On the origin of the radio emission in IRAS galaxies with high and ultrahigh luminosity: the starburst–AGN controversy

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ABSTRACT
In the scenario of a violent nuclear/circumnuclear starburst, the radio luminosity detected in high-luminosity (HLIRG) and ultraluminous (ULIRG) IRAS galaxies is explained as non-thermal radio emission generated in radio supernovae and their remnants, created in an ongoing massive starburst process. These supernovae and their remnants must have peak radio luminosities 100 to 1000 times the luminosity of Cas A, and thus be radio hypernovae. The presence of radio hypernovae in a circumnuclear starburst naturally explains the radio excess observed in these regions with respect to disc H II regions, and the FIR–radio luminosity relation.

Considering the empirical radio luminosity curve of the well-monitored radio hypernova SN1979c, supernova rates $T_{SN II} \sim 0.7–3$ and $\sim 1.5–10$ yr$^{-1}$ are predicted for HLIRG and ULIRG, respectively.

The observed far-infrared (FIR) luminosity, $q$ parameter and emission-line luminosities are best accounted for by a starburst characterized by a Salpeter initial mass function (IMF), with upper mass limit $M_u = 60 M_\odot$. If the lower mass limit $M_l = 3 M_\odot$, the star formation rate corresponds to $\sim 40–150$ and $\sim 80–500$ M$\odot$ yr$^{-1}$ for HLIRG and ULIRG, respectively.

The FIR spectral energy distribution of HLIRG and ULIRG differs from that of starburst galaxies and active galactic nuclei (AGN). It is consistent with blackbody dust reradiation at a lower temperature than in normal starbursts.

Although there is evidence, at least in some sample galaxies like Mrk 231 or NGC 7469, for an AGN, the radio and hard X-ray luminosities indicate that this will not, in general, be a luminous QSO. Thus the central AGN will not be the main heating and ionizing source in these galaxies.

Key words: galaxies: active – galaxies: nuclei – galaxies: starburst – galaxies: Seyfert – infrared: galaxies – radio continuum: galaxies.

1 INTRODUCTION
IRAS galaxies with high (HLIRG, $10^{11} \leq L_{FIR} < 10^{12} L_\odot$) and ultrahigh luminosity (ULIRG, $L_{FIR} \geq 10^{11} L_\odot$) in the far-infrared (FIR) have been the subject of numerous investigations recently and have become key targets in the study of the relationship between galaxy interactions, enhanced circumnuclear star formation (see Heckman 1990 for a review), and the possible creation of massive nuclear black holes as the end product of the star formation (Weedman 1983; Norman & Scoville 1988).

Spectroscopic surveys (Sanders et al. 1988b; Armus, Heckman & Miley 1989; Leech et al. 1989) show that the excitation mechanisms present in these galaxies change as the infrared luminosity increases. While 90 per cent of the moderate-luminosity ($10^{10} \leq L_{FIR} < 10^{11} L_\odot$) and 70 per cent of the high-luminosity ($10^{11} \leq L_{FIR} < 10^{12} L_\odot$) IRAS galaxies have emission-line spectra like those of H II regions (Leech et al. 1989), 90 per cent of the ultraluminous IRAS galaxies ($L_{FIR} \geq 10^{12} L_\odot$) show Seyfert 2/Liner emission-line spectra (Sanders et al. 1988b).

Most studies based on the emission-line rates and H$\alpha$ or IR luminosities (Armus et al. 1989; Leech et al. 1989) suggest that luminous IRAS galaxies are places where intense star formation is taking place. Unlike the star-forming regions in blue compact dwarf galaxies where no massive stars have yet evolved into supernovae, starbursts in IRAS galaxies are believed to be old enough to have evolved massive stars and,
therefore, supernova explosions. Extraordinarily large star formation rates, up to a few hundred solar masses per year, and winds with velocities of the order of 500 km s\(^{-1}\), have been invoked to explain the double-peaked narrow-line profiles, the emission-line ratios and the energy budget in high-luminosity \textit{IRAS} galaxies (Heckman, Armus & Miley 1990).

Moreover, specific models to explain the emission-line profiles, the line ratios and the H\(\alpha\) luminosity in the 'Superantennae' galaxy (Colina, Lipari & Macchetto 1991a) show the need, on certain assumptions, for an intense ongoing star formation process together with a hidden quasar-like source at the centre of that ultra-luminous \textit{IRAS} galaxy. This is consistent with the hypothesis by Sanders et al. (1988b) that all ultraluminous galaxies are quasars obscured by dust; also the detection of broad Pa\(\alpha\) emission lines in two luminous \textit{IRAS} galaxies with Seyfert 2 optical spectra (Hines 1991), and the recognition of \textit{IRAS} 02366−3101 as an accretion disc candidate among luminous \textit{IRAS} galaxies (Colina, Lipari & Macchetto 1991b). Similar obscuration effects have also been detected in nearby Seyfert 2 galaxies like IC5063 (Colina, Sparks & Macchetto 1991 and references therein).

Recent high-resolution radio maps have added to the AGN–starburst controversy. Sopp & Alexander (1991) concluded that almost all the radio and far-infrared emission measured in these galaxies is associated with a circumnuclear starburst and not with an active nucleus. In addition, these authors found that the FIR–radio relationship for ULIRG fits with that for normal star-forming galaxies. Norris et al. (1990), on the other hand, concluded that some extremely luminous far-infrared galaxies, with Seyfert-like optical spectra, are powered by radio quasar cores, whereas others, including some of the most luminous, require a different mechanism such as a giant starburst. Finally, Condon et al. (1991), in the most complete study of high-luminosity and ultraluminous \textit{IRAS} galaxies to date, based on high-resolution VLA radio maps, showed that, while many of the less luminous \textit{IRAS} galaxies contain diffuse sources, most of the more luminous ones are dominated by a compact radio component. On the assumption that the radio emission at 1.49 GHz in ULIRG and HLRG is suppressed by free–free absorption, Condon et al. concluded that only one ULIRG, namely Mrk 231, does not fit the universal FIR-radio correlation measured in spiral and starburst galaxies (Helou, Soifer & Rowan-Robinson 1985).

In the present paper, the starburst–AGN controversy will be investigated by means of the radio properties of \textit{IRAS} galaxies with high and ultraluminous luminosity. In Section 2 we describe the galaxy sample characterized by infrared and radio properties. In Section 3 the origin of the radio emission in starbursts as a combination of thermal and non-thermal emission is discussed, while in Section 4 the results of the previous section are used to study the prototype starburst galaxies M82 and NGC 253. In Section 5 we investigate the HLIRG and ULIRG samples in the starburst scenario, constraining and characterizing the properties of the starburst, IMF and star formation rate (SFR), while in Section 6 the need for a central non-thermal source is considered.

Throughout the paper a Hubble constant \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\) is assumed, so that 1 arcsec corresponds to 1 kpc at a distance of 200 Mpc, a typical distance for the sample galaxies.

2 GALAXY SAMPLE

Our galaxy sample consists of HLIRG and ULIRG for which high-resolution VLA maps exist in the literature (Condon et al. 1991). It contains 40 galaxies, including all ultraluminous \textit{IRAS} galaxies selected by Sanders et al. (1988b). Tables 1(a) and (b) list the FIR and radio properties of the HLIRG and ULIRG. Column 1 gives the name of the galaxy while columns 2 and 3 give the FIR spectral indices \(\alpha(60, 25)\) and \(\alpha(100, 60)\), defined by \(F \propto \nu^\alpha\), i.e. \(\alpha(\lambda_1, \lambda_2) = -\log(F_{\nu_1}/F_{\nu_2})/\log(\lambda_1/\lambda_2)\) with \(\lambda_1 > \lambda_2\), and derived from the \textit{IRAS} flux values listed by Condon et al. Columns 4 and 5 give the radio luminosities derived from the corresponding fluxes and distances listed by Condon et al. These values represent the radio luminosity with resolutions of 1.5 arcsec FWHM and of \(-0.3\) arcsec FWHM for the 1.49- and 8.44-GHz observations, respectively.

