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A MORE DIRECT MEASURE OF SUPERNOVA RATES IN STARBURST GALAXIES

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ABSTRACT

We determine ages for young supernova remnants in the starburst galaxies M82 and NGC 253 by applying Chevalier's model for radio emission from supernova blast waves expanding into the ejecta of their precursor stars. Absolute ages are determined by calibrating the model with radio observations of Cas A. We derive supernova rates of 0.10 and 0.08 yr^{-1} for M82 and NGC 253, respectively. Assuming L_{FIR} to be proportional to the supernova rate, we find $r_{\mathrm{SN}} \approx 2 \times 10^{-12} \times L_{\mathrm{FIR},\odot}\ \mathrm{yr}^{-1}$ for these archetypal starburst galaxies. This approach is unique in that the supernova rate is derived from direct observation of supernova remnants rather than from star formation rates and an assumed initial mass function (IMF). We suggest that the approach presented here can be used to derive star-formation rates that are more directly related to observable quantities than those derived by other methods. We find that the supernova rate, FIR luminosity, and dynamical mass of the M82 starburst place few constraints on the IMF slope and mass limits.

Subject headings: galaxies: starburst — galaxies: stellar content — supernova remnants

1. INTRODUCTION

A fundamental quantity in starburst models is the formation rate of massive stars. Unfortunately, the formation of stars is very difficult to observe, so there is no direct measure of star formation rates as yet. Luckily, massive stars go through a single evolutionary event of profound observability—core collapse and subsequent supernova explosion. While no supernova explosion has yet been seen in a starburst region, the aftermath of the explosion leaves a remnant with strong nonthermal radio emission. Many compact nonthermal radio sources, interpreted as supernova remnants, have been found in the starburst galaxies M82 (Kronberg, Biermann, & Schwab 1985), NGC 253 (Antonucci & Ulvestad 1988; Turner & Ho 1985), and NGC 3448 (Noreau & Kronberg 1987).

Current starburst models predict that the *e*-folding time of typical starbursts is several times longer than the lifetime of the lowest mass stars that produce supernovae. Under the assumption of constant star-formation rate during the starburst phase, the supernova rate equals the star-formation rate for stars massive enough to undergo core collapse. The supernova rate of starbursts is usually estimated by scaling an adopted initial mass function (IMF) to the bolometric luminosity of the galaxy, assuming that this luminosity is produced by emission from the most massive stars of the burst. One then chooses a lower mass limit to supernova progenitors to find the supernova rate that such a population of stars would produce (e.g., Reike 1980). In this short paper, we provide a more direct measure of the supernova rate by counting remnants and estimating their ages. We then find an empirical relation between the supernova rate and far-infrared bolometric luminosity for starbursts and close by discussing constraints on the IMF in M82's starburst.

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2. DISCUSSION

2.1. *Starburst Supernova Remnants*

High-resolution VLA maps of M82, NGC 253, and NGC 3448 reveal a population of millijansky point sources with nonthermal spectra most easily interpreted as young supernova remnants. Examination of the radio images and lists of individual source fluxes leads to the conclusion that confusion limits the source counts. We adopt a completeness limit of 2 mJy for M82 sources and 3 mJy for the sources in NGC 253. The point sources in NGC 3448 appear to be confused at all flux levels. Our conclusions will not be sensitive to these choices. Choosing a completeness limit that is too high reduces the source counts and hence the statistical significance of the deduced supernova rate. Using a limit that is too low will include only a fraction of the faintest remnants and will also lead to an error in the rate. At the fainter fluxes, the identification of a source as a supernova remnant is no longer secure, since the fluxes fall in the range of luminous H II regions.

