Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Stellar populations in starburst galaxies

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Abstract. Many galaxies emit a dominant fraction of their bolometric luminosity in the infrared. The small mass-luminosity ratios suggest that these infrared luminosities cannot be sustained by a normal stellar population over a Hubble time. The commonly held explanation is that there has been a burst of star formation sufficiently recently that the full spectrum of the initial mass function up to the highest mass stars is contributing to the luminosity. Starburst galaxies therefore provide laboratories for studying the upper end of the initial mass function.

After a briefly summarizing studies of the IMF in the solar neighborhood and in nearby 'normal' galaxies, I will turn to studies of environments in which there appears to be evidence for a somewhat different IMF, *viz.*, in starburst galaxies. I will discuss infrared spectroscopic diagnostics of a sample of the most luminous starburst galaxies and what this implies for the IMFs in these 'violent' star formation events.

1. Properties of starburst galaxies

In this talk I will be discussing starbursts in classic spiral galaxies. I will not be considering the extreme and spectacular but generally lower-luminosity starburst activity in irregular-type galaxies, nor the relatively low-level ongoing star formation that takes place in the interstellar medium. Kennicutt has provided an excellent review on starbursts in his Saas-Fee lectures (Kennicutt 1998).

1.1. Some historical highlights

It may be difficult for the younger members of this audience to appreciate that it has not been that long that we have been able to study galaxies in the infrared. Extragalactic photometry was not possible until detectors of sufficient sensitivity were developed in the 1960s. It was only in the 1980s that the first small-format infrared detector arrays were introduced. In the early 1990s arrays as large as 256×256 pixels became available, finally permitting development of instruments of sufficient sensitivity for imaging and spectroscopy of galaxies in the 1–5 μm spectral region.

The discovery that the centers of many spiral galaxies are bright in the infrared is one of the outstanding achievements of infrared astronomy. The seminal discovery paper was published by Rieke & Low (1972). They showed that a heterogeneous group of galaxies including 'normal' spirals, Seyferts, and QSOs had spectral energy distributions longward of 2 μm that turned sharply upward and the bolometric luminosity was dominated by the infrared spectral region. The spectral energy distributions for a number of starburst galaxies

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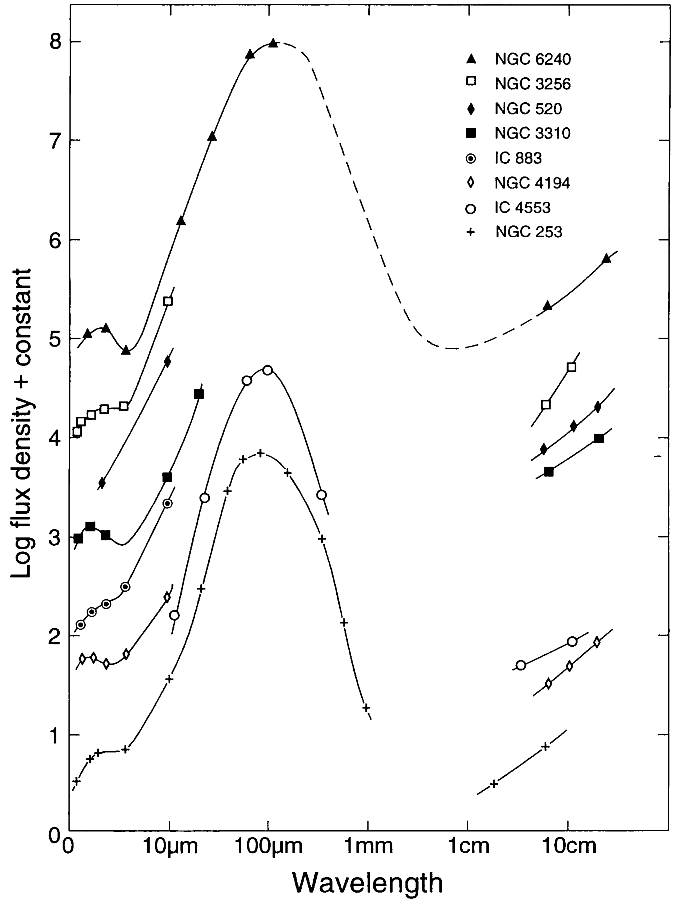

Figure 1. Spectral energy distributions of some infrared-bright galaxies (Joseph & Wright 1985).

shown in Fig. 1 illustrate the dramatic rise by three orders of magnitude in the infrared that characterizes this class of 'infrared-bright' galaxies.

