NEUTRINO EMISSION, MASS LOSS, AND THE FREQUENCY OF SUPERNOVAE

RICHARD STOTHERS*
Goddard Institute for Space Studies, National Aeronautics and Space Administration
Received June 8, 1963; revised August 7, 1963

ABSTRACT

Without steady mass loss during the red-giant phase, most stars with mass above the Chandrasekhar limit should evolve into Type II supernovae, but the predicted number of supernovae is much larger than the observed number. Although mass loss considerably lowers the predicted number, its effect will be reduced because of neutrino emission which decreases the time scale of the late phases. However, by use of presently known rates of stellar evolution and mass ejection, it is shown that loss of mass *with or without* neutrino emission will roughly account for the observed number of Type II supernovae. Thus neutrino emission is not contradicted by observations of supernova frequency.

INTRODUCTION

Against the current theory of progressive nucleosynthesis in stars (Burbidge, Burbidge, Fowler, and Hoyle 1957) is raised the serious objection that far more supernovae should be observed than is the actual case. For instance, on the assumption that every star with mass above the Chandrasekhar limit (1.4 $\mathfrak{M}_{\odot}$) gets rid of its excess mass by supernova explosion, we compute for the Galaxy with $\sim 2 \times 10^9$ stars of $\mathfrak{M} > 1.4\, \mathfrak{M}_{\odot}$ and average lifetime $\sim 3 \times 10^9$ years (Schwarzschild 1958) a frequency of at least 200 supernovae per 300 years. This is too large by two orders of magnitude, compared with the observed frequency of about 1 supernova every 300 years (Zwicky 1958). This well-known result was obtained by Schwarzschild (1958) in two slightly different ways, using the death-rate function and the observed numbers of white dwarfs.

It is now apparent that many stars undergo extensive mass loss in the form of "winds" during the red-giant phase of their evolution (Deutsch 1956*a;* Weymann 1962). This is believed to account for most of the excess mass that must be expelled. On the neutrino theory of late stellar evolution, however, the time scale is so shrunken that mass loss due to winds may be ineffective, and the neutrino luminosity rises so high that energy requirements can force stars of relatively low mass to evolve to the supernova stage (see, e.g., Chiu 1961*a*, *b*). These considerations would lead us to expect again a higher frequency of supernova outbursts. It is the purpose of this paper to see whether the theory of neutrino emission is in conflict with observations.

EVOLUTIONARY TIME SCALES

Detailed stellar models have been computed for the late evolutionary phases only in the case of three masses $\geq 1.3\, \mathfrak{M}_{\odot}$ (see Table 1 and references). Accordingly we list the three closest masses from the observed mass-spectrum relation tabulated by Schwarzschild (1958). The main sequence lifetime, τ_{ms}, is defined as the time required for a star to burn 13 per cent of its hydrogen.

Hayashi and Cameron (1962*a*, *b*) and Hayashi, Hoshi, and Sugimoto (1962) have computed models for a star of 15.6 $\mathfrak{M}_{\odot}$ as a red supergiant. The lifetime of carbon-burning is 2.3×10^5 years and of the later phases, $\sim 6 \times 10^5$ years, without neutrino emission. These lifetimes are shortened to a total of at most 8×10^4 years if neutrino emission is included. Reeves (1962) also estimates that the time scale is reduced by a factor of 10 because of neutrino emission.

A star of intermediate mass (4 $\mathfrak{M}_{\odot}$) makes a brief excursion into the G and K giant

* Now at Harvard College Observatory.

region during helium-burning, but does not become a red supergiant until the onset of carbon-burning (Hayashi, Nishida, and Sugimoto 1962; Hayashi, Hoshi, and Sugimoto 1962). It spends 1×10^6 years burning carbon, and, extrapolating from the results on the star of 15.6 $\mathfrak{M}_\odot$, we estimate that it spends at least 3×10^6 years in the later phases. This number may be considerably underestimated, as degeneracy in the core will occur in the case of a star of 4 $\mathfrak{M}_\odot$, whereas in the case of 15.6 $\mathfrak{M}_\odot$ it is very slight. In fact, Hayashi, Nishida, and Sugimoto (1963) found that $\sim$4 $\mathfrak{M}_\odot$ represents a critical mass below which degeneracy occurs in the core just before helium-burning. The red-giant lifetime with neutrino emission included is 10^6 years (Hayashi, Hoshi, and Sugimoto 1962).

