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Global Properties of Star Formation in Spiral Galaxies

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Abstract. Samples of spiral galaxies from two catalogues of 21 cm line observations and a catalogue of near-infrared observations of nearby galaxies have been used in conjunction with Infrared Astronomical Satellite data to study correlations involving M_G, the dynamic mass of the galaxies, the luminosities in the H band (1.6 μm), the blue band and the far infrared bands and the mass of atomic hydrogen, it is found that both the blue and the far-IR luminosities which are indicators of star formation averaged over ~3 × 10^9 and ~10^7 years respectively, have a linear dependence on M_G. On the other hand, the H luminosity which is a measure of star formation averaged over the lifetime of galaxies, has a steeper power law dependence on M_G. The correlations observed do not have significant dependence on the morophological type of the galaxies There is a poor correlation between the far-infrared luminosity and the mass of atomic hydrogen. The mass of atomic hydrogen has a dependence of the form M_G. Because of the decrease in the mean mass for later morphological types and due to differences in power law dependences of luminosities in different bands on M_G, the mean value of luminosity-to-mass ratio is a constant for blue and far-IR bands, decreases for the H band and the gas-to-mass ratio increases as morphological type increases.

Key words: galaxies, star formation–galaxies, infrared radiation–galaxies, neutral hydrogen

1. Introduction

A study of large scale properties of star formation in spiral galaxies is of great interest to understand the process of star formation (SF), its history over the galactic lifetime and possible factors governing the morphological appearance of galaxies. In recent times, there have been several studies in this regard making use of relationships between luminosites in various bands and also their relationships to the gas content of galaxies (Gallagher, Hunter & Tutukov 1984; Iyengar, Rengarajan & Verma 1985; Rengarajan & Verma 1986; Young *et al.* 1986; Young 1986; Young 1987; Sandage 1986; Persson & Helou 1987; Thronson & Telesco 1986; Jackson *et al.* 1987). Luminosities in different bands are indicators of star-formation rate averaged over different periods. In the study of Gallagher, Hunter & Tutukov (1984), Hα luminosity was used as a probe for the current star formation rate (SFR) averaged over ~ 10^7 years, the blue band luminosity as SFR over ~3 × 10^9 yr and the mass of the galaxy itself as a probe of SFR over the life of the galaxy. With the advent of Infrared Astronomical Satellite (IRAS), it has been possible to use the far-infrared (far-IR) observations of a large sample of galaxies for a study of the present day SF. Further, it has been shown that there is an intimate connection between the amount of molecular hydrogen and the far-IR activity of galaxies (Rengarajan & Verma 1986; Young 1986; Young 1987). For a few galaxies, it has also been shown that the radial distribution of L_{IR}, the far-IR luminosity, L_B, the blue luminosity, and M_{H_2}, the mass of molecular hydrogen gas as revealed through ^{12}CO observations, are very similar while the radial distribution of $M_{H\,I}$, the atomic hydrogen mass is quite different (Scoville & Young 1983; Tacconi & Young 1986; Kenney & Young 1986). Since $M_{H\,I}$ is expected to be the reservoir of gas for eventual conversion to H_2 and hence to star formation, it is of interest to study the relationship between the H I gas content and other indicators of SF. Since the mass of a galaxy is an important parameter governing the history of star formation (Sandage 1986), one would like to study SF as a function of the mass of the galaxy.

In the present study, we make use of samples of spiral galaxies that have been observed in the 21 cm line of atomic hydrogen and for which a measure of the dynamic mass of the galaxy is available from the measurement of the 21 cm line width. We also make use of a sample of nearby galaxies with measurements of *H* (1.6 μm) magnitude along with 21 cm observations. *H* magnitude essentially samples old late-type giants (Aaronson, Huchra & Mould 1979; Rieke & Lebofsky 1979) and thus provides a measure of SFR over the life of the galaxy. We then study the correlations involving luminosities in various bands, M_G, the dynamic mass of the galaxy, and $M_{H\,I}$.

2. Data

A measure of the dynamic mass of the galaxy is provided by W_{20}, the width of the 21 cm line at 20 per cent of the peak. Tully & Fisher (1977) first discovered the relationship between W_{20} and the absolute blue magnitude of galaxies. Following this, they have published a catalogue of 21 cm observations of a large sample of spiral galaxies (Fisher & Tully 1981; hereafter FT). In this catalogue they have also listed besides the intrinsic properties of galaxies, derived and corrected quantities like the absolute blue magnitudes and dynamic mass of the galaxy. We use this catalogue as our primary source of information of M_G and L_B . In order to be able to assess selection effects, sample composition, etc. on the parameters studied, we also make use of another catalogue of 21 cm observations viz., the high signal-to-noise ratio observations of Lewis, Helou & Salpeter (1985; hereafter LHS) of galaxies lying in the plane of the local supercluster. Finally, for a sample of *H* magnitude observations we use the catalogue of nearby galaxies (with inclination >45°) published by Aaronson *et al.* (1982; hereafter AHM) which is the basis for the infrared counterpart of Tully-Fisher relation and use the derived and corrected quantities as given by them. Most of the galaxies in this sample are also found in the FT sample and H I information for them is also taken mostly from FT.

