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GAS LOSS IN GROUPS OF GALAXIES

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Estimates are made of the total amount of mass and the total amount of heavy elements expected to be lost during the early evolution of the galaxies in a typical group or cluster. The estimated amount of gas lost is roughly one quarter of the mass present in galaxies, and the metal abundance of the lost gas is essentially solar. Several possibilities concerning the fate of the gas lost from galaxies are discussed.

Key words: galaxies — galactic winds — intergalactic gas

I. Introduction

During their early evolution, galaxies of small or moderate mass may lose a significant fraction of their initial mass as a result of supernova heating of the residual gas and its expulsion in a hot galactic wind (Larson 1974*b*). The continuing presence of such winds during later stages of galactic evolution may account for the general absence of significant amounts of gas not only in elliptical galaxies but also in the bulge components of spirals (Mathews and Baker 1971; Faber and Gallagher 1975). In the present paper we estimate how much gas is likely to be lost in this way and returned to the intergalactic medium from the galaxies in a typical group or cluster; this question is of obvious interest for an understanding of the evolution of the intergalactic medium in or near a group of galaxies. The gas lost from galaxies is expected to be significantly enriched in heavy elements, and therefore it is also of interest to estimate the quantity of heavy elements added to the intergalactic medium by gas loss from galaxies.

On simple energetic grounds, it may be predicted that the fractional mass lost from a galaxy increases with decreasing galactic mass (Larson 1974*b*). Since the chemical enrichment of a galaxy is terminated when the residual gas is lost and further star formation ceases, the resulting average metal abundance is predicted to decrease with decreasing galactic mass, in qualitative agreement with the observations. In the absence of a plausible alternative explanation, this observed variation of metal abundance with galactic mass may be taken as evidence that the less massive galaxies have indeed lost significant amounts of metal-enriched gas at early stages of evolution. If it is assumed that star formation in galaxies always follows a "normal" initial mass function (Larson and Tinsley 1974), it is possible to calculate the amount of heavy elements produced during the early evolution of a galaxy of given mass and therefore, knowing the metal content retained in the galaxy, the amount of heavy elements lost to the intergalactic medium. The total amount of gas and heavy elements lost to the intergalactic medium from any collection of galaxies can then be calculated by integrating over the galactic mass spectrum.

II. Mass Loss from Individual Galaxies

Assuming that all of the residual gas in a forming galaxy is lost when the thermal energy deposited in the gas by supernovae becomes equal to the gravitational binding energy, Larson (1974*b*) derived a relation of the following form between the mass $\mathfrak{M}_g$ of gas lost, the mass $\mathfrak{M}_s$ remaining in the form of stars, and the total mass $\mathfrak{M} = \mathfrak{M}_g + \mathfrak{M}_s$:

$$\frac{\mathfrak{M}_g}{\mathfrak{M}_s} = \left(\frac{\mathfrak{M}}{\mathfrak{M}_1} \right)^{-2/3} = \left(\frac{\mathfrak{M}_g + \mathfrak{M}_s}{\mathfrak{M}_1} \right)^{-2/3} . \quad (1)$$

If one supernova is produced for each $100\mathfrak{M}_\odot$ of stars formed, if 10% of the supernova energy or 10^{50} ergs is available for driving a galactic wind, and if the escape velocity for a galaxy of $10^{11}\,\mathfrak{M}_\odot$ is taken to be 800 km s^{-1}, the value of the constant $\mathfrak{M}_1$ in equation (1) is $6 \times 10^9\,\mathfrak{M}_\odot$. However, since all of the above assumptions are uncertain, we have here simply regarded $\mathfrak{M}_1$ as a parameter, for which values of 10^9, 10^{10}, and $10^{11}\,\mathfrak{M}_\odot$ have been adopted. A comparison of the corresponding predicted $Z(\mathfrak{M})$ relations with the observations of Baum (1959) and Faber (1973) suggests that a value for $\mathfrak{M}_1$ of $10^{10}\,\mathfrak{M}_\odot$ may provide the best representation of the observations, but values of 10^9 or $10^{11}\,\mathfrak{M}_\odot$ can probably not be ruled out, pending the availability of more data and more accurate calibrations in terms of metal abundances.