3 THE ORIGIN OF THE RADIO EMISSION IN STARBURSTS

The radio luminosity generated in an ongoing nuclear/circumnuclear starburst, where evolved massive stars are and have been exploding as supernovae at a constant rate, is the combination of three components: (1) thermal radio emission from the ionized gas; (2) non-thermal radio emission due to supernovae and extremely young supernova remnants, and (3) non-thermal radio emission due to old supernova remnants. In the following expressions, for the radio emission of each of these components will be obtained, and their relative contributions to the total radio luminosity discussed. We then examine the hypothesis that supernovae alone can explain the radio emission from a starburst, and evaluate the contribution from cosmic rays accelerated in the general magnetic field of a galaxy.

3.1 Thermal radio continuum

The thermal radio emission is due to free–free collisions in the ionized gas. Following Rubin (1968), the relationship between the number of ionizing photons per unit time \(N_{\text{UV}}\) and the thermal radio emission is

\[
 N_{\text{UV}} = 6.3 \times 10^{32} L_{\text{Br}\alpha} (\nu)^{0.1} T_{e}^{-0.45} \text{ s}^{-1},
\]

where \(L_{\text{Br}\alpha}\) represents the thermal free–free radio emission in W Hz\(^{-1}\), \(\nu\) is the frequency in GHz, and \(T_e\) is the electron temperature in units of 10\(^4\) K.

On the other hand, the number of ionizing photons per unit time can be obtained, as usual, through the H\(\alpha\) luminosity as

\[
 N_{\text{UV}} = \frac{a_{\beta}(H^0, T)}{a_{\beta}(H_{\text{H}_\alpha}, T)} \frac{L(\text{H}\alpha)}{h\nu_{\text{H}_\alpha}} = 7.35 \times 10^{11} L(\text{H}\alpha) \text{ s}^{-1},
\]

where \(H^0\) refers to neutral atomic hydrogen, or, using the \(\text{Br}\alpha\) line,

\[
 N_{\text{UV}} = 2.66 \times 10^{13} L(\text{Br}\alpha) \text{ s}^{-1},
\]

where \(T_e = 10^4\) K is assumed, and \(L(\text{H}\alpha)\) and \(L(\text{Br}\alpha)\) are the H\(\alpha\) and \(\text{Br}\alpha\) line luminosities in erg s\(^{-1}\) corrected for internal extinction. For the galaxies which are the object of this study, namely HLIRG and ULIRG, large amounts of dust are
mixed with the line-emitting gas. Thus internal extinction effects will be important, and the Brα luminosities will give more reliable results, when available.

By combining expressions (1) and (2) or (1) and (3), one obtains

\[ L^{\text{Br\alpha}}(v) = 1.17 \times 10^{-21} L(\text{Ha}) \nu^{-0.1} T_d^{0.45} \text{ W Hz}^{-1} \]

\[ = 4.23 \times 10^{-20} L(\text{Br\alpha}) \nu^{-0.1} T_d^{0.45} \text{ W Hz}^{-1}, \]

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which relate the observed luminosity of the hydrogen lines with the expected thermal radio emission from the ionized gas.

3.2 Non-thermal radio emission from radio supernovae

By considering a starburst model with constant IMF and SFR over large periods of time, i.e. a few \( \times 10^7 \) yr, one can calculate the radio emission originating in supernovae and young supernova remnants, if the supernova explosion rate has been constant over the radio lifetime of the supernova remnants. Since this time-scale is very short, \( t_{\text{radio}} \sim 20000 \) yr or less, this is a good hypothesis. The non-thermal radio luminosity is then

\[ L_{\text{NT}}(v) = 4\pi D^2 \int_0^{t_{\text{radio}}} S_\nu(t) T_{\text{SN}}(v) dt, \]

where \( L_{\text{NT}}(v) \) is the radio luminosity in W Hz\(^{-1}\), \( D \) is the distance to the galaxy, \( t_{\text{radio}} \) is the lifetime of the supernova remnant as a radio source in years, \( S_\nu(t) \) is the radio flux curve emitted by a single supernova, and \( T_{\text{SN}} \) is the supernova rate in number of supernovae per year.

The temporal behaviours of a few type II (SN1979c, 1980k) and type Ib (SN1983n, radio supernovae have been investigated in detail by Weiler et al. (1986, 1991) using radio observations over 10 yr. They found that the temporal evolution of radio supernovae and extremely young supernova remnants follows a power-law decay given by the expression

\[ S_\nu(t) = K(t/5 \text{ GHz})^{-2} \left[(t-t_0)/1 \text{ yr}\right]^{\delta} \text{ mJy,} \]

where

\[ \tau = K(t/5 \text{ GHz})^{-2} \left[(t-t_0)/1 \text{ yr}\right]^{\delta} \]

and \( K \), \( \tau \), \( \alpha \), \( \beta \), and \( \delta \) are the fitting parameters for each individual supernova, as in Table 2.

Therefore, if one considers young supernova remnants with radio lifetimes of \( t_{\text{radio}} = 10 \) yr, and enters expressions (6) and (7), with the parameters as listed in Table 2, into equation (5), one obtains the total radio luminosities due to these supernovae and young supernova remnants:

\[ L_{\text{NT}}^{\text{YSN}}(v) = 1.58 \times 10^{21} L(\text{Ha}) \nu^{-0.1} T_d^{0.45} \text{ W Hz}^{-1}, \]

\[ L_{\text{NT}}^{\text{YSN}}(v) = 4.40 \times 10^{19} L(\text{Ha}) \nu^{-0.1} T_d^{0.45} \text{ W Hz}^{-1}, \]

where they follow the SN1979c, 1980k, and 1982n radio flux curves, respectively (the corresponding values for different radio lifetimes from 10 to \( \times 10^4 \) yr are presented in Table 3). Although the body of data concerning the radio emission

Table 2. Parameters of the radio luminosity curves of supernovae.

<table>
<thead>
<tr>
<th>SN Name</th>
<th>SN Type</th>
<th>( K_1 )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \delta )</th>
<th>( K_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN1979c</td>
<td>IIb</td>
<td>1146</td>
<td>-0.74</td>
<td>-0.78</td>
<td>-2.96</td>
<td>3.64 ( 10^7 )</td>
</tr>
<tr>
<td>SN1980k</td>
<td>IIb</td>
<td>69</td>
<td>-0.50</td>
<td>-0.64</td>
<td>-2.82</td>
<td>2.4 ( 10^7 )</td>
</tr>
<tr>
<td>SN1983n</td>
<td>IIP</td>
<td>4400</td>
<td>-1.03</td>
<td>-1.59</td>
<td>-2.44</td>
<td>5.3 ( 10^7 )</td>
</tr>
<tr>
<td>SN Mrk297A</td>
<td>IIP</td>
<td>38</td>
<td>-0.74</td>
<td>-1.34</td>
<td>-2.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

of supernovae is not large (see Sramek & Weiler 1990 for a review), it is clear that the peak radio emission spans a range of two orders of magnitude. In fact, supernovae like SN1986J in NGC 891, SN1973C in M100, or 41.9 + 58 in M82, have peak luminosities 1340, 370 and 530 times the luminosity of Cas A (so are radio hypernovae according to Wilkinson & de Bruyn 1990), while most of the well-studied radio supernovae (Weiler et al. 1986) have peak luminosities of a few times the luminosity of Cas A. Also, it seems that type II supernovae share a frequency dependence and temporal behaviour which can be clearly distinguished from those of type Ib supernovae. Type II supernovae have a flatter spectrum ($\alpha \approx -0.7$) and a less steep temporal dependence ($\beta \approx -0.7$) than type Ib ($\alpha \approx -1$ and $\beta \approx -1.5$). The combination of these effects produces the differences obtained in expressions (8)-(10) depending on the particular supernova used.

Recently, Yin & Heeschen (1991) reported the radio luminosity curve of what could be the brightest radio supernova ever observed. They detected this in the clumpy irregular galaxy Mrk 297 at a distance of 64 Mpc and with a peak luminosity $1.5 \times 10^4$ times the luminosity of Cas A. By assuming a functional dependence similar to that of the previous radio supernova (expression (6) and Table 2), one finds

$$L_{\text{NT}}(v) = 3.27 \times 10^{22}(v/8.44 \text{ GHz})^{-0.74} T_{\text{SN}} \text{ W Hz}^{-1}.$$  

This result comes from only five measurements well before and well after the radio emission peak, so further monitoring of this source at radio wavelengths is needed in order to define the time evolution better.

