MASS LOSS FROM STARS AND THE CHEMICAL EVOLUTION OF THE INTERSTELLAR MEDIUM

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Abstract: Mass loss from stars returns processed as well as unprocessed material to the interstellar medium, and thus enriches it in helium and heavy elements. In this very brief review we outline the theory of the chemical evolution of the interstellar medium.

1. Introduction

The formation of stars consumes gas. Evolving stars, such as red giants or supergiants, or planetary nebulae and supernovae expel mass. Since remnants like white dwarfs or neutron stars are the last known stage of stellar evolution, there is a net consumption of gas.

The amount and chemical composition of the gas expelled by evolving stars is rather uncertain. Schmidt (1959) has estimated a total of $\sim 5 \ 10^{-10}\ M_\odot\ pc^{-2}\ yr^{-1}$; Tinsley and Ostriker (1976) find about $8 \cdot 10^{-10}\ M_\odot\ pc^{-2}\ yr^{-1}$.

a) The mass loss from red giants and supergiants has been estimated by Fusi-Pecci and Renzini (1975a, b, 1976), Reimers (1975, 1977), Sanner (1976), Bernat (1977) and others. The contribution (including Miras) is $\sim 1 - 4 \ 10^{-10}\ M_\odot\ pc^{-2}\ yr^{-1}$. The observed chemical composition of the returned material is essentially normal *i.e.*, Solar System (cf. Cameron 1970), as derived from abundance determinations of the atmospheres. Some enrichment in ^{13}C is well established (Day et al., 1973, Lambert et al., 1974, Tomkin and Lambert 1974, Tomkin et al., 1975, Dearborn et al., 1975, Hinkle et al., 1976, Tomkin et al., 1976, Lambert and Sneden 1977).

b) The mass loss from planetary nebulae has been estimated by Osterbrock (1973), Alloin et al. (1976), and others. The contribution is of the order $1 - 2 \ 10^{-10}\ M_\odot\ pc^{-2} yr^{-1}$. The observed chemical composition does not present a homogeneous picture. Enrichment as well as deficiency of some elements is found (Peimbert and Torres-Peimbert 1971, Boeshaar 1975, Osmer 1976).

c) The mass loss from supernovae has two parts: First, the part that is expelled before the explosion while the star is still a red giant or supergiant, and second, the part which is expelled in the explosion. There is no good observational evidence as to the enrichment produced by supernovae; there is only indirect evidence (Gunn and Ostriker 1970, Ostriker and Gunn 1971). The mass range of stars which produce supernovae has been discussed recently by Tinsley (1975a), Fusi-Pecci and Renzini (1976), Taylor and Manchester (1977),

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Weidemann (1977), Wood and Cahn (1977), and Tinsley (1977a). Because of the observational uncertainties, the calculated contribution of supernovae to the enrichment of the interstellar medium is usually based on several assumptions: 1) An adopted luminosity function for high mass stars; 2) Arnett's calculations of the late stages of stellar evolution (cf. Talbot and Arnett 1974); 3) an adopted remnant mass, and 4) an adopted mass range for the progenitor stars. The contribution in enriched material is then of the order of a few percent of the total return rate from stars.

d) There is no well established evidence that any other stage of stellar evolution contributes significantly to the entire mass loss from stars; the contributors listed above can account for the required return rate within the uncertainties. However, Coleman and Worden (1976) find that flare stars provide the dominant contribution; this suggestion should be checked because of its obvious bearing on our understanding of galactic evolution. On the other hand the contributions of novae, and quite possibly other stars (OB stars, Wolf-Rayet stars, carbon stars,...), to the enrichment of the interstellar medium in certain isotopes is likely to be important. The observational evidence has been reviewed at this conference.

A number of conferences and reviews have concentrated on the subject. The most recent reviews are Trimble (1975), Audouze and Tinsley (1976), and Tinsley and Ostriker (1976). A large part of the theory is contained in Tinsley (1974).

In the following we'll discuss star formation and the consumption of gas in section 2, the enrichment in primary nucleosynthesis elements in section 3, and the enrichment in secondary nucleosynthesis elements and isotopes in section 4. In section 5 we'll briefly mention deuterium and other isotopes. In section 6 we'll conclude by listing various unproven assumptions that go into these considerations. For lack of space, we'll not discuss the interesting observations and calculations of s-, p- and r-process elements. For such a discussion the reader is referred to Trimble (1975).