We searched for IRAS counterparts for all the galaxies having H I width information in the Catalogued Galaxies in the IRAS Survey (1985). We selected only those galaxies for which definite flux densities were available for both the 60 and 100 μm bands. The listed values of FIR (W m^{-2}) were taken as measures of the broad band 40–120 μm far-IR flux. The statistics of IRAS detections for the three catalogues are given in Table 1.

The diameters, morphological types, distances and other properties of galaxies were

Table 1. Fraction of IRAS detections at both 60 and 100 μm.

Sample	Fraction of detections	
	dia. ⩽ 5 arcmin	dia. ⩽ 20 arcmin
FT	151/354	399/694
LHS	130/239	133/243
AHM	170/216	213/305

taken from the respective catalogues. All distances were, however, normalized to a Hubble constant H_0 = 100 km s^{-1} Mpc^{-1}. Distances in AHM are given relative to Virgo cluster. These were converted to absolute distances by assuming a distance of 10.7 Mpc to the Virgo cluster. The observed and derived quantities of interest to this study are listed below.

B_0: the corrected apparent blue magnitude of the galaxy.
H: the corrected *H* band (1.6 μm) apparent magnitude referred to an isophote of log A/D_i,= –0.5.
H I: 21 cm flux density integral (Jy km s^{-1}).
W_{20}: the corrected width of the 21 cm line at 20 per cent of the peak.
FIR: 40–120 μm flux (W m^{-2}) listed in the IRAS Catalogue.
M_G: = $\kappa\theta D$ W_{20}, dynamic mass of the galaxy within diameter θ (optical diameter) where D is the distance to the galaxy and κ is a constant. This assumes that the velocity-maximum is within the optical diameter which is likely to be realized in most of the galaxies (FT).
B_0(abs), L_B: the absolute blue magnitude and luminosity derived using the listed distances.
H_0(abs), L_H: the absolute *H* magnitude and the *H* band luminosity.
L_{IR}: the 40–120 μm luminosity.
$M_{H\,I}$: the mass of atomic hydrogen.

It may be noted that diameters and distances given in the catalogues are derived from different sources. We do not therefore attempt to compare absolute values of parameters, but will only be concerned with relative changes.

3. Analysis

3.1 *Correlations Involving Luminosities*

(i) L_B versus M_G

In Fig. 1 we show a plot of B_0(abs) against log ($M_G/M_\odot$) for all galaxies in the FT sample. The various symbols represent galaxies of different morphological types. It is seen that there is a good correlation between the two plotted quantities. The line in Fig. 1 is obtained from a least squares fit to the data points; the parameters of the fit are

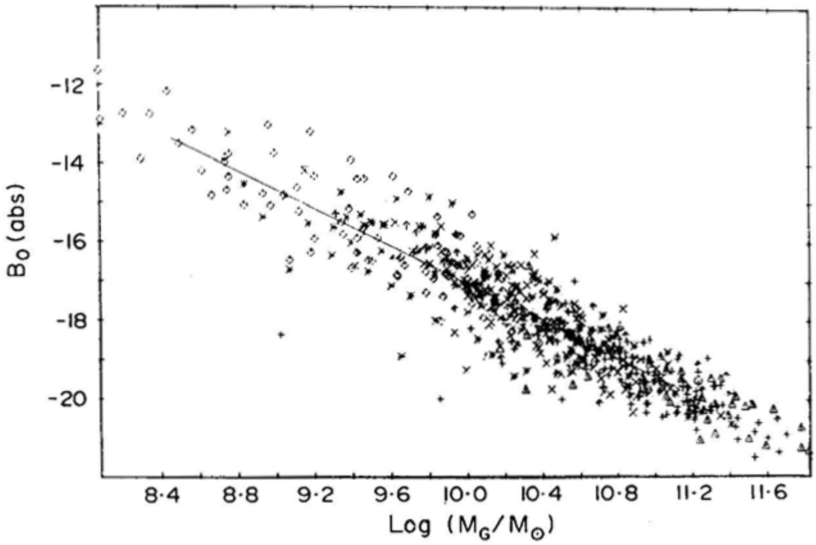

Figure 1. B_0(abs), the absolute blue magnitude of galaxies in the FT sample plotted against log($M_G/M_\odot$) where M_G is the dynamic mass of the galaxy. The symbols identifying the morphological types are: ⬡ types 0, 1; Δ types 2, 3; + types 4, 5; × types 6, 7; ∗ types 8, 9; ◇ types 10, 11; ⍋ ambiguous subclasses. The solid line drawn is the least-squares best fit line

