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A STARBURST REVEALED—LUMINOUS RADIO SUPERNOVAE IN THE NUCLEI OF ARP 220

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ABSTRACT

We report 18 cm VLBI continuum imaging observations of Arp 220, the prototype luminous infrared galaxy (log $L_{\rm fir} = 12.11\ L_{\odot}$). In previous work, we showed that Arp 220 has compact, high-T_b nuclear radio emission that might be interpreted as a dust-enshrouded active galactic nucleus (AGN) radio core, or, alternately, as multiple, very luminous radio supernovae from a very active nuclear starburst. In this work, we present a new 18 cm VLBI image, with 3 × 8 mas angular resolution, showing approximately a dozen unresolved sources, $S_{18\,\rm cm}$ = 0.2–1.2 mJy, within a 0".2 × 0".4 (75 × 150 pc) region centered on the NW nucleus of this merging system. At least two additional sources are detected in the SE nucleus. These point sources account for about 3% of the total 18 cm radio emission associated with Arp 220 and for all the estimated radio flux density with $T_b > 10^6$ K. No other 18 cm emission is detected on scales from 3 to 100 mas (1–30 pc). We interpret these compact radio sources as luminous radio supernovae of the class in which RSN 1986J is a prototype. This interpretation is consistent with a simple starburst model for the infrared luminosity of Arp 220 that has a star formation rate of 50–100 $M_{\odot}$ yr^{-1} and a luminous supernova rate, $\nu_{\rm sn}$ = 1.75–3.5 yr^{-1}. In this model prescription, virtually *all* supernova explosions in Arp 220 must result in luminous RSNe, comparable to the most luminous RSNe observed. We discuss possible mechanisms for the origin of very luminous RSNe in luminous infrared galaxies and suggest that it is likely due to the dense, compact starburst environment. Although our observations do not rule out the presence of an AGN that may contribute to the infrared luminosity in Arp 220, it is not necessary to appeal to AGN activity to account for the overall radio/infrared characteristics of Arp 220.

Subject headings: galaxies: active — infrared: galaxies — radio continuum: galaxies

1. INTRODUCTION

The discovery of infrared galaxies with quasar-like luminosity has stimulated considerable speculation regarding the nature of these systems, which focuses on whether the dominant energy source originates in an active nucleus or a compact, luminous starburst. In an 18 cm VLBI survey of a complete sample of luminous infrared galaxies (LIGs), Lonsdale, Smith, & Lonsdale (1993, hereafter Paper I) show that milliarcsecond scale emission with $T_b \gg 10^7$ K is common, perhaps universal, in LIGs. Furthermore, the LIGs follow the same relationship between core radio power and bolometric luminosity as radio-quiet QSOs (Lonsdale, Smith, & Lonsdale 1995). This work lends support to the interpretation of LIGs as dust-enshrouded active galactic nuclei (AGNs). On the other hand, in a recent detailed analysis of our VLBI survey data, Smith, Lonsdale, & Lonsdale (1998, hereafter Paper II) investigated a starburst origin for LIGs in which the compact, high-T_b emission is produced by luminous radio supernovae (RSNe). This analysis indicates that most, but not all, LIG VLBI-scale emission may be modeled with starburst-generated RSNe, provided the RSNe are *all extremely luminous*; in most cases, spatial clumping of RSNe is also required. In particular, the VLBI visibility data for Arp 220 may be modeled by a starburst with supernova frequency, $\nu_{\rm sn} = 2.7$ yr^{-1}, in which the RSNe all exhibit an 18 cm radio power comparable to that of RSN 1986J, the well-studied luminous Type IIn radio supernova in NGC 891 (Weiler, Panagia, & Stramek 1990).

Arp 220 (=IC 4553/4 = UGC 9913 = IRAS 15327+2340) is the archetype LIG with $L_{\rm fir} \approx 10^{12}\ L_{\odot}$ at a distance of 76 Mpc (H_0 = 75). Arp 220 is a merging system with a pair of radio/infrared nuclei separated by approximately 1" (=370 pc). Arp 220 has been interpreted as an AGN based on its optical and near-infrared spectrum (Sanders et al. 1988; Armus et al. 1995), but recent *Infrared Space Observatory* observations show that the mid-infrared spectrum has very low excitation, characteristic of a starburst rather than an AGN (Sturm et al. 1996). Arp 220 is also the prototype OH megamaser galaxy (Baan, Wood, & Haschick 1982). In a previous VLBI observation of Arp 220, we discovered that the OH 1667 MHz maser emission is very compact, concentrated in structures with scales of order 1–10 pc, with high amplification (Lonsdale et al. 1994, hereafter LDSL). In order to determine the morphology and kinematics of the compact maser emission, we carried out a major spectral VLBI imaging experiment on Arp 220. The OH spectral data will be discussed in other papers (Diamond et al. 1998; Lonsdale et al. 1998). In this Letter, we discuss the 18 cm continuum structure in Arp 220.

