PART II

INTERACTION OF STARS AND INTERSTELLAR MEDIUM

14. MASS BALANCE OF INTERSTELLAR GAS AND STARS

Introductory Report

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1. Introduction

In this paper I will deal almost exclusively with the interchange of matter between the interstellar gas and the stars. Other possible forms of interchange, such as mass-loss to and accretion from intergalactic matter *e.g.*, Oort's (1969) views on mass flowing into our Galaxy, will be discussed later I hope.

One topic of interest is the empirical study of the present-day rates of the mass interchange between gas and stars in our Galaxy. The present value of the birthrate of massive, short-lived stars can be obtained directly from the observed luminosity function and from the theoretically known lifetimes of stars on the main sequence. The rate at which mass is returned from ageing stars to the gas can also be obtained in principle, but this requires a theoretical knowledge of *late* stages of evolution of stars and is quantitatively less reliable. These rates are discussed in Section 2.

In Section 3 we review theoretical models of a semi-empirical kind for the evolution of our Galaxy, in particular for the variation with time of the stellar birthrate function and of the total mass of the interstellar gas $M_{\text{gas}}(t)$. We also discuss briefly the evolution of other types of galaxies from the point of view of such models. Such models are of interest for two reasons. First, they are required to infer the present birthrate of stars of low mass, whose main-sequence lifetimes are very long. Second, they should shed some light on the correlation between the birthrate function and some physical variables, such as the mean gas density (and possibly angular momentum, chemical composition, etc.). Unfortunately we shall find too many unknowns and too few observations at present for any definitive conclusions on such models. In Section 4 I shall review briefly physical theories which attempt to derive the mass interchange between gas and stars from first principles.

This paper should be considered as an introduction to the topics, not a review of them. Few references will be made to the recent literature, especially for the topics of Section 3, for the simple reason that I am not sufficiently familiar with it. Nevertheless, I hope that even a dated introduction can stimulate discussion.

2. Present Rates

Throughout this paper we shall be concerned with the birthrate function $\xi(M, t)$

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* Dr. L. Mestel read this paper for Dr. Salpeter who, for personal reasons, could not be present.

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which determines the rate at which stars of mass M are formed out of the interstellar gas at time t after the formation of the Galaxy. We define this function so that the number of stars dN formed in mass-interval dM and time-interval dt is given by

$$\mathrm{d}N = \xi(M, t)\frac{\mathrm{d}M}{M}\,\mathrm{d}t\, M_{\mathrm{gas}}(t), \tag{1}$$

where M_{gas} is the total mass of the gas in which the stars are formed. If

$$f(t) = \int_0^\infty \xi(M, t)\,\mathrm{d}M \tag{2}$$

then f^{-1} is the exponential decaytime of the unprocessed gas. One question we shall ask is how strongly ξ and hence f depend on time t.

The present age t_0 of our Galaxy lies in the range of (8 to 20) × 10^9 yr, probably close to 10×10^9 yr (Rood and Iben, 1968). We shall express time t in units of t_0 and shall find that the precise value of t_0 is important only for a few considerations. For the total mass M_{Gal} of our Galaxy we adopt a value of $1.0 \times 10^{11}\, M_\odot$ (Inanen, 1966). The fractional mass in gaseous form, $M_{\mathrm{gas}}(t)/M_{\mathrm{Gal}}$, is also of interest and we assume the present value of this ratio to be about 0.2 in the vicinity of the Sun (integrated over a column perpendicular to the galactic disk) and about 0.04 for the whole Galaxy.