The next major milestone for me was the interpretation of these infrared luminosities by Harwit & Pacini (1975) in terms of a recent burst of star formation. This interpretation was largely based on analogy with the infrared spectral energy distributions of galactic H II regions, in which the infrared was understood to arise from thermal emission by dust heated by the visible and ultraviolet light emitted by recently formed hot, early-type stars, which also provided the ionization responsible for forming the H II region. This interpretation received further support when the Markarian blue/emission-line survey turned up samples of galaxies most easily interpreted in terms of recent star formation events (*e.g.*, Balzano 1983). The term 'starburst' was first introduced by Weedman *et al.* (1981) in their study of a recent powerful episode of star formation in NGC 7714.

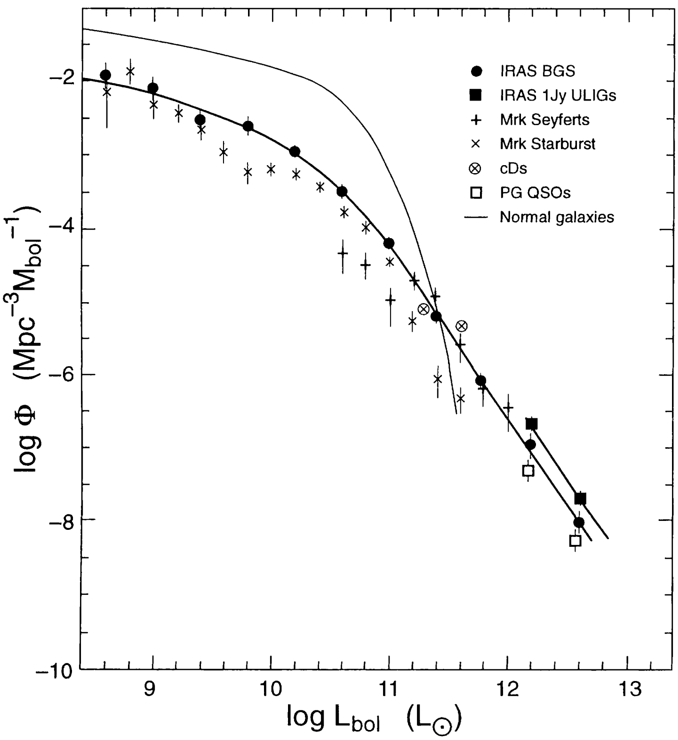

Figure 2. Luminosity functions for various classes of galaxies (Sanders & Mirabel 1996).

The growing evidence for a recent burst of star formation in a few percent of spiral galaxies raised the question of what triggers starbursts. Larson & Tinsley (1978) had compared the *UBV* colors of a sample of interacting galaxies with a sample from the *Hubble Atlas*, and found that the interacting galaxies showed both larger dispersion in colors and a systematically blue envelope to the distribution. They interpreted this in terms of recent star formation triggered by the tidal effects of the interactions. Joseph *et al.* (1984) showed that the spectral energy distributions of a sample of strongly interacting galaxies showed the increase toward longer infrared wavelengths that characterized starburst activity, and Joseph & Wright (1985) showed the effect was even more pronounced in galaxies thought to be the recent mergers of two spirals.

The *IRAS* infrared sky survey revealed that there are many infrared-bright galaxies, ~20 000 in the original survey complete to ~0.5 Jy. More than 50 000 are now known from deeper survey analysis. Most *IRAS* galaxies are not in optical catalogues, and it is obvious that *IRAS* has revolutionized our picture of the extragalactic universe. Infrared-bright galaxies appear to dominate the extragalactic luminosity function at the highest luminosity, as shown in Fig. 2.

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1.2. How do we know there is a starburst?

In general, neither visual evidence for young stars nor large infrared luminosities are by themselves sufficient to guarantee the presence of a starburst. How does one decide a starburst is present?