listed in Table 2. The significance of the correlation as shown by the correlation coefficient r^2 is quite high. The plot is nothing but the original Tully-Fisher relation, but with M_G as the variable. The best fit line is represented by

$$L_B \propto M_G^{\alpha_B}$$

where α_B = 0.95. The rms scatter in log L_B with respect to the fitted line is 0.27. Though M_G is not the total mass of the galaxy, under the assumption that it represents a constant fraction of the total mass, the correlation implies that the mass-to-luminosity ratio is a constant. If we divide the sample as a function of morphological type, it is found that there is small increase in α_B, its value changing from 0.84 for types 1–3 to 0.95 for types 7–10.

(ii) L_H versus M_G

Fig. 2 shows a plot of H_0(abs) against log ($M_G/M_\odot$). Again this is the infrared counterpart of Tully-Fisher relation, but plotted with M_G as the variable. It is seen that

$$L_H \propto M_G^{\alpha_H}$$

where α_H = 1.34. Aaronson, Huchra & Mould (1979) found that $L_H \propto W_{20}$ and argued that this implies that $L_H \propto M_G$. The deviation of α_H from unity is most probably due to correlations between diameter and W_{20} (Shostak 1978). As in the case of α_B, there is a small increase in the value of α_H as one proceeds from earlier morphological types to later ones.

Table 2. Luminosity correlations in spiral galaxies: Fits for log $Y = A + \alpha$ log X.

X mag	Y $\mathrm{W\,m^{-2}}$	Sample	Size limit	No.	α	r^2	$(\delta \log Y)_{\rm rms}$
M_G	L_B	FT	20	618	0.95 ± 0.03	0.92	0.26
M_G	L_H	AHM	20	305	1.34 ± 0.04	0.95	0.20
W_{20}	L_{IR}	AHM	20	213	3.27 ± 0.19	0.65	0.36
M_G	L_{IR}	AHM	20	213	0.98 ± 0.05	0.78	0.35
M_G	L_{IR}	LHS	20	133	0.76 ± 0.07	0.68	0.45
M_G	L_{IR}	FT	20	399	0.92 ± 0.04	0.75	0.40
M_G	L_{IR}	AHM	5	170	1.05 ± 0.06	0.80	0.33
M_G	L_{IR}	FT	5	151	0.85 ± 0.06	0.74	0.37
M_G	L_{IR} [(b)]	FT	20	399	0.91 ± 0.04	0.77	0.38
M_G	M_d	FT	20	399	1.12 ± 0.04	0.84	0.35
H [(a)]	FIR	AHM	20	213	-0.29 ± 0.02	-0.79	0.28

[(a)] Magnitude used in place of log X.
[(b)] For 82 galaxies L_{IR} is from the IRAS Small Scale Structures Catalogue.

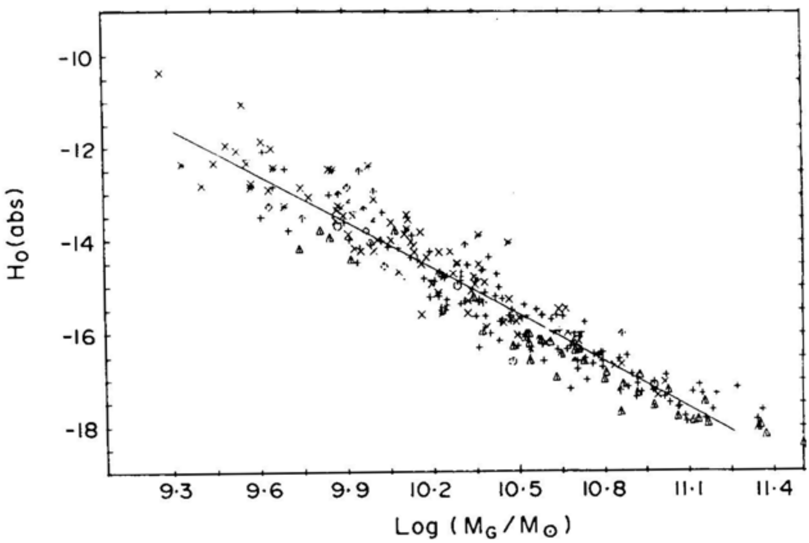

Figure 2. H_0(abs), the absolute H magnitude plotted against log ($M_G/M_\odot$) for galaxies in the AHM sample. Symbols are as in Fig.1.