The evolutionary track of a star of 1.3 $\mathfrak{M}_\odot$ enters the G–K red-giant region during gravitational contraction and the onset of helium-burning. Degeneracy in the core raises the time scale to $\tau_{rg} > 2.5 \times 10^7$ years (Schwarzschild and Selberg 1962; Schwarzschild and Härm 1962). Presumably, after a brief period of non-degeneracy following the helium flash, the further evolution of the star is finally limited by renewed degeneracy, and the star becomes a white dwarf or Type I supernova (Population II and due to an entirely different mechanism; see Hoyle and Fowler 1960) without returning to the red-giant region. Plasma neutrino emission will have some effect on the luminosity of the core of the star, but not on the total luminosity (Chiu 1963*b*), and is therefore not believed to affect the time scale significantly.

Although the models for these three stars had different assumed initial chemical compositions, the time scales of evolution, especially during the later phases, should not be affected too much by a change in initial composition, at least to within the accuracy we require (cf. Table 1).

MASS LOSS

We now turn to the problem of mass loss by stars in the form of winds or ejection of shells. The solar wind carries away 3×10^{-14} $\mathfrak{M}_\odot$/year, which is completely negligible (Parker 1963). Underhill (private communication) obtains observationally a mass loss of 10^{-6} to 10^{-7} $\mathfrak{M}_\odot$/year for Wolf-Rayet stars and believes that the normal O stars would have this rate reduced by a factor of 10. For a Be shell star (10 $\mathfrak{M}_\odot$), Underhill (1960) obtains 10^{-7} $\mathfrak{M}_\odot$/year, to be reduced by a similar factor for the normal B stars. Hence with main-sequence lifetimes of 5×10^6 and 1×10^8 years, respectively, the mass loss even from O and B stars is negligible during the main-sequence phase of evolution.

During the red-giant phase, however, observations show that mass loss can be considerable. Weymann (1962) obtains for α Orionis an outflow of 4×10^{-6} $\mathfrak{M}_\odot$/year. Allen (1955) gives for a star with its spectral type (M2 Iab) a mass of $\sim$20 $\mathfrak{M}_\odot$. The corresponding escape velocity is consistent with the assumption of outflow of material. Deutsch (1956*a*) obtains a mass loss of 3×10^{-8} $\mathfrak{M}_\odot$/year for α Herculis. This star is a visual binary with a computed mass of 15 $\mathfrak{M}_\odot$ for the more massive M component. However, its spectral and luminosity class (M5 II) would indicate a mass more like 4 $\mathfrak{M}_\odot$ (Allen 1955). Moreover, Weymann (1960) has pointed out that the interpreted velocity of outflow is not consistent with the escape velocity calculated for 15 $\mathfrak{M}_\odot$. He uses Wilson's (1960) distance determination for α Herculis and inspection of the H-R diagram of galactic clusters to suggest that the mass of the M component is $\sim$4 $\mathfrak{M}_\odot$. We adopt this mass in Table 1.

Hayashi, Hoshi, and Sugimoto (1962) found that the main effect of mass loss is to reduce the effective temperature. Now Deutsch (1960) showed that mass loss is vastly more efficient at the lower temperatures. Since stars with $\mathfrak{M} \geq 4$ $\mathfrak{M}_\odot$ spend less time in carbon-burning than in the later phases (without neutrino emission), the average rate of mass loss will be greater than that indicated in Table 1. Moreover, Deutsch's value of the loss from α Herculis is a lower limit, and he points out that significant loss may even occur at the earlier spectral types, which would include part of the helium-burning phase of a star of 4 $\mathfrak{M}_\odot$ (Deutsch 1960). Since the rate of loss should be roughly independent of stellar mass, perhaps Weymann's value is a better average. Therefore it seems that mass loss will be effective in reducing the mass of a star with initial 4 $\mathfrak{M}_\odot$ to below the Chandrasekhar limit. The star will then become either a white dwarf with a core composed of the products of carbon-burning or perhaps a supernova of Type I. Table 1 also suggests that mass loss will be effective even up to 15–20 $\mathfrak{M}_\odot$ (main-sequence spectrum B2) for the case of no neutrino loss. Stars with $\mathfrak{M} < 4\,\mathfrak{M}_\odot$ will almost certainly lose some mass, cool off, and avoid Type II supernova explosion, with or without neutrino emission.