1. A starburst is probably present if the M/L ratio in the central region is $\ll 1\,\mathrm{M_\odot/L_\odot}$. For an evolved stellar population with luminosity provided by thermonuclear reactions in stars, with star formation efficiency ε and age τ,

$$M/L \simeq M/(0.007\varepsilon Mc^2/\tau) \simeq 1(\mathrm{M_\odot/L_\odot}) \text{ if } \tau \simeq \mathrm{H}_0^{-1} \text{and } \varepsilon \simeq 0.1.$$

If the $M/L \ll 1$, this implies a recent burst of star formation, with luminosity largely powered by early-type stars.

2. Another approach is to show that the star formation rate implies a gas depletion time that is short, say $< 10^9$ yr.

3. A starburst is implicated if the ratio of infrared to blue luminosity, $L_{\mathrm{IR}}/L_{\mathrm{B}}$, is > 10; it is actually found to be in excess of 100 for some highly luminous objects (*cf.* Sanders & Mirabel 1996). This would be expected if there were recent star formation with the newly formed stars buried in their gas and dust 'cocoons'. Other evidence that most luminous infrared galaxies are powered by starbursts includes the following correlations, which are most easily understood in terms of an underlying starburst.

4. There is a fairly good correlation between the luminosity in the Br-γ line of hydrogen and the total infrared luminosity (*cf.* Goldader *et al.* 1997a,b) for infrared-bright galaxies. This suggests that the infrared luminosity is powered by hot *young* stars that are also ionizing the surrounding gas.

5. One of the most astonishing results from analysis of the *IRAS* survey was an unusually tight correlation between radio and infrared continuum fluxes over several orders of magnitude for spiral galaxies (*cf.* Sanders & Mirabel 1996). Since the radio (synchrotron) continuum is thought to be powered by supernova remnants, the correlation may again be understood in terms of a starburst model in which the infrared flux is dominantly powered by the rate of recent star formation and the radio represents the rate of evolution of massive stars into supernovae.

1.3. General features of starbursts

Starbursts are characterized by the following general features:

1. Infrared luminosities range from 10^6 to $> 10^{12}\,\mathrm{L_\odot}$, but a typical luminosity would be $\sim 5 \times 10^{10}\,\mathrm{L_\odot}$.

2. The extinction is high, with measured $A_V \simeq 2$–10, but A_V is generally larger the longer the wavelength of the diagnostic used to measure extinction.

3. Starbursts tend to be associated with galaxy-galaxy interactions. For luminosities $> 10^{11}\,\mathrm{L_\odot}$, $\sim 50\%$ are associated with interactions; at luminosities $> 10^{12}\,\mathrm{L_\odot}$, $\sim 100\%$ are associated with mergers (*cf.* Sanders & Mirabel 1996).

4. The mass consumption rate for OBA-type stars in a burst of luminosity L is estimated to be (Scoville & Young 1983):

$$dm/dt = 7.7 \times 10^{-11} (L/\mathrm{L_\odot}) \mathrm{M_\odot yr^{-1}}$$

so starbursts consume 3–30 $\mathrm{M_\odot yr^{-1}}$ for medium luminosity ($5 \times 10^{10-11}\,\mathrm{L_\odot}$) starbursts.

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5. Such star formation episodes produce $\sim 10^5$ O-type stars.

6. Infrared galaxies are highly gas-rich, with 2–60 $\times 10^9\,M_\odot$ of molecular gas. The mass consumption rate implies depletion times of $\sim 10^{7-9}$ yr. This is another argument that the star formation powering these large infrared luminosities is a relatively recent event.

7. Molecular gas, recombination line emission, and far-infrared emission all tend to arise in the central ~ 1 kpc. But at higher resolution, measurements of more nearby objects suggest one is actually seeing the integrated emission from many individual giant star-forming regions.

In summary, a starburst should contain the full spectrum of the IMF up to the most massive stars formed. Thus starburst galaxies provide excellent laboratories for study of the upper end of the IMF, and the associated Wolf-Rayet phase in particular.

2. Stellar populations in normal galaxies

I will use the following notation for the IMF: $\Psi(m)dm \propto m^{-\alpha}dm$, integrated from a lower mass cutoff m_ℓ to an upper mass cutoff m_u. To provide a context for comparison with starburst galaxies, let me first summarize what we know about stellar populations in nearby 'normal' galaxies.