We present the cumulative log N–log S relation for the M82 sources in Figure 1. The solid line represents the source counts, and the dashed lines are the 1 σ uncertainties from the counting statistics. While the source counts are consistent with a single power law, they can also be interpreted as due to two populations: supernova remnants and H II regions. At higher flux levels, $S_{6\,\mathrm{cm}} > 3$ mJy, the source counts are all remnants. At $S_{6\,\mathrm{cm}} < 3$ mJy, giant H II regions contaminate the sample, leading to a steepening of the source counts at low fluxes. Below about 1.5–2 mJy, the confusion limit is reached and individual sources are no longer detected against the extended emission of the galaxy. In support of the notion that there are two source populations, we note that only two of 11 sources observed at 2 cm by Kronberg et al. (1985) were found to have positive spectral indices. Both of these thermal sources (39.7 + 55.6 and 42.2 + 59.0) are fainter than 3 mJy. The remaining 6 cm sources were not detected at 2 cm by Kronberg et al. (1985). These undetected 2 cm sources are among the faintest 6

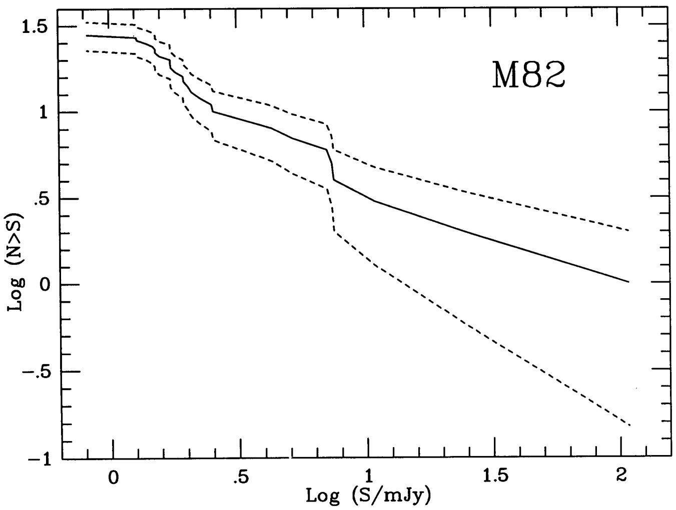


FIG. 1.—The cumulative log N–log S relation for M82 6 cm point sources found by Kronberg, Biermann, & Schwab (1985). The counts are consistent with two populations: supernova remnants with $S_{6\,\mathrm{cm}} > 3$ mJy and a contaminating population of H II regions at lower flux levels.

cm sources. We suggest that when they are detected by future observations, a sizable fraction will have thermal spectral indices.

To determine the age of the remnants from their radio fluxes, we adopt the model of Chevalier (1982) for the evolution of Type II supernova blast waves expanding into red giant ejecta. A crucial assumption we make is that this model applies to all the remnants seen in the radio continuum. This model applies as long as the emission is optically thin and the blast wave is interacting with the red supergiant ejecta within roughly 1 to several hundred years after the outburst. The time dependence of the 6 cm flux density of Chevalier's self-similar models is $t^{-(\gamma+5-6\zeta)/2}$, where the energy distribution of nonthermal electrons is parameterized by the power-law index γ. We set γ to be -2.5. The density distribution of the red giant ejecta is parameterized by ζ, which ranges from the value 0.8 to 0.9. We choose $\zeta = 0.85$, but the results change little by choosing extreme values. With these choices, the 6 cm flux density $S_{6\,\mathrm{cm}} \propto t^{-1.30}$. The spectral luminosity density at 6 cm is $l_{6\,\mathrm{cm}} = 4\pi D^2 S_{6\,\mathrm{cm}}$ and $t' = l_{6\,\mathrm{cm}}^{-0.77}$ is proportional to the age of the remnant. From a continuity analysis of the M82 sources, Kronberg (1988) found that the ages are proportional to the quantity $l_{6\,\mathrm{cm}}^{-\alpha}$ with $\alpha = -0.9 \pm 0.2$, motivating our choice of Chevalier's model.

