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MEASURING STAR FORMATION RATES IN BLUE GALAXIES *

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ABSTRACT. The problems associated with measurements of star formation rates in galaxies are briefly reviewed, and specific models are presented for determinations of current star formation rates from H α and FIR luminosities. The models are applied to a sample of optically blue irregular galaxies, and the results are discussed in terms of star forming histories. It appears likely that typical irregular galaxies are forming stars at nearly constant rates, although a few examples of systems with enhanced star forming activity are found among HII regions and luminous irregular galaxies.

1. INTRODUCTION

In this paper we briefly review methods for deriving star formation rates (SFRs) in galaxies with an emphasis on techniques based on the H α and IRAS infrared luminosities (see also Güsten and Mezger 1982). Conversion of measured quantities into SFRs involves model-dependent assumptions, and it is interesting to intercompare SFRs derived by different methods as a means to test the reliability of the models. The blue irregular galaxies which we discuss include objects that are especially well suited for this test for a variety of intrinsic and practical reasons outlined in Hunter and Gallagher (1986).

The strong emission lines and blue colors of galaxies in our sample sometimes are taken as evidence for "star burst" events. This view conflicts with results from the analysis of Gallagher, Hunter and Tutukov (1984; hereafter GHT), where a near constant SFR was found to fit most blue Irrs in agreement with earlier studies by Searle, Sargent and Bagnuolo (1973). The IRAS data base provides a new way to explore the star burst issue (as emphasized in many talks and poster papers during this conference), and we have developed a working definition for star bursts that is applicable to most types of galaxies.

2. MEASURING CURRENT STAR FORMATION RATES IN GALAXIES

To illustrate the factors involved in calculating SFRs, consider some quantity Q which is a measurable property of a stellar population in a galaxy (i.e. Q could be a luminosity, color, or mass estimate). Formally we then have

$$Q = \int_t \int_V \int_m q(m) \phi(m) w(\underline{r}) g(t) dm dV dt \cdot H(D). \quad (1)$$

* See erratum, page 257.

This equation illustrates the many parameters that affect any apparently simple measurement of Q : $q(m)$ is the weighting factor in stellar mass, $\phi(m)$ is the stellar initial mass function, $g(t)$ is a description of the time evolution of the system, $w(r)$ takes internal structural properties such as extinction into account, and $H(D)$ is the distance factor which is $(4\pi D)^{-2}$ for fluxes. Thus we require either good models or simple galaxies if we are to obtain reliable measurements of Q s that can be converted into SFRs, and in our work we have chosen the latter route in concentrating on studies of irregular galaxies (see Gallagher and Hunter 1984; Hunter and Gallagher 1986).

To get a current SFR for a galaxy, we must observe a Q that is sensitive to short-lived stars. If τ_g is the time scale for significant variations in SFRs over galactic scales, then we require that $q(m^*) \rightarrow 0$, where the stellar evolution lifetime τ for stars of mass m^* is $\tau(m^*) \sim \tau_g$. Unfortunately, we do not currently have good theoretical predictions for τ_g , and furthermore τ_g may vary between galaxies. A reasonable choice is $\tau_g < 10^8$ yr, which corresponds to typical dynamical time scales within galaxies. For $\tau_g = 10^8$ yr, the critical stellar mass is $m^* \sim 5 M_\odot$. On the other hand, one should not choose too narrow a time interval to probe SFRs, since statistical noise associated with small samples of objects or small numbers of star forming sites will become a problem. For example, counting the luminosities of HII regions in the short-lived compact phase (Habing and Israel 1979) would not necessarily give a statistically reliable indicator of the current SFR in a galaxy.