In the solar neighborhood, the average IMF spectrum from 0.1 to $100\,M_\odot$ is consistent with a Salpeter index $\alpha \simeq 2.35$, but the slope is flatter ($\alpha \simeq 1.35$) for $M < 0.5\,M_\odot$, and steeper ($\alpha \simeq 2.7$) for $M > 1\,M_\odot$ (*e.g.*, Scalo 1986; Basu & Rana 1992; Kroupa *et al.* 1993).

For fourteen OB associations in the Galaxy, Massey *et al.* (1995) found a mean $\alpha = 2.1$ over the range 4–$100\,M_\odot$.

In 30 Dor in the Large Magellanic Cloud, $\alpha = 2.22$ over 3–$100\,M_\odot$ (*e.g.*, Parker & Garmany 1993; Hunter *et al.* 1996).

In nearby spiral galaxies, Kennicutt *et al.* (1994) used *UBV* and Hα measurements and found the IMF to be consistent with a Salpeter slope.

In summary, most observations are broadly consistent with solar neighborhood IMF, *i.e.*, a Salpeter slope with $\alpha \simeq 2.35$, and a slightly flatter slope below one solar mass.

3. Stellar populations in luminous starbursts

3.1. Earlier studies of stellar populations in starbursts

Evidence has been growing over the past few years suggesting that in starburst galaxies the IMF is deficient in high-mass stars. Rieke *et al.* (1980, 1991) were the first to suggest that the IMF may have some surprises in starburst galaxies. They showed that for M 82, $m_u \simeq 25\,M_\odot$ and $m_\ell > 3\,M_\odot$. Wright *et al.* (1988) found $m_\ell > 3\,M_\odot$ in sample of IR-bright interacting galaxies. Ho *et al.* (1990) measured infrared recombination lines in seven infrared-bright galaxies and concluded that $m_u \simeq 30$–$60\,M_\odot$. Doyon *et al.* (1994) obtained excellent infrared spectroscopy for the powerful starburst galaxy NGC 3256, and they compared their results with a starburst population synthesis to show that the

IMF is truncated at both the low- and high-mass ends, with $m_u \simeq 30\,M_\odot$ and $m_\ell \simeq 1\,M_\odot$.

3.2. Goldader et al. study of stellar populations in starbursts

Observations. The above-mentioned results were based on studies of one or a few galaxies. Goldader *et al.* (1997a,b) approached this issue in a more comprehensive way by identifying a complete sample of ~ 95 galaxies with infrared luminosities $> 2 \times 10^{11}\,L_\odot$. Using a new and powerful infrared array spectrometer (CGS4) that had just been commissioned on *UKIRT*, they obtained spectra across the K window, $\sim 1.95\,\mu$m to $\sim 2.5\,\mu$m. This was a low-resolution survey with slit width 3″ and spectral resolution $R \simeq 350$ (FWHM $\simeq 900\,\mathrm{km\,s^{-1}}$). Examples of the spectra are shown in Fig. 3. They then compared several measured infrared spectroscopic diagnostics with predictions from the most recent population synthesis models calculated by Leitherer & Heckman (1995), with the aim of finding the IMF that best characterized this sample of powerful infrared galaxies.

Analysis. Goldader *et al.* used the following four diagnostics: L_{bol}, which they took as the total infrared luminosity, L_{IR}; L_K, the luminosity in the standard K (2.2 μm) filter; $L_{\mathrm{Br}\gamma}$, the luminosity in the Brackett-γ line of hydrogen; and the CO index, *i.e.*, the depth of luminosity-dependent CO absorption band in the late-type stars that dominate the 2 μm continuum (the CO index is strongest in