(iii) L_{IR} versus M_G

First we look for correlations between L_{IR} and W_{20}, the result of which is shown in Table 2 for the AHM sample. The power-law index for the relation $L_{IR} \propto W_{20}^{\alpha}$ is almost the same as that for the blue band (Tully & Fisher 1977), but significantly less than that for the H band (Aaronson, Huchra & Mould 1979). We now use M_G instead of W_{20} as a variable, and list the results in Table 2. Since the IRAS beams are about 5 arcmin, the flux densities as given in the Point Source Catalogue (PSC) are likely to be underestimated for galaxies of larger diameters. In order to see the effect of this, we studied the correlations for galaxies with $\theta < 5$ arcmin and also for $\theta < 20$ arcmin. It is seen from Table 2 that the correlations for both the groups as well as for the three samples are all very similar. Eightytwo galaxies in the FT sample also appear in the IRAS Small Scale Structures Catalogue (1986). For these galaxies, we determined the quantity FIR using the flux densities listed in this catalogue. We studied the L_{IR}–M_G correlation using these values along with the FIR values from the PSC for the rest of the galaxies and the results are also shown in Table 2. Once again, the correlation is almost the same as for the data based entirely on the PSC data.

In Fig. 3, we show the plot of log ($L_{IR}/L_{\odot}$) computed using the PSC data against log($M_G/M_{\odot}$) for all galaxies ($\theta < 20$ arcmin) in the largest FT sample. The mean value of α_{IR} is 0.9 which is about the same as α_B, but significantly less than α_H. As for the other bands, for the far-IR band also, α_{IR} increases slightly for later morphological types.

If we group the galaxies as function of T_c, the colour temperature obtained from the ratio of 60 and 100 μm flux densities we find that the correlations are tighter. In fact, instead of L_{IR}, we can use M_d, the amount of warm dust responsible for the far-IR emission given by

$$M_d \propto L_{IR}/(\int B(\nu, T_c)\, \varepsilon(\nu)\, d\nu$$

where $\varepsilon(\nu)$ is the emissivity of dust ($\propto \lambda^{-1}$) and $B(\nu, T_c)$ is the Planck function and the integration is performed from 40 to 120 μm. Since the total luminosity is $\propto T^5$ for $\varepsilon \propto \lambda^{-1}$, we can also write

$$M_d \propto L_{IR}\, R(T_c)/T_c^5$$

where $R(T_c)$ is the factor by which the 40–120 μm luminosity is to be multiplied to get the total luminosity and is listed as a function of T_c in the Catalogued Galaxies in the IRAS Survey (1985). For all the three samples, the correlations between M_d and M_G

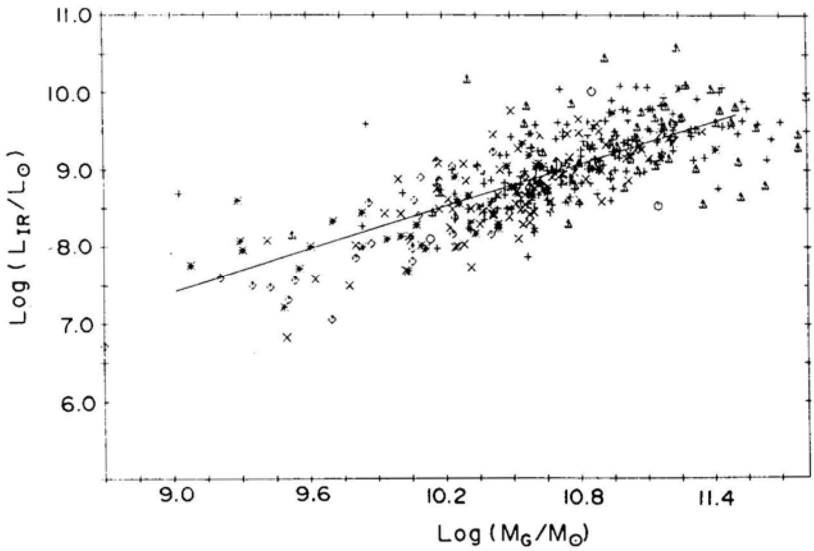

Figure 3. Log($L_{IR}/L_{\odot}$) plotted against log ($M_G/M_{\odot}$) for the FT sample. L_{IR} is the 40–120 μm luminosity. Symbols are as in Fig. 1.

are tighter than those between L_{IR} and M_G. The slope of the fit is also ~20 per cent higher. Fig. 4 shows a plot of log M_d against log($M_G/M_\odot$).

