thus for a given method of detection the minimum mass loss rate detectable is proportinal to the velocity of the wind. The wind velocity is quite generally within a factor of 2 of the stellar escape velocity. Warm winds from giants with flow velocities ~25–50 km/s are observable by current techniques for mass loss rates >~10^{-9} $M_\odot$/yr. For the main sequence stars, expected outflow velocities are 10 times higher, implying that only mass loss rates in excess of 10^{-8} $M_\odot$/yr are likely to have been noticed. For the main sequence mass loss we do not expect very dusty winds, although the IRAS detection of infrared excesses indicating disks around Vega, β Pic and other early A stars[7,8] suggest that this possibility should not be dismissed completely.

The cases where we are most likely to detect the mass loss are cases where the mass flux is high, and the resulting wind temperature is low; in this case, the atmospheric density structure will be sufficiently altered to give us the impression that we are dealing with an abnormal or pre-main sequence object. The Herbig Ae stars, a number of which show P Cygni profiles indicative of mass loss,[9] have been classified as pre-main sequence stars on the basis of their apparent location above/to the right of the main sequence. However, the values $v_{\rm wind} \sim 370$–500 km/s, $M = 2.5$–$3.0\ M_\odot$, $R = 2.5$–$3.3\ R_\odot$, $\log L/L_\odot = 1.8$–2.0 quoted by Praderie *et al.*[10] for AB Aur are normal main sequence values. We suspect that some if not all of the Herbig Ae stars are young main sequence stars currently undergoing heavy mass loss.

Observations of High Mass Loss Rates in Related Objects

Although most stars, like the sun, have mass loss rates considerably less than the maximum possible rate, there are some stars which appear to have mass loss rates close to this limit. Radio observations of a number of pre-main sequence stars[11] give wind energy fluxes comparable to the luminous energy flux on the assumption of isotropic flow. While the total mass loss rate would be lower if the flow is confined to a small solid angle, it would still be necessary for the driving mechanism over at least that portion of the star to be extremely efficient. Observations of T Tauri star "chromospheres" and winds show that the winds are cool and relatively dense,[12] consistent with large mass fluxes from these $\sim 1\ M_\odot$ objects.[13] Edwards and Snell[14] also concluded on the basis of momentum conservation in regions where winds from 1–3 $M_\odot$ pre-main sequence stars are colliding with nearby clouds of material that typical mass loss rates are $> \sim 10^{-7}\ M_\odot$/yr.

The proposed mass loss may be considered simply as an extension to the main sequence of the observed pre-main sequence winds. Hartmann[15] derives a model for T Tau with $\dot{M} \sim 3 \times 10^{-8}$ $M_\odot$/yr by scaling a 1 $M_\odot$ Alfvén-wave model, using $\dot{M} \sim R^2$; we can reverse the process to find possible main sequence mass loss rates $<\sim 10^{-8}$ $M_\odot$/yr from observed pre-main sequence rates $<\sim 10^{-7}$ $M_\odot$/yr. While there is still considerable debate about the nature of the driving mechanism for the pre-main sequence winds, there is no compelling reason to assume that it stops being effective as soon as the stellar core commences hydrogen burning.

Upper and Lower Limits on Masses of Stars Expected to Have Substantial Main Sequence Mass Loss

According to our hypothesis, the maximum mass of stars undergoing main-sequence mass loss due to pulsation is the mass, M_1, of a star that arrives on the main sequence at the blue edge of the instability strip. This in turn depends on Z (which affects the mass–luminosity relation) and on Y (which affects both the location of the blue edge in the HR diagram and the mass–luminosity relation).[16] The mass loss process is expected to end at M_2 when (a) the pulsation is no longer able to drive mass loss efficiently (due to decreasing amplitude and/or a change in the mode(s) at the red edge of the instability strip) and/or (b) strong, dynamo-generated magnetic fields develop. Magnetic fields will both provide stronger rotational braking and directly inhibit mass loss by forming closed loops. The observed red edge of the δ Scuti strip is ~F2, although nonradial pulsation persists down to and including the sun. Based on observational constraints to be discusssed below, we suspect that the mass loss rate decreases by perhaps an order of magnitude as the star moves out of the classical instability strip, but persists at a rate sufficient to keep the star moving down the main sequence until strong magnetic fields develop and magnetic braking occurs. The development of strong localized magnetic fields is believed to be a result of the presence of a sufficiently massive convective envelope; the mass of the convective envelope is a very steep function of stellar effective temperature in theoretical models.[17]