We assume throughout the conventional picture of a standard big-bang (Wagoner 1973), in which all of the ^1H, all of the ^2H, some of the ^3He, most of the ^4He, some of the ^7Li and little else was originally there.

2. Star formation and the consumption of gas

We define b(m,t) dm dt as the number of stars born in the mass interval m, m + dm and the time interval t, t + dt. Then the following integral gives the total consumption of gas by star formation per unit of time:

$$\Psi(t) = \int_0^\infty m\ b(m,t)\, dm\ .$$

If the distribution of stars formed over different masses is constant, then b(m,t) can be

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split up into

$$b(m,t) = \varphi(m)\ \Psi(t)$$

with

$$\int_0^\infty m\ \varphi(m)\, dm = 1 .$$

We will use this assumption in the following. The initial mass function, IMF, $\varphi(m)$ can be derived from open stellar clusters, or the luminosity function in the solar neighborhood and an adopted history of star formation (Salpeter 1955, Schmidt 1963, Truran and Cameron 1971, Quirk and Tinsley 1973, Biermann and Tinsley 1974, Torres-Peimbert et al. 1974, Ostriker et al. 1974, Wielen 1974, Tinsley and Ostriker 1976). Often a power-law distribution is adopted. There are only few attempts to derive this function theoretically, by Larson (1973) and Silk (1977a,b,c). Theoretical work on the lower end of the IMF (Low and Lynden-Bell 1976, Rees 1976) as well as on the upper end (Larson and Starrfield 1971, Kahn 1974) suggests that the IMF varies with the abundance of the heavy elements. The observational evidence (van den Bergh 1976, Olson and Pena 1976) indeed indicates varying fractions of OB stars among new stars formed in different galaxies. The net consumption of the gas present, M_g, in an isolated zone of a galaxy is governed by the formation of stars, $-\Psi(t)$, and the mass loss from stars during their evolution (mostly at the end of their lifetime). We define as r_m the mass which a star of mass m returns at the end of its life τ_m to the interstellar medium, and as $m(t)$ the mass of those stars which live for time t (i.e. the inverse of τ_m). Then

$$\frac{dMg}{dt} = -\Psi(t) + \int_{m(t)}^{\infty} r_m\ \varphi(m)\ \Psi(t-\tau_m)\ dm . \qquad (1)$$

If τ_m for those stars that put out most of all the mass ejected is small compared to the relevant time scale of the evolution of the interstellar medium, we can approximate the integral as a constant independent of time:

$$\begin{aligned}\frac{dMg}{dt} &\simeq -\Psi(t) + \Psi(t) \int_{m(t_1)}^{\infty} r_m\ \varphi(m)\ dm \\ &= -\Psi(t)\ (1-R) .\end{aligned} \qquad (2)$$

where t_1 is today. The approximation used here is called the "instantaneous recycling approximation", IRA.

For the very simple assumed law $\Psi = M_g/\tau_F$ we find then $M_g = M_{go} \exp(- t\frac{1-R}{\tau_F})$.

The index "zero" refers to the initial state. In the solar neighborhood, τ_F is of the order of several billion years (Tinsley 1977b). We have neglected here loss or infall of gas into the zone considered; infall has been considered by, e.g., Tinsley (1974, 1976), loss has

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been considered by Biermann (1977).

3. The enrichment in primary nucleosynthesis elements

The available theoretical evidence as to what stars of a given mass contribute in ^4He, ^{12}C, ^{16}O,... to the interstellar medium has been summarized by Talbot and Arnett (1974). The total amount of mass in heavy elements $Z\ M_g$ is governed by consumption of gas of the present composition $Z(t)$ (i.e. mass fraction), ejection of gas from old stars of the original composition $Z(t-\tau_m)$, and enrichment of the gas by newly processed material. We define as p_m the mass a star of mass m contributes to the heavy elements at the end of its life. Then

$$\frac{dZM_g}{dt} = -Z(t)\ \Psi(t) + \int_{m(t)}^{\infty} [(r_m - p_m)\ Z\ (t-\tau_m) + p_m]\ \varphi(m)\ \Psi(t-\tau_m)\ dm$$

$$\simeq -\Psi(t)\ Z\ (t)\ (1-R+P) + P\,\Psi\ . \tag{3}$$

Corresponding equations can be written for each element or isotope (cf. Talbot and Arnett 1973a, and Tinsley 1974). The second part of the equation again uses the IRA. Here the additional assumption is made that the interstellar medium, ISM, is well mixed. For a theory of metal-enhanced star formation and slow mixing of the ISM, see Talbot (1974) and Talbot and Arnett (1973b).