In the massive starburst model, the non-thermal radio emission from young supernova remnants is generated by type Ib and type II supernovae. The relative contribution of each supernova type will be given by expressions (8) or (9) for type II and expression (10) for type Ib as a function of the supernova formation rates. To estimate these rates, one can calculate the relative number of progenitors. Since type II supernova progenitors are stars with main-sequence masses $10 \leq M \leq 25 \ M_{\odot}$ and type Ib progenitors have masses in the range $25 \ M_{\odot} < M < M_{\alpha}$, the relative number of type II and type Ib supernova progenitors is given by

$$N(\text{SNII}) = \left( \frac{10^{-a+1} - 25^{-a+1}}{a-1} \right) \left( \frac{25^{-a+1} - M_{\alpha}^{-a+1}}{a-1} \right)^{-1}$$

for a given IMF slope, with $M_{\alpha}$ in units of $M_{\odot}$. As an example, for an upper mass limit of $M_{\alpha} = 100 \ M_{\odot}$ and IMF slopes $\alpha$ of 1.35, 2.35 and 3.35, the relative numbers are $N(\text{SNII})/N(\text{SNIb}) = 1.289$ and 7.92 respectively. Consequently, for a constant SFR with a given IMF, the expected radio non-thermal contribution for type Ib supernovae would be, at most, a few per cent of that of type II supernovae. Therefore, a starburst will be a bright radio source mainly due to type II supernovae.

3.3 Non-thermal radio emission from old supernova remnants

The physical connection between the previous young radio supernovae and the old galactic supernova remnants like the Crab nebula or Tycho and Kepler supernova remnants is not yet clear. To estimate the contribution from old supernova remnants, two different approaches have been considered. The first, and standard one, is to assume that the old supernova remnants located in circumnuclear starburst regions follow the surface brightness–diameter ratio measured for galactic supernova remnants (Clark & Caswell 1976). This approach has already been used by Ulvestad (1982) and by Condon & Yin (1990). Following these authors,

$$\Sigma_{400 \text{ MHz}} = 10^{-15} d^{-3} \text{ W Hz}^{-1} \text{ m}^{-2} \text{ sr}^{-1}$$

and

$$d = 0.43 (E_{50}/n_{e})^{1/5} r_{\text{radio}}^{0.4} \text{ pc},$$

where $d$ is the diameter of the supernova remnant, $E_{50}$ is the supernova energy in units of $10^{50}$ erg, and $n_{e}$ is the electron density (in unit of cm$^{-3}$) of the interstellar medium into which the supernova expands.

By assuming that the radio lifetime of a supernova remnant is identified with the adiabatic phase of the remnant (Woltjer 1972),

$$t_{\text{radio}} = t_{\text{adiabatic}} = 2.0 \times 10^{4} E_{50}^{4/17} n_{e}^{-9/17} \text{ yr},$$

one obtains, following Condon & Yin (1990) or Ulvestad (1982),

$$L_{\text{SNR}}(v) = \int_{0}^{t_{\text{radio}}} L_{\text{SN}}(v, t) T_{\text{SN}} dt$$

$$= 1.679 \times 10^{21} E_{50}^{-1/17} n_{e}^{-2/17} (v/8.44 \text{ GHz})^{-a} T_{\text{SN}} \text{ W Hz}^{-1},$$

where we take $a = 0.7$ and the remaining physical parameters the same as in previous expressions. Here $T_{\text{SN}}$ represents the total types II plus Ib supernova rate, since the previous surface brightness versus diameter and diameter versus time ratios are independent of the supernova type. Therefore, since the dependence of the total non-thermal radio luminosity on the supernova energy and electron density is very weak, one will have $L_{\text{SNR}}(v) = 1.68 \times 10^{21} T_{\text{SN}} v W Hz^{-1}$ at a frequency of 8.44 GHz.

Our second approach will be to extrapolate the time behaviour observed in young radio supernovae (see Section 3.2) up to a typical radio lifetime of $t_{\text{radio}} = 2 \times 10^{4}$ yr. This approach can be considered as an ad hoc hypothesis with no physical basis, but we will justify it posteriori when comparing our results with the measurements of the compact radio sources detected in the two prototype starburst galaxies M82 and NGC 253 (see Section 4). Therefore, following the procedure outlined in Section 3.2, but for a lifetime $t_{\text{radio}} = 2 \times 10^{4}$ yr, the total luminosity due to old supernova remnants is

$$L_{\text{NT}}(v) = 1.77 \times 10^{22} (v/8.44 \text{ GHz})^{-0.74} T_{\text{SN}} \text{ W Hz}^{-1},$$
\[ L_{\text{SN}}(\nu) = 8.23 \times 10^{20}(\nu/8.44 \text{ GHz})^{-0.50} T_{\text{SN}} \text{ W Hz}^{-1}, \]

\[ L_{\text{SN}}(\nu) = 2.34 \times 10^{19}(\nu/8.44 \text{ GHz})^{-1.03} T_{\text{SN}} \text{ W Hz}^{-1}, \]

(17)

(18)

if supernova remnants in starburst regions follow the SN1979c, 1980k and 1983n radio flux curves, respectively.

The same calculation for SN Mrk 297A gives

\[ L_{\text{SN}}(\nu) = 5.30 \times 10^{22}(\nu/8.44 \text{ GHz})^{-0.74} T_{\text{SN}} \text{ W Hz}^{-1}. \]

In Section 4 we discuss which of the previous expressions for the integrated radio luminosity of supernova remnants gives the best results when compared with observations.

### 3.4 Thermal versus non-thermal radio emission

For H II regions and nuclear starbursts, the typical Hα luminosities lie in the range \( L(\text{Hα}) \sim 10^{39} - 10^{41} \text{ erg s}^{-1} \) (Kennicutt, Keel & Blaha 1989). Thus the thermal radio emission as calculated from expression (4) will have values of the order of \( 10^{18} - 10^{20} \text{ W Hz}^{-1} \), i.e. one to two orders of magnitude below that of non-thermal radio emission from supernovae and supernova remnants. Consequently, in a starburst with a continuous SFR, a constant IMF, and old enough to have evolved massive stars that are exploding as supernovae, the radio emission will be dominated by the non-thermal process associated with the supernovae and their remnants. This conclusion would not be valid for young star-forming regions like those of blue compact dwarf galaxies where the thermal radio emission can account for as much as 50 per cent of the observed radio emission (Mas-Hesse, private communication).

### 3.5 The contribution from cosmic rays

From the universal FIR-radio luminosity correlation observed in spiral galaxies, many authors (Helou et al. 1985; Cox et al. 1988) argued that the non-thermal radio emission is mostly generated by cosmic rays accelerated in the general magnetic field of the galaxy. Consequently, the radio emission is associated with the star formation history of the galaxy over the lifetime of relativistic electrons emitting at radio frequencies.

The synchrotron radio emission emitted by an ensemble of electrons distributed in energy according to a power law of slope \( x \) is given by (see Longair 1981)

\[ L_{\text{NT}}(\nu) = 1.7 \times 10^{-28} (6.26 \times 10^{18} e^a(x)) V N_0 B^{a+1} \nu^{-a} \text{ W Hz}^{-1}, \]

(19)

where \( a = (x-1)/2 \), \( a(x) \) is a parameter, \( B \) is the galactic magnetic field density in gauss, \( V \) is the volume of the emitting region, and \( N_0 \) is the density of relativistic electrons. The radio emission measured in nuclear starburst regions has a mean value of \( L(1.49 \text{ GHz}) = 1.2 \times 10^{20} \text{ W Hz}^{-1} \) (see Kennicutt et al. 1989, and references therein). This is about 10 per cent of that of a whole spiral galaxy like the Milky Way (Condon & Yin 1990), while the volume is several orders of magnitude smaller. Thus we do not believe that the cosmic rays accelerated in the general magnetic field of the galaxy will produce a significant contribution to the observed radio emission unless the magnetic field or the density of relativistic electrons (or both) is increased by large factors relative to mean values. This situation could be associated with the presence of a large number of supernova remnants in a small volume, as considered in our working hypothesis.