(iv) L_H versus L_{IR}

In Fig. 5, we show a plot of observed quantities, *viz.,* *H* magnitude against log FIR. The relationship between the two can be represented by $L_{IR} \propto L_H^{0.73}$. This correlation is due to correlation of L_H and L_{IR} individually with M_G.

3.2 *Correleations Involving* $M_{H\,I}$

It is known that the average mass of the galaxy decreases and the fractional mass of atomic hydrogen increases as one goes from early morphological types to later types (Shostak 1978). In Fig. 6, we show a plot of log ($M_{H\,I}/M_\odot$) against log($M_G/M_\odot$) for the FT sample having the largest number of galaxies. As shown in Table 3, the relationship is of the form

$$M_{H\,I} \propto M_G^{\alpha_{H\,I}}$$

where $\alpha_{H\,I}$ =0.78. The correlation coefficient is 0.84 and the rms scatter in log $M_{H\,I}$ is 0.3, *i.e.,* a factor of only 2 in mass. The value of $\alpha_{H\,I}$ is found to be essentially the same for different morphological types. It is clear that since $\alpha_{H\,I} < 1$, the mean value of M_{HI}/M_G will increase as the mean value of M_G decreases for later morphological types.

Next, we look for correlations in the observed quantities, *viz.,* between H I and FIR. As seen in Table 3, the correlations are poor for both FT and LHS samples. If we plot the derived quantities, *viz.,* log ($L_{IR}/L_\odot$) against log ($M_{H\,I}/M_\odot$) instead of the observed

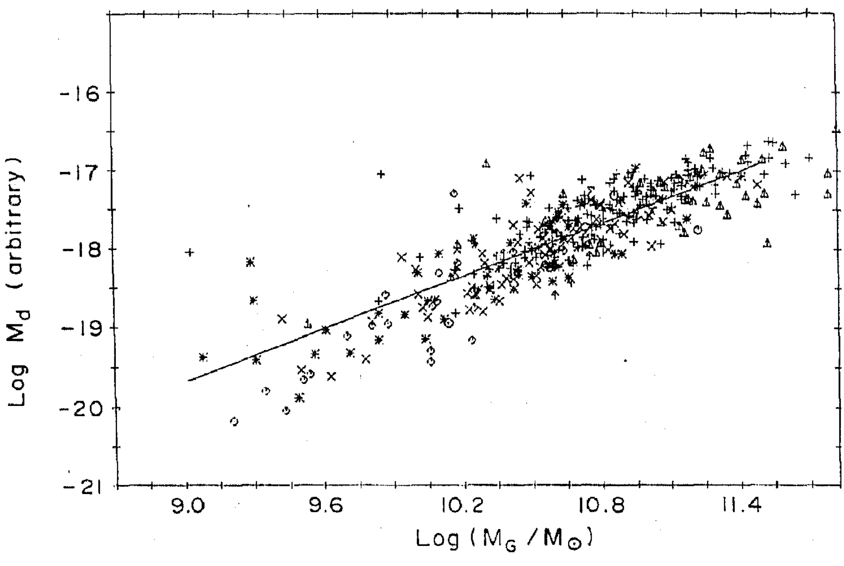

Figure 4. Plot of log M_d against log ($M_G/M_\odot$) for the FT sample. M_d is the mass of warm dust radiating in the 40–120 μm band. Symbols are as in Fig. 1.

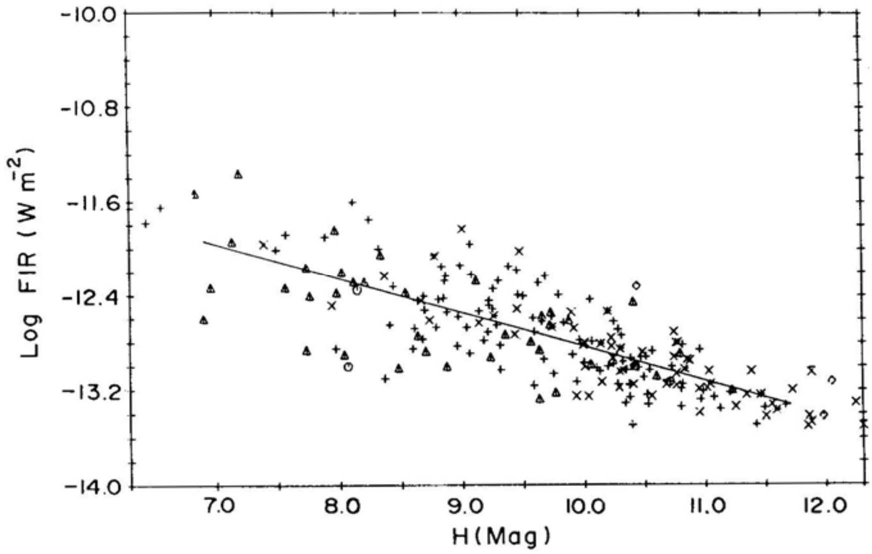

Figure 5. Log (FIR) plotted against apparent H magnitude where FIR is the 40–120 μm flux in units of W m^{-2}. Symbols are as in Fig. 1.