To measure current galactic star formation rates, we therefore must estimate the numbers of OB stars, which is a well known result. A variety of measurable quantities Q can be used to trace OB stellar populations in galaxies: (1) Rocket ultraviolet luminosities reflect the numbers of hot stars in galaxies, but the interpretation is complicated by major extinction effects which are not easily disentangled (e.g. Huchra *et al.* 1983; Donas and Deharveng 1984; Lamb, Hunter and Gallagher 1986). (2) In a few nearby galaxies, OB stars can be directly counted and the resulting luminosity functions converted to star formation rates (Dennefeld and Tammann 1980; Hoessel and Danielson 1983). A difficulty in this approach lies in obtaining complete samples of OB stars, which is proving to be a major challenge even in the Magellanic Clouds. (3) Thermal radio emission and hydrogen recombination line luminosities measure the fluxes of Lyman continuum photons and thus the populations of hot, young stars. This approach has been successfully adopted by several groups including Smith, Biermann and Mezger (1978), GHT, Hunter and Gallagher (1986), Israel (1980), and Kennicutt (1983). These results also are sensitive to effects of dust and to the choice of model to convert observables into Lyman continuum luminosities (see the excellent summary by Güsten and Mezger 1982). (4) The far infrared luminosity may arise from dust heated primarily by OB stars. Our lack of understanding of the details of radiation processes responsible for $L(\text{FIR})$, as discussed by several papers during this meeting, introduce uncertainties into the choices of $w(r)$ and $q(m)$ that are needed to drive SFRs. In the pre-IRAS era, $L(\text{FIR})$ primarily was used to probe SFRs in 'star burst' galaxy candidates (e.g. Telesco and Harper 1980; Rieke *et al.* 1980; Gehrz, Sramek and Weedman 1983) and only recently has this Q been applied to galaxy populations in the general sense. (5) Radio continuum luminosities of galaxies are well-correlated with all other indicators of

current SFRs (see Klein 1982; Kennicutt 1983; de Jong *et al.* 1985; Helou *et al.* 1985; Sanders and Mirabell 1985), but suffer from a lack of understanding of the basic physical process which produces the correlation (i.e. both $w(r)$ and $q(m)$ are not properly known). Thus at present radio continuum data must be taken as a secondary method for deriving SFRs, which relies on other techniques for absolute calibration.

3. A COMPARISON OF SFRS BASED ON FIR AND H α LUMINOSITIES

In the spirit of eq. (1), we compress the problem of measuring a corrected H α luminosity $L^\circ(\text{H}\alpha)$ from an H α flux corrected for Galactic extinction $F^\circ(\text{H}\alpha)$,

$$L^\circ(\text{H}\alpha) = F^\circ(\text{H}\alpha) \cdot \exp \tau(\text{H}\alpha) \cdot (1+\gamma^*) \cdot (4\pi D^2). \quad (2)$$

Here D is the distance, γ^* is a correction factor for underlying H α stellar absorption, and $\tau(\text{H}\alpha)$ is some mean optical depth in the H α line due to internal dust in the galaxy. From simple recombination theory, the Lyman continuum photon luminosity N_c is proportional to $L^\circ(\text{H}\alpha)$, $N_c = 7.3 \times 10^{11} L^\circ(\text{H}\alpha) \text{ s}^{-1}$.

N_c is linked to the stellar population through the initial mass function (IMF), and following the notation of GHT with a Salpeter IMF,

$$N_c = \alpha_c \int_{m_*}^{m_u} (m^{-2.35}) [\overline{n_c(m)t(m)}] \eta \, dm. \quad (3)$$

We have adopted the Renzini-Tinsley approach in assuming a constant SFR over the time interval of interest here, in which case the time evolution of the luminosity for stars of mass m , $n_c(m)$, is replaced by an average over the appropriate stellar lifetime at mass m for the production of H-ionizing photons (see Renzini 1981). The other parameter η is an efficiency factor, and we wish to solve for the normalized SFR, $\dot{M}(\text{H}\alpha) = 5.8 \alpha_c M_\odot \text{ yr}^{-1}$ with a minimum stellar mass of $0.1 M_\odot$; see GHT for details.)

The integral in eq. (3) is also sensitive to the choice of the maximum stellar mass m_u , as $\overline{n_c(m)t(m)}$ rises nearly as steeply as the Salpeter IMF falls to masses of $\gtrsim 100 M_\odot$ (Güsten and Mezger 1982). For an $m_u = 100 m_\odot$, we estimate

$$\dot{M}(\text{H}\alpha) = (2.5 \times 10^{-8}) \eta^{-1} L^\circ(\text{H}\alpha) M_\odot \text{ yr}^{-1} \quad (4)$$

where $L^\circ(\text{H}\alpha)$ is measured in units of the sun's bolometric luminosity. The coefficient in eq. (4) depends on several factors, including the choice of IMF parameters, stellar evolution models, and the derivation of $n_c(m)$ as a function of time, effective temperature, surface gravity, abundance, etc. Hidden in the efficiency factor η are the escape of ionizing photons and the loss of ionizing photons due to the effects of dust. Since most of the contribution to $\dot{M}(\text{H}\alpha)$ must come from stars with lifetimes $\tau(m^*) \lesssim 10^7 \text{ yr}$; H α observations in principle provide particularly clean snapshots of star forming processes in galaxies.

