19. MASS LOSS FROM STARS

Introductory Report

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1. Introduction

In this summary we shall attempt to evaluate the mass loss from several kinds of high luminosity stars, especially planetary nebulae, OB supergiants and M giants and supergiants. The purpose is to give an observational basis for the discussion of the mechanism of mass loss and of the consequences of stellar mass loss for the interstellar medium and for stellar evolution. For reasons which will presently be discussed, we are now certain that mass loss is occurring in all the objects mentioned, and probably to a similar extent in all high luminosity stars as well. The precise values of the mass loss rate are uncertain at present; for some objects the uncertainty will be large (two orders of magnitude) and have important influence on the consequences of the mass loss. Therefore we shall discuss in some detail how the different loss rates quoted in the literature have been obtained and what assumptions have been made (see also the Report by Boyarchuk, p. 281). On the basis of this discussion we will indicate the most probable loss rates and their consequences, always remembering the possible influence of the uncertainties.

When comparing space densities and rates of mass loss over the whole Galaxy, we assume that the space density given is an average over a volume of 10^{12} pc^3 (a radius of 15 kpc and an extent in the z direction of 600 pc on either side of the plane). For most of the objects discussed this is a reasonable assumption. Only in the case of the OB supergiants is the z extent substantially smaller, about 200 pc. We have therefore lowered the space density artificially by a factor of 3, so that the total mass loss will be approximately correct.

2. The Sun

For comparison we will briefly discuss the Sun (see also the Report by Lüst, p. 249). Biermann (1951) was the first to demonstrate that particles flow from the Sun. Since then much work on this subject culminated in the actual measurement of a 'solar wind' by space probes removed from the influence of the Earth. Measurements for quiet periods on the Sun (Ness, 1968) are shown in Table I. The velocity observed, about 350 km sec^{-1}, is considerably in excess of the solar escape velocity at the Earth orbit, 42 km sec^{-1}, and there can be no doubt that this material is being lost from the Sun. The mass-loss rate, given in column 6, is typical of the quiet Sun. At times of solar activity the mass-loss rate increases, sometimes considerably, but it is difficult to determine the precise average increase. There is also a variation with the solar cycle.

In column 7 the space density of F, G, and K dwarf stars is given. If it is assumed

Habing (ed.), Interstellar Gas Dynamics, 272–280. *All Rights Reserved. Copyright* © 1970 *by IAU*

TABLE I

Mass loss rates for various kinds of objects

1	2 Observed velocity (km sec^{-1})	3 Distance R from star at which velocity observed (cm)	4 V_{escape} at R (km sec^{-1})	5 V_{escape} at surface (km sec^{-1})	6 Mass loss rate ($M_\odot$ yr^{-1})	7 Space density (stars pc^{-3})	8 Mass loss to interstellar medium ($M_\odot$ pc^{-3} yr^{-1})
Sun	400	1.5×10^{13}	42	618	2×10^{-14}	2×10^{-2}	4×10^{-16}
Planetary nebulae	20	4×10^{17}	0.4	800	[a] 1.1×10^{-5}	1.5×10^{-8}	1.5×10^{-13}
OB	1400	3×10^{12}	500	600	1.5×10^{-6}	[b] 10^{-7}	1.5×10^{-13}
MI	10	3×10^{15}	2.5	125	4×10^{-6}	2×10^{-8}	8×10^{-14}
MII	10	3×10^{15}	2.5	125	4×10^{-7}	4×10^{-7}	1.5×10^{-13}
M5–8 III	8	10^{15}	2	120	2×10^{-8}	3×10^{-7}	6×10^{-15}
M3–4 III	12	10^{15}	2	140	4×10^{-9}	2×10^{-6}	8×10^{-15}
Novae	1000				10^{-4} $M_\odot$	(40 yr^{-1})	4×10^{-15}
Supernovae	5000				1 $M_\odot$	(10^{-2} yr^{-1})	10^{-14}

[a] A lifetime is assumed of 35 000 yr.