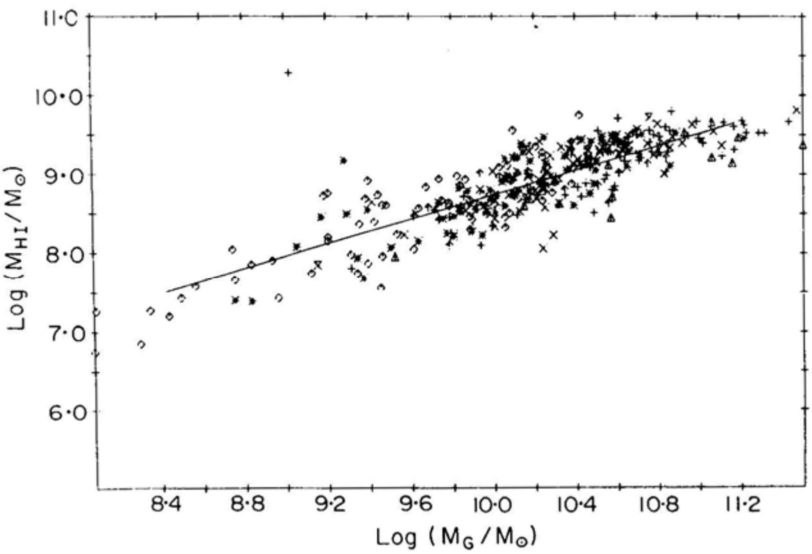

Figure 6. Plot of log $M_{\text{H I}}/M_{\odot}$) against log($M_G/M_{\odot}$) for the FT sample. $M_{\text{H I}}$ is the mass of atomic hydrogen in the galaxy. Symbols are as in Fig. 1.

quantities, it is seen from Table 3 that the significance of correlation increases and the slope is ~0.9. Figs 7 and 8 show the FIR versus H I and L_{IR} versus $M_{\text{H I}}$ plots respectively, for the FT sample. The increased significance in the plot for derived quantities is most probably due to the increased range in derived quantities resulting from the multiplicative factor of D^2 for both the quantities. The correlation between

Table 3. Correlations involving atomic hydrogen: Fits for log $Y=A + \alpha \log X$

X	Y	Sample	α	r^2	$(\delta \log Y)_{rms}$
FIR ($W\,m^{-2}$)	H I ($Jy\,km\,s^{-1}$)	FT	0.54 ± 0.06	0.43	0.44
"	"	LHS	0.15 ± 0.1	0.12	0.33
$M_{H\,I}$	L_{IR}	FT	0.89 ± 0.06	0.65	0.46
$M_{H\,I}$	L_{IR}	LHS	0.89 ± 0.06	0.78	0.39
M_G	$M_{H\,I}$	FT	0.78 ± 0.03	0.84	0.30
$M_{H\,I}$	L_H	AHM	1.13 ± 0.07	0.72	0.44

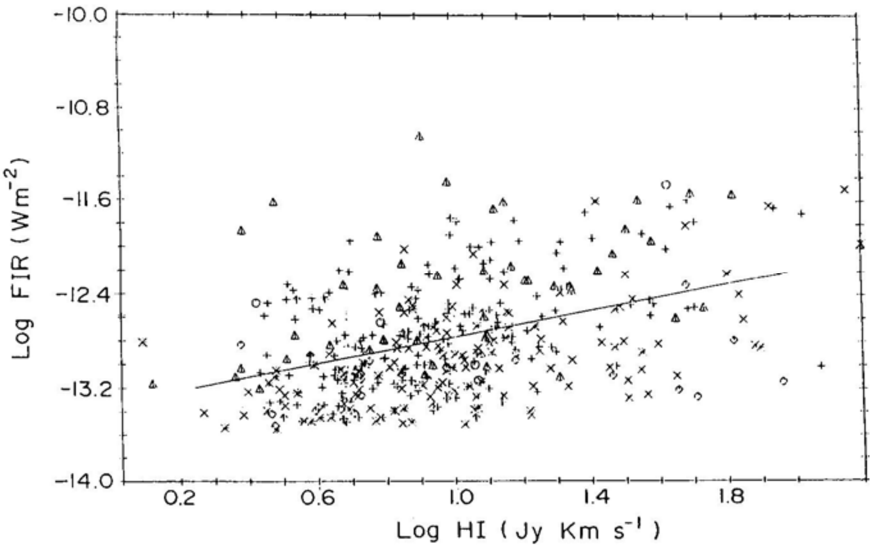

Figure 7. Plot of log FIR (W m^{-2}) against log H I (Jy km s^{-1}) for the FT sample.