An SFR can be derived from measurements of $L(\text{IR})$ under the assumption that massive stars play a major role in heating dust. The analog to eq. (3) is then (cf. Hunter *et al.* 1986a)

$$L^*(\text{FIR}) = \alpha_I \int_{m^*}^{m_u} (m^{-2.35}) \sum_j (\overline{L(m)} \tau(m))_j \beta \, dm. \quad (5)$$

This is a more extreme simplification than in the $\text{H}\alpha$ case, as the efficiency factor β should be a function of stellar temperature and the geometry of the galaxy should be taken into account in calculating the absorption of radiation. We will assume that $\beta \sim 0.5$ for all stars with an effective temperature above some threshold. The sum is over stellar evolutionary phases, and following the Renzini-Tinsley approach, we need only bolometric energies which stellar evolution models predict reasonably well (cf. Renzini 1981). Finally, we must account for infrared luminosity that is not associated with young stars, e.g. we probably should exclude the cold dust luminosity component (see Hunter *et al.* 1986a). Thus for an observed $L^\circ(\text{IR})$, we have $L^*(\text{FIR}) = \delta L^\circ(\text{IR})$ where $\delta \ll 1$.

For $m^* = 10 M_\odot$ and modern stellar evolution models which include mass loss (e.g. from Maeder 1981; Brunish and Truran 1982), we find

$$\dot{M}_1(\text{FIR}) = 2.5 \times 10^{-10} \beta^{-1} \delta L^\circ(\text{IR}) M_\odot \text{yr}^{-1} \quad (6)$$

where $L^\circ(\text{IR})$ is again in bolometric solar units. The relevant time scale for eq. (5) is $\tau(m^*) \sim 2 \times 10^7$ yr, and we are including only stars and evolutionary phases with $\log T_e > 4.3$. If cooler stars are effectively heating dust, then the coefficient in eq. (6) is reduced. For example, reduction of the stellar temperature limit to $\log T_e > 4.0$ corresponds to $m^* \sim 2 M_\odot$ and $\tau(m^*) \sim 10^9$ yr, while the coefficient changes only slightly to $2.1 \times 10^{-10} M_\odot \text{yr}^{-1} L_\odot^{-1}$.

Taken on their own, the FIR data thus involve a time average of the SFR over a somewhat indeterminate period, which could vary depending on physical conditions within galaxies. Dusty galaxies can have high optical depths for the absorption of radiation at visible wavelengths, and even comparatively cool stars can contribute to $L^\circ(\text{IR})$. Most blue irregular galaxies lie at the opposite extreme, and have low dust optical depths in the visible (Hunter and Gallagher 1986). In these types of galaxies, UV heatings by younger stars is likely to be favored, and thus $L^\circ(\text{IR})$ may be a good indicator of the current SFR.

4. APPLICATIONS TO REAL GALAXIES

4.1 Current SFRs

Blue irregular galaxies provide a way to test our ideas about SFRs and evolutionary processes in galaxies for the following reasons: (1) We have collected a large body of optical data, which includes $\text{H}\alpha$ fluxes (cf. Hunter and Gallagher 1986). (2) Due to the low internal optical depths found in most Irrs, star forming sites usually are optically visible (Hunter 1982). (3) Irrs have the bluest optical colors for 'normal' (i.e. non-active) galaxies, and thus are logical candidates for star formation bursts on galactic

scales. (4) The majority of the less luminous Irrs are structurally simple and close to single zone systems, which allows primitive models to be used in interpreting observations.

We have recently collected IRAS observations of Irr galaxies included in our various optical samples (see Hunter and Gallagher 1986; Hunter *et al.* 1986a,b). These data are shown in Figure 1, where the Irrs basically form a continuation of the normal spirals to higher far infrared color temperatures, and perhaps somewhat more surprisingly, to higher values of $L(\text{IR})/L(\text{B})$. A complete discussion of these data is currently in preparation by Hunter, Rice, Gallagher and Gillett.