Strong, dynamo-generated magnetic fields are often presumed to be present in stars on the main sequence up to ~A4 (see, e.g., Rosner, Golub and Vaiana[18]), to account for the presence of coronae on the assumption that Alfvén waves provide the necessary mechanical energy flux. However, for the A and F stars, pulsations are equally capable of producing coronae, without the necessity of postulating strong magnetic fields. Theoretically, magnetic dynamos are not expected to be efficient for spectral types earlier than ~F5 or so; observationally, there is no direct evidence for dynamo-generated magnetic fields in stars much earlier than spectral type G.[19]

The mass M_2 at which the surface convection zone reaches its critical value for the onset of magnetic activity depends on the composition of the star; for a reasonable range of helium abundances, M_2 is most sensitive to the metal abundance, Z. The solar convection zone contains ~2% of $M_\odot$[20]; we shall next argue that the assumption that M_2 is the mass that gives $M_{cz} \sim 0.01$–$0.02\ M_*$ leads to a picture that is consistent with a range of observational constraints.

CONSEQUENCES OF MAIN SEQUENCE MASS LOSS

The Sun

Evolutionary models for the sun including mass loss from an initial mass ~2 $M_\odot$ have been calculated for several prescriptions for the mass loss rate.[20] For models with $L = L_\odot$, $R = R_\odot$ and $M = M_\odot$ at an age of 4.6×10^9 yrs the internal temperature and density distributions are very close to those of standard models. To match the present solar luminosity at the age of the solar system with a model including an early massive and high luminosity phase requires a lower initial He abundance and produces a current model with a higher central He concentration. Mass-losing models have in common with standard models a predicted overproduction of neutrinos. It is noteworthy that as these models evolve down the main sequence from 2 $M_\odot$ to 1 $M_\odot$ they follow very closely the empirical main sequence mass–luminosity relation (e.g., from Habets and Heintze[21]).

In solar models with early mass loss, the present surface material was initially inside the star and was subjected to $T > 10^7$ K for a time that depends on the assumed mass loss law (a few times 10^8 yrs for the cases we have considered). This would have eliminated the primordial Li and Be, and would have erased all memory of the initial He^3 in the present surface layer. Guzik *et al.* have proposed that coronal and flare spallation following the epoch of rapid mass loss, together with processing at 2×10^6 K at the base of the convection zone, has produced the currently observed solar abundances of Li^6, Li^7 and Be^7; they discuss the cosmological implications of this altered interpretation of light element abundances. The mass losing models have CN processed material extending to $\sim 0.5\ M_\odot$, compared with $<\sim 0.2\ M_\odot$ in standard models; this provides a possible explanation for the presence of CN processed material on the surfaces of subgiants and giants well before standard theory predicts that such material should be dredged up.

The Early Solar System

If the early Sun was indeed a more massive star there would have been dramatic consequences for the early solar system because of the Sun's stronger gravity, greater luminosity, and higher effective temperature and because of the strong solar wind. Calculations have been carried out and will be reported elsewhere[22] for a number of effects. Although the results often differ strikingly from those predicted by conventional stellar evolution theory, none appears to be inconsistent with observations. In fact the effects seem likely to help resolve various persistent problems related to the solar system, including the tidal spin-down of Venus, the intense early bombardment of the Moon, the warm climate of the early Earth and Mars, and the exceptionally high iron content of Mercury. We interpret this as giving indirect support to the main-sequence mass-loss hypothesis as well as new insight into solar system evolution.