Consider the cumulative age counts of M82 remnants: the number of remnants with age indicator greater than or equal to t' as a function of t'. A Kolmogorov-Smirnov test (Kolmogorov 1933; Smirnov 1939) on the M82 data with $S_{6\,\mathrm{cm}} > 3$ mJy indicates that the age counts grow linearly with t'. We interpret this result as showing that the age counts can be explained by a recent uniform supernova rate and a decay of remnant radio fluxes proportional to $t^{-\alpha}$, with $\alpha = 0.85 \pm 0.15$. The range includes all values of α for which the Kolmogorov-Smirnov significance exceeds 0.99. This range allows the value 0.77 given by the Chevalier model and is also consistent with Kronberg's continuity results. A similar result is found for NGC 253, with $\alpha = 0.90 \pm 0.14$. Because there is strong confusion at all flux levels in the NGC 3448 sources, we do not perform a similar analysis for that galaxy.

2.2. *Absolute Ages of the Remnants*

In order to estimate the true ages from the observed flux densities and distances, we now wish to calibrate the evolution of the 6 cm luminosity density of starburst supernova remnants,

$$l_{6\,\mathrm{cm}} = l^*_{6\,\mathrm{cm}}\, t_{\mathrm{yr}}^{-1.30}\,, \tag{1}$$

where $l^*_{6\,\mathrm{cm}}$ is the spectral luminosity density at an age of 1 yr. The Galactic supernova remnant Cas A provides a good calibrator on the basis of its known age and 6 cm flux. We use the data of Whitfield (1957), from which we derive for $t_{\mathrm{yr}} = 314$ $S_{6\,\mathrm{cm}} = 650$ Jy. Adopting a distance $D = 3$ kpc yields $l_{6\,\mathrm{cm}}$(314 yr) $= 7 \times 10^{24}$ ergs s^{-1} Hz^{-1}. This gives us

$$l_{6\,\mathrm{cm}} = 1.2 \times 10^{28} t_{\mathrm{yr}}^{-1.30} \text{ ergs s}^{-1}\text{ Hz}^{-1}\,. \tag{2}$$

We can write the 6 cm flux density in terms of the age and distance as

$$S_{6\,\mathrm{cm}} = 1.0 \times 10^{4} t_{\mathrm{yr}}^{-1.30} D_{\mathrm{Mpc}}^{-2} \text{ mJy}\,. \tag{3}$$

Note that the onset of radio emission occurs when the blast wave hits the red giant ejecta, but t is measured from the time of the explosion. If the inner parts of the ejecta have been swept up by an intervening blue supergiant phase, as is likely the case with SN 1987A (Luo & McCray 1991), a decade or two could elapse between the explosion and the radio outburst.

2.3. *Supernova Rate of M82 and NGC 253*

Rather than present a long list of derived supernova remnant ages in the two galaxies, we give instead our estimates of the ages of the remnant populations in the flux intervals over which the counts are complete, using the inverted form of equation (3),

$$t_{\mathrm{yr}} = 1.2 \times 10^{3} S_{6\,\mathrm{cm}}^{-0.77} D_{\mathrm{Mpc}}^{-1.54} \text{ yr}\,. \tag{4}$$

Taking $D = 3.2$ Mpc, we find that M82 has nine remnants above the uncontaminated sample limit of 3 mJy, so the age of the sample is 86 yr. Similarly, the 10 remnants in the complete sample for NGC 253 ($D = 4.2$ Mpc) brighter than 3 mJy have accumulated in the last 123 yr. We derive supernova rates of 0.10 and 0.08 yr^{-1} for M82 and NGC 253, respectively.

Very long baseline interferometry (VLBI) of the M82 remnants by Bartel et al. (1987) show that several are extended. By assuming an expansion velocity of 12,000 km s^{-1} for each object, they determine ages of 25 ± 1, 23 ± 1, and 80 ± 20 yr for 41.9+58, 43.3+591, and 45.2+612, respectively. Our estimates of the ages based on equation (4) are 5, 31, and 42 yr. We know from Bash (1968) that 41.9+58 has existed since at least 1965.6, when it had a 2.7 GHz flux of about 0.5 Jy, so the age estimated by our formula is an underestimate relative to the VLBI results. An interpretation is that 41.9 is overluminous with respect to the Chevalier model, which could occur if this remnant is expanding into an unusually dense medium. The expansion ages of the other two objects are in adequate agreement with those we derive.