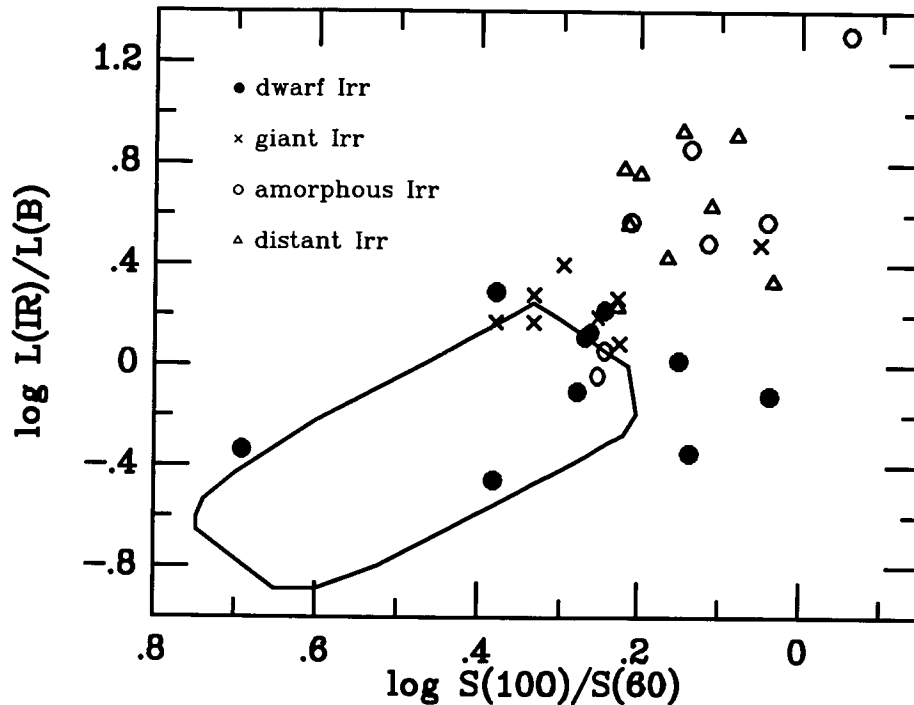


Figure 1. Irr galaxies are plotted on a luminosity-color diagram after de Jong *et al.* (1984). $L(\text{B})$ is the blue luminosity, and $S(60)$ and $S(100)$ are IRAS flux measurements at 60 and 100 microns. $L(\text{IR})$ is derived from $\nu f(\nu)$ at 80 microns. The various structural class samples of Irr galaxies defined by Hunter and Gallagher (1986) are shown, and the approximate area occupied by spirals is outlined.

The two indicators for current SFRs, $\dot{M}(\text{H}\alpha)$ and $\dot{M}_1(\text{IR})$, can be directly intercompared using the data for Irrs. Making the approximation that $(1+\gamma^*) = 1.0$ in eq. (2), we have

$$\frac{\dot{M}(\text{H}\alpha)}{\dot{M}_1(\text{IR})} = 100 \frac{\exp \frac{\tau(\text{H}\alpha)\beta L(\text{H}\alpha)}{\eta \delta L(\text{IR})}}{L(\text{IR})}. \quad (7)$$

For the assumptions of high efficiencies, ($\beta = \eta \approx 1$) and low $\overline{\tau(H\alpha)}$, we obtain the limit that $L(IR) = 100 L(H\alpha)$ if both luminosities measure the current SFR, and star formation has continued at a constant rate over $> 2 \times 10^7$ yr (cf. eqns. 5 and 6). A minimum ratio of $L(IR) = 16 L(H\alpha)$ can also be derived by assuming that, as in HII regions, equal amounts of power from O stars goes into dust heating and the eventual production of H α emission (see Hunter *et al.* 1986a). The minimum model thus is appropriate where L(IR) is dominated by contributions from HII regions. The results of these models are shown in Figure 2.