The effects that have been studied provide useful and fairly tight constraints on the parameters characterizing the zero-age main-sequence Sun. Satisfactory results are obtained in all cases from the same set of initial values: $M \simeq 2.0\ M_\odot$, $L = 14$–$15\ L_0$, $T_{\mathrm{eff}} =$ 9100–9200 K, $\dot{M} \sim 5 \times 10^{-9}\ M_\odot$/yr, and a time constant for the mass loss process of $\sim 2 \times 10^8$ yrs. These values are entirely consistent with those found from quite independent considerations in this Comment.

Blue Stragglers

After an elapsed time $\sim M_1/M_0$, most of the stars which reached the main sequence between M_1 and M_2 will have reached $M \sim$

M_2; this will appear to be the top of the main sequence. Stars above M_1, and stars in the instability strip which are inhibited from losing mass, for example, because they are unusually slowly rotating, will appear to lie above the main sequence turn-off. This suggests a natural explanation for the existence of sometimes numerous blue stragglers in intermediate age clusters, one which is consistent with the observed properties of these stars.[23,24] These blue stragglers typically have masses around 2–2.5 $M_\odot$, and can have masses more than twice that of the apparent turn-off mass—an observation difficult to explain for most theories of blue stragglers. However, if the blue stragglers are those stars which do not lose much or any mass, they can have any mass which will alow them to remain on the main sequence at least until a significant gap has developed (a few 10^8 to 10^9 yrs).

This hypothesis for the origin of blue stragglers is consistent with the observation that these stars (a) tend to have a high proportion of the slowly rotating A_P stars and (b) appear to be indistinguishable from A and A_P stars which are not blue stragglers.[25] The fraction of the A stars which are A_P stars increases with the age of the cluster,[26,27] but this cannot be a consequence of the stars spinning down to become A_P stars, since observations of the distribution of rotation periods for A_P stars of different ages indicate little if any braking on the main sequence.[28] What is observed is exactly what would be expected, however, if only the more rapidly rotating A stars lose enough mass to become F or G stars, leaving the slowly rotating A_P stars behind. This explanation for the blue stragglers also accounts for the anomalous binaries[29] where the age derived from the brighter component differs substantially from that derived from the fainter star; most other explanations for blue stragglers are unable to account for these binary cases.

The Ages of Clusters

Although the lifetimes of stars are not much altered in our picture (for the solar case, the required increase in the initial H abundance offsets the effects of the early high-luminosity phases), we do find a dramatic effect of our proposed mass loss on the determination of the ages of star clusters. The age of a star cluster is usually determined by fitting a theoretical isochrone to the stars near the top of the main sequence. In our hypothesis the maximum mass on the main sequence, the apparent main sequence turn-off mass, will be $\sim M_2$ for clusters with ages anywhere between $t_{ms}(M_1)$ and $t_{ms}(M_2)$—or about 2–10 $\times$ 10^9 yrs for the solar-composition example. Thus the usual means of determining the ages of clusters will give incorrect results for clusters in that age range. Since M_2 depends on the metallicity, Z, the apparent age of a cluster will depend on Z and not on the true age for ages between $t_{ms}(M_1)$ and $t_{ms}(M_2)$.

Assuming that M_2 is the mass at which the convection zone becomes the same fraction of the stellar mass or radius as is the convection zone in the Sun, and that the depth of the convection zone is determined primarily by the effective temperature,[30] we can determine M_2 as a function of Z from theoretical models. The "apparent age" of a globular cluster with maximum main sequence mass M_2 can then be computed by setting M_2 equal to the turn-off mass on a standard-model isochrone. The "apparent ages" deduced in this fashion from the isochrones of Ciardullo and Demarque[31] for a wide range of stellar compositions are displayed in Fig. 1. If $M_2 = 1$ for solar composition, $M_2 \sim 0.8$ for extremely metal deficient stars. A consequence of this is that all clusters with metallicities less than a tenth of the solar value and ages more than a few times 10^9 yrs will appear to be 14–18 $\times$ 10^9 yrs old.