The most important observational datum for our present purposes is the present luminosity function φ for main-sequence stars near the Sun (also integrated over a column perpendicular to the galactic disk). At least for stellar masses M in the range $0.2\,M_\odot$ to $10\,M_\odot$, we know the visual magnitude, bolometric luminosity and lifetime t_{MS} on the main sequence as a function of M. It is convenient to discuss separately three mass-ranges of stars. For massive stars, $M \gtrsim 2\,M_\odot$, the main-sequence lifetime t_{MS} (which is roughly proportional to M^{-3}) is very much shorter than the present age t_0 of the Galaxy. Changes of the birthrate function $\xi(M, t)$ or of the gas-mass over the lifetime of one star can then be neglected. With the present luminosity function φ also re-expressed per logarithmic stellar mass interval and per gas mass, this gives

$$\varphi(M) = t_{MS}\xi(M, 1). \tag{3}$$

For stars of low mass on the other hand, $M \lesssim 0.5\,M_\odot$, we have $t_{MS} \gg t_0$. In this case stellar evolution can be neglected but galactic evolution enters the relation between φ and ξ,

$$\varphi(M) = \int_0^{t_0} \mathrm{d}t\, \xi(M, t)\,[M_{\mathrm{gas}}(t)/M_{\mathrm{gas}}(1)]. \tag{4}$$

For the intermediate mass range, (0.5 to 2) $M_\odot$, the relationship is more complicated.

The relation between ξ and φ (each multiplied by M, on an arbitrary scale) is shown schematically in Figure 1. The original suggestion by Salpeter (1954) of Equation (3) is gratifying in two ways: (i) the combination $M\varphi/t_{MS}(M)$ is a slowly-varying

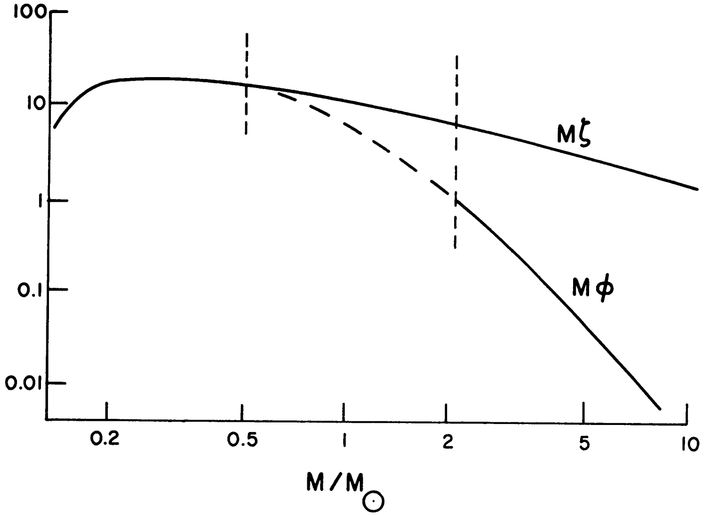

Fig. 1. A schematic plot of the present luminosity function φ and of the birthrate function ξ (on a logarithmic scale) as a function of stellar mass M.

function of M for the massive stars, as is $M\ \varphi$ for the stars of low mass; (ii) the shape of the observed luminosity function for massive stars in very young clusters (Sandage, 1957; Van den Bergh, 1957) (where even massive stars have not yet evolved away from the main sequence) agrees with the shape of ξ (as given by Equation (3) for the vicinity of the Sun).

For the massive stars, $M \gtrsim 2\ M_\odot$, observations plus Equation (3) give the present value of the birthrate function ξ (in the solar vicinity) with little ambiguity (but we have no direct information on values of ξ at earlier epochs). For the low-mass stars, on the other hand, Equation (4) only gives a weighted time-average of ξ and a model for the time-dependence is needed to infer the present value of ξ. Adopting such a model (discussed in the next section) one can then estimate ξ (M, 1) for all M in the solar vicinity. If one uses the same value of ξ (M, 1) throughout the Galaxy, the total rate of processing mass from interstellar gas into stars is about 1 $M_\odot$ yr^{-1} for the whole Galaxy, i.e. about 2.5 M_{gas}/t_0. This value is uncertain by factors of about 2 or 3, partly because of the uncertainty in the models for galactic evolution and partly because φ (and hence ξ) for stars of very low luminosity and mass ($M < 0.1\ M_\odot$) is poorly known (Luyten, 1968).