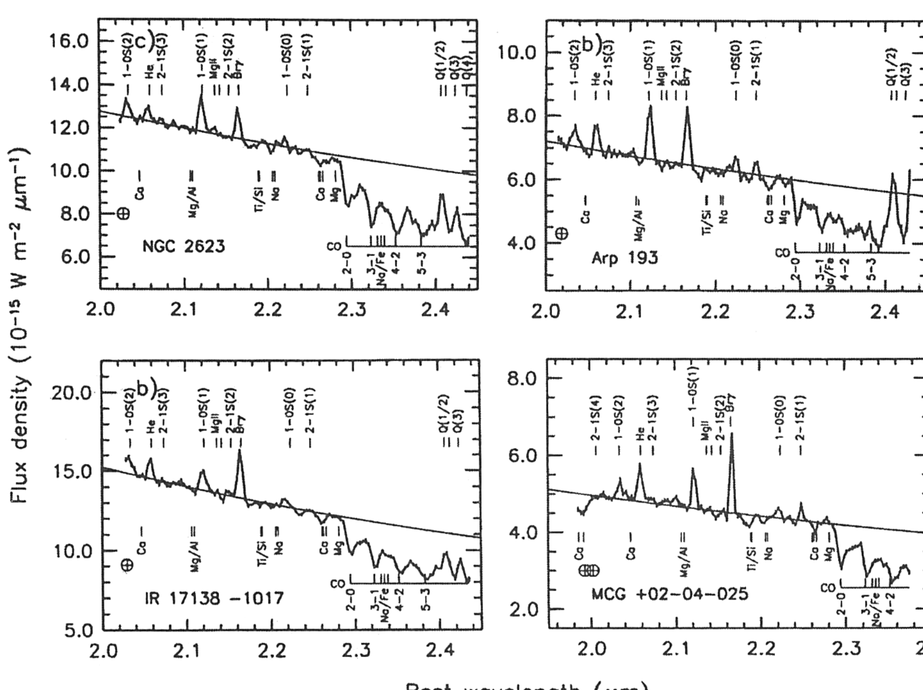

Figure 3. Typical infrared spectra obtained by Goldader *et al.* (1997a).

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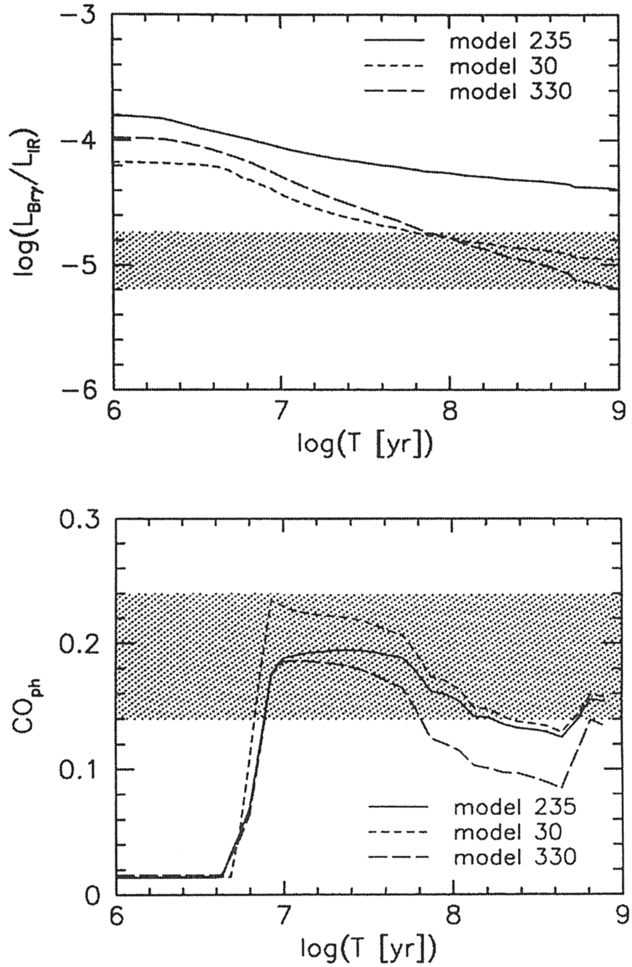

Figure 4. Comparison of measured infrared spectroscopic diagnostics by Goldader *et al.* (1997b) with the predictions of the Leitherer & Heckman (1995) population synthesis, as a function of the age of continuous star formation models. The shaded area represents the mean $\pm 1\,\sigma$ for the Goldader *et al.* measurements. Model-235 is the standard Salpeter IMF, and Model-30 and -330 are relatively deficient in high-mass stars, as described in the text.