Also indicated in Fig. 1 is the range and the average values of the ages and metallicities determined for globular clusters, from Demarque,[32] and the age–metallicity relation of Twarog[33] for old disk stars. The remarkable agreement between the predictions and the observations suggests that it is the metallicity, i.e., M_2, and not the age which determines the maximum mass on the main sequence for these stellar populations.

This interpretation of the maximum main sequence masses in globular clusters may provide a means of reconciling apparent globular cluster ages with other determinations which appear to imply a universe $<\sim 12 \times 10^9$ yrs old: Hubble age,[34] age from nuclear chronometers,[35] and age from the low luminosity limit on the white dwarfs.[36] This would allow all the stars in the galactic disk to be younger than $\sim$5–7 $\times$ 10^9 yrs without having a large gap between the time of formation of the disk and the time of formation of the youngest globular clusters. We conclude that it is possible that no stars in our galaxy are older than 7–10 $\times$ 10^9 yrs old. A new method for determining the ages of globular clusters

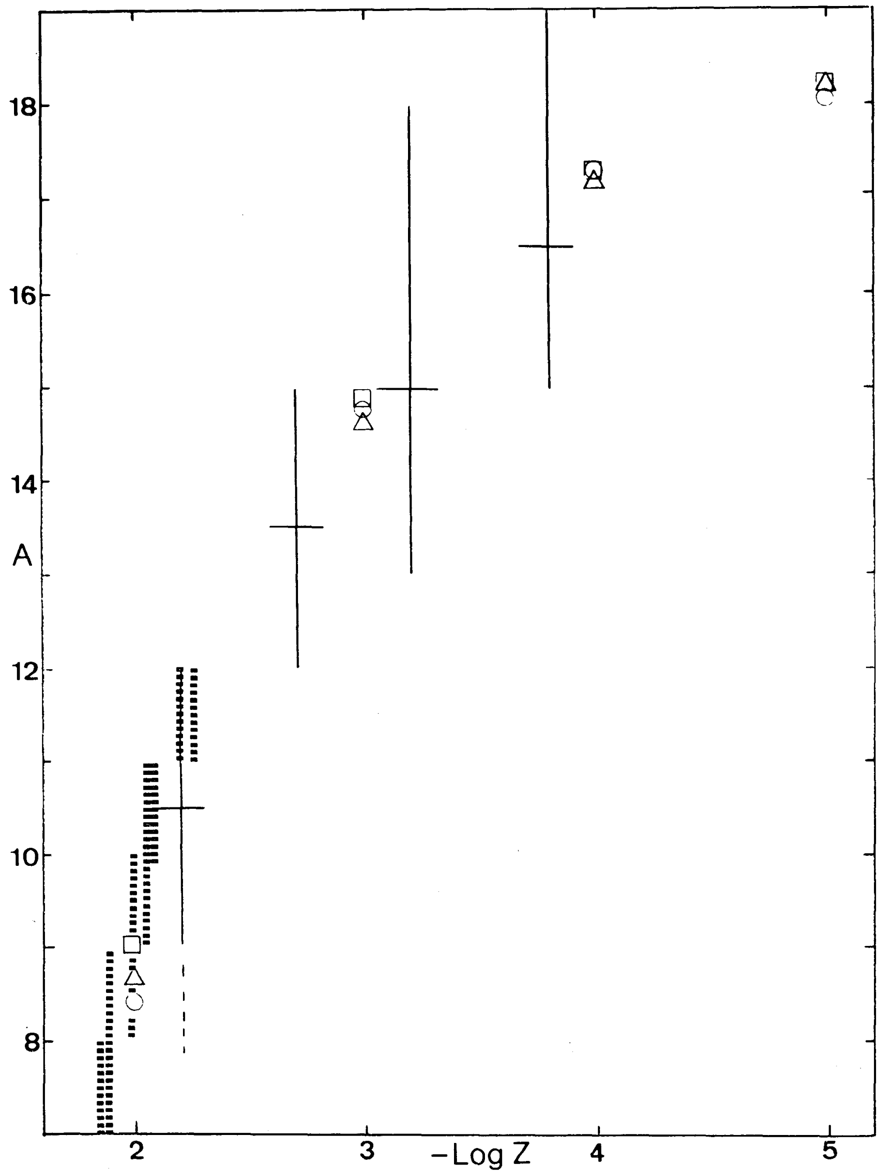

FIGURE 1 The relation between the apparent age of a cluster with a maximum main sequence mass equal to M_2, the mass at which the mass loss process stops, and the metallicity of the cluster. The M_2 estimates were derived from Ciardullo and Demarque's (Ref. 31) theoretical isochrones, assuming M_2 = the mass at which the effective temperature is equal to that of the Sun at 5×10^9 yrs. The apparent age, A (in units of 10^9 yrs), is then taken to be the age at which M_2 is the mass of the bluest star. These computed apparent ages are indicated by the open symbols for three assumed initial helium abundances: ○, △, □ for $Y = 0.1$, 0.2, 0.3, respectively. For comparison, the average "age" of globular clusters in the indicated range of Z was found from Fig. 1 of Demarque (Ref. 32—large crosses). The horizontal bar indicates the range of metallicity of the clusters included in the average; the vertical bar indicates the total range of quoted ages. For the average at $\log Z = -2.2$, only clusters older than 9×10^9 yrs were included in the average; the original plot also contained a cluster at 4×10^9 yrs. For the older open clusters and field stars, the observed "age"–metallicity relation for $Y = 0.2$ and 0.3 from Twarog (Ref. 33) has also been indicated (striped vertical bars).