$M_{H\,I}$ and L_{IR} is hence to be treated with caution. It may be noted that because of correlation of $M_{H\,I}$ and L_{IR} individually with M_G, we do expect to see some correlation between $M_{H\,I}$ and L_{IR}. Similarly, we also see a correlation between L_H and $M_{H\,I}$. In summary, we can state that the correlation of atomic hydrogen mass with L_{IR} is not as good as that seen for M_{H_2}, the mass of molecular hydrogen gas (Rengarajan & Verma 1986).

4. Discussion

The integrated luminosity in a given band is the result of contributions from stars of different masses. In general one can write

$$L = \int \xi(M) L(M)\, T(M)\, f(M)\, dM$$

where $\xi(M)$, the IMF is the number of stars per unit mass interval at mass M born per unit time, $L(M)$ is the total luminosity of a star of mass M, $f(M)$ is the fraction of the

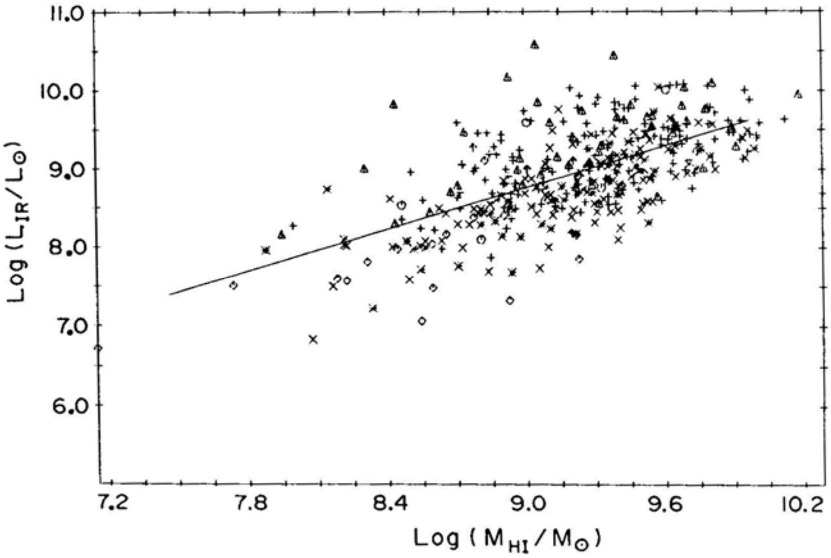

Figure 8. Plot of log ($L_{IR}/L_{\odot}$) against log ($M_{HI}/M_{\odot}$) for the FT sample.

total luminosity that is radiated in the given band and $T(M)$ is the lifetime of the star or that of the galaxy whichever is lower. For the far-IR band, if we assume a dust re-radiation mechanism, $f(M)$ represents the fraction of bolometric luminosity that is absorbed and reradiated by the dust. For more massive stars ($>30M_{\odot}$) having lifetime of $<10^7$ yr, the dust column density surrounding them could be large enough for $f(M)$ to be ~ 1 resulting in most of the stellar luminosity being radiated in the far-IR. As mass decreases, the star lives longer, the dust environment depletes, and $f(M)$ will decrease. Since the parent molecular clouds have probably lifetime of ~ 10^8 yr (Solomon & Sanders, 1980), $f(M)$ becomes $\ll 1$ by this time. With an IMF similar to that in the solar neighbourhood (Scalo 1986) one then finds that the period over which contribution to L_{IR} is effective is ~ 10^7 yr.

Some authors (Cox, Krugel & Mezger 1986; Persson & Helou 1987) have proposed that the far-infrared emission of galaxies consists of two components: a warm one associated with OB stars and a cooler one from dust in the interstellar medium with a significant contribution from nonionising stars with the two components having approximately the same luminosity. For the average temperatures quoted for these two components, we estimate for an $1/\lambda$ emissivity dependence, the contribution of the cold component to the 40–120 μm luminosity to be ~30 per cent. Since about 70 per cent of the 40–120 μm luminosity is from the warm dust component associated with OB stars it is reasonable to take it as a measure of recent star-formation activity Thronson & Telesco (1986) are also of this view. Even if the average dust optical depth is such that only a fraction of the OB star luminosity is reradiated in the warm dust environment, 40–120 μm luminosity can still be Used as a measure of the OB star luminosity as long as the contribution to this band from the cooler component is small.