In the dynamical models of Larson (1974*a*), the mass of heavy elements produced in a galaxy is approximately proportional to the mass of stars formed, the ratio or 'yield' being about 0.02. For models with gas loss, the average metal abundance $\langle Z \rangle_s$ of the remaining stars is given in Figure 4 of Larson (1974*b*) as a function of the ratio $\mathfrak{M}_s/\mathfrak{M}$. Since the total mass of heavy elements produced is $0.02\,\mathfrak{M}_s$ and the amount remaining in the galaxy is $\langle Z \rangle_s\,\mathfrak{M}_s$, the amount $\mathfrak{M}_Z$ lost from the galaxy is just the difference between these quantities, or

$$\mathfrak{M}_Z = (0.02 - \langle Z \rangle_s)\,\mathfrak{M}_s \quad . \qquad (2)$$

For a galaxy of any mass $\mathfrak{M}_s$, we can now calculate from equation (1) the mass $\mathfrak{M}_g$ of gas lost and from equation (2) the mass $\mathfrak{M}_Z$ of heavy elements lost during the early evolution of the galaxy.

III. The Luminosity Function of Galaxies

In view of the uncertainties and the possible variations in the luminosity function and hence in the mass distribution of galaxies, we have used simple analytic approximations for the galaxy luminosity function with parameters that hopefully span the likely range of possibilities. For the best studied system of galaxies, the Coma cluster, Abell (1965) has suggested that the integrated luminosity function can be approximated by two power laws intersecting at an absolute visual magnitude of about -21 (for a Hubble constant of $H = 50$ km s^{-1} Mpc^{-1}). This implies a discontinuity in the differential luminosity function at $M_V = -21$, but a similar analytic form consisting of two power laws can also be used to provide a rough approximation to the differential luminosity function. We have adopted the following representation for $\phi(M_V)$, the number of galaxies per unit interval of absolute magnitude

$$\left.\begin{array}{ll} \log\phi(M_V) = A + 0.75\,M_V, & M_V < -21 \\ \log\phi(M_V) = B + \alpha M_V, & M_V > -21 \end{array}\right\} , \qquad (3)$$

where A and B are chosen to equalize the two expressions for $\log\phi(M_V)$ at $M_V = -21$. Recent data of Rood and Abell (1973) for the Coma cluster luminosity function are roughly represented by equation (3) with a slope $\alpha \sim 0.15$ over the interval $-21 < M_V < -17$, and the data of Oemler (1974) for 'spiral-poor' and 'cD' clusters are also approximately represented by equation (3) with $\alpha = 0.15$ for $-21 < M_V < -18$. The data of Shapiro (1971) and Christensen (1975) for field spirals yield somewhat steeper slopes, with $\alpha \sim 0.25$ (Shapiro) and $\alpha \sim 0.35$ (Christensen) for $-21 < M_V < -15$. The slope for field ellipticals appears to be relatively small, but is poorly determined because of the small number of such systems. In the present calculations we have considered three values of α: $\alpha = 0$, $\alpha = 0.15$, and $\alpha = 0.25$.

For galaxies fainter than $M_V \sim -15$, data are available only for the Local Group (van den Bergh 1968). Although the number of galaxies is small, there is no indication in the Local Group of any continuing increase in the luminosity function for magnitudes fainter than ~ -15; the number of galaxies per magnitude interval is roughly constant at the fainter magnitudes, and does not vary by more than about a factor of 2 over the entire interval $-21 < M_V < -9$. Thus $\alpha \sim 0$ for the Local Group, and it appears that an extrapolation of the luminosity function to magnitudes fainter than -15 using $\alpha = 0.25$ or even $\alpha = 0.15$ would considerably overestimate the number of faint galaxies. To obtain limits on the contribution that might be made by such faint galaxies, we have carried out the calculations with the analytic luminosity function cut off at $M_V = -15$ and at $M_V = -10$. The contribution to any quantity of interest due to galaxies or globular clusters fainter than $M_V = -10$ is found to be unimportant even if all of the globular clusters associated with Local Group galaxies are counted as separate systems.

To convert the luminosity function into a mass distribution, we have simply assumed a constant mass-to-light ratio of $\mathfrak{M}/L = 20$ for all galaxies; a more refined approach allowing for the dependence of $\mathfrak{M}/L$ on galaxy type and luminosity has not been considered worthwhile, in view of the uncertainty in the luminosity function and in the estimated mass loss from galaxies. Also, in lumping together different types of galaxies we have ignored probable differences in the efficiency of gas loss for different types. Any uncertainties or variations in $\mathfrak{M}/L$ may be regarded as being absorbed into the parameter $\mathfrak{M}_1$ in equation (1); for example, an increase in $\mathfrak{M}/L$ is equivalent to a decrease in $\mathfrak{M}_1$ by the same factor.

