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RATE OF STAR FORMATION AND GAS DENSITY IN IRREGULAR GALAXIES

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RESUMEN

Un estudio estadístico de la correlación entre la tasa de formación de estrellas por unidad de masa de gas y la densidad media de gas en galaxias irregulares sugiere que esta tasa disminuye cuando aumenta la densidad media. El significado de esta correlación negativa e inesperada, que no parece afectada por efectos de selección, es un misterio.

ABSTRACT

A statistical study of the correlation between the rate of star formation per unit mass of gas and the average gas density in irregular galaxies suggests that this rate decreases with increasing average density. The physical significance of this unexpected negative correlation, which seems free from important biases due to selection effects, is a mystery.

Key words: **GALAXIES, EVOLUTION — GALAXIES, GENERAL — INTERSTELLAR MATTER — STARS, FORMATION.**

I. INTRODUCTION

It is generally believed that the birthrate of stars is governed by the density of interstellar gas from which they form, as well as by other factors like compression of this gas in shocks associated with galactic density waves or supernova remnants (see e. g., Roberts 1975). Schmidt (1959) has proposed that on a large scale the rate of star formation varies as a power $\simeq 2$ of the density of interstellar gas. A recent attempt (Guibert *et al.* 1978) to check Schmidt's law in the case of our Galaxy has been rather inconclusive, in spite of the abundance of observational data which are presently available. The present study is another attempt to derive empirically the possible relation between rate of star formation and gas density, which bears on irregular galaxies.

Irregular galaxies have been chosen because they are relatively simple, unevolved systems in which large-scale density waves are probably absent, or at least of less importance than in spiral galaxies. Moreover, their small rate of star formation is such that the role of supernova shocks in triggering star formation is probably also less important than in spirals. One might thus expect to separate more clearly in these objects than in spirals the role of gas density in star formation. I consider here only bulk properties of these objects, thus the average rate of star formation will be correlated with the average gas density. Part II describes the data and the results, and Part III discusses these results.

II. DATA AND RESULTS

For such unevolved objects as irregular galaxies, the integrated blue or ultraviolet luminosity is a

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measure of the average rate of star formation in a recent past. Their very blue colors show that this light is dominated by young stars formed during the last few 10^8 years. More precisely, Larson and Tinsley (1978) have shown that those systems have a particularly large present rate of star formation compared to the average rate since the time of their formation. In the case of the solar neighborhood, which is more evolved than irregular galaxies and has less blue colors, I have shown using star counts that half of the *B* light is produced by stars earlier than A8 and thus younger than 1.3×10^9 years (Lequeux 1979*b*). Finally, for the few galaxies for which counts of very bright young stars are possible, I have shown that they indicate a rate of star formation which is proportional to the blue luminosity (Lequeux 1979*a*). It thus appears that one can use the *B* or photographic luminosity corrected for extinction, L_B^o or L_{pg}^o, as an indicator of the present rate of star formation (or more exactly of the average rate in a recent past). The exact relation between the luminosity and the rate would require elaborate model calculations which would involve somewhat arbitrary assumptions about the Initial Mass Function and the past history of star formation in those galaxies, and I did not consider it necessary to enter into such details for the present study.

Since stars are formed from gas, the physically meaningful parameter to consider is the rate of formation per unit mass of gas. 21-cm line studies provide the total mass of atomic hydrogen M_H in the considered galaxies, and if one neglects molecular hydrogen the rate of star formation per unit mass of gas is measured by L_B^o/M_H (or L_{pg}^o/M_H). Note that this ratio is distance-independent.

The average gas density is of course proportional to the ratio of M_H to the volume of the gas in the galaxy. Unfortunately, the dimensions of irregular galaxies in the 21-cm line are known only in a few cases, and one is forced to use optical dimensions for statistical purposes. I have checked that the ratio of 21-cm dimensions (when they are known) to the optical Holmberg dimensions is constant within a factor of 2 for irregular galaxies. The degree of flattening of the galaxy must also be known if one wishes to calculate its volume. Figure 1 shows the distribution of apparent axis ratio as a function of absolute photographic or *B* magnitude for the galaxies of the sample. It is consistent with a random distribution of orientation of oblate spheroids with a true axis ratio of about 0.3 (Fisher and Tully, 1975, take 0.25 but this makes little difference for estimating the volume); apparently there is no systematic variation in this axis ratio with absolute magnitude. We thus define the volume of the galaxy as the volume of an