Subtracting eq. (2), after multiplying with Z, from eq. (3), and then dividing by eq. (2) gives

$$\frac{dZ}{1-Z} = -\frac{P}{1-R}\ d\ \ln\ M_g/M_{go}\ .$$

which yields upon integration with $Z_o = O$:

$$Z = 1 - (M_g/M_{go})^{P/(1-R)} \tag{4}$$

For $Z \ll 1$ this changes to the familiar form (Searle and Sargent 1972)

$$Z = -\frac{P}{1-R}\ \ln\ M_g/M_{go} \tag{5}$$

Here we have to emphasize that eqs. (4) and (5) do not depend on the history of star formation. They do, obviously, depend on the assumption that the IMF is constant (since P and R are assumed constant). Again we have neglected losses and gains of the zone considered, as well as sinks of heavy elements such as comets might be (Tinsley and Cameron 1974).

Adopting again $\bar{\Psi} = M_g/\tau_F$ we find

$$Z = P \cdot t/\tau_F\ . \tag{6}$$

Detailed computer calculations with the above law of star formation also show this linear

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behaviour and thus confirm the reliability of the IRA for τ_F greater than about 2 billion years.

This latter linear behaviour of Z with time is commonly referred to as the "standard model". Present observational evidence does not allow a definite conclusion as to whether this law is reflected in reality, but this linear behaviour would be somewhat surprising (cf. Tinsley 1957b, Biermann and Biermann 1977).

Equation (5) has the important consequence that to within the validity of the IRA all primary abundances should vary together, including the enrichment in helium. The observational evidence is not entirely clearcut (e.g. Hearnshaw 1972, Smith 1975, Bell and Branch 1976, Nissen 1976, Peterson 1976, D'Odorico et al. 1976, Henry et al. 1977, Demarque and McClure 1977); this point has been discussed also in some detail by Tinsley (1976).

4. Enrichment in secondary nucleosynthesis elements and isotopes

Trimble (1975) discusses in her review a large number of isotopes of interest here. We will concentrate on the well observed isotope ^{13}C, and the curious case of nitrogen. ^{13}C is found in relatively large amounts in red giants (see above) for which the abundance ratio $^{12}C/^{13}C$ is typically much smaller than 89, the terrestrial value. The ratio $^{12}C/^{13}C$ in the interstellar medium (i.e. molecular clouds) has been reviewed by Wannier et al. (1976) and by Wilson and Bieging (1977); a value of about 40-50 seems to be indicated for our galaxy. The sources for the various isotopes of the elements C, N, O have been discussed by Audouze et al. (1975) and by Cowan and Rose (1977). In the same vein as before the enrichment can be written as an integral which in turn can be approximated with the IRA as:

$$\frac{d\, M_g Z_{sec}}{dt} = - Z_{sec}\, \Psi(t)\, (1-R) + P_{sec}\, Z\, \Psi\, . \qquad (7)$$

Here $M_g Z_{sec}$ is total mass of secondary nucleosynthesis elements in the ISM, and we have adopted the simple relation P_{sec} Z for the production. Combining eq. (7) with eqs. (3) and (2) we again get an expression which is <u>independent</u> of the history of star formation:

$$\frac{d\, Z_{sec}}{dZ} = \frac{P_{sec}}{P}\, \frac{Z}{1-Z}\, .$$

This is integrated to

$$Z_{sec} = - \frac{P_{sec}}{P} \left\{ \ln (1-Z) + Z \right\} \simeq \frac{1}{2}\, \frac{P_{sec}}{P}\, Z^2\, . \quad (8)$$

for $Z_{sec}(t=0) = 0$ and $Z \ll 1$ (right hand side). Detailed numerical calculations again show that the relation $Z_{sec} \sim Z^2$ is good for $\tau_F > 2\ 10^9$ years.

An important conclusion can be drawn from eq. (8): If we observe a radial abundance gradient in a galaxy for Z (carbon, oxygen,...), then $Z_{sec}/Z \sim Z$ should show the same gradient. If, for instance, nitrogen were all secondary, then N/O should show the same gradient as O/H. The observational evidence (Smith 1975, D'Odorico et al. 1976) implies that a considerable fraction of nitrogen is indeed secondary. Observations of the SMC (Dufour and Harlow 1977) suggest the opposite. In short, the history of nitrogen is not understood at present.