Supernova rates for M82 ranging from 0.1 to 0.4 yr^{-1} have been predicted from starburst models produced by Rieke et al. (1980). The rate we derive is most consistent with model "A" of Rieke et al. (1980), which is based on the solar neighborhood IMF derived by Miller & Scalo (1979). A number of spectral synthesis models for the M82 starburst were recently calculated by Bernlöhr (1992) and may be interpreted as giving supernova rates if one assigns a mass of 1.4 $M_\odot$ per remnant.

The best match with our suprnova rate occurs for Bernlöhr's model 4 in Table 4, with an inferred model rate of 0.15 yr^{-1}. A recent paper by Colina & Pérez-Olea (1992) uses the radio supernova remnants in M82 and NGC 253 to estimate supernova rates of ultraluminous infrared galaxies, although they follow a different formalism with different assumptions than ours. They find after calibrating the infrared luminosity to supernova rate, the rates in M82 and NGC 253 are 0.2 yr^{-1} and 0.05 yr^{-1}, respectively.

Suppose for a moment that the M82 object 41.9+58 is very different from Cas A and the Chevalier model. In an extreme (but very unlikely) case it may not even be a SNR. Then the rate for M82 would decrease by a factor of 8/9. If it is a remnant, but less than 86 yr old, the rate remains unchanged. If it is older, then we have overestimated the rate by a factor 9/8. In any case, this one object does not overly bias the result. There is another worry: what if the typical supernova evolves into a medium much less dense than suggested by the Chevalier model? In this case, we have underestimated the supernova rate, since a number of lower luminosity remnants would actually be quite young. The answer to this question lies in observing the rate of new supernovae using 2 μm imaging over a period of decades.

2.4. *Supernova Rate versus Far Infrared Luminosity*

In a model where the far-infrared bolometric luminosity L_{FIR} of the galaxy is powered by the young stellar population, one expects that the supernova rate is directly proportional to L_{FIR}. Averaging the rates for M82 and NGC 253 gives.

$$r_{SN} = 2.3 \times 10^{-12} L_{FIR,\odot}\ yr^{-1}\ . \tag{5}$$

This rate is high enough that the ultraluminous infrared galaxies with $L_{FIR,\odot} > 10^{12}$ can be expected to have one or more supernovae near their peak luminosities at any instant, provided that the contribution of a compact nuclear object to the L_{FIR} is small.

The relation we derive above is consistent with that derived from star formation rates in other similar galaxies. Star formation rates in the general class of active dwarf galaxies were studied by Thronson & Telesco (1986) using archival optical, far-infrared, and radio data. Their analysis makes critical assumptions about the shape of the IMF and the timescale over which star-forming clouds are disrupted. Subject to these assumptions, they derive from *IRAS* fluxes the rate $\dot{M}_{IR}$(OBA) at which mass accumulates into O, B, and A stars. This rate can be converted into a supernova rate, provided that the lower mass limit of supernova progenitors is known. We take this limit to be 8 $M_\odot$ and find $r_{SN}^{T\&T} = 5 \times 10^{-12} L_{FIR}$ from $\dot{M}_{IR}$(OBA). This rate is larger but consistent with the rate we derive for M82 using observed remnants. This consistency suggests that the stellar content of M82 is unremarkable compared to active dwarf galaxies.

2.5. *Implications for the Starburst IMF*

In the steady state attained 30–50 Myr after the beginning of a burst of star formation, the supernova rate will equal the birth rate of progenitors. Taking the IMF to be $\Phi = \Phi_0 m^{-\alpha}$, with Φ_0 corresponding to the entire galaxy (in studies of the local IMF it is defined in terms of unit area or volume of the galactic disk) and the stellar mass m, the supernova rate is

$$r_{SN} = \int_{m_l}^{m_u} \Phi_0 m^{-\alpha}\, dm\ . \tag{6}$$

Here m_l is the lower initial mass limit of Type II supernova progenitors, which we take to be 8 $M_\odot$. A particular choice for the upper mass limit, m_u, usually has a small effect unless the slope α is taken to be very flat. Figure 2*a* shows the region of (Φ, α) parameter space allowed by the M82 supernovae. In computing this diagram, we used an upper mass limit of 120 $M_\odot$, corresponding to the most massive stars known in our galaxy, but there is no significant difference if 200 $M_\odot$ is used. Note that $2.0 \leq \alpha \leq 3.0$ encompasses the range found by specific studies of the local IMF (Scalo 1986).