will need to be found, if indeed it is mass loss, not nuclear evolution, that is determining the "turn-off" mass.

Effects of Main Sequence Mass Loss on Stellar Mass Functions

If the globular clusters are much younger than is usually supposed, they should also be deficient in red giants, since the red giants will have had originally more massive, and less numerous, main sequence progenitors than is usually assumed. At least some globular clusters do appear to be deficient in red giants.[37]

The expected effect of main sequence, instability strip, mass loss on the main sequence mass functions of clusters is sketched in Fig. 2. Since the time scale for mass loss from the middle and late A stars is not much faster than the evolutionary time scale, there is a "gap" in the main sequence mass function only for clusters in a relatively narrow range of ages. Stars above the gap ($M > M_1$) and/or stars which linger within the gap will tend to be labeled blue stragglers after most of the stars in the gap have moved to M_2. The net effect, then, is that the mass function for older clusters appears much steeper than the initial mass function, and that the older cluster and field mass functions will tend to show a peak $\sim$1 $M_{\odot}$, where the originally more massive stars are added to the stars that arrived on the main sequence near $M = 1\ M_{\odot}$. Such a peak has been identified in the mass function for field stars.[38]

Chemical Evolution

An investigation of the effects of main sequence mass loss on the chemical evolution of the galaxy is in progress.[39] The proposed mass loss affects chemical evolution models in several ways: (1) there is a large quantity of relatively unprocessed material returned to the interstellar medium on a time scale $\sim 10^9$ yrs; (2) the observed metal abundance vs. time is altered by the change in the dating of clusters; and (3) stars which we expect to find in a range of masses $<\sim M_1$ shift to $\sim M_2$.