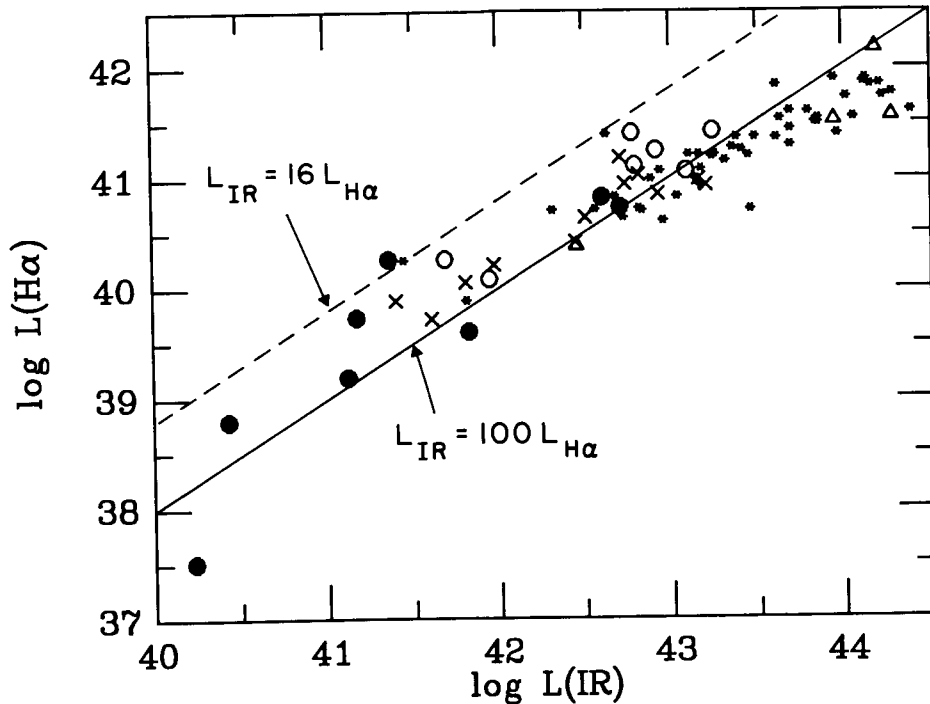


Figure 2. H α and FIR luminosities are plotted for Irr galaxies (same symbols as in Figure 1) and spiral galaxies for which H α fluxes have been measured by Kennicutt and Kent (1983) (plotted as stars). Model relationships are also shown.

Figure 2 is encouraging in that $L(IR) \propto L(H\alpha)$ over a factor of $\sim 10^4$ in luminosity and the proportionality constant lies near the expected value of 100. Thus we see that L(IR) empirically is a useful tracer of the current SFR. This diagram also shows that many details remain to be sorted out. Luminous spirals and Irrs have high $L(IR)/L(H\alpha)$ ratios, which could be due to high optical depths or heating by older stellar populations. Just as puzzling are the normal Irrs where $L(IR)/L(H\alpha)$ falls near our minimum estimate. It is possible that only very massive stars are contributing to the observed L(IR) in these systems, and further work is needed.

4.2 Star Formation Histories and the Existence of Star Formation Bursts

Following the approach of GHT, we can chart the evolutionary histories of galaxies by comparing SFR indicators that are sensitive to long term integrals over the SFR with estimates of current SFRs. GHT and Kennicutt (1983) have argued that most disk galaxies with active star formation have produced new stars at roughly time-constant rates during the past several Gyr. We can test the constant SFR, fixed IMF model by using the blue luminosity $L(B)$ to estimate the average SFR over ~ 3 Gyr (GHT).

In this case, a simple model which includes evolved stars as in eq. (5) and adopts a Salpeter IMF predicts $L(B)/L(IR) \sim 1$, where we have taken a mean optical depth at B of $\tau_B = 1.0$. Note that $L(B)$ is the luminosity in terms of solar luminosities on the Johnson B system (one must be careful to properly define luminosities in the various color bands!). The results of this model are shown in Figure 3. Most galactic SFRs are within a factor of 3 (which is still quite large, but our model is primitive) of the constant SFR line. We will define a 'star burst' to be an epoch in which the SFR has increased by a substantial (> 3) factor over its historical mean value. Thus short-lived bursts (this diagram is most sensitive to bursts over time intervals of $\lesssim 10^9$ yr) are not common in field blue galaxies, and the only obvious burst candidate in our sample is the extragalactic HII region IIZw40. A similar result has been found by Thronson and Telesco (1986), although we have used a slightly different approach in analyzing our data.