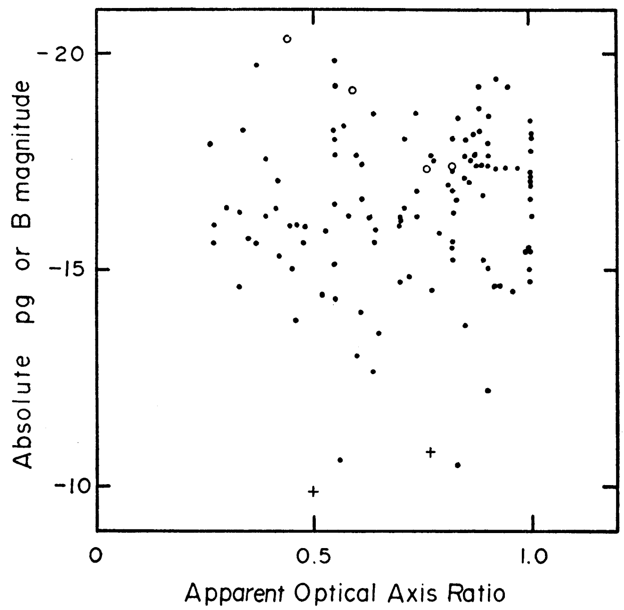

FIG. 1. Distribution of apparent optical axis ratios of irregular galaxies as a function of absolute magnitudes. Filled circles: objects in Fisher and Tully (1975), absolute magnitude is M_{pg}; circles: objects in Shostak (1978), absolute magnitude is M_B; crosses: Sagittarius and Sculptor dwarf irregular galaxies. The dimensions are Holmberg apparent dimensions estimated by Fisher and Tully (1975) for almost all objects, and by the author for the rest.

oblate spheroid with flattening 0.3 and major axis equal to the linear major Holmberg diameter. Thus the average hydrogen density $\langle n_H \rangle$ is defined as:

$$\langle n_H \rangle = (M_H/m_H)\,(0.3\pi\ a^3D^3/2)^{-1} \qquad (1)$$

m_H being the mass of the proton, M_H the mass of neutral hydrogen in the galaxy, *a* its major angular diameter in the Holmberg system and *D* its distance. $\langle n_H \rangle$ is proportional to D^{-1} since M_H, which is obtained from the 21-cm line intensity, is proportional to D^2. For those galaxies for which no direct determination of distance exists, I have estimated the distance from the 21-cm redshift using a Hubble constant H = 75 km s^{-1} Mpc^{-1}. The adopted value is a compromise between recent determinations of Durand (1975), Tully and Fisher (1977) and Shostak (1978) who find respectively H = 70, 80 and 80 km s^{-1} Mpc^{-1}. Observational data are mainly from Fisher and Tully (1975) to which I added a few galaxies observed by Shostak (1978) as well as two dwarf irregular galaxies discovered recently, the Sculptor dwarf irregular galaxy (Cesarsky *et al.* 1977*a*) and the Sagittarius dwarf irregular galaxy (Cesarsky *et al.* 1977*b*). A few numbers contained in these papers have been revised in the light of recent works which are too numerous to be cited here (details are available on request). Fisher and Tully's optical diameters (given in the Holmberg system) and photographic magnitudes have been used as they stand: their neglect of internal reddening is probably of little consequence because it is probably very small in the considered systems. *B* magnitudes have been used for other galaxies. I have expressed the photographic (or *B*) luminosity/hydrogen mass ratio in solar units, using for the Sun absolute magnitudes $M_{pg} = 5.37$ and $M_B = 5.48$ and mass 2×10^{33} g, respectively.

In Figure 2, the relation (L_{blue}/M_H) versus $\langle n_H \rangle$ is plotted for irregular galaxies with distance $D < 13.3$ Mpc classified Im (T = 10) by de Vaucouleurs *et al.* (1976). Galaxies with distances known independently from redshift are indicated by symbols different from others (see figure caption). It appears that the choice of H = 75 km s^{-1} Mpc^{-1} produces consistent results between the two sets of objects. Using H = 50 km s^{-1} Mpc^{-1} would systematically shift to the left the second set of points by $\Delta \log n\langle_H\rangle = -0.18$ and this would give a less good agreement.

There is a clear negative correlation between (L_{blue}/M_H) and $\langle n_H \rangle$. Including more distant and generally more luminous Im galaxies essentially adds points at the upper left of the figure, but keeps the relation unchanged (Figure 3). This is also true if one adds galaxies of somewhat earlier type, 7 to 9. I have also built the same graph using the sample of dwarf galaxies studied by Thuan and Seitzer (1979) with very similar results.