IV. Results

The amount of mass and the amount of heavy elements lost from galaxies of different masses have been calculated from equations (1) and (2), and the results have been integrated over the analytic luminosity functions discussed above to obtain the total amounts of mass and heavy elements lost from all of the galaxies in groups or clusters with each assumed luminosity function. The results are shown in Table I, which lists the ratio $\mathfrak{M}_g/\mathfrak{M}_s$ of the total mass lost to the total mass remaining in galaxies for each value of the parameter $\mathfrak{M}_1$ and each assumed luminosity function. Also shown in Table I is the average metal abundance $\langle Z\rangle_g = \mathfrak{M}_Z/\mathfrak{M}_g$ of the lost gas in each case. These quantities have also been calculated for the Local Group by adding the contributions from all of the known galaxies; for the reasons discussed below, the Local Group has for this purpose been divided into a 'Galaxy subgroup' and an 'M31 subgroup'.

It is evident from Table I that the predicted fractional mass loss of a group of galaxies is less dependent on the assumed luminosity function than on the value of the parameter $\mathfrak{M}_1$, which is related to the efficiency of the gas loss mechanism. The maximum range of the estimates obtained for different luminosity functions is less than a factor of 3, and the Local Group values fall well inside this range. However, a variation in $\mathfrak{M}_1$ by a factor of 10 changes the calculated fractional mass loss by almost a factor of 4 in either direction. Our 'best guess' value $\mathfrak{M}_1 = 10^{10}$, which is close to the value $\mathfrak{M}_1 = 6 \times 10^9$ estimated by Larson (1974*b*), gives a typical fractional mass loss of the order of 0.2, but a realistic uncertainty for this estimate is probably at least a factor of 3.

By contrast, the average metal abundance of the lost gas is relatively well determined, and none of the calculated values of $\langle Z\rangle_g$ differs by more than a factor of 1.6 from a typical value of $\langle Z\rangle_g = 0.02$, which is equal to the assumed 'yield' or ratio of the mass of heavy elements produced to the mass of stars formed. The metal abundance of the intergalactic gas in the vicinity of a group of galaxies will in general be lower than this because of dilution by an unknown (but possibly small, Gott et al. 1974) amount of primordial gas, but the total mass of heavy elements lost to the intergalactic medium may be estimated as roughly 0.2×0.02 or 4×10^{-3} times the mass in galaxies.

The above estimates refer only to the amount of initial protogalactic gas lost during the early evolution of galaxies, i.e., during the first $\sim 10^9$ years after their formation. If the gas shed by dying stars at later stages of evolution is also

TABLE I

FRACTIONAL MASS LOSS AND METAL ABUNDANCE OF LOST GAS

	Analytic luminosity function cut off at				Local Group	
	$M_V = -15$		$M_V = -10$			
$\mathfrak{M}_1$	$\alpha = 0.25$	$\alpha = 0.15$	$\alpha = 0.15$	$\alpha = 0$	Galaxy subgroup	M31 subgroup
	Ratio ($\mathfrak{M}_g/\mathfrak{M}_s$) of mass lost to mass in galaxies:					
10^9	0.07	0.05	0.06	0.03	0.05	0.03
10^{10}	0.28	0.18	0.23	0.11	0.22	0.13
10^{11}	0.90	0.60	0.74	0.41	0.76	0.48
	Average metal abundance ($\mathfrak{M}_Z/\mathfrak{M}_g$) of lost gas:					
10^9	0.028	0.030	0.024	0.032	0.031	0.032
10^{10}	0.020	0.024	0.019	0.028	0.025	0.027
10^{11}	0.012	0.015	0.013	0.020	0.015	0.019

removed by galactic winds, it will make a further contribution to the total amount of mass and heavy elements lost from galaxies. In the dynamical models of Larson (1974*a*), the fractional mass lost from the stars in a galaxy after the first 10^9 years is in the range 0.05 to 0.10; if this is added to the above estimates for the initial gas loss, the total fractional mass predicted to be lost from a collection of galaxies increases to a typical value of the order of 0.3.

V. Discussion

The significance of the results obtained above is tied to the question of the ultimate fate of the gas lost from galaxies. Several possibilities exist: The gas may remain in the vicinity of the galaxies from which it was lost or, in a cluster of galaxies, it may remain in the cluster and contribute to an intracluster gaseous medium. If the gas is heated to sufficiently high temperatures, it may not remain bound in clusters but may be completely dispersed into a nearly uniform hot intergalactic medium. Finally, if heating is not important, some of the escaped gas may fall back into galaxies, or even form new galaxies.