[b] This number is lowered by a factor of 3 (see text, p. 272).

that these stars have a mass loss similar to the Sun (why should the Sun be an exception?) then the total mass loss to interstellar medium is given in column 8.

3. Planetary Nebulae

Our knowledge of mass loss from planetary nebulae is more certain than from the other objects we shall discuss. This is because we observe the mass lost in the form of a nebula which is optically thin in many important lines. The velocity of expansion of the nebulae can be directly observed: it is at least an order of magnitude higher than the escape velocity at the distance of the nebula (assuming 1 $M_\odot$ for the mass of the central star).

To obtain the mass of the nebula, one needs to know the density, and the distance of the nebula. The density of the ionized material follows directly from measurements of the forbidden lines, or of the Balmer lines, but in the latter case the square root of the distance also enters. The distance of the nebula is a more difficult question which I do not wish to discuss here (see Aller and Liller, 1968, for a summary). Suffice it to say that distances appear to be known for individual objects with about 50 per cent uncertainty. Statistically the distances are considerably better.

The mass thus derived is the mass of ionized hydrogen in the nebula. In some nebulae a correction must be made for the fact that the entire nebula is not ionized and in all nebulae the total mass must be increased by about 40 per cent to take helium into account. While all these considerations introduce uncertainties in the mass determination, it seems generally accepted that for an average nebula a value of 0.4 $M_\odot$ will be correct within a factor of 2.

The average rate of formation of planetary nebulae is probably somewhat more difficult to assess. In addition to the usual problems associated with space density, we are also required to know the lifetime of a planetary nebula and assume that only one shell has been emitted in this lifetime. Knowledge of the size of the largest nebulae, together with the velocity of expansion which is probably constant during the existence of the nebula, leads to a lifetime of about 35 000 yr. From this lifetime the rate of formation and the average mass-loss rate follow.

The space density listed in Table I, column 7, is an average of two very similar estimates by Cahn (1968) and O'Dell (1968). That these estimates are so similar leads us to regard the value as reasonably well determined. It is likely that the mass lost to the interstellar medium by planetary nebulae, given in column 8, is reliable to within a factor of 3.

4. M Giants and Supergiants

It has been known for more than 30 years that in all high-luminosity M-type stars, the strong absorption lines arising from the ground state of atoms and ions are composed of two components. In addition to a broad, relatively shallow line probably formed in the 'photosphere', there is a deep, narrow component with near-zero central intensity. The component is displaced toward the violet by a small amount, perhaps 10 km $\sec^{-1}$.

This is evidence that material is moving away from the star; since the escape velocity of the surface of these stars is at least 100 km sec^{-1}, it is not direct evidence for mass loss.

That mass loss occurs was first demonstrated by Deutsch (1956). He analyzed the spectrum of the visual companion of the binary star α Hercules, the primary being an M giant. In the spectrum of the companion the sharp lines are still seen, indicating that the absorbing material is present at a distance of at least 10^{16} cm (=700 AU) from the M giant and is still expanding at essentially the same velocity, 10 km sec^{-1}. At a distance of 10^{16} cm, the escape velocity is between 1 and 2 km sec^{-1}, thus indicating quite definitely that the matter is being lost from the star. This picture is confirmed by observations in spectroscopic binaries, where these narrow, circumstellar lines remain at a fixed velocity, while the photospheric lines shift with the changing position and velocity in the orbit.

The determination of a quantitative value for the mass loss is more uncertain. This is generally done in the following steps:

(1) the surface density of Ca^+ ions is measured from the H and K lines using the curve of growth;

(2) the density is related to the total number of Ca atoms in the line of sight and thus to the total number of H atoms, provided an abundance of Ca is assumed;

(3) the size of the emitting region is determined; if in addition spherical symmetry and constant velocity are assumed the value of the mass loss can be derived.