One difficulty we face is that we do not know how typical the solar vicinity is for the overall pattern of the interstellar gas and dust in other parts of the galactic disk. The *mean* density of neutral atomic hydrogen is not very different in regions closer to the galactic nucleus (where the density of stars is very much higher), but we have little direct information from these regions on dust density and on the nature of density fluctuations (regarding chemical composition, see Section 3). Since we do not even know in what direction these uncertainties affect the rate of star formation, we had to assume a uniform value for $\xi(M,\ 1)$ in the estimate above. Another unsolved and important question (especially regarding chemical composition) is whether thorough interchange (or net flow) of interstellar gas between various regions of the galactic disk can take place in timescales of the order of 10^{10} years.

We consider next the other aspect of the gas-star mass-interchange, the matter put back into the interstellar gas from highly evolved stars (see also in this volume the Introductory Reports by Pottasch, p. 272, and by Boyarchuk, p. 281). There are a number of possibilities: (i) continuous mass-loss (in the red-giant stage or in later evolutionary stages) leads to a white dwarf as the remnant star. Supernovae explosions could lead to a remnant core in the form of (ii) a white dwarf or (iii) a neutron star or (iv) a collapsed 'invisible' object. Observed masses of white dwarfs (Weidemann, 1968) lie mainly in the range of (0.4 to 1) $M_\odot$, with $0.6\,M_\odot$, or slightly larger (Greenstein and Trimble, 1967), a 'typical' value. Neutron star masses can only be estimated theoretically but are likely to be comparable to white dwarf masses. There is no upper limit to the mass of collapsed objects and in case (iv) it is possible that little mass returns to the interstellar gas. Estimates for the present rate of supernovae explosions (Minkowski, 1964; Katgert and Oort, 1968) vary from one per 300 years to one per 30 years, but even the higher rate would represent only about half of the present rate of star deaths. For the present Galaxy we shall therefore assume that for a star of initial mass M an amount $(M - 0.6\,M_\odot)$ is eventually returned to the interstellar gas.

For the star deaths it is again convenient to discuss the three separate ranges of stellar mass. The low-mass stars, $M \lesssim 0.5\,M_\odot$, have not evolved from the main sequence and mass loss from these stars can be neglected. For the massive stars, $M \gtrsim 2\,M_\odot$, the uncertainty in the returned mass $(M - 0.6\,M_\odot)$ due to uncertainty in the mass of the remnant star is small. Further, the time delay between birth and death for these massive stars is short, so that the rate of mass return from them is proportional to the present gas mass. This contributes about $0.5\,M_{\mathrm{gas}}/t_0$ (about $0.2\,M_\odot\,\mathrm{yr}^{-1}$ for the whole Galaxy) or about one fifth of the rate of mass transfer from the gas to stars.

The situation is more complicated and more uncertain for the stars of intermediate mass. Uncertainties in the present age of the Galaxy and inaccuracies in stellar evolution calculations lead to an uncertainty in the initial mass of Population II stars (of age near t_0) which have evolved past the red-giant stage. The value lies in the range (0.8 to 1.0) $M_\odot$ (Rood and Iben, 1968). Since white-dwarf masses are not much smaller and are also slightly uncertain, there is considerable uncertainty in the average mass returned to the gas from old stars of intermediate mass. For the solar vicinity this rate, and hence its uncertainty, is not very great and the total rate of mass conversion from stars back into gas is probably 0.3 to 0.4 times the rate from gas into stars. There is thus no doubt that the net result in the solar vicinity is mass drainage away from the gas. For the Galaxy as a whole the ratio of old stars to gas is very much greater, the mass interchange from gas to stars and back again is more nearly balanced (Partridge and Peebles, 1967). (The backward rate is probably 0.5 to 1 times the forward rate.) There is then the possibility that near the galactic nucleus the net result is actually a slight enhancement of the interstellar gas from the stars (with approximate balance most likely).

3. Evolutionary Models

We review next evolutionary models of a galaxy, i.e. the time-dependence of the birthrate function $\xi(M, t)$ and of the mass in gaseous form $M_{\text{gas}}(t)$. There clearly is not enough observational data to determine ξ uniquely, so one has to assume certain forms and study their consequences.