In rich clusters like the Coma cluster where the velocity dispersion is large and the crossing time is short compared with the age of the cluster, the gas lost from the galaxies is likely to be heated by collisions to temperatures of the order of 10^{8} ° K and thus form a hot diffuse medium with a distribution similar to that of the galaxies in the cluster. X-ray observations show that many rich clusters contain just such a hot intracluster medium; in the Coma cluster, the amount of gas observed is about one-quarter of the mass in galaxies (Field 1974), in good agreement with the amount of gas that we predict to be lost from the galaxies. If this is the origin of the observed gas, we predict that this gas should have essentially a Population I metal abundance, i.e., $Z_g \sim 0.02$.

If additional large sources of energy are present, such as violent events in galactic nuclei, the gas in a cluster of galaxies may be driven out of the cluster in a hot wind analogous to the winds produced by supernova heating in individual galaxies (Yahil and Ostriker 1973). The power required is, however, very large and is comparable to that of a luminous quasar. Possibly such phenomena would be more important in smaller clusters with smaller binding energies than the Coma cluster.

Perhaps the most interesting possibility occurs in the case of relatively small and loosely bound or unbound groups of galaxies (de Vaucouleurs 1975). Much of the gas lost from the galaxies in such a group may remain within the group or in the vicinity of the galaxies from which it was lost, especially if it is decelerated by interacting with residual primordial gas. Because the velocity dispersions in such groups are relatively small and the crossing times are often comparable with the Hubble time, collisions should be relatively unimportant in heating the intracluster gas, and some of it may remain relatively cool and nonuniformly distributed, perhaps still concentrated around the galaxies.

A tendency for the escaped gas to remain concentrated around galaxies or in subgroups of galaxies seems particularly likely when the distribution of galaxies in systems like the Local Group is taken into account. Nearly all of the smaller galaxies in the Local Group are clustered around either our galaxy or M31, forming two subsystems each consisting of a giant spiral with a group of smaller satellites around it. Considering for example the Galaxy subgroup, we find that the escape energy for the satellite galaxies is typically about an order of magnitude smaller than the energy required to escape from the gravitational field of our galaxy, so that most of the gas lost from the satellite galaxies (about half of the total mass predicted to be lost from galaxies in the subgroup) is likely to remain bound to the Galaxy subgroup. A similar conclusion seems likely to hold for the M31 subgroup, and therefore it appears that in studying the evolution of its intergalactic gas, the Local Group should be divided into two gravitational domains centered on the two large spirals, which should then be treated separately as has been done in Table I. Although information is less complete for other groups of galaxies, it is probably true in general that much of the gas lost from small galaxies may remain bound to the larger galaxies with which they are associated as satellites.

We note that there appears to be accumulating evidence for circumgalactic gas associated with several nearby small groups of galaxies.

Associated with our own galaxy and its satellites is the Magellanic Stream of neutral hydrogen (Mathewson, Cleary, and Murray 1974), which appears to be a long stream of gas orbiting around our galaxy with the Magellanic Clouds. Some of the well-known "high-velocity hydrogen clouds" may also be extragalactic clouds associated with the Magellanic Stream. Observations by Mathewson et al. (1975) of the Sculptor group, the nearest group outside the Local Group, have shown the presence of several neutral hydrogen clouds around the galaxies NGC 55 and NGC 300. The next nearest group, the M81 group, also contains an extended H I cloud surrounding the giant spiral M81 and its satellite galaxies, including M82 and NGC 3077 (Roberts 1972; Davies 1974).

It is not known how much of the circumgalactic gas observed in the groups mentioned above is primordial and how much has been lost from the galaxies, but in any case the present calculations allow us to predict that the circumgalactic gas should be significantly enriched in heavy elements by the addition of metal-rich gas ejected from the galaxies. Since dust grains probably survive ejection from galaxies in galactic winds (Faber and Gallagher 1975), the circumgalactic gas may also contain significant amounts of dust. The presence of heavy elements in this gas will be important for its thermal properties and may be instrumental in allowing it to cool and form clouds. This will in turn have an important influence on any interactions that may ocur between the circumgalactic gas and the galaxies; for example, a relatively low temperature ($\lesssim 10^{6}$ ° K) will make it easier for this gas to be accreted by the galaxies, or perhaps even to condense into new galaxies. The likely presence of dust in any such newly accreted gas may add plausibility to the interpretation of certain peculiar dusty galaxies like M82 and NGC 5128 as systems that have recently accreted fresh material (Larson 1972, 1975). Gallagher, Faber, and Balick (1975) have also called attention to a number of peculiar S0 and Irr II galaxies with anomalously high hydrogen content, which could be a result of recent interactions with intergalactic or circumgalactic material. At any rate it seems possible that interactions between galaxies and the surrounding intergalactic gas, involving both losses and gains of material, may be of considerable importance for the evolution of many galaxies, particularly those displaying various short-lived active phenomena or structural peculiarities.

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