5. Deuterium and other isotopes

There is no evidence that deuterium is made anywhere in the universe after the big-bang; however, this question is not finally settled (Wagoner 1973, Reeves et al. 1973, Audouze et al. 1976, Epstein 1977). Deuterium is destroyed in stars and the ejected material contains no deuterium. Thus, in the IRA, the amount of deuterium Z_D in the ISM is given by

$$\frac{d\, M_g\, Z_D}{dt} = -\Psi(t)\, Z_D \qquad (9)$$

Combination with eq. (2) gives

$$Z_D / Z_{Do} = (M_g / M_{go})^{R/(1-R)} \qquad (10)$$

again <u>independent</u> of the history of star formation. Measured abundances of deuterium in the ISM (Rogerson and York 1973, York and Rogerson 1976, Vidal-Madjar et al. 1977) give $N(D)/N(H) = 1 - 2\ 10^{-5}$ and are consistent with this relation and the standard big-bang (Gott et al. 1974).

^{3}He is discussed by Rood et al. (1976).

Most of the isotopes of the light elements Li, Be, B can be accounted for by spallation of the ISM by galactic cosmic rays (Meneguzzi et al. 1971, Reeves 1974, Audouze and Tinsley 1974, Epstein et al. 1976, Hainebach et al. 1976, Clayton and Dwek 1976, Scalo 1976).

Radioactive isotopes are studied as abundance ratios which can be used as chronometers for galactic evolution (cf. Hainebach and Schramm 1976, 1977, Tinsley 1977b).

For a detailed discussion of other elements the reader is referred to Trimble (1975).

6. Uncertainties and questions

Some of the uncertainties involved in studies of the chemical evolution have been listed above. We will comment on some more points here (cf. also Audouze and Tinsley 1976):

a) We have assumed that the fate of a star is only determined by its mass, and <u>not</u> by rotation, magnetic fields or binary nature. We know from novae that this is wrong. We may suspect that rotation also plays a role (cf. Weidemann 1971, 1977).

b) We have assumed that the evolution of a star does not depend on its initial composition. Also this is known to be wrong, since the lifetimes of stars (e.g. Wagner 1974) depend on

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their chemical composition, and quite likely their fate does so too.

c) Since the prime source of enrichment is supernovae, a considerable effort should be made to determine the mass range of the stars that explode. Discoveries of supernovae remnants in open clusters (Pauls 1977) can provide a unique way of getting the masses of the stars involved.

d) Obviously, our understanding of mass loss in red giants and supergiants should be improved beyond the semiempirical stage.

e) Since novae seem to be good candidates for the sources of some interesting isotopes of the CNO-group, work on them should be continued (cf. Starrfield et al. 1972, 1974a,b, Sparks et al. 1976, Colvin et al. 1977; Williams, Thomas, and Shaviv at this conference).

f) Other sources of relevant mass loss should be checked like flare stars (Coleman and Worden 1976), P Cygni stars (de Groot 1969; Appenzeller 1970), OB stars (Lucy 1975, Barlow and Cohen 1977), Wolf-Rayet stars (Underhill 1969), carbon stars,... . They all might be relevant, and we don't know at present.

So, as a theoretician, I close with an appeal to the observes: observe more!

Acknowledgements: *This work was supported by the DFG (SFB 131). I wish to thank* Dr. T. L. Wilson for discussions about the material in this manuscript.

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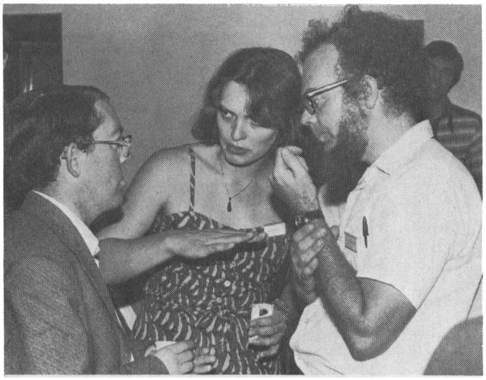

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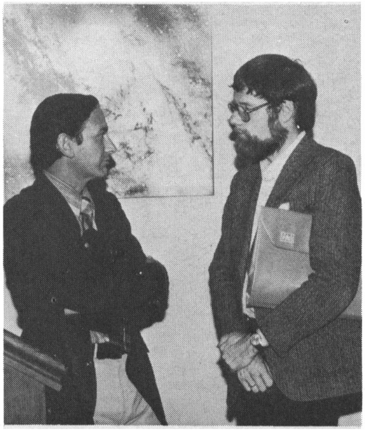