### 4 RADIO EMISSION OF THE STARBURST GALAXIES M82 AND NGC 253

In the previous section, the rate of supernovae was related to the observed radio luminosity by considering the emission to be associated with supernovae generated in an ongoing starburst process.

If we want to use these results, together with the observed radio luminosities of HLIRG and ULIRG, to characterize the hypothesized starbursts located in the nuclear regions of these galaxies, we first need to validate the method by comparing our results of Section 3 with those of other authors using different physical quantities. To this end we consider the two nearby prototype starburst galaxies M82 and NGC 253.

#### 4.1 The compact radio sources in M82 and NGC 253 as supernova remnants

Distances to the HLIRG and ULIRG galaxies are such that we cannot resolve individual radio supernovae or supernova remnants in these objects. The evolution of individual radio supernovae can only be studied in the circumnuclear regions of standard nearby starburst galaxies like M82 (Kronberg, Biermann & Schwab 1985) and NGC 253 (Antonucci & Ulvestad 1988; Ulvestad & Antonucci 1991) where the compact radio sources are believed to be young supernovae or supernova remnants.

A comparison between some of the compact sources in M82 and NGC 253, old galactic supernova remnants, and the radio emission of young supernovae (Weiler et al. 1986, 1991) is made in Table 4. In this table, column 1 gives the name of the source, column 2 presents the measured age of the galactic supernova remnants or the expected age of the M82 and NGC 253 radio sources if these follow the different supernova radio flux curves, and column 3 indicates the observed non-thermal luminosity of individual sources in M82 from Kronberg et al. (1985), of individual sources in NGC 253 from Ulvestad & Antonucci (1991), and of galactic supernova remnants from Weiler et al. (1986). Finally, columns 4–6 present the expected luminosities at the ages listed in the second column if the sources follow the SN1979c, 1980k and 1983n radio flux curves, so that expressions (6) and (7) are applied with the corresponding parameters listed in Table 2.

Several conclusions can be drawn from these comparisons. First, it is clear that the radio luminosity of the M82 sources is consistent with extremely young supernova remnants, while the sources in NGC 253 can be divided in two groups: one consistent with young supernova remnants and the second with Cas A type remnants, i.e. bright old supernova remnants.

Secondly, if we compare the luminosities of the M82 and NGC 253 compact radio sources with the expected values using SN1979c, 1980k and 1983n radio flux curves, it is clear that the only one giving luminosities at the same level is the brightest of well-studied (Weiler et al. 1986, 1991) radio supernovae, i.e. type II supernova SN1979c. Type Ib supernova SN1983n could also give a luminosity level similar to...
Table 4. Radio luminosities of RSN, SNR and radio sources in M82 and NGC 253.

<table>
<thead>
<tr>
<th>Name</th>
<th>Age (years)</th>
<th>( L_{\text{NH}}^{20 \text{cm}} \times 10^{27} \text{ W Hz}^{-1} )</th>
<th>( L_{\text{NH}}^{18 \text{cm}} \times 10^{27} \text{ W Hz}^{-1} )</th>
<th>( L_{\text{NH}}^{10 \text{cm}} \times 10^{27} \text{ W Hz}^{-1} )</th>
<th>( L_{\text{NH}}^{4 \text{cm}} \times 10^{27} \text{ W Hz}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82 (a)</td>
<td>100</td>
<td>125.2</td>
<td>138.2</td>
<td>4.8</td>
<td>1.44 ( 10^{-8} )</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>125.2</td>
<td>5.4 ( 10^{-6} )</td>
<td>130.4</td>
<td>6.55 ( 10^{51} )</td>
</tr>
<tr>
<td>41.9 +58 (b)</td>
<td>10</td>
<td>1352.6</td>
<td>832.7</td>
<td>16.1</td>
<td>5.6 ( 10^{-7} )</td>
</tr>
<tr>
<td></td>
<td>0.04</td>
<td>1352.6</td>
<td>0.0</td>
<td>0.0</td>
<td>1.17 ( 10^{53} )</td>
</tr>
<tr>
<td>NGC253 (c)</td>
<td>100</td>
<td>80.0</td>
<td>138.2</td>
<td>4.8</td>
<td>1.4 ( 10^{-8} )</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>80.0</td>
<td>1.9 ( 10^{-3} )</td>
<td>91.4</td>
<td>2.2 ( 10^{-5} )</td>
</tr>
<tr>
<td>NGC253 (d)</td>
<td>10000</td>
<td>2.9</td>
<td>3.8</td>
<td>0.25</td>
<td>3.7 ( 10^{-10} )</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>2.9</td>
<td>22.9</td>
<td>1.1</td>
<td>9.5 ( 10^{-12} )</td>
</tr>
<tr>
<td>0045-233342 (e)</td>
<td>50</td>
<td>210.2</td>
<td>237.3</td>
<td>3.24</td>
<td></td>
</tr>
<tr>
<td>0045-253339 (f)</td>
<td>50</td>
<td>293.5</td>
<td>237.3</td>
<td>3.24</td>
<td></td>
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<tr>
<td>SN1054 (Crab)</td>
<td>930</td>
<td>3.0</td>
<td>24.3</td>
<td>1.15</td>
<td></td>
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<tr>
<td>SN1572 (Tycho)</td>
<td>410</td>
<td>0.1</td>
<td>46.0</td>
<td>1.94</td>
<td></td>
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<tr>
<td>SN1604 (Kepler)</td>
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<td>48.8</td>
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<td>314</td>
<td>7.0</td>
<td>56.6</td>
<td>2.3</td>
<td></td>
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</tbody>
</table>

* For the M82 and NGC 253 sources, this column indicates the expected age obtained using the different radio luminosity curve models of columns 4 - 6. For the galactic radio supernova remnants it represents the observed age of the remnant. (b) The luminosity in column 3 represents the mean of the five unresolved compact radio sources as listed in Kronberg et al. (1985), except 41.9 +58. (c) This source is the brightest detected compact radio source in M82. Its observed radio luminosity is given in column 3. (d) The luminosity in column 3 represents the mean of all sources with observed flux larger than 2 mJy at 6 cm, as listed in Ulvestad & Antonucci (1991). (e) The luminosity in column 3 represents the mean of all sources with observed flux smaller than 2 mJy at 6 cm, as listed in Ulvestad & Antonucci (1991). (f) These are the two brightest radio compact sources detected in NGC 253 with observed radio luminosities as given in column 3.

that of the brightest M82 source, 41.9 +58, but only 15 d after the explosion. This is inconsistent with the observations, since this source was first detected 25 years ago by Bash (1968) and studied in detail by Wilkinson & de Bruyn (1990). These authors conclude that this source is a radio hypernova with a peak luminosity 530 times the luminosity of Cas A, and that it exploded 40-50 yr ago.

Thirdly, the observed radio luminosities of the galactic supernova remnants agree with the extrapolation of the SN1980k radio luminosity curve to ages between 400 and 900 yr. This source is a factor of 20 times fainter than SN1979c.

Finally, all the observed compact radio sources in M82 and NGC 253 agree within factors of less than 2 with the SN1979c extrapolated radio luminosities. If we consider these compact radio sources as type II SN1979c radio supernovae and supernova remnants, the expected ages will range from a few decades for 41.9 +58 to about 10^4 yr for the faintest radio sources in NGC 253.

All these results support the idea that radio supernovae and supernova remnants in circumnuclear starburst environments seem to be one to two orders of magnitude brighter than otherwise, i.e. they are radio hypernovae (Wilkinson & de Bruyn 1990). These high radio luminosities could be the result of differences in the magnetic fields and electron densities in the surrounding interstellar medium, or due to intrinsic properties like pre-supernova mass-loss rates, and expansion velocities in massive stars producing massive circumstellar shells.

4.2 The supernova rates in M82 and NGC 253

The conclusion that the time evolution of the radio hypernova SN1979c is consistent with the observed luminosities of the compact radio sources in M82 and NGC 253 is also reached by comparing our estimate of the supernova rates with those of different authors using various physical parameters.