For the blue luminosity an analysis similar to the above indicates that the effective period of contribution is $\sim 3 \times 10^9$ yr.

To convert the observed luminosities to SFR, *viz.,* the average rate of production of stellar mass per unit time, we need a knowledge of $\xi(M)\ f\ (M)$. Because of the uncertainties in these we do not attempt to get absolute rates.

The linear relationship observed between L_B and L_{IR} has been interpreted to imply that both L_B and L_{IR} originate from newly formed massive stars (Rickard & Harvey 1984). However, it has been argued that the presence of correlation between T_c, the dust temperature derived from the ratio of 60 and 100 μm IRAS flux densities and L_{IR}, and the absence of such a correlation between T_c and L_B imply different sources for the two luminosities (Iyengar, Rengarajan & Verma 1985; Rieke & Labofsky 1986; Soifer *et al.* 1987). The correlation between L_B and L_{IR} ($L_{H\alpha}$) is then a result of connection through the mass function. Our analysis shows that the primary correlation is between the luminosity and M_{G}. The correlations between luminosities are a result of individual correlations with mass. Since both α_B and α_{IR} are about the same, we get a linear dependence between L_B and L_{IR} leading to the conclusion that the current SFR and SFR over 10^9 yr is the same.

The situation is different with *H* band luminosity which measures SFR over the life of the galaxy. The steeper dependence of L_H on M_{G} implies that more massive galaxies have had more star formation in the past than the less massive galaxies. Since the luminosities in different bands are sensitive to different ranges of steller masses, the increased *H* luminosity can arise either due to a change in the SFR itself or due to changes in the IMF. The changes in power law indices also lead to changes in the mean values of *L*/*M* for different bands as a function of morphological type. We have shown in Table 4 the logarithmic mean values of M_{G}, L_H/M_G, L_B/M_G, L_{IR}/M_G and $M_{\mathrm{H\,I}}/M_G$ for three groups of morphological types. It is seen that while the luminosity-to-mass ratio is a constant for *B* and far-IR, it decreases for *H* and the fractional gas mass increases as morphological type increases and the mean galaxy mass decreases. The anti-correlation between the mean values of L_H/M_G and $M_{\mathrm{H\,I}}/M_{\mathrm{G}}$ simply reflects the fact that more star formation means a larger use of available gas.

It is clear that mass of the galaxy plays an important role in the process of star-formation. However, it is also seen that the mass dependence of various luminosities does not change much with morphological type. Further, the change in mean mass as morphological type increases is small compared to the range in the masses of the galaxies. Thus, galaxies of same mass can be of different morphological types. The morphological appearance is probably determined by the very early history of star-formation during the stage in which the collapse to a disc took place.

Table 4. Mean values *versus* morphology (arbitrary units).

	Type					
	1, 2, 3		4, 5, 6		7, 8, 9, 10	
	mean	rms	mean	rms	mean	rms
$\mathrm{Log}(M_{\mathrm{G}}/M_{\odot})$	10.98	0.47	10.71	0.42	10.01	0.59
$\log(L_B/M_{\mathrm{G}})$	−3.22	0.23	−3.14	0.25	−3.04	0.44
$\log(L_H/M_{\mathrm{G}})$	−4.1	0.15	−4.28	0.21	−4.54	0.20
$\log(L_{\mathrm{IR}}/M_{\mathrm{G}})$	−1.56	0.35	−1.47	0.32	−1.57	0.31
$\log(M_{\mathrm{H\,I}}/M_{\mathrm{G}})$	−0.88	0.27	−0.63	0.25	−0.45	0.20

5. Conclusions

We have made use of data on spiral galaxies from three catalogues of 21 cm observations and studied the correlations between dynamic mass of the galaxy and luminosities in various bands.

(1) We find the following correlations:

$$L_H \propto M_G^{1.3},$$

$$L_B \propto M_G,$$

$$L_{IR} \propto M_G,$$

$$M_{H\,I} \propto M_G^{0.78}.$$

It is seen that while the blue and infrared luminosities are, within errors, linearly dependent on the mass of the galaxy, the H luminosity is a steeper function of M_G.

(2) Correlations are also observed between L_B and L_{IR}, L_{IR} and L_H etc. which reflect individual correlations with M_G

(3) The mass of atomic hydrogen is poorly correlated with L_{IR}.

(4) More massive galaxies have had larger SFR in the past as compared to the present $\sim 10^9$ years. This leads to the anti-correlation between mean L_H per unit galaxy mass and mean gas mass (H I) per unit galaxy mass as the morphological type increases (mean galaxy mass decreases).

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