This picture leads to a natural explanation for the failure of observational searches to find any Population III giants, although a substantial number of $Z = 0$ stars must have existed to provide the nonzero metallicities of even the most metal-poor Pop. II stars observed (see, e.g., Caloi, Caputo and Castellani[40]). According to

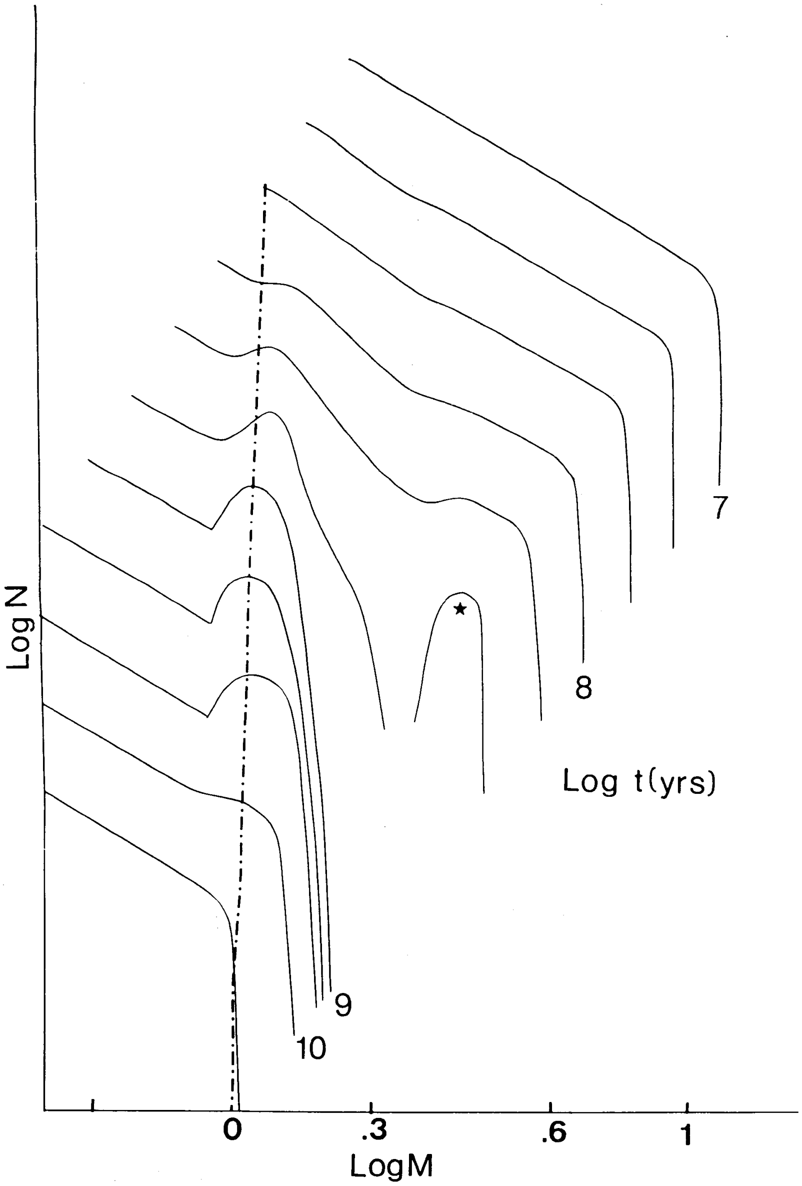

FIGURE 2 The mass function, i.e., the number of stars in each interval of $\Delta \log M$ as a function of $\log M$, for a representative (Population I) cluster at different ages with a power law initial mass function assuming initial mass loss rates $1–5 \times 10^{-9}$ $M_{\odot}$/yr with $\tau_{\dot{M}} \sim 1–10 \times 10^8$ yr. At each time, the low mass limit is the mass of a star just arriving on the main sequence; the turn-down at high mass indicates those stars which are evolving off the main sequence. Each mass function is displaced downward by $\Delta \log N = 1$ from the mass function at the previous time.

our hypothesis, most Pop. III stars now have masses $\leq M_2$ ($Z = 0$) $< \sim 0.8\ M_{\odot}$. Since this mass is low enough that relatively few of the stars will have exhausted their core hydrogen supply, even with the early high-mass, high-luminosity stage, virtually all the Pop.

III stars will now be faint main sequence stars. The only Pop. III red giants we should expect to see would be the few that evolved from the (probably common) blue stragglers of that population.

Is There a Gap on the Main Sequence?