Salpeter (1959) investigated in detail the consequences of the simplest form, namely a time-independent 'universal' birthrate function $\xi(M)$. The quantity f in Equation (2) is then also time-independent and the fraction of the galactic mass in gaseous form would simply decay exponentially as e^{-ft} if there were no transfer of mass back from stars to gas. With this transfer included, the gas mass $M_{\text{gas}}(t)$ for the whole Galaxy drops rapidly at first as a function of time and then almost levels off. The next simplest assumption keeps a 'universal shape' for the birthrate function but allows the overall rate function $f(t)$ in Equation (2) to depend on time through the gas density. Schmidt (1959) discussed the specific form

$$\xi(M, t) = \xi(M)\left[M_{\text{gas}}(t)/M_{\text{gas}}(1)\right]^{n-1}. \tag{5}$$

These two papers suggest that $f(t)$ must have decreased with time. The data are probably compatible with $n \approx 2$ in Equation (5), although some arguments have been advanced (Reddish, 1962) against a unique dependence of the form of Equation (5) with $n > 2$.

The assumption of a 'universal shape' of $\xi(M, t) = \xi(M) f(t)$ has encountered difficulties (Limber, 1960). One manifestation is a difference in the shape of the observed luminosity function between star clusters (young and old) and the solar vicinity in the mass-range from $0.2\,M_{\odot}$ to $0.8\,M_{\odot}$: in the clusters the stars of lowest mass are less dominant, even though effects of stellar evolution are negligible in this mass-range. This discrepancy may in part be due to evaporation of stars from clusters, but at any rate clusters cannot furnish a 'universal function' and the time-dependence of $f(t)$ cannot be evaluated quantitatively at the moment.

Two important and relevant topics, which I will only mention but not discuss, are the helium abundance in the interior and surface of various stars and the spectroscopically-determined metal abundance Z in the surface of various stars (Cayrel and Cayrel-de Strobel, 1966). Very detailed correlations exist (Eggen *et al.*, 1962) between Z and the kinematics and age of a star, as expected from the continual enrichment of the interstellar gas from star deaths. The data indicates that the Galaxy started without any metals and that an appreciable fraction of the Population II stars formed (Eggen *et al.*, 1962) in much less than 10^9 years. Statistical data on Z also provides evidence against the universality of the birthrate function: an argument by Schmidt (1963) (independent of the quantitative time-development) shows that the earliest star formation favored stars which were more efficient at metal production, which probably means massive stars.

An interesting but unsolved question for these evolutionary models is whether they can give the helium abundance in the Sun and in the present-day gas in terms of He formation in stars (assuming pure H for the proto-Galaxy). The answer depends on details of mass-loss from various stars and on the age and state of mixing of the Galaxy. If t_0 is appreciably larger than 10×10^9 years and if the chemical composition is fairly uniform throughout the Galaxy, the answer is yes (Truran *et al.*, 1965). If $t_0 \lesssim 10 \times 10^9$ years and if the interstellar gas is unmixed, much of the helium in the solar vicinity would have to be primordial (but with appreciable He enrichment from stars near the galactic nucleus). There is conflicting evidence from the analysis of individual old stars, on the actual helium abundance of the primordial gas (Burbidge, 1969).

For other types of galaxies the present mass-ratio of gas to stars increases strongly from elliptical through spiral to irregular galaxies. The different galaxy types are not believed to be due to different ages (Tinsley, 1968) but must reflect differences in the birthrate function $\xi(M, t)$. With what physical properties of different galaxies are these differences correlated? It has been suggested that the generally higher total mass density in elliptical galaxies is the main cause (Holmberg, 1967; see also Fish, 1964; Salpeter, 1965). This requires a birthrate function positively correlated with mean gas density (such as Equation (5) with $n \gtrsim 2$) and predicts a present absolute gas density almost the same for different types of galaxies. This is more or less the case and, although there are some difficulties with Holmberg's hypothesis, there seem to be no attractive alternative suggestions for correlations with other physical variables (Reddish, 1968). Comparison between elliptical galaxies and the extreme stellar Population II in our Galaxy again indicates a lack in universality of the birthrate as a function of mass: although both represent old stars with little gas present, the mass-to-light ratio is appreciably greater for the elliptical galaxies. This indicates a preponderance of stars of low luminosity and presumably low mass. However, this could be due to either of two different features of $\xi(M)$ for ellipticals (i) a preponderance of faint main-sequence stars of very low mass ($M < 0.4\,M_\odot$) or (ii) predominant production at early times of very massive stars ($M > 2\,M_\odot$) which had a high luminosity then, but have become low-luminosity white dwarfs or neutron stars since.