III. DISCUSSION

The negative correlation of Figures 2 and 3 between (L_{blue}/M_H) which measures the rate of star formation per unit mass of gas, and the average gas density $\langle n_H \rangle$, is very surprising since from any star

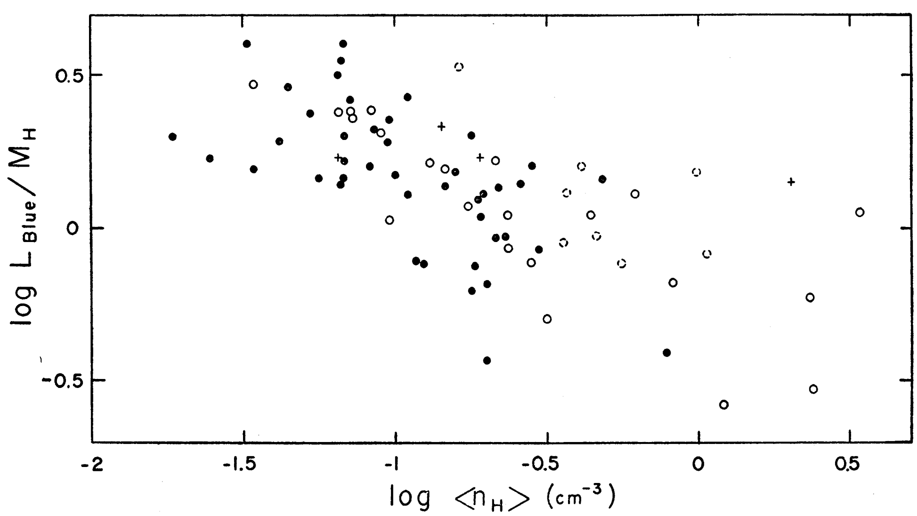

FIG. 2. The relation between L_{blue}/M_H in solar units and $\langle n_H \rangle$ for irregular galaxies of morphological type Im with distances closer than 13.3 Mpc. L_{blue}/M_H is a measure of the average rate of star formation per unit mass of gas, and $\langle m_H \rangle$ is the average density of neutral hydrogen, as defined in the text. L_{blue} is taken as the photographic luminosity for most systems, and the *B* luminosity for a few. The dots correspond to objects whose distance is evaluated from the redshift, taking a Hubble constant H = 75 km s^{-1} Mpc^{-1}. The circles are for objects with relatively well-known distances independent from redshift (mainly from the studies by Sandage and Tammann), and the incomplete circles are for objects with less well-known redshift-independent distances. Crosses correspond to blue compact galaxies: for these objects, distances are evaluated from the redshifts.

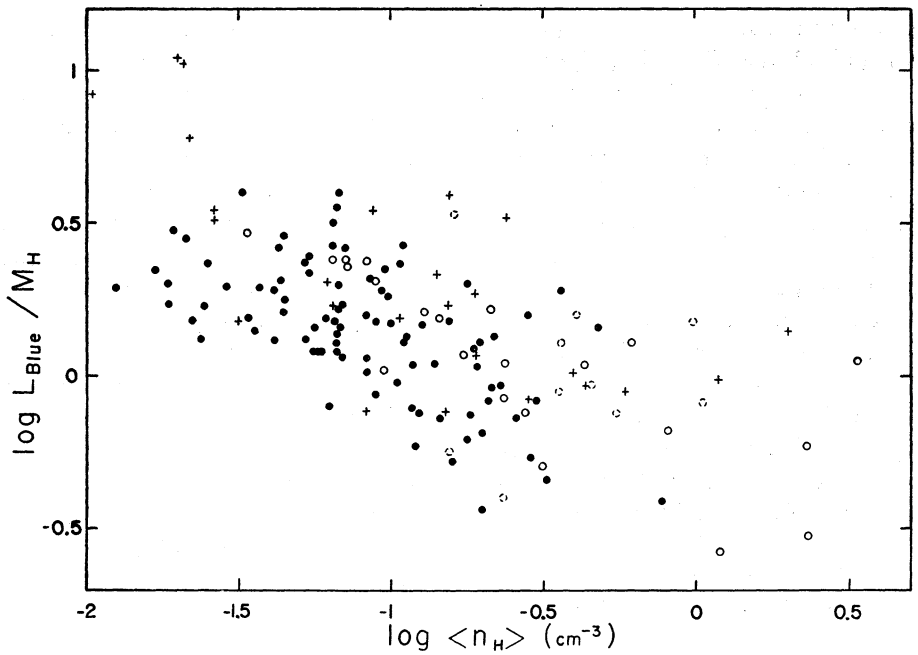

Fig. 3. Same as Figure 2 but for all Im and blue compact galaxies for which data have been found in the literature. The meaning of symbols and the distance estimates are the same as for Figure 2. The galaxies of Thuan and Seitzer (1979) have not been plotted but they give a similar relation.

formation law like the Schmidt's law one would expect a positive correlation. Before examining the consequences of this correlation, I discuss the errors and selection effects which could affect Figures 2 and 3.