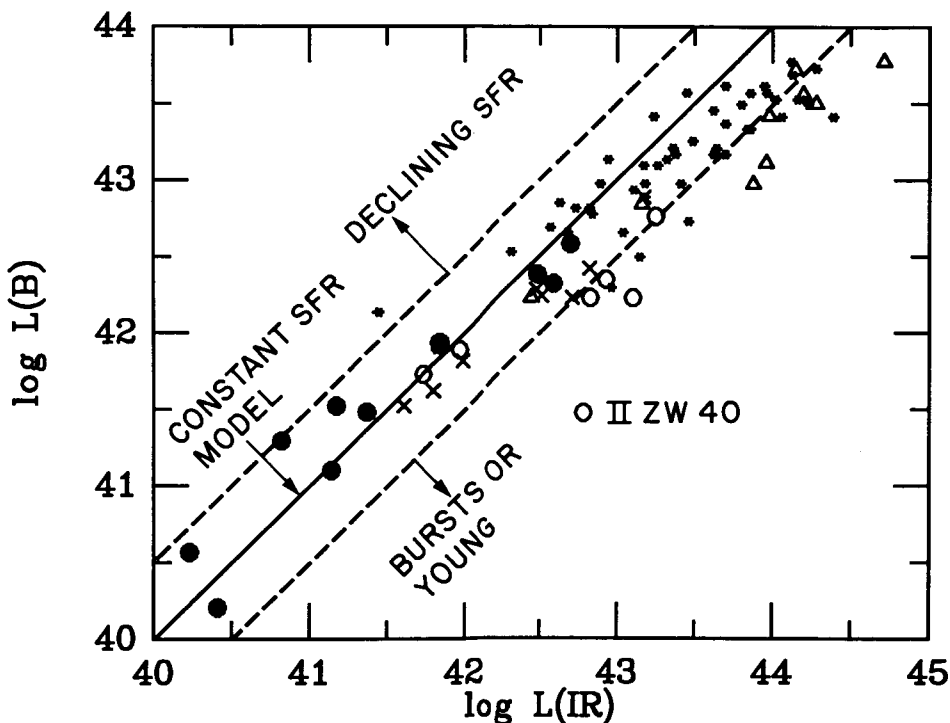


Figure 3. Predicted correlations for $L(B)$ vs. $L(IR)$ are shown with observed properties of spiral and irregular galaxies.

The $L(B)$ vs. $L(IR)$ diagram is not a useful diagnostic for systems such as M82, where τ_B is high. In these cases one can use mass-to-light ratios to detect anomalously luminous stellar populations. This approach was pioneered by Telesco and Harper (1980) and by Rieke *et al.* (1980), who pointed out that very low values of stellar mass-to-light ratios are indicative of overpopulations of massive stars. Using our models, we would predict $M_*/L(IR) = 2.5$ in solar units for a constant SFR, and $M_*/L(IR) \lesssim 0.5$ for high amplitude SFR bursts. Observed $M_*/L(IR)$ values in the centers of galaxies suspected of harboring star bursts are often < 0.1 , which argues very strongly for the existence of bursts or some other anomaly, such as an IMF that is skewed in favor of massive stars (see Telesco 1985).

Another way to look at star formation histories is shown in Figure 4. Galaxies in region 1 have near constant SFRs in combination with either moderate $\tau(H\alpha)$ or dust heating by older stars to give high values of $L(IR)$ relative to optical luminosities. Area 2 contains galaxies where both $L(B)$ and $L(H\alpha)$ are very low, and these systems are likely to be very dusty and effectively opaque at visible wavelengths. The physical nature of the power sources in these hidden galaxies cannot be determined from optical observations. Area 3 contains optically thin, constant SFR galaxies, and area