To summarize the evidence on the birthrate function $\xi(M, t)$ and its integral $f(t)$, as defined in Equations (1) and (2): f has been decreasing with time in our Galaxy as the total gas mass has been decreasing. One cannot be quantitative yet, but f might well be proportional to the average gas density $\bar{\varrho}$ i.e. star formation rate per unit volume might be proportional to the square of $\bar{\varrho}$ (or possibly a slightly weaker dependence on $\bar{\varrho}$). The distribution of the birthrate among stars of different mass cannot be 'universal'; the more massive stars are probably favored at early times when $\bar{\varrho}$ was higher. The correlation of the birthrate function with chemical composition, turbulence, and angular momentum of the interstellar gas or with magnetic field intensity and cosmic-ray fluxes (which also may vary with time) is not yet known.

4. Physical Theories

I shall briefly review Oort's (1954) physical picture of small gas clouds coalescing, followed by star formation, followed by bright stars re-dispersing small clouds. Such physical theories are slightly modified in the light of more modern ideas (Pikel'ner, 1967; Field *et al.*, 1969) on static pressure equilibrium between interstellar clouds and a hotter, partially-ionized medium in H I regions [see the Report by Field, p. 51 and the remark by Pikel'ner, p. 359 (Ed.)].

When an interstellar gas cloud becomes large enough for gravitational instability, some stars are formed during the contraction and fragmentation. Some of these newly-formed stars are hot enough to produce copious ionization and dynamic effects. The dynamic effects are pictured as the dispersal of small clouds with velocities comparable with that of a hydrogen atom of kinetic energy equal to its ionization potential, $V \approx 51$ km sec^{-1}. If all the clouds coalesce after colliding (and remain at constant internal density) until they reach a critical mass for star formation, the mass-spectrum (Field and Saslaw, 1965) and velocity distribution (Penston *et al.*, 1969) of the clouds can be predicted. Such estimates are in reasonably good agreement with observation, although the observed velocity dispersion decreases more slowly with increasing cloud mass then predicted.

The overall rate of star formation as a function of average gas density can be calculated with such a picture only if an assumption is made on how the internal density ϱ_i in a cloud depends on $\bar{\varrho}$, the overall gas density. If one assumes with Field and Saslaw (1965) that ϱ_i is independent of $\bar{\varrho}$ (assuming $\varrho_i \gg \bar{\varrho}$, of course), then the rate per unit volume of cloud-cloud collisions and hence of star formation is proportional to $\bar{\varrho}^2$. If the thickness of the galactic disk did not change with time, then $\bar{\varrho}$ decreased proportionally to M_{gas} and the picture would lead to $n=2$ in Equation (5). However, to dissipate enough energy by radiation after a cloud-cloud collision, the temperature (and possibly magnetic field strengths) would have to be correlated with $\bar{\varrho}$. The thickness of the galactic disk might also have evolved slightly with time.

Attempts at deriving the birthrate ξ as a function of stellar mass M from first principles have so far been made only for one rather specific model (Reddish and Wickramasinghe, 1969) – fragmentation in clouds which have been cooled to about 3 K by efficient grain radiation. This model predicts $\xi \propto M^{-(1 \text{ to } 1.5)}$ within a certain range of masses, in rough agreement with observation. On this model, and probably more generally, the dominant masses of the forming stars are inversely correlated with the internal density in the condensed cloud at the onset of fragmentation. Unfortunately, it is not clear how this density is related to the density ϱ_i of a cloud before its gravitational contraction, or to the mean gas density $\bar{\varrho}$ of the galactic disk.

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