Clear evidence for a deficiency of stars in the instability strip in clusters or among field stars would provide strong support for this hypothesis. A compilation and detailed discussion of such evidence is in preparation; here we will mention briefly some interesting examples.

For eclipsing double-lined spectroscopic binaries it is possible to derive the masses, luminosities and radii of the components and thus to restrict the sample to main sequence objects. Figure 3 is an HR diagram based the data of Popper[41] for main sequence detached binaries. These data show a clear gap in the region between 2.0 and 2.3 $M_\odot$ along the main sequence. A histogram of the masses of the components of such binaries from the more extensive list published by Habets and Heintze[21] is presented in Fig. 4. In the latter data set the gap between 2 and 2.3 $M_\odot$ is much more pronounced than the gap in spectral type, and the assigned spectral types for the stars in these lists include roughly equal numbers of stars for each spectral type A0–F5, arguing that the gap is not due to observational selection effects. The blue edge of the instability strip for young stars[9] agrees with the 2.3 $M_\odot$ (B9/A0) limit; the observed red edge of the δ Scuti strip[42] coincides with the abrupt increase in numbers per unit mass interval at 1.4 $M_\odot$ (~F2).

There is a deficiency of main sequence A stars in the magnitude-limited sample of stars observed for the Michigan Spectral Atlas.[43] While the rapid variation of spectral type with mass where convective envelopes become important contributes to this gap,[44] if the temperature effect is eliminated by summing up the number of stars at each luminosity, then a significant gap still remains.

Intermediate Age Clusters

According to our hypothesis there should also be a deficiency of clusters with turn-off spectral types A and F. Most galactic clusters are young, with turn-off spectral types ~B8/B9. Globular clusters have turn-off types ~F8–early G. There are relatively few clusters