The observed radio luminosities of M82 and NGC 253 are compared in Table 5 with the expected thermal and non-thermal radio emission on the starburst hypothesis. Column 2 gives the frequency at which the radio observations were made by Hargrave (1974) and Beck et al. (1979) respectively, column 3 presents the corresponding luminosity assuming a distance of 3.2 Mpc for M82 and of 2.5 Mpc for NGC 253, column 4 gives the expected thermal radio emission according to expression (4), obtained using the Bρ fluxes corrected for internal extinction from Ho, Beck & Turner (1990), columns 5-7 give the results according to expressions (8), (15) and (16), respectively, as a function of type II supernova rate (Tsnl).
Table 5. Observed and modelled radio luminosities for M82 and NGC 253.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Frequency (GHz)</th>
<th>$L_{\text{radio}}^{\text{obs}}$ (10^{21} W Hz^{-1})</th>
<th>$L_{\text{radio}}^{\text{fit}}$ (10^{20} W Hz^{-1})</th>
<th>$L_{\text{YSN}}^{\text{SNR}}$ NT</th>
<th>$L_{\text{YSN}}^{\text{SNR}}$ NT</th>
<th>$L_{\text{YSN}}^{\text{SNR}}$ NT</th>
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<tbody>
<tr>
<td>M82</td>
<td>5</td>
<td>3.80</td>
<td>5.29</td>
<td>2.32</td>
<td>2.42</td>
<td>2.60</td>
</tr>
<tr>
<td>NGC253</td>
<td>8.7</td>
<td>0.73</td>
<td>1.58</td>
<td>1.54</td>
<td>1.64</td>
<td>1.73</td>
</tr>
</tbody>
</table>

*Measurements from Hargrave (1974) and Beck et al. (1979) for M82 and NGC 253, respectively.
†Obtained from expression (4) in text using the extinction-corrected Brα fluxes listed in Ho, Beck & Turner (1990). *In units of 10^{13} T_{\text{SNR}} W Hz^{-1} obtained by integrating the SN1979c radio flux curve over 10 yr, i.e. expression (8) in text. ††In units of 10^{12} T_{\text{SNR}} W Hz^{-1} obtained by assuming emission from old galactic supernova remnants (expression 15 in text). ‡In units of 10^{12} T_{\text{SNR}} W Hz^{-1} obtained by integrating the SN1979c radio flux curve over 20,000 yr, i.e. expression (16) in text.

Since the thermal radio emission accounts for at most a few per cent of the observed radio emission, we consider that all radio emission is non-thermal and is generated in supernova remnants. On this hypothesis, if the observed radio emission is the addition of young and old SN1979c-type remnants (cf. equation 16), the supernova explosion rate will correspond, for a Salpeter IMF (IMF ≈ m^{-α}, α = 2.35) and upper mass limit $M_u = 100 M_\odot$, to $T_{\text{SNR}} = 0.2$ and 0.05 yr^{-1} for M82 and NGC 253, respectively. These values agree with those found for M82 and NGC 253 by different techniques. More precisely, Rieke et al. (1980) gave a value of $T_{\text{SNR}} = 0.3$ yr^{-1} for M82 while Heckman et al. (1990) estimated $T_{\text{SNR}} = 0.07$ and 0.06 yr^{-1} for M82 and NGC 253, respectively.

If, on the other hand, one considers that the radio luminosity in M82 and NGC 253 is generated by the combined flux of young remnants, i.e. equation (8), and old galactic remnants, i.e. equation (15), our supernova explosion rate will be increased by a factor of 3 and will therefore not agree with that obtained by the previous authors. The disagreement would be even worse if only young radio supernovae or old galactic supernova remnants were considered.

These comparisons therefore validate empirically the use of equation (16) to calculate the rate of supernova explosions in circumnuclear starbursts, although one must bear in mind that the fact that our method gives results in good agreement with other methods does not mean that the physical processes associated with the radio emission of supernovae in circumnuclear starburst environments are well understood. It is difficult to believe that the physical mechanisms and physical parameters (expansion velocity of the supernova material, sweeping of circumstellar/interstellar matter, electron and magnetic field density) involved in the generation of non-thermal synchrotron radiation will produce a time dependence of the radio emission of old supernova remnants that would be a simple extrapolation of that detected by Weiler and collaborators in radio supernovae and young supernova remnants. Thus detailed modeling of the conditions encountered by supernovae and their remnants in circumnuclear starburst environments is needed to validate the previous conclusion obtained from empirical arguments. Despite these uncertainties, we believe that our empirical conclusion, namely the need for radio hypernovae, remains valid, since it is based on the energy output of a supernova and its remnant over its entire life as a radio emitter.

5 LUMINOUS IRAS GALAXIES AS CIRCUMNUCLEAR MASSIVE STARBURSTS

5.1 Characteristics of the radio emission in luminous IRAS galaxies

The high-resolution 8.44-GHz VLA radio maps by Condon et al. (1991) with an effective FWHM of about 0.30 × 0.25 arcsec^2 show the presence of diffuse well-resolved sources within the less luminous galaxies of the sample ($\log L_{\text{YSN}}/L_\odot \leq 11.7$), while the ultraluminous galaxies often show compact sources at the previous resolution. These observations support the idea of an extended emission source, a circumnuclear starburst, in HLRG, but also indicate that the dominant radio source in ULIRG has a mean upper limit of about 250 pc in diameter. Therefore, in these galaxies, both a non-thermal source and a compact starburst could coexist in the nucleus. Even in HLRG, a large fraction of the measured radio emission could come from a compact source, as in NGC 7469 (see Section 6.1). Nevertheless, based on the FIR–radio relationship, Condon et al. (1991) concluded that 39 out of the 40 galaxies in their sample agree with a circumnuclear starburst.

The radio luminosities of these galaxies are in the range $L(8.44 \text{ GHz}) \approx 22–24 \text{ W Hz}^{-1}$, the ultraluminous IRAS galaxies being also the brightest in radio luminosity. Histograms of the radio luminosity distributions of HLRG and ULIRG at 1.49 and 8.44 GHz are shown in Figs 1(a) and (b), respectively.

In the starburst model, the expected thermal free–free radio emission at 8.44 GHz, obtained from the Hα luminosities corrected for internal extinction when available (see Tables 6a and b), is in the range $2 \times 10^{20}–3 \times 10^{21} \text{ W Hz}^{-1}$. Such values correspond to only a few per cent of the observed radio luminosities (see Tables 1a and b). Furthermore, for the two galaxies of our sample for which the luminosity of the Brα emission line has been measured (Ho et al. 1990), the expected radio thermal emission corresponds to almost 30 per cent of the observed radio luminosity in NGC 1614 and to only 4 per cent in NGC 3690. These results must be considered as upper limits to the contribution of the thermal emission to the observed radio luminosity. While the Hα and Brα observations were made with beams of about $2 \times 4$ arcsec^2 (Armus et al. 1989) and $7.2 \times 7.2$ arcsec^2 (Ho et al. 1990), respectively, the 8.44-GHz radio luminosities listed in Tables 1(a) and (b) were obtained with beams of about 0.3 arcsec FWHM. Thus the
Ha and Brα luminosities within these small 0.3-arcsec beams will be a fraction of those measured by the previous authors. In the starburst model, therefore, non-thermal radio emission from radio supernovae and supernova remnants must be the main contributor to the radio luminosity in HLRG and ULIRG.

5.2 The properties of the massive circumnuclear starburst

In the massive starburst model, the properties of the star formation in these environments may be obtained by using as empirical constraints the observed radio, far-infrared and Ha or Brα luminosities. Since these observables map a different region in the mass spectrum of the IMF, we should be able to constrain the upper mass limit and the slope of the IMF. A similar analysis has been used by Cox et al. (1988) to estimate the FIR–radio relation expected from a starburst.