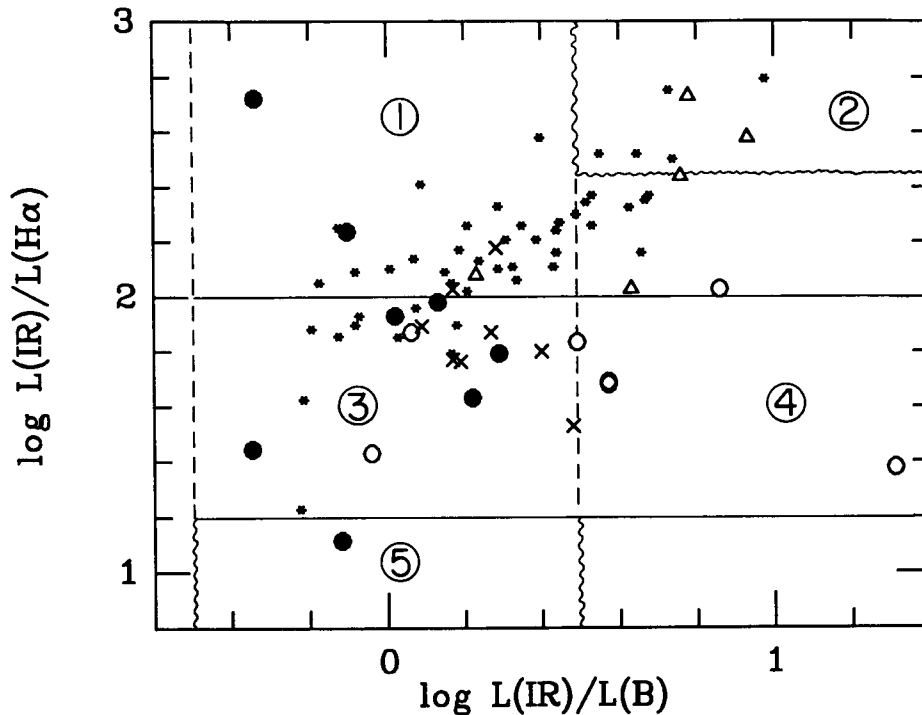


Figure 4. Irregular and spiral galaxies are plotted on a color-color diagram which can be used to study star forming histories. Different numbered regions are discussed in the text. Galaxies with high optical depths, which are effectively hidden at optical wavelengths, are found in the upper right corner, HII-region-like objects fall to the center right, and constant SFR galaxies cluster near the left-center.

4 shows the presence of a few low optical depth burst galaxy candidates. Finally Zone 5 includes galaxies which have extreme excesses of $L(H\alpha)$. Very metal-poor galaxies with low dust-to-gas ratios could populate this region of the diagram, but we have no outstanding candidates for such galaxies.

5. CONCLUSIONS AND CAUTIONS

i) Both $L(IR)$ and $L(H\alpha)$ provide useful measures of current SFRs in galaxies, at least to the levels of factors of 2 or 3. It is not clear, however, what stellar lifetime should be associated with $L(IR)$, and there are indications that the average age of the stellar populations responsible for $L(IR)$ varies between galaxies.

ii) The majority of normal blue Irrs in our sample (which is not a complete sample; see Hunter and Gallagher 1986) have properties consistent with constant SFRs over the past 2-4 Gyr. Thus the IR observations give results that agree with the GHT optical studies (see also Thronson and Telesco 1986), and one cannot assume that galaxies with blue colors or strong emission lines are in a star burst phase. Furthermore, if the SFR is roughly constant over time, luminosities arising from different age stellar population components are correlated, and thus it is not easy to isolate the stellar population component responsible for $L(IR)$.

iii) Optical depths may play a substantial role in determining properties of FIR-luminous galaxies. In general we expect that as the internal optical depth increases, $L(IR)$ rises while $L(H\alpha)$ and $L(B)$ decline. We see some evidence for this trend to occur among the luminous Irrs (see Figure 4) which suggests that optical SFR measurements do not give a complete picture in these systems.

iv) SFR bursts are not common among the dwarf and normal Irr galaxies in our sample. IIZw40 has all the properties that would be expected for a high amplitude SFR burst in a small system. The very high values of $L(IR)/L(B)$ and $L(IR)/L(H\alpha)$ in combination with the substantial optical luminosities of the luminous Irrs suggest that many of these galaxies could also be in SFR burst evolutionary phases. We suspect, on the basis of optical observations, that the majority of the luminous Irrs are results of enhanced star forming activity associated with galaxy-galaxy interactions. High levels of star formation are also seen in the strongly interacting galaxy sample being investigated by H. Bushouse (1986a,b) and interactions thus may be the main source of star bursts among more luminous galaxies in nearby samples.

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DISCUSSION

YOUNG:

In your plot of $L_{H\alpha}$ vs. L_B was NGC 1569 included?

GALLAGHER:

Yes, it looks normal. This is probably an indication that the epoch of enhanced star formation has been going on for $\sim 10^9$ yr. For time scales of $\gtrsim 10^9$ yr, the $L_B/L_{H\alpha}$ ratios rapidly approach their equilibrium values for constant SFR systems.