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STELLAR WINDS AND AGES OF OLD CLUSTERS

The calculated age of our Galaxy has soared in the last six years from Schwarzschild's (1958) estimate of 6×10^9 year to Sandage's (1962) age of 26×10^9 year for the globular cluster M3 based on Hoyle's (1959) evolutionary tracks. Sandage attached little weight to the latter high age, however, noting (1) the lack of agreement between the shapes of the observed and computed H-R diagrams, (2) Woolf's (1962) *reductio ad absurdum* of such a large age, (3) the attendant excess of age over that compatible with cosmological theory (Sandage 1961), and (4) that the derived ages are upper limits with respect to the helium content. Radioactive chronologies suggest, furthermore, that nucleosynthesis began about 13×10^9 years ago in the Galaxy (Clayton 1964*a, b*). Arp (1962) has suggested interstellar reddening of the globular clusters as a possibility for lowering the computed ages—a possibility that has been considerably strengthened by Sandage's (1964) photometric survey of local subdwarfs. It is the purpose of this note to point out that the derived ages are also upper limits with respect to the effects of stellar winds and to present a simple perturbation calculation to quantitatively isolate the effect of such winds.

The possible effects of mass loss upon evolution on the main sequence have received little attention, a fact that is largely due to (1) lack of evidence for the strength of stellar winds, (2) lack of a complete theory that can predict the winds from the spectral type, and (3) the hope that stellar evolution can account for the observations without this added complexity. But stellar winds are to be expected generally from stars having coronas (Parker 1963). Many authors, furthermore, have tacitly assumed that stellar winds are much too small to alter significantly evolutionary ages. To emphasize the importance of further observational evidence and to quantitatively evaluate how strong the winds must be to alter the computed age, I present the following brief calculations. It should be emphasized that accurate sequences of stellar models are required to compute the age of a constant-time H-R locus, whereas the following perturbation calculation can evaluate only the shift in that age due to weak stellar winds.

Lower main-sequence stars (all that remain in the main sequence in old clusters) evolve off the main sequence after they have converted a certain fraction f of their mass into helium, where f depends on the initial mass and composition of the star and is of the order $f \simeq 0.12$. The helium production is strongly peaked toward the center of the star; for example in the present Sun 55 per cent of the helium production occurs in the central 10 per cent of the solar mass, and 79 per cent occurs in the central 20 per cent (Sears 1964). The total amount of He^4 production in static models is given by

$$\frac{d\text{He}^4}{dt} = kL \simeq kM^4, \quad (1)$$

where k is a constant, L and M are the luminosity and mass of the star in solar units. The second approximate equality in equation (1) is the so-called mass-luminosity relationship for main-sequence stars and is accurate enough for the purposes of this note.

Much current research in space science is directed toward understanding the solar wind, an ionized plasma extension of the solar corona which moves outward at the supersonic velocity of about 500 km/sec carrying away a mass of about $10^{-13} M_\odot$ /year from the Sun. Winds of this type may be expected to be the usual situation for lower main-sequence stars, but there is as yet no adequate way to predict the manner in which the strength of the stellar wind depends upon the mass of the star, because the stellar wind depends upon the properties of stellar coronas, which are not known in general. It is quite conceivable that stellar winds may carry off a few per cent of a stellar mass during its main-sequence lifetime, a loss capable of producing only a small effect on the structure

of the star but that is nonetheless capable of effecting a significant change in the main-sequence lifetime. This situation comes about because of strong dependence of $d\text{He}^4/dt$ upon the stellar mass implicit in the mass-luminosity relationship.

The age of an old stellar cluster is given by the main-sequence evolutionary lifetime T_E of those stars at the turn-off point from the main sequence. For those stars, T_E must satisfy the relationship

$$\langle L \rangle T_E / M = 100 f, \quad (2)$$

where

$$\langle L \rangle = \int_0^{T_E} L dt / T_E$$

is the average luminosity expressed in solar units, T_E is in billions of years (Gyr), and M is the mass in solar units. If it be assumed that $\langle L \rangle = M^4$, the main-sequence evolutionary lifetime becomes, *without mass loss*,

$$M^3 T_E = 100 f. \quad (3)$$

This result is, by itself, inadequate for the computation of cluster ages because f depends upon M and because the simple mass-mean luminosity relationship assumed is imprecise. The *shift* in age due to the perturbing effects of stellar winds may be approximately calculated, however, by assuming $L = M^4$. If, in that case, the mass is a slowly varying function of time via a quiescent mass-loss mechanism, the true main-sequence lifetime is given by an equation analogous to equation (2); viz.,

$$\frac{1}{M(T)} \int_0^T M^4(t) dt = 100 f. \quad (4)$$

Since the centers of lower main-sequence stars are in radiative equilibrium, and since the production of He^4 is so sharply centralized in that stable zone, we may be confident that the fraction f applicable to a star of constant mass is equal to the fraction f for a star of the same final mass that has lost a *small* fraction of its total mass during its main-sequence lifetime. The combination of equations (3) and (4) indicates that the equality

$$\int_0^T M^4(t) dt = M^4(T) T_E \quad (5)$$

provides a good comparison of the evolutionary ages with and without stellar winds.

I have evaluated equation (5) for constant stellar winds in the range of $10^{-13} M_\odot/\text{year}$ (e.g., the Sun) to $10^{-10} M_\odot/\text{year}$ to determine the range of stellar winds for which the age shift is significant. The results of this calculation are shown in Figure 1, where the parameter labeling each curve is the rate of mass loss. Evidently the effect is negligible at $10^{-13} M_\odot/\text{year}$ but becomes important for rates as great as $10^{-11} M_\odot/\text{year}$. Of course, Figure 1 is by no means exact. Exact comparisons demand that two sequences of stellar models be generated on high-speed computers. Since a stellar radius expands slightly and the luminosity increases considerably during the main-sequence lifetime, stellar winds in dwarf stars may well be a function of the age.

There may be no certain way at present to determine realistically the general behavior of stellar winds, but it is obvious that some experimental or theoretical limit to the rate of mass loss on the main sequence due to stellar winds is required before static evolutionary models can be used with confidence to predict the ages of old stellar clusters. The Sun is the only main-sequence dwarf for which experimental data exist. Non-catastrophic winds as great as $10^{-7} M_\odot/\text{year}$ are observed in T Tauri stars (Kuhi 1964) and red

giants (Deutsch 1960). In view of these large loss rates, the relatively modest winds required to alter the evolutionary ages of old clusters must be taken seriously. In fact, Figure 1 shows that a main-sequence mass loss of $1 M_{\odot}$ per million years from a globular cluster is sufficient to reduce the computed age from 22 to 15 billion years.

FIG. 1.—The comparison of the true age T of an old star cluster and the evolutionary time without mass loss T_E . The curves are labeled by the rate of mass loss (assumed constant) in units of $M_{\odot}/\text{year}$.

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