5.2.1 The initial mass function

For a starburst characterized by the IMF and the SFR, the radio, FIR and Hα luminosities will be given by

\[
L_{\text{IR}}(8.44 \text{ GHz}) = \int_{0}^{M_{\odot}} L_v^{\text{SNR}}(8.44 \text{ GHz}) \tau_{\text{SNR}} \, dt \, W \text{ Hz}^{-1},
\]

(20)

\[
L_{\text{FIR}} = \eta k \int_{M_{\odot}}^{M_{\ast}} L(M) \tau_{\text{MS}}(M) M^{-\alpha} \, dM \times L_{\odot},
\]

(21)

\[
L(\text{H}\alpha) = 1.36 \times 10^{-10} \Omega k \int_{2M_{\odot}}^{M_{\ast}} N_{\phi}(M) \tau_{\text{MS}}(M) M^{-\alpha} \times dM \text{ erg s}^{-1},
\]

(22)

where \( L_{\text{IR}}(8.44 \text{ GHz}) \) will be given by (16), \( N_{\phi}(M) \) is the number of ionizing photons of a star of mass \( M \) in photons s\(^{-1} \), \( L(M) \) is the luminosity of a star of mass \( M \) in erg s\(^{-1} \), \( t_{\text{MS}} \) is the main-sequence lifetime of a star of mass \( M \), and \( \alpha \) is the slope of the IMF (where IMF = \( kM^{-\alpha} \)). Also, \( \eta \) and \( \Omega \) represent the fraction of the ionizing luminosity that goes into dust heating and gas ionization, respectively. We use \( L(M) \) and \( t_{\text{MS}}(M) \) as presented by Scoville & Soifer (1991). These are adopted from Maeder (1987) and are given by

\[
L(M) = 18.621 M^{2.35} \times L_{\odot} \text{ for } 10 < M < 40 M_{\odot},
\]

(23)

\[
= 263.03 M^{1.84} \times L_{\odot} \text{ for } M \geq 40 M_{\odot},
\]

\[
t_{\text{MS}}(M) = 1.535 \times 10^{6} M^{-0.963} \text{ yr for } 10 < M \leq 40 M_{\odot},
\]

(24)

\[
= 2.188 \times 10^{7} M^{-0.43} \text{ yr for } M \geq 40 M_{\odot}.
\]

(25)

The number of ionizing photons is obtained from Gehrz, Sramek & Weedman (1983) for \( 10 < M < 40 M_{\odot} \) and from Mas-Hesse & Künth (1991) for \( M \geq 40 M_{\odot} \):

\[
N_{\phi}(M) = 1.026 \times 10^{43} M^{4} \text{ photon s}^{-1} \text{ for } 10 < M < 40 M_{\odot},
\]

(26)

\[
= 2.018 \times 10^{46} M^{-0.377} \text{ photon s}^{-1} \text{ for } M \geq 40 M_{\odot},
\]

Introducing equations (23)–(25) into (21) and (22), one obtains

\[
L_{\text{FIR}} = \eta k \left( 2.858 \times 10^{-7} \frac{4 \Omega^{2.87} - 10^{2.87}}{2.87 - \alpha} + 5.755 \times 10^{9} \frac{M^{2.41} - 40^{2.41}}{2.41 - \alpha} \right) L_{\odot},
\]

where \( L_{\odot} \) is the solar luminosity.
The origin of radio emission in IRAS galaxies

where the Brα luminosity is obtained from the Hα luminosity by applying the recombination theory. \( M_u \) is the upper mass limit of the IMF, and \( k \) is given by the expression

\[
k = \frac{T_{SNR} \left( \frac{10^{-a-1}}{\alpha - 1} \right)^{-1}}{1 - 25^{-a-1}}.
\]

The results of these calculations for a Salpeter IMF, with mass limits \( M_i = 3 \, M_\odot \), \( M_u = 60 \, M_\odot \) and \( \eta = 0.5, \) are presented in Tables 6(a) and (b) together with the corre-

Table 6. (a) Observed and predicted* physical quantities of HLRG.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>log ( L_{\text{FR}}^{\text{obs}} )</th>
<th>( q^{\text{obs}} )</th>
<th>( L_{\text{Hα}}^{\text{obs}} )</th>
<th>( T_{\text{SNR}}^{\text{predicted}} )</th>
<th>SFR model</th>
<th>log ( L_{\text{FR}}^{\text{model}} )</th>
<th>( q^{\text{model}} )</th>
<th>( L_{\text{Hα}}^{\text{model}} )</th>
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<td>32.9</td>
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<td>2.58</td>
<td>0.90</td>
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<tr>
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<td>2.14</td>
<td>2.01</td>
<td>108.1</td>
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<td>2.58</td>
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<td></td>
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<td>2.58</td>
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*Calculated using a Salpeter IMF with mass limits \( M_i = 3 \, M_\odot \) and \( M_u = 60 \, M_\odot \), and parameters \( \eta = 0.5 \) (see Sections 5.2.1 and 5.2.2).

†These values represent the Hα luminosity corrected for internal extinction, in units of \( 10^{43} \, \text{erg s}^{-1} \) from Armus et al. (1989) and Leech et al. (1989). The galaxies NGC 1614 and 3690 also have Brα luminosity measurements (Ho et al. 1990) with values \( L(\text{Brα}) = 3.7 \times 10^{41} \) and \( > 1.8 \times 10^{41} \, \text{erg s}^{-1} \), respectively.

‡Predicted Hα luminosity in units of \( 10^{43} \, \text{erg s}^{-1} \). The modelled \( L(\text{Brα}) \) luminosities for NGC 1614 and 3690 are \( 3.0 \times 10^{41} \) and \( 4.9 \times 10^{41} \, \text{erg s}^{-1} \), respectively.

*The supernova rates \( T_{SNR} \) are based on the 1.49-GHz luminosity (1.5 arcsec FWHM resolution) instead of the 8.44-GHz luminosity.

†The supernova rate \( T_{SNR} \) has been obtained from the \( 0.19 \times 0.17 \) arcsec\(^2\) resolution 8.44-GHz value of Condon et al. (1991).
sponding observed values. Column 1 lists the name of the galaxy, column 2 presents the FIR luminosity as calculated from the 60- and 100-μm IRAS fluxes using the prescription given by Fullmer & Lonsdale (1989) and the distance listed in column 7 of table 1 of Condon et al. (1991), column 3 gives the observed q parameter (see Section 5.3.2), column 4 gives the Hα or Brα luminosity corrected for internal extinction when available, column 5 gives the rate of type II supernovae obtained using the 8.44-GHz luminosity and equation (16), column 6 gives the corresponding star formation rate, calculated for a Salpeter IMF slope with mass limits \( M_1 = 3 \, M_\odot \) and \( M_1 = 60 \, M_\odot \) and parameters \( \eta = \Omega = 0.5 \), and columns 7 and 8 give the corresponding FIR and Hα emission-line luminosities. Physical quantities for different IMF slopes and mass limits are listed in Table 7.

For HLRG, a type II supernova explosion rate of \( T_{\text{SNR}} \approx 0.7 - 3 \text{ yr}^{-1} \) is obtained, while for the ULIRG sample it ranges between 1.5 and 10 yr\(^{-1}\), with the exception of Mrk 231 where \( T_{\text{SNR}} \approx 53.5 \text{ yr}^{-1} \) was obtained. In this particular galaxy, it is believed that the nucleus harbours a QSO-type nonthermal source (see Section 6.1). In general there is a good agreement between the observed physical quantities, FIR luminosity and q parameter, and our results for a Salpeter IMF with an upper mass limit \( M_1 = 60 \, M_\odot \). The mean log(\( L_{\text{FIR}} / L_{\text{model}} \)) corresponds to \( -0.06 \) and \( -0.03 \) for the HLRG and ULIRG samples, respectively. On the other hand, the q parameter (see Section 5.3.2) obtained with the previous IMF parameters, \( q_{\text{model}} = 2.58 \), agrees with the means of the samples, \( q(\text{HLIRG}) = 2.43 \pm 0.20 \) and \( q(\text{ULIRG}) = 2.60 \pm 0.32 \).

There is, however, a large discrepancy, usually by a factor of 10, between our expected Hα luminosities and the values corrected for internal extinction, when available (Armus et al. 1989; Leech et al. 1989). This result can be interpreted in three different ways. One is that the ionizing source is not related to the starburst itself but to a centrally located nonthermal source, i.e. non-local ionizing source. In this case, the covering factor (\( \Omega \)) of the gas clouds could drop by a large factor and the Hα luminosity would decrease by the corresponding factor (see equation 27).

Secondly, one could consider that the IMF is deficient in young massive stars. If the upper mass limit is taken to be \( M_1 = 30 \, M_\odot \), the emission-line luminosity will drop dramatically by an order of magnitude in luminosity, while the FIR luminosity and the q parameter will change by small factors (see Table 7).