If mass loss is not efficient enough, however, ordinary evolutionary processes will make supernovae out of all stars with $\mathfrak{M} > 4\,\mathfrak{M}_\odot$ (B8); with neutrino emission, mass loss will certainly be inefficient for the more massive stars because of the drastically reduced time scale, as indicated in Table 1 for 18 $\mathfrak{M}_\odot$ (B2). So we shall regard ~B8 as the critical spectral class for which earlier stars become supernovae on the neutrino theory.

TABLE 1

STELLAR LIFETIMES AND MASS LOSS DURING THE RED-GIANT PHASE

$\mathfrak{M}/\mathfrak{M}_\odot$*	Sp*	log τ_{ms}† (yr)	log τ_{rg} (yr) without ν-loss	log τ_{rg} (yr) with ν-loss	$-\dot{\mathfrak{M}}$‡ ($\mathfrak{M}_\odot$/yr)	References for τ_{rg}§
18	B2	7 6	6 0	<4.9	4×10^{-6}	1, 4
4	B8	8 4	>6 6	6 0	$>3\times10^{-8}$	2, 4
1 4	F1	9 6	>7 4	>7 4	. . . . .	3

* Observed mass-spectrum relation for the main sequence (Schwarzschild 1958, p 277)

† Computed by Schwarzschild (1958, p 277) as the time required to burn 13 per cent of the hydrogen

‡ Observed by Deutsch (1956) and Weymann (1962) for α Her (~4 $\mathfrak{M}_\odot$, Weymann 1960) and α Ori (~20 $\mathfrak{M}_\odot$), respectively.

§ Sources are (1) Hayashi and Cameron (1962*a*, *b*) for a star of 15 6 $\mathfrak{M}_\odot$; (2) Hayashi, Nishida, and Sugimoto (1962) for a star of 4 $\mathfrak{M}_\odot$; (3) Schwarzschild and Selberg (1962) and Schwarzschild and Härm (1962) for a star of 1 3 $\mathfrak{M}_\odot$; (4) improved values of Hayashi, Hoshi, and Sugimoto (1962).

We note, parenthetically, that observations of globular and open clusters support the theoretical results that main-sequence stars evolve into red giants (at least the stars of low and intermediate mass). For the massive stars the evidence from OB clusters is suggestive (Hayashi and Cameron 1962*a*, *b*), even though not required (Chiu 1963*a*). Moreover, star-counts and the distribution of M giants in the field (Deutsch 1956*b*) support this view of evolution.

STELLAR STATISTICS AND FREQUENCY OF SUPERNOVAE

We must now estimate the number of O and B stars in the Galaxy. Roberts (1957) used Shnirelman's (1952) value of 1.8×10^6 B0–B5 stars to obtain 2.5×10^6 B0–B7 stars. Rubin, Burley, Kiasatpoor, Klock, Pease, Rutscheidt, and Smith (1962) list 1440 O–B5 stars within a radius of 3 kpc around the sun; this value is estimated to be 5 per cent complete. If we assume with Rubin *et al.* that the radius of the Galaxy is 15 kpc, we obtain a total of 7×10^5 O–B5 stars in the Galaxy. By extrapolation we get 1×10^6 O–B7 stars. Parenago (1948) and Roberts (1957) obtain 6×10^3 O stars in the Galaxy. Therefore we estimate that there are 5×10^4 O–B2 stars. Using the main-sequence lifetime of the latest star in a small spectral interval, we divide the number of stars in the interval by τ_{ms} to obtain the predicted number of supernovae (SN). The cumulative spectral intervals and numbers of supernovae are listed in Table 2.

The observed frequency of both Type I and Type II supernovae in external galaxies is one in 300–400 years (Zwicky 1958). The uncertain completeness of the searches and intragalactic extinction indicate a true frequency that is higher by an unknown factor. The three, well-authenticated supernovae in our own Galaxy were of Type I and show an apparent frequency of 1 SN/300 years. Other supernovae have been recorded in our Galaxy (Kukarkin, Parenago, Efremov, and Kholopov 1958), but their type is unknown. However, Type II supernovae are known to be more common in general (Payne-Gaposchkin 1957). Hence we shall accept for our own Galaxy the "true" extragalactic rate of Type II supernovae as >1 SN/300 years.