First the coordinates are not independent and errors in the hydrogen mass M_H will be reflected in both: they will displace the representative points along a regression line with a slope of -1. However the errors on the integrated 21-cm line intensities are probably less than 50%. An error on distance D will not change L/M_H but n_H which is proportional to D; errors on distances are probably smaller than 50%. These two effects cannot affect the relation significantly. More serious is the effect of errors on the angular diameters and true axial ratios, which will introduce a scatter in the abscissae of Figs. 2 and 3. This scatter could change the slope of the discussed relation, but not its sign. Possible systematic effects in the ratio 21-cm diameter/optical diameter could also affect the relation. However I have not been able to find any significant correlation between the ratio 21-cm diameter to optical diameter, and parameters in these figures. The limited sample of irregular galaxies with known 21-cm diameters produces a relation with the same slope as in Figures 2 and 3 when $\langle n_H \rangle$ is calculated using the 21-cm major axis instead of the optical major axis in equation (1).

The bottom of the figures corresponds to objects with very low optical luminosity for their hydrogen mass, i. e., "intergalactic clouds". Systematic 21-cm searches for such clouds have been recently conducted by a number of authors (see the review by Haynes 1978). These searches have failed to uncover a population of isolated intergalactic clouds and has only demonstrated a frequent presence of HI tidal debris close to galaxies. Even the hydrogen clouds apparently associated with the Sculptor group of galaxies might rather be high-velocity galactic clouds or parts of the Magellanic Stream (Haynes and Roberts 1979). Although isolated clouds of low hydrogen mass ($M_H \lesssim 10^8\ M_\odot$) may exist, clouds with larger hydrogen mass ($M_H \gtrsim 10^9\ M_\odot$) comparable to those of many galaxies of our sample are obviously rare; thus it is likely that the absence of objects in the lower part of Figure 2 is not due to a selection effect.

What about the upper part? The objects there should be luminous for their hydrogen mass. Spiral galaxies are obvious candidates but their (generally) large masses show that they are probably genetically unrelated to dwarf irregular galaxies. Moreover, the average gas density of our Galaxy and of a few other spiral galaxies where it can be estimated is rather smaller than 1 cm^{-3} thus they would not populate the upper right part of Figures 2 and 3. Blue compact galaxies may seem better candidates for populating this region. I have plotted in Figures 2 and 3 representative points for the blue compact galaxies which have been measured in the 21-cm line, always using the same definition of $\langle n_H \rangle$. Data are from Chamaraux (1977) and Balkowski *et al.* (1978). The distribution of apparent optical axial ratios for these objects is not significantly different from that for irregular galaxies. The representative points for blue compact galaxies cluster in the upper region of the relation for irregular galaxies, but not in the upper right of Figures 2 and 3, and in any case do not destroy the relation: blue compact galaxies can be considered as irregular galaxies with a higher-than-average present rate of star formation, but their average gas density is not significantly larger than that of ordinary irregulars.

Finally the neglect of molecular hydrogen in the estimates of the gas mass and gas density might introduce systematic effects. No direct information exists on the molecular hydrogen content of such systems. However their low abundances in heavy elements do not favor the formation of the dust grains which are required to produce H_2 from H; it is thus likely that the total mass of H_2 is not large compared to that of H, and that its neglect is not producing large systematic errors in the considered relation. Note that adding molecular hydrogen would displace the representative points of Figures 2 and 3 along a line of slope —1: it is hard to imagine how the sign of the considered relation could be changed by taking molecular hydrogen into account.

It thus appears that the negative correlation between the rate of star formation per unit mass of gas and the gas density in irregular galaxies is real, although completely unexpected. It shows that another factor(s) than the average gas density governs star formation in these apparently simple systems. One could imagine that the gas velocity dispersion ΔV, which is measured by the width of the 21-cm line, could play a major role in triggering star formation through cloud collisions (the rate of cloud collisions per unit gas mass is proportional to $\langle n_H \rangle \Delta V$ if clouds are similar in all galaxies). However a plot of (L_{blue}/M_H) versus ΔV does not show any correlation at all.

The origin of the negative correlation is a mystery. One should remark that the galaxies which have the largest $\langle n_H \rangle$ are also in general the less massive systems: the four galaxies with the largest $\langle n_H \rangle$ in Figure 2 are DDO 155, the Sculptor dwarf irregular galaxy NGC 6822 and the Sagittarius dwarf irregular galaxy: with the (notable) exception of NGC 6822, they are amongst the galaxies in our sample which contain the less neutral hydrogen and also are apparently the less massive. This might be in part a selection effect but this is rather difficult to decide. Total mass could play a role in star formation, rather than density, through formation of density waves. In any case, it appears that much work remains to be done before we understand even the basic principles of star formation.

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