The third alternative considers that the internal extinction, as obtained from the Hα/Hβ emission-line ratio, gives a lower limit to the extinction and consequently is not reliable in these galaxies where large amounts of dust are found. In fact, for the few galaxies where Brα measurements exist (Ho et al. 1996), there is a good agreement between our results and the observations. The NGC 1614 and 3690 Brα luminosities obtained from the extinction-corrected flux measurements by Ho et al. are \( L(\text{Br}\alpha) = 3.7 \times 10^{44} \) and \( 1.8 \times 10^{44} \text{ erg} \text{ s}^{-1} \), respectively. The expected Brα emission-line luminosities obtained from the supernova rate listed in Table 6(a) and the Salpeter IMF slope with upper mass limit \( M_1 = 60 \, M_\odot \) are \( L(\text{Br}\alpha) = 3.0 \times 10^{44} \) and \( 4.9 \times 10^{44} \text{ erg} \text{ s}^{-1} \), respectively.

Therefore, a Salpeter IMF with an upper mass limit \( M_1 = 60 \, M_\odot \) gives a good fit to the observed far-infrared, radio and Brα emission-line luminosities. This conclusion is consistent with that obtained by several authors studying individual starburst galaxies. Rieke et al. (1980) found that the star formation models for M82, constrained by the observed radio, infrared, optical, ultraviolet and X-ray fluxes, must have an IMF slope between 2 and 3, and mass limits \( M_1 \sim 3 \) and \( M_1 \sim 30 \, M_\odot \). Also, Gehrz et al. (1983) concluded that the starburst observed in NGC 3690 must have an upper mass limit of \( M_1 = 25 \, M_\odot \), while Ho et al. (1990) found that the Brα luminosity measured in a sample of starburst...
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### Table 7. Predicted physical quantities for different IMFs.

<table>
<thead>
<tr>
<th>IMF</th>
<th>$T_{SN}^*$</th>
<th>SFR*</th>
<th>$L_{FIR}^+$</th>
<th>$L(\text{H}α)^+$</th>
<th>$L(\text{Br}γ)^+$</th>
<th>$q^+$</th>
<th>$E^{44}(8.44\text{GHz})$</th>
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<tr>
<td>$(\alpha, M_i, M_u)$</td>
<td></td>
<td></td>
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<td>1.09</td>
<td>235.4</td>
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<td>0.83</td>
<td>2.29</td>
<td>2.63</td>
<td>0.78</td>
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<td>2.63</td>
<td>0.78</td>
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<tr>
<td>(2.35, 0.1, 60)</td>
<td>1.28</td>
<td>243.3</td>
<td>4.70</td>
<td>2.92</td>
<td>8.00</td>
<td>2.88</td>
<td>2.73</td>
</tr>
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<td>8.00</td>
<td>2.88</td>
<td>2.73</td>
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<tr>
<td>(2.35, 0.1, 120)</td>
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<td>6.92</td>
<td>4.69</td>
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<td>3.31</td>
<td>2.66</td>
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<td>99.4</td>
<td>3.24</td>
<td>1.47</td>
<td>4.14</td>
<td>2.72</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Notes: *in units of $T_{SN}^*\text{yr}^{-1}$; 1 in units of $M_{SN}^*\text{yr}^{-1}$; 2 in units of $10^{11} \gamma_{SN}^*\text{yr}^{-1}$; 3 in units of $10^{41} \Omega_{SN}^*\text{erg}^{-1} \text{s}^{-1}$; 4 in units of $10^{41} \Omega_{SN}^*\text{erg}^{-1} \text{s}^{-1}$; 5 calculated for $\eta = 1$, otherwise $q$ will be the value listed in the table plus log $\eta$, with $\eta$ less than 1; 6 in units of $10^{22} T_{SN}^*\text{W} \text{Hz}^{-1}$ and $T = 10^4$ K.

### 5.2.2 The star formation rate

By assuming a starburst with a constant IMF and SFR over the duration of the violent star formation process, one can calculate the rate of star formation from the expression

$$\text{SFR} = k \left( \frac{M_1^{-\alpha+2} - M_u^{-\alpha+2}}{a - 2} \right) M_\odot \text{yr}^{-1},$$

where $k$ is given by (29). From our empirical $L_{FIR}^+$, $L_{radio}$ and $L_{Ha}$ luminosities, there is no way to obtain a lower mass limit for the IMF, but mass/luminosity ratios measured in starburst galaxies (Wright et al. 1988) suggest that the low-mass limit is in the range $M_u = 3 - 6 M_\odot$. Otherwise, if $M_1$ were to be as low as 0.1 $M_\odot$, the starburst mass would be greater than the dynamical mass estimated from rotation curves. Among the starburst galaxies studied by Wright et al. is the southern bright infrared galaxy NGC 3256. It has properties similar to our HLRG and ULIRG; its infrared luminosity is $3 \times 10^{11} L_\odot$ (Sargent, Sanders & Phillips 1989) and it shows two tidal tails indicative of a merger between two equally massive gas-rich spiral galaxies.

Therefore, the corresponding SFR in HLRG and ULIRG has been obtained by considering a lower mass cut-off $M_1 = 3 M_\odot$, while the dependence of the SFR on the lower mass limit is shown in Table 7. If we assume, as in the previous section, a Salpeter IMF slope and upper mass limit $M_u = 60 M_\odot$, the star formation rates will range between $\sim 40 - 150$ and $\sim 80 - 500 M_\odot \text{yr}^{-1}$ for the HLRG and ULIRG samples, respectively.

### 5.3 HLRG and ULIRG versus nuclear H II regions

#### 5.3.1 Radio versus Ha luminosity

Kennicutt et al. (1989) found that, normalized to the thermal radio emission expected from a $10^4$K extinction-free gas, the nuclear H II regions have a radio to emission-line luminosity ratio, $L_{radio}(20 \text{cm})/L(\text{H}α)$, larger by factors of 10 to 100 than those measured in disc H II regions. Since the internal extinction is similar in both samples, they interpreted the excess in the radio luminosity of the nuclear H II regions as due to the strong non-thermal emission originating in the supernova remnants. Following the starburst scenario and the expressions (4) and (16) of Section 3, we obtain

$$\frac{L_{radio}}{L(\text{H}α)} = \left( \frac{L_{radio}^*}{L(\text{H}α)^+} \right)^{-1} = 7.321 \times 10^{15} \nu^{-0.64}$$

$$\times L(\text{H}α)^{-1} T_{SN}^* T_{\alpha}^{-0.45}.$$
5.3.2 Radio versus FIR luminosity

There is a universal correlation between the FIR and radio luminosities in spiral galaxies covering a wide range of activity from normal to starburst galaxies. Helou et al. (1985) measured the $q$ parameter defined as $q = \log [L_{\text{FIR}}/(S_{1.4} \times 10^{12} \text{ Hz})]/S_{\nu}(1.4 \text{ GHz})$. Here $L_{\text{FIR}}$ is the FIR flux obtained using the Fullmer & Lonsdale (1989) prescription, and $S_{\nu}(1.4 \text{ GHz})$ is the radio flux.

Fig. 2 shows $S_{1.4 \text{ GHz}}$ versus $S_{\text{FIR}}$ for our HLRG and ULIRG samples together with the results for spirals from Helou et al. (1985), while the mean $q$ values are presented in Table 8. The measured $q$ parameter for the HLRG and ULIRG samples (particularly the latter) is larger and has more scatter than for other sample galaxies. Do HLRG and ULIRG stand out of the universal radio–FIR luminosity relationship? Can the $q$ parameter be explained in the starburst scenario?

Cox et al. (1988) concluded that radio emission from cosmic rays should contribute substantially to the radio emission generated in galaxies and could therefore explain the observed FIR–radio relation. As already discussed in Section 3.5, we believe cosmic rays play a minor role in HLRG and ULIRG. Condon et al. (1991) were able to match the $q$ parameter of HLRG and ULIRG with that of the starburst galaxies ($q \sim 2.21–2.34$) by assuming that the interstellar medium in these compact radio-emitting regions is thick to the radio emission at 1.49 GHz. Alternatively, from our starburst model, we obtain a $q$ parameter given by

$$q = \log L_{\text{FIR}} - \log L_{\text{NT}}(1.49 \text{ GHz}) - 12.57,$$

where $L_{\text{FIR}}$ and $L_{\text{NT}}(1.49 \text{ GHz})$ are given by expressions (26) and (16), respectively. Thus the $q$ parameter obtained in this way depends only on the slope of the IMF, its upper mass limit, and the fraction of the ionizing radiation that goes into dust heating, but not on the supernova rate. Consequently, we are able to obtain a range of values for the $q$ parameter, $q \sim 2.54–3.55$ (see Table 7), which agrees with the observed values.