There are uncertainties in each of these steps. Consider the first step. Since the H and K lines lie on the flat portion of the curve of growth, small errors in the equivalent width determination will lead to large uncertainties in the number of ions integrated over the line of sight. For example the values given by Deutsch (1956) and Weymann (1962) for α Hercules differ by a factor of 20, which is mostly due to this effect. In the second step the computation of the ionization equilibrium introduces an uncertainty. Deutsch assumed that the Ca is predominantly singly ionized throughout the expanding envelope, while Weymann has suggested that no Ca^+ is found within about 10 stellar radii of the M star (the Ca probably being in the form of Ca^{++}). If Weymann is correct, it would be necessary to increase Deutsch's estimate of the mass loss by an order of magnitude again. This demonstrates that the present estimate of the mass loss rate for M stars is uncertain by at least a factor of 10.

There are two additional effects which are also shown in the table. First, the more luminous the star, the higher its mass loss. There is about an order of magnitude difference between each of the luminosity classes listed (Deutsch, 1960). Second, the giants may show an increase in mass loss for decreasing surface temperature. The supergiants do not seem to show this effect and in all likelihood the mass loss is roughly the same for all spectral types. In the giants however there is a pronounced relation between the spectral type and the strength of the narrow H and K, in the sense that the lower temperature stars show stronger lines. We have here assumed that this effect means more mass loss for the later spectral types. But it might simply mean an increase in ionization of Ca^+ in earlier spectral types and in that case the mass loss might actually be as high in the earlier M giants as in the late M giants. Notice that many of the uncertainties point in the direction of a higher mass loss than is listed in Table I.

It appears that the kinetic temperatures in the outflowing mass in M type stars are significantly lower than in the solar wind. First, lines of several neutral elements, e.g., Fe, Ca, and Cr, are observed. Second, the level of excitation is quite low: absorption is observed principally from the ground level, although weak absorption occurs from lines as high as 1 eV above the ground state. Far from the star only the ground level absorptions are seen.

The space density of the M stars is given in column 7. It is taken from Blanco (1965) for the giants and from the compilation of Allen (1963) for the supergiants. The values of Blanco agree quite well with the earlier results of Neckel (1958); they are probably quite reliable. On the other hand the supergiant densities are less reliable. I have considered MII stars to have an M_v between -1.5 and -3.5, and all brighter objects to be MI. The values of total average mass loss to the interstellar medium is given in column 8. The estimates are rather conservative. It can be seen that similar amounts of material are lost from the M supergiants as from the planetary nebulae. But the uncertainties are such that the mass loss from M supergiants may be an order of magnitude higher.

5. OB Supergiants

The qualitative evidence for mass loss from the early type supergiants is derived essentially from the following argument: The spectrum shows the presence of emission lines with violet displaced absorption edges, the so-called P Cygni profiles. These are thought to be formed in an outer expanding atmosphere with an excitation temperature lower than the stellar photosphere. That is a reasonable explanation of the P Cygni profiles can be shown by analogy to the novae where similar profiles are observed near maximum light and where we later see the shell expanding at about the same velocity as was indicated by the absorption line.

When we restrict ourselves to observations in the visible part of the spectrum, the velocities of expansion indicated by the P Cygni profiles are rather on the low side, between 100 km $\sec^{-1}$ to 500 km $\sec^{-1}$. P Cygni itself shows 200 km $\sec^{-1}$. These velocities are rather smaller than the escape velocity from the surface of the star, about 600 km $\sec^{-1}$. Since there is no indication in the spectra of material returning to the star, one has assumed that the material is accelerated to still higher velocities further out in the atmosphere. Actually there are indications for a velocity gradient in the atmosphere, e.g., those Balmer lines which have the highest absorption coefficient and are thus formed further out in the atmosphere, show systematically higher velocities. Hα always has the highest velocity.

Morton (1967) has recently observed the spectra of three OB supergiants between 1000 Å and 2000 Å. He found P Cygni profiles for all strong lines, but now the velocity shift of the absorption component was about 1400 km $\sec^{-1}$, indicating definite mass loss. Interestingly, all the lines observed showed roughly the same absorption velocity shift, not only in a given star, but in all three stars!