TABLE 2

PREDICTED FREQUENCY OF SUPERNOVAE FOR VARIOUS SPECTRAL GROUPS

Sp. Group	No. of Stars	log τ_{ms} (yr)	SN/300 yr
O.... .	6×10^3	6 6	0.5
O–B2.	5×10^4	7.6	1
O–B5.	$7–18\times10^5$	8.0	4–6
O–B7	$1–2.5\times10^6$	8.3	6–10

We recall from the first paragraph of this paper that without mass loss the frequency of supernovae should be greater than 200 per 300 years. This is too large by about two orders of magnitude. From Table 2 we note that on the basis of mass loss *with or without* neutrino emission the predicted frequencies (despite the uncertainties in arriving at them) fall within a reasonable range of the observed frequency. In fact, if Payne-Gaposchkin's (1957) estimate of at least 8 Type II SN/300 years in the Galaxy is correct, the neutrino hypothesis improves the agreement.

Hence we conclude that the assumption of neutrino emission is at least not contradicted by observations of supernova frequency.

I am indebted to Drs. Hong-Yee Chiu and A. G. W. Cameron for criticisms and discussion. It is a pleasure to thank Dr. Robert Jastrow for the hospitality of the Institute for Space Studies.

REFERENCES

Allen, C. W. 1955, *Astrophysical Quantities* (London: Athlone Press).
Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F. 1957, *Revs. Mod. Phys.*, **29**, 547.
Chiu, H.-Y. 1961*a*, *Ann. Phys.*, **15**, 1.
———. 1961*b*, *ibid.*, **16**, 321.
———. 1963*a*, *A.J.*, **68**, 70.
———. 1963*b*, *Ap. J.*, **137**, 343.
Deutsch, A. J. 1956*a*, *Ap. J.*, **123**, 210.
———. 1956*b*, *Pub. A.S.P.*, **68**, 308.
———. 1960, *Stellar Atmospheres*, ed. J. Greenstein (Chicago: University of Chicago Press), p. 543.
Hayashi, C., and Cameron, R. C. 1962*a*, *Ap. J.*, **136**, 166.
———. 1962*b*, *A.J.*, **67**, 577.
Hayashi, C., Hoshi, R., and Sugimoto, D. 1962. *Prog. Theoret. Phys. Suppl.* (Kyoto), No. 22.
Hayashi, C., Nishida, M., and Sugimoto, D. 1962, *Prog. Theoret. Phys.* (Kyoto), **27**, 1233.
Hoyle, F., and Fowler, W. A. 1960, *Ap. J.*, **132**, 565.
Kukarkin, B. V., Parenago, P. P., Efremov, Y. I., and Kholopov, P. N. 1958, *General Catalogue of Variable Stars* (Moscow: Academy of Sciences of the U.S.S.R. Press).
Parenago, P. P. 1948, *Russian A.J.*, **25**, 123.
Parker, E. N. 1963, Colloquium, Institute for Space Studies, New York.

Payne-Gaposchkin, C. 1957, *The Galactic Novae* (New York: Interscience Publishers).
Reeves, H. 1963, *Ap. J.*, **138**, 79.
Roberts, M. S. 1957, *Pub. A.S.P.*, **69**, 59.
Rubin, V. C., Burley J., Kiasatpoor, A., Klock, B., Pease, G., Rutscheidt, E., and Smith, C. 1962, *A.J.*, **67**, 491.
Schwarzschild, M. 1958, *Structure and Evolution of the Stars* (Princeton, N.J.: Princeton University Press).
Schwarzschild, M., and Härm, R. 1962, *Ap. J.*, **136**, 158.
Schwarzschild, M., and Selberg, H. 1962, *Ap. J.*, **136**, 150.
Shnirelman, P. G. 1952, *Russian A.J.*, **29**, 179.
Underhill, A. B. 1960, *Stellar Atmospheres*, ed. J. Greenstein (Chicago: University of Chicago Press), p. 411.
Weymann, R. 1960, *Ap. J.*, **132**, 380.
———. 1962, *ibid.*, **136**, 844.
Wilson, O. C. 1960, *Ap. J.*, **131**, 75.
Zwicky, F. 1958, *Handbuch der Physik*, ed. S. Flügge (Berlin: Springer-Verlag), **51**, 766.