5.3.3 FIR spectral energy distribution

The far-infrared energy distribution can be used to investigate the heating mechanism present in HLRG and ULIRG. For this purpose, the IR spectral indices for the two samples are presented in Tables 1(a) and (b), respectively. Also, their mean IRAS spectral indices together with those of several

![Figure 2](https://academic.oup.com/mnras/article-abstract/259/4/709/997249/714491)
samples ranging from IR colour-selected quasars to non-active spirals (Low et al. 1988; Miley, Neugebauer & Soifer 1985; Sekiguchi 1987) are presented in Table 9. The corresponding plots are shown in Figs 3(a) and (b).

None of the galaxies in the ULIRG sample has an FIR spectral energy distribution consistent with a power law and thus similar to those of bare AGN like the infrared-selected quasars, Seyfert 1 or even Seyfert 2 galaxies. They have a spectral energy distribution consistent with blackbody radiation at temperatures lower than those of normal starbursts. Even a well-known quasar like Mrk 231 has a FIR energy distribution close to that of a blackbody. On the other hand, galaxies in the HLIRG sample cover a range in $\alpha(100, 60)$ similar to that of nuclear starbursts, while having a steeper spectrum between 25 and 60 $\mu$m, indicating cooler dust emission than that of standard starbursts.

The fact that both HLIRG and ULIRG samples show a spectral energy distribution indicating dust temperatures cooler than those of starbursts demonstrates a lack of heating photons at the regions where the dust is located. This can be because the heating source is not powerful enough, there are no massive stars, or the interstellar medium surrounding the heating source acts as an efficient screen, cutting down the flux of photons.

As already discussed in Section 5.2.1, the Br$\alpha$ luminosities measured in some of the sample galaxies cannot be obtained if the upper mass limit $M_{\star} \approx 30 M_\odot$. Although detailed modelling is needed, it is likely that the ISM is playing the main role. As measured by Mirabel & Sanders (1989), the ratio of molecular to neutral gas in the central regions of luminous IRAS galaxies is of the order of $M(H_2)/M(HI) \approx 5-25$, well above that of normal spirals. These large amounts of molecular gas will therefore act as a very efficient screen.

### 6 LUMINOUS IRAS GALAXIES AS DUST-ENSHROUDED QUASARS

So far, we have considered that the energy observed in HLIRG and ULIRG at all wavelengths is supplied by massive main-sequence and evolved stars formed in an ongoing starburst process in the nuclear/circumnuclear regions of these galaxies. In the following, we review the evidence for the presence of AGN and discuss how luminous and how important such sources would be in the heating and ionization of the surrounding ISM.

#### 6.1 Evidence from radio emission of AGN in HLIRG and ULIRG

HLIRG and ULIRG have radio luminosities (see Figs 1a and b) similar to those of Seyfert 1 and Seyfert 2 galaxies (Ulvestad & Wilson 1989). In addition, Condon et al. (1991) found that a large fraction of the radio emission of ULIRG and HLIRG is generated in regions of 200–350 pc in diameter, or even smaller. This conclusion was also reached by Sopp & Alexander (1991) from a study of five ULIRG.

There are some individual galaxies for which there is good evidence for the presence of AGN. Recent observations of Mrk 231 by Neff & Ulvestad (1988) show that the radio source in this ULIRG is variable with 10–20 per cent variations over time-scales of months. Also, the central compact radio source with a size of less than 36 $\times$ 15 mas$^2$ emits almost 50 per cent of the total radio flux measured from the circumnuclear regions (size $\sim 1.5$ kpc). Thus, for Mrk 231, most of the radio emission is generated in an AGN with an upper size of the order of 30 pc. This conclusion was indicated by our results since the type II supernova rate was $53.5$ yr$^{-1}$.

The galaxy NGC 7469 is another example of a well-known AGN (Wilson et al. 1986, 1991), within the HLIRG sample. High-resolution VLA measurements by these authors (Wilson et al. 1991) show that the 4.9-GHz radio emission is dominated by a strong compact source. This has a size of $0.2 \times 0.1$ arcsec$^2$ (i.e. $66 \times 33$ pc$^2$ at the distance of NGC 7469), and emits 30 per cent of the total 4.9-GHz emission detected within 5 arcsec (i.e. 1 kpc) of the nucleus.

The previous results provided evidence that large fractions of the radio emission are generated in the very inner regions of these galaxies, of size $< 50–100$ pc. Although a stellar origin cannot be ruled out completely, it is more likely that some of the radio emission is associated with the presence of moderately luminous AGN in these galaxies.

#### 6.2 Evidence from X-ray emission of AGN in HLIRG and ULIRG

Detection of hard X-ray emission in the spectral range 2–10 keV is a good indicator for the presence of AGN in galaxies. In a survey of ULIRG and a few HLIRG, Rieke (1988) could find no ULIRG as X-ray emitters, with an upper limit of $L_X (2-10 \text{ keV}) < 9 \times 10^{41} \text{ erg s}^{-1}$. He concluded that HLIRG and ULIRG are underluminous in X-rays by factors of from 6–600 relative to the optically or X-ray selected AGN.

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Figure 3. (a) Far-infrared spectral energy distribution of the high-luminosity (HLIRG) and ultraluminous (ULIRG) galaxy samples as viewed in the $\alpha(60, 25)$ versus $\alpha(100, 60)$ diagram. For comparison, points corresponding to IR-selected QSOs and Seyfert 1 galaxies, Seyfert 2, starburst and H II galaxies, and normal spiral galaxies are plotted as well as the expected spectral indices for a power law and blackbody radiation (see Section 5.3.3 for details). (b) As (a), but only showing the mean values of the spectral indices together with the sample standard deviations.
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These supernovae must in fact be radio hypernovae, for which SN1979c is a prototype. Free–free radio thermal emission is a minor contributor to the observed radio emission. Cosmic rays accelerated in the general magnetic field of the galaxy would also be unimportant in such small volumes.

(5) The number of type II supernovae required to explain the radio luminosity has a mean value of $T_{\text{SNII}} = 1.57$ and 4.31 yr$^{-1}$ for HLIRG and ULIRG, respectively.

(6) The observed FIR luminosities, $q$ parameters, and $Br$ luminosities in HLIRG and ULIRG are best explained by a Salpeter IMF with an upper mass limit $M_\ast = 60 M_\odot$. This result agrees with that obtained by other authors for individual starburst galaxies.

(7) From our $T_{\text{SNII}}$ supernova rates, we are unable to explain the extinction-corrected Hα luminosities of HLIRG and ULIRG with any IMF slope, unless the upper mass limit is $M_\ast = 30 M_\odot$.

(8) If the lower mass limit $M_\ast = 3 M_\odot$, as measured in other starburst galaxies, the star formation rate lies in the range SFR $\sim 40 - 150$ and $80 - 500 M_\odot$ yr$^{-1}$ for HLIRG and ULIRG, respectively.

(9) The infrared spectral energy distributions of HLIRG and ULIRG bear no similarity to those of starburst galaxies and bare AGN. They show FIR spectral indices consistent with blackbody radiation, suggesting that the FIR luminosity comes from dust reprocessing emission corresponding to a temperature lower than that measured in starbursts galaxies.

(10) Radio, hard X-ray, optical emission-line luminosities, and optical emission-line ratios suggest that HLIRG and ULIRG could still harbour Seyfert 2 or low-luminosity Seyfert 1 nuclei, as exemplified by the existence of compact (diameter $\leq 50$ pc) radio sources in Mrk 231 and NGC 7469.

This work thus supports the hypothesis that, in general, a violent circumnuclear starburst is the main source of heating and ionization in HLIRG, and even in ULIRG. Supernovae generated in a nuclear/circumnuclear starburst must be brighter than normal, at least at radio wavelengths, so these supernovae must be radio hypernovae. Otherwise, the radio emission would support the AGN model instead of the starburst model.

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