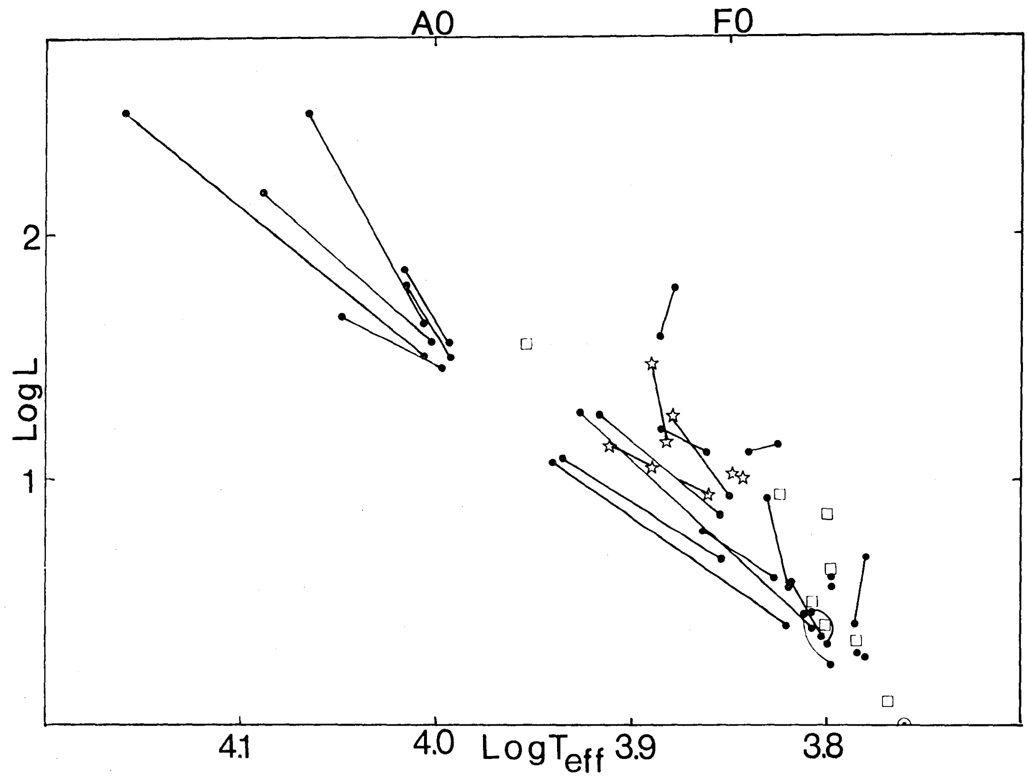

FIGURE 3 HR diagram of main-sequence detached double-lined eclipsing binaries based on data from Popper (Ref. 41). A line connects the two components of each binary system. Squares indicate binaries with two components of equal mass, and stars designate Am stars. The position of the Sun is indicated by the semicircle along the temperature axis. The apparent turn-off of an older low mass population around log T = 3.9 is somewhat misleading, as the members of the apparently most evolved system both have M = 2.3 $M_\odot$.

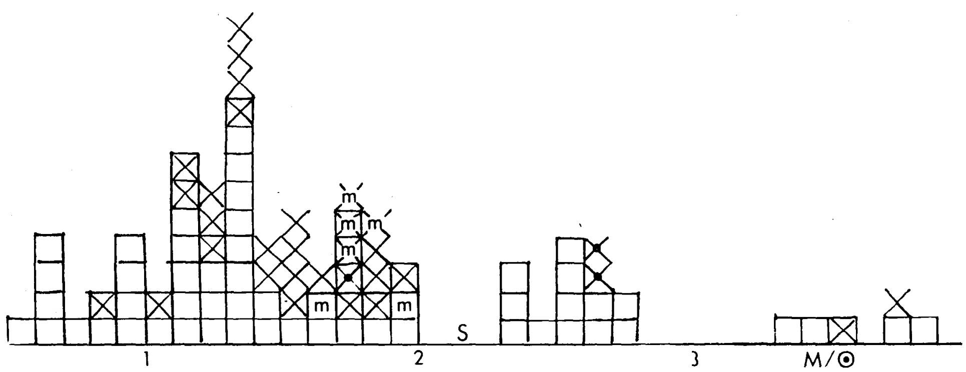

FIGURE 4 Histogram of stellar masses for members of double-lined spectroscopic eclipsing binary systems, from the compilation by Habets and Heintze. Squares: normal main sequence stars; ×: main sequence mass–luminosity but luminosity class IV; heavy dots: luminosity class III; m: Am stars; S: Sirius. As Sirius has a 1 $M_\odot$ white dwarf companion, which therefore presumably originated from a 5–7 $M_\odot$ star, Sirius very likely accreted at least several tenths of a solar mass during the companion's AGB mass loss phase.

with turn-off types in the A and early F types; these typically have blue stragglers of late B/early A types.[25] A histogram of cluster types is thus very similar to the histogram of stellar types; this similarity is a coincidence in the standard picture, but is a natural consequence of our hypothesis.

CONCLUSIONS

The hypothesis that stars with initial masses in the range ~1–2.5 $M_\odot$ lose substantial amounts of mass after they reach the main sequence appears to be capable of resolving a number of problems with our present understanding of stellar evolution. Models with a history of substantial mass loss are consistent with constraints on the present Sun, with the exception of the predicted neutrino fluxes, and promise to solve a number of problems associated with the early evolution of our solar system. The limits on the mass loss process (M_1, M_2, maximum $\dot{M}$, time scale) expected theoretically and those derived from diverse observational constraints agree very well. The gap in the main sequence required by our hypothesis appears to be consistent with presently available data on field stars, on eclipsing binaries, and on clusters, although much more detailed analyses will be required before the existence of the mass-loss gap is confirmed. While other explanations exist to account for these data, ours is the only one that (1) specifies *a priori* that this gap must coincide with the instability strip and (2) accounts for these diverse data with a single explanation.

The consequences of the proposed main sequence mass loss extend beyond stellar astrophysics: the chemical evolution of the galaxy, the determination of astronomical ages, and in fact all constraints on cosmology based on stellar observations will be profoundly affected.

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