The lines observed in the UV are resonance lines of abundant elements, and originate therefore further out in the atmosphere. This verifies the hypothesis that the velocity of expansion increases outward in the atmosphere until it exceeds the escape velocity.

Interesting also is the comparison of the UV spectra with the visible spectra of the same star. For one of the stars (δ Ori, O9.5 II) there is no indication for mass loss in the visible spectrum. For the other two stars (ζ Ori, O9.5 Ib and ε Ori, B0 Ia) only a very weak Hα P Cygni profile is seen, giving a velocity shift of 100 km sec^{-1}, and no other emission lines. A possible conclusion from this fact is that stars, which show stronger mass loss indications in their visible spectrum, are actually losing mass at a higher rate than δ, ε, and ζ Ori.

The actual values of the mass loss are more difficult to ascertain. There are several estimates in the literature (e.g., Morton, 1967; Hutchings, 1968, 1969a, b). It is my opinion that Morton's analysis of the three Orion stars is the most trustworthy since he makes the minimum of assumptions. I do not wish to go through his analysis here, but I will point out his principal assumptions:

(1) the weak N v absorption line is unsaturated;

(2) the absorption all takes place in a region where the velocity is uniform;

(3) the ionization equilibrium is determined by photo-ionization (due to the stellar radiation) and radiative recombination. Together with assumption 2 and the continuity equation, this leads to an ionization equilibrium independent of distance.

Morton finds similar values for the mass loss for the three stars. The average value is given in Table I, which may be an underestimate since, as I have said above, other OB supergiants may be losing substantially more material. The analysis by Hutchings seems to be less solidly based. He attempts (and succeeds to a limited extent) to reproduce the observed P Cygni profile in different stars. To do this he must assume velocity, density, excitation temperature and ionization as a function of distance in the atmosphere. It is my opinion that the single observational fact, the line profile, is not sufficient to decide whether he has chosen a correct model. It may be that he has sufficient insight into OB atmospheres that his results are reasonable. But these model quantities are still so uncertain in the outer solar atmosphere with so much better observational material that one is sceptical. In addition his models do not satisfy the equation of continuity, so that his computed mass loss varies with height in the atmosphere. For example in the star HD 152408, for which Hutchings quotes a mass loss of 10^{-4} $M_\odot$ yr^{-1}, his actual values are 10^{-5} $M_\odot$ yr^{-1} at the surface of the star, increasing to almost 10^{-2} $M_\odot$ yr^{-1} at 7×10^{12} cm (or 0.5 AU) above the surface.

Hutchings finds similar mass loss values to Morton for the Orion stars. For other stars he finds higher values. For P Cygni itself he finds a value of 5×10^{-4} $M_\odot$ yr^{-1}. De Groot (1969) derived a similar value for the mass loss in this star, but here again the analysis (specifically, the density determination) makes one very sceptical of the resultant value.

Turning to the space density of OB supergiants, there is again a good deal of uncertainty. Allen (1963) gives a space density of OB stars brighter than $M_v = -6$ as

4×10^{-9} pc^{-3}. Sharpless (1965), however, in a less definite statement, says that several thousand OB supergiants have been found in surveys and that most of these are probably within a distance of 2–3 kpc. If we have 10^3 stars within a cylinder of radius 2.5 kpc and 600 pc thickness*, the space density is at least 10^{-7} star pc^{-3}, more than an order of magnitude higher than the previous estimate. We shall adopt this rough estimate of Sharpless, however, noting the uncertainty.