supergiants and weakest in dwarfs). These diagnostics were measured from the (extinction-corrected) K-band spectra ($L_{\rm IR}$ was determined from *IRAS* data) and compared with values of these quantities in the stellar population synthesis models calculated by Leitherer & Heckman (1995). Since extinction at these infrared wavelengths is $\sim 10\%$ of the extinction in the visible, these diagnostics should provide a more realistic comparison to the extinction-free values calculated in the synthesis models. Leitherer & Heckman provided the values of these diagnostics as a function of the age of the starburst, for a continuous, constant

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rate of star formation, with three different assumptions about the IMF. Model-235 assumed a Salpeter index $\alpha = 2.35$, $m_u = 100\,\mathrm{M}_\odot$; this is the model with the largest production of massive stars. Model-30 also assumed a Salpeter index $\alpha = 2.35$, but the upper mass cutoff was reduced to $m_u = 30\,\mathrm{M}_\odot$. Model-330 assumed a much steeper IMF slope, $\alpha = 3.30$, $m_u = 100\,\mathrm{M}_\odot$; this and the Model-30 have fewer high-mass stars. Leitherer & Heckman assumed that the lower mass cutoff, $m_\ell = 1\,\mathrm{M}_\odot$ in all cases, since none of the diagnostics are sensitive to the choice of the lower mass cutoff.

The analysis for Goldader *et al.* was then to find which model best fits the observations, with starburst age as the independent variable. They calculated the mean and standard error for each of the diagnostics and plotted them on the Leitherer & Heckman evolutionary model diagrams. Examples for the Br-γ and the CO index diagnostics are shown in Fig. 4. It is evident that these diagnostics imply a mean starburst age for the sample of $10^{7.8-8.2}$ yr, but only for models poor in high mass stars.

Results for the mean IMF of the sample. The overlap of similar results for all four diagnostics implies an age of $10^{7.8-8.2}$ yr for continuous star formation, *with an IMF deficient in high-mass stars compared to the standard Salpeter IMF extending to 100* $\mathrm{M}_\odot$. Apparently these violent starburst events — tending to be triggered by interactions and mergers of spiral galaxies — do not produce as many high-mass stars as are seen in the more quiescent star formation regions described in Section 2 above.

Limits on the lower mass cutoff. The star formation rate given by the Leitherer & Heckman models (for $m_\ell = 1\,\mathrm{M}_\odot$) is ~ 20–$60\,\mathrm{M}_\odot \mathrm{yr}^{-1}$. For the typical lifetime of 10^8 yr which Goldader *et al.* found, this implies a total mass of stars formed of ~ 2–$6 \times 10^9\,\mathrm{M}_\odot$. Since the typical central mass of H_2 is $\leq 10^{10}\,\mathrm{M}_\odot$, *it would take extraordinary* H_2 *conversion efficiency to fuel an IMF extending to 1* $\mathrm{M}_\odot$.

If, however, one extends the lower mass cutoff m_ℓ to $0.1\,\mathrm{M}_\odot$, the star formation rate (solar masses per year) increases by a factor of 2 to 20, depending on how much flattening of the IMF slope is assumed. This then increases the total mass of the starburst to a range of 4–$120 \times 10^9\,\mathrm{M}_\odot$. Since the typical central mass of H_2 is $\leq 10^{10}\,\mathrm{M}_\odot$, *there is simply not sufficient fuel available to produce these starbursts if* m_ℓ *extends to 0.1* $\mathrm{M}_\odot$.

One is forced to conclude that the IMF is deficient in low-mass stars in these powerful interaction-induced starbursts, compared to the more quiescent star formation IMF found in the local solar neighborhood.

4. Conclusions

For $\sim 85\%$ of the Goldader *et al.* sample, the infrared spectral features found are those expected for *starbursts*. Population synthesis models suggest there is recent, continuous star formation with an average age $\sim 10^8$ yr; the IMF is deficient in high-mass stars compared to the solar neighborhood, and the IMF also seems to be deficient in stars $\leq 1\,\mathrm{M}_\odot$. This suggests that fewer Wolf-Rayet stars may be present in starburst galaxies than might be expected from the high star formation rates these galaxies exhibit.

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Discussion

Beck: If you put a few of the SSCs we have been talking about into your 1.5 kpc beam, (which is a size comparable to all of He2-10), would they be seen? Would they influence the spectrum at all?