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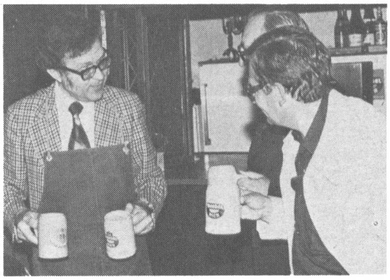

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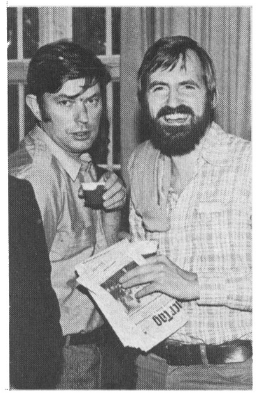

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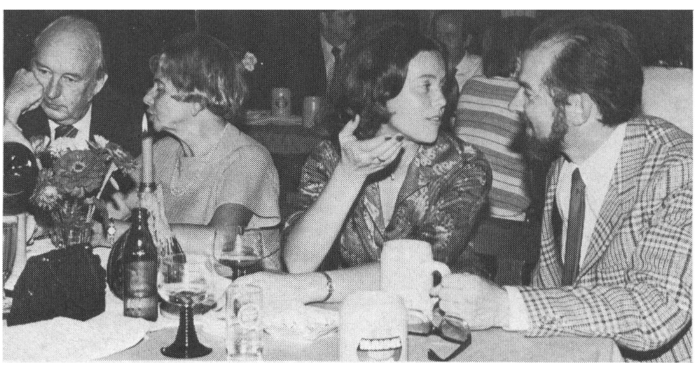

Wood Mrs. Gerneth Mrs. Knigge Mauder

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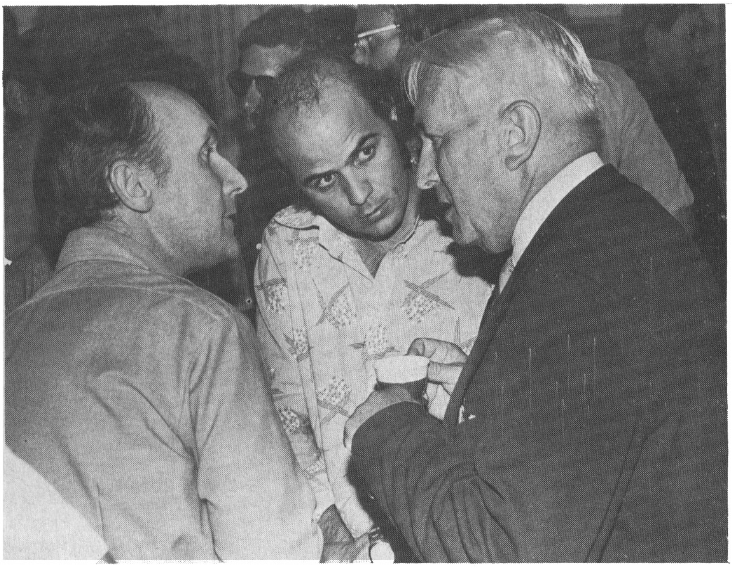

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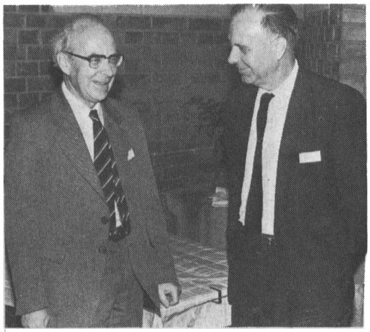
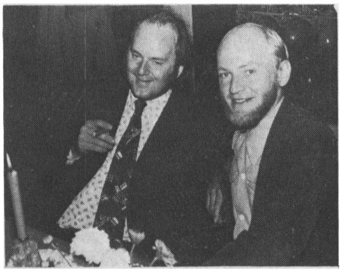


Hinderer Walker

Budding Wilson



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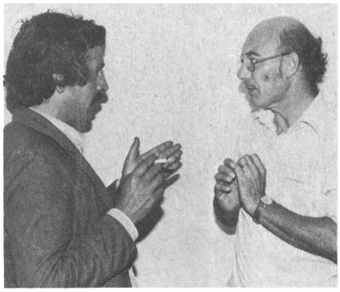

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