6. Discussion

A. MASS LOSS TO THE INTERSTELLAR MEDIUM

The mass loss rates are given in the last column of Table I. (We have also included the novae and supernovae in this table for comparison). The main-sequence stars of about the solar type probably do not contribute an important amount of material to the interstellar medium, nor do the novae. It appears that the planetary nebulae, the OB supergiants, the M supergiants, and to a lesser extent, the supernovae contribute roughly equal amounts to the interstellar medium. Is this amount significant? The total listed in column 8 is 6×10^{-13} $M_\odot$ pc^{-3} yr^{-1} $= 2.5 \times 10^{-11}$ particle cm^{-3} yr^{-1}, which in 10^{10} yr amounts to 0.25 particle cm^{-3}. This is of the same order as the gas density observed at present, averaged over a region 500 to 600 pc on either side of the galactic plane – roughly the region occupied by these various objects (with the exception of the OB supergiants). It is doubtful that all four mass-loss rates have been substantially overestimated and it is likely that this total mass-loss rate is on the low side; the mass loss from the OB supergiants and from the M supergiants may both be substantially higher. It may also be that substantial mass loss occurs in an as yet unrecognized form, perhaps in the K giants or perhaps in the M dwarfs. If the mass loss were a factor of 10 higher it would mean that stellar mass loss is replenishing the interstellar medium in 10 per cent of the lifetime of the Galaxy.

B. IMPORTANCE FOR STELLAR EVOLUTION

There are 0.13 star pc^{-3} near the Sun, yielding a mass density in stars of 5×10^{-2} $M_\odot$ pc^{-3}. With a mass-loss rate of 6×10^{-13} $M_\odot$ pc^{-3} yr^{-1}, this means that in 10^{10} yr 10 per cent of the observed stellar mass is being lost from the stars. This is a strong indication that mass loss will be important in stellar evolution. The consequences of a mass-loss rate 10 times higher would have to be very carefully considered.

C. ENERGY TRANSFER TO THE INTERSTELLAR MEDIUM

In the second column of Table II the kinetic energy which can be transferred to the interstellar medium is given. The energy is appreciable only for the OB stars and the supernovae. Even for these objects it does not reach the value 6×10^{-26} erg sec^{-1} cm^{-3} given by Spitzer (1968) as the energy which the hot stars radiate below the Lyman limit. And it may be that cosmic rays or X-rays are a more important source

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* This thickness has been adopted to facilitate comparison with the other stars, instead of 200 pc, which is probably a limit to the actual spatial extent of these objects.

TABLE II

Energy considerations

1	2 Kinetic energy of flow at R (erg sec^{-1} cm^{-3})	3 Potential energy required to bring the material from the surface to infinity (erg sec^{-1})	4 Stellar luminosity (erg sec^{-1})	5 Ratio of potential energy loss and stellar luminosity
Sun	4×10^{-31}	2×10^{27}	3.9×10^{33}	5×10^{-7}
Planetary nebulae	6×10^{-31}			
OB stars	3×10^{-27}	2×10^{35} $^{a}10^{36}$	10^{39}	10^{-3}
MI	10^{-31}	2×10^{34}	3×10^{38}	7×10^{-5}
MII	2×10^{-31}	2×10^{33}	4×10^{37}	5×10^{-5}
M5–8 III	5×10^{-33}	10^{32}	7×10^{36}	1.5×10^{-5}
M3–4 III	10^{-32}	3×10^{31}	4×10^{36}	8×10^{-6}
Novae	5×10^{-29}			
Supernovae	3×10^{-27}			

[a] The kinetic energy is given because in this case it is greater than the potential energy. In all the other cases it is substantially less.

of energy than the hot stars. We can therefore conclude that, while stellar mass loss may supply the material to the interstellar medium, it does not at the same time supply the energy.

D. ENERGY SOURCE FOR THE MASS LOSS

The loss of potential energy required to carry the material from the surface of the star to infinity is given in column 3, Table II. It is generally greater than the kinetic energy in the mass flow, except in the case of the OB stars, where the kinetic energy is also listed in the table. We may compare this energy with the energy which the star radiates, its luminosity shown in column 4. This ratio is given in column 5. The ratio is seen to vary by several orders of magnitude for the different objects; it may be an important number in considering the origin of the mass loss. For example if the radiation pressure drove the mass flow in OB supergiants it would have to be quite an efficient process [see also the relevant remarks made in the following Discussion (Ed.)].

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