The far-infrared luminosity is also given in terms of the IMF, assuming that only the starburst population contributes. We write the luminosity at a time t in terms of the IMF, stellar lifetimes $\tau(m)$, and the mass-luminosity relation $L(m) = L_0 m^{-\beta}$ as the sum of two contributions:

$$L_{FIR} = \int_{m_l}^{m_u} \Phi_0 m^{-\alpha} \tau(m) L_0 m^{-\beta_0}\, dm + \int_{m_0}^{m_l} \Phi_0 m^{-\alpha} t L_1 m^{-\beta_1}\, dm\ , \tag{7}$$

one from the short-lived supernova progenitors and the other from lower mass stars. The break point m_l is the mass of a star whose evolutionary time is the age of the starburst, which we take for convenience to also be the lower mass limit of supernova progenitors. From a large collection of published evolutionary models (Van Buren 1985), we find that the lifetimes τ can be written as

$$\tau(m) = 1.16 \times 10^2\ m^{-0.82}\ \text{Myr}\ , \tag{8}$$

and the mass-luminosity relation as

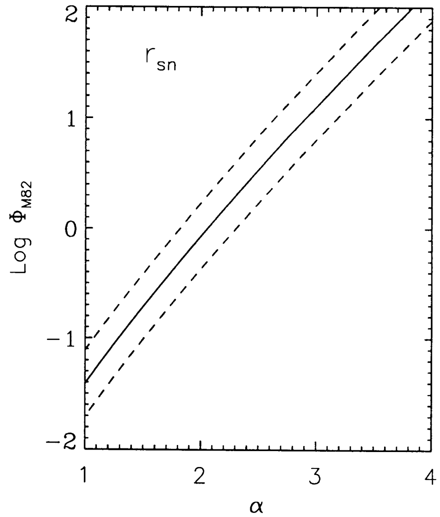
$$L_0(m) = 1.8 \times 10^2\ m^2\ L_\odot\ , \quad m \geq 8\ M_\odot\ ,$$
$$L_1(m) = 3.2 \times 10^2\ m^{3.5}\ L_\odot\ , \quad 3 \leq m < 8\ M_\odot\ . \tag{9}$$

In our calculations, we use $m_0 = 1\ M_\odot$, but the results are only weakly dependent on this choice. Figure 2*b* illustrates how the M82 far-infrared luminosity, $L_{FIR} = 4.7 \times 10^{10}\ L_\odot$ (Rice et al. 1988), constrains the IMF parameters α and Φ_0.

We can also get some information from the dynamical limits of the starburst mass, $2.5 \times 10^8\ M_\odot$ (Carlstrom 1989). Figure 2*c* shows the constraints on IMF parameters imposed by these data, with the region above the line disallowed because it requires more mass than is observed. The qualitative similarity of Figures 2*a* and 2*c* indicates that a starburst model for M82 with any plausible IMF is capable of reproducing the essential observables. The reason the constraint on the IMF is so weak is that for almost any observable, a high-mass star contributes more than a low-mass star. Similar plots could be made for *K*-band flux and thermal radio continuum flux, but extinction is significant at *K*, and dust competes effectively for Lyman continuum photons, rendering modeling difficult and inconclusive.