Joseph: It depends on the proximity of the galaxy; obviously the more distant the more SSCs would be needed for detection of their lines — say Br-γ. If I understand correctly the subtext of your question, you are asking whether the characteristics of 'instantaneous' bursts seen in dwarf galaxy SSCs would be observable. If the SSC bursts we were to occur over a time interval $\lesssim 10^7$ yr, one would measure the features of an instantaneous burst; otherwise a random distribution of many SSC-bursts would mimic the continuous star-formation characteristics we found.

de Mello: Is there any correlation between the stage of interaction and the age of the burst? Have you looked for late mergers such as Arp 220?

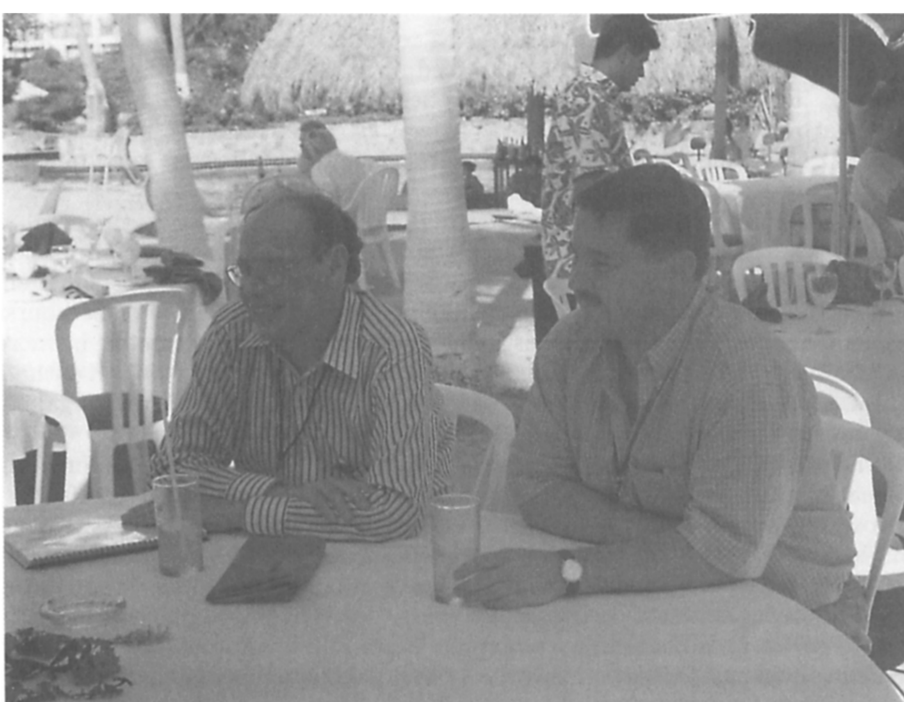
Joseph: The majority of this sample is interacting/merging (and it includes Arp 220 and NGC 6240). We have not attempted to estimate the age of interactions and to correlate these with the starburst age. It's an interesting idea, but to estimate an interaction age from morphological features is extremely subjective, as well as difficult. A few years ago, Gillian Wright and I did compare estimated merger ages with the infrared luminosity (Joseph & Wright 1985) and found that 'young' and 'old' mergers were less luminous than those of intermediate age, so perhaps we should explore this idea. Thank you for suggesting this.

Heckman: As you emphasized, the correlation between the far-IR and the non-thermal radio power is extremely tight. I think this argues very strongly that the duration of starbursts can not be less than the time-scale for the production of type II SNe (10's of Myr). This is consistent with your estimate of a burst-duration of 100 Myr, but inconsistent with some interpretations, of Wolf-Rayet galaxies (which require 'instantaneous' bursts with durations less than a few Myr).

Joseph: I agree, the fact that one gets strong Br-γ (indicative of hot O-type stars) and deep CO absorption (indicative of RSGs dominating the 2 μm continuum) simultaneously is another indication that one is not observing the coeval population of an 'instantaneous' burst.

Origlia: I have just a comment on the contamination by an underlying, older stellar population. On average, if the star-burst mass, as traced by RSGs, is less than a few percent of the older SP mass, it dominates the near-IR luminosity.

Joseph: Yes, of course. I'm just a bit concerned that we are systematically diluting the star-burst diagnostics for the more distant objects in this sample.



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