2.6. *An Alternate Approach to Determining Star-Formation Rates*

We note that the direct method of determining r_{SN} that we present can be used to derive star-formation rates with fewer assumptions than other popular methods. Currently, the most usual method used to determine star formation rates in starburst galaxies is to start with a collection of stellar evolution models, an assumed IMF, and an assumed star formation history. The resulting model is then fitted to broadband fluxes (see, e.g., Huchra 1977) using a simplified treatment for radiative transfer through obscuring dust. While it is not the intent



FIG, 2*a*

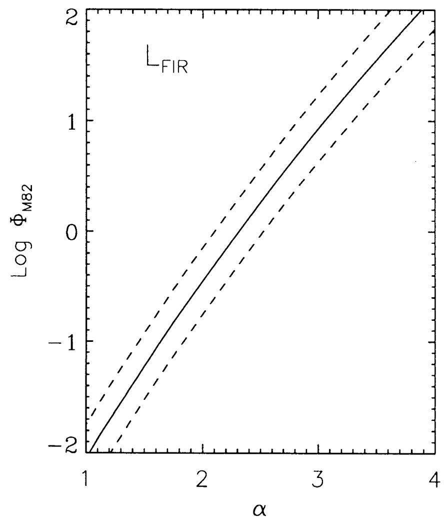


FIG. 2*b*

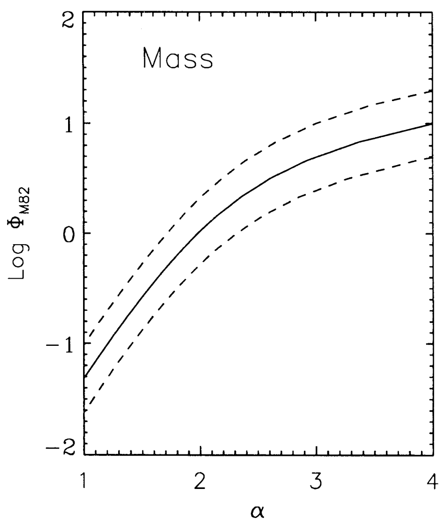


FIG. 2*c*

FIG. 2.—Each panel shows the constraints on the IMF log $(\Phi_0)m^{-\alpha}$ placed by the observables (*a*) supernova rate (0.1 yr^{-1}), (*b*) far-infrared (bolometric) luminosity (4.7×10^{10} $L_{\odot}$), and (*c*) dynamical mass (2.5×10^8 $M_{\odot}$). The IMF has no artificial high or low mass cutoffs; in practice, these were 1 $M_{\odot}$ and 120 $M_{\odot}$. Dotted lines represent factor of two increases and decreases in the observed quantities.

of this paper to find star formation rates, this is how to apply our approach. Start with the log *N*–log *S* relation for supernova remnants in a galaxy and apply a simple but surprisingly consistent model for their evolution to estimate the age of the sample to get the supernova rate. Then choose a star formation history over the most recent 10^8 yr and an IMF to find the overall star-formation rate. We have simplified the process by eliminating the need to match diagnostics using a synthesis of stellar models and treating radiative transfer. In addition, this approach makes no assumption about the energy source for L_{FIR} in galaxies. Instead, we apply an easily calibrated model for supernova remnant evolution. This technique can be used for nearby galaxies where remnants can be spatially resolved in the radio continuum, but for more distant galaxies, one must directly observe the supernova with a monitoring program (Van Buren, Jarrett, & Beichman 1994) or use a radiative diagnostic for supernova remnants such as near-infrared [Fe II] luminosities (see, e.g., Greenhouse et al. 1991).

3. SUMMARY

By modeling the supernova remnant populations of the archetypal starburst galaxies M82 and NGC 253 in terms of blast waves evolving into red supergiant ejecta, we determine Type II supernova rates of 0.10 and 0.08 yr^{-1} for M82 and NGC 253, respectively. In addition, we find that the supernova rate in terms of the far-infrared luminosity is $r_{SN} = 2.3 \times 10^{-12} L_{FIR,\odot}$ yr^{-1} for similar galaxies. This approach is unique in that the supernova rate is derived from direct observation of supernova remnants rather than from star formation rates and an assumed IMF. We find that the derived supernova rates do not constrain the IMF of the M82 starburst to be artificially truncated and place only weak constraints on IMF slope.

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