2. VLBI OBSERVATIONS AND RESULTS

The observations, involving 17 telescopes in Europe and the US, were carried out on 1994 November 13. Arp 220 received a continuous 7 hr track, of which 4.2 hr was spent on-source, yielding excellent *u-v* coverage. After correlation in 1996 April, standard reduction techniques were used as described in the accompanying paper (Lonsdale et al. 1998). The resulting continuum maps of the Arp 220 nuclei, with 3.1 × 8.0 mas resolution (1.1 × 2.9 pc for Arp 220 at 76 Mpc), are shown in Figure 1. Positions are relative to the peak of the brighter maser complex in the NW nucleus, W1. The rms noise level on the

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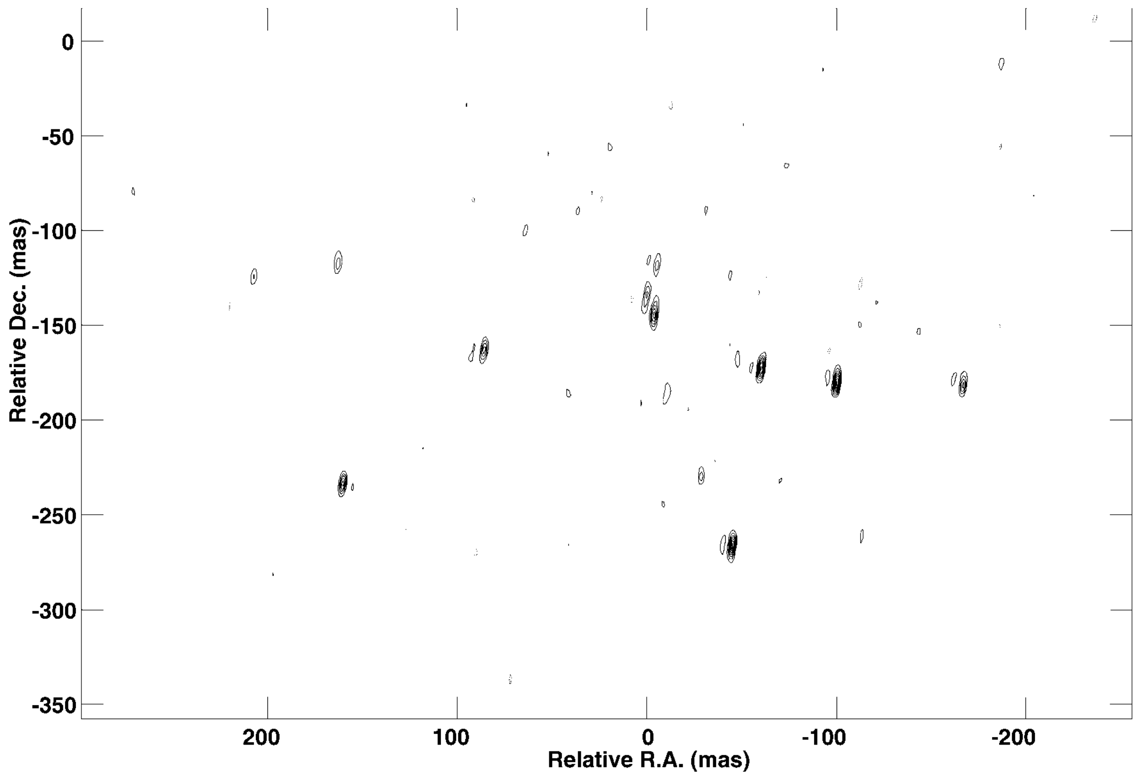

FIG. 1*a*

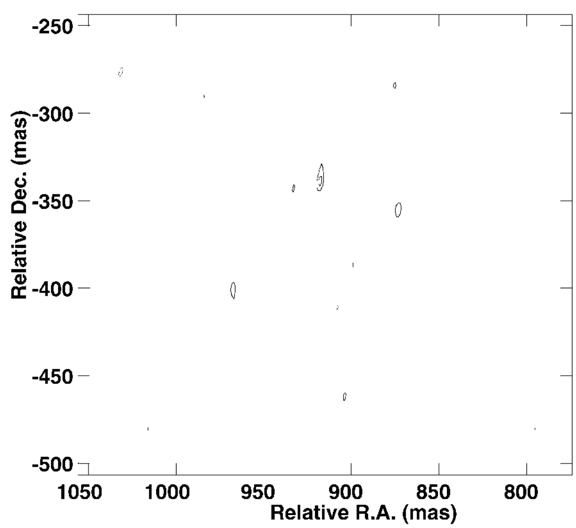

FIG. 1*b*

FIG. 1.—VLBI continuum images of the (*a*) NW nucleus and the (*b*) SE nucleus of Arp 220 at 1659.35 MHz. The angular resolution is 3.1 × 8.0 mas (1.1 × 2.9 pc). The zero point for positions is the peak of the stronger compact maser complex W1 (Lonsdale et al. 1998) at $\alpha_{2000} = 15^{\rm h}34^{\rm m}57\overset{\rm s}{.}2246$, $\delta_{2000} = 23^\circ30'11\overset{''}{.}564$. The contour levels are $-2, -1, 1, 2, 3, 4, \ldots \times 0.12$ mJy beam^{-1}. A phase error of unknown origin is responsible for faint ghost images, comprising about 15% of the flux density, visible to the E-NE of the brighter sources. The flux densities in Table 1 have been scaled upward to account for this factor.

images is approximately 30 μJy beam^{-1} in the continuum with ∼26 MHz bandwidth.

Our previous VLBI imaging observations of Arp 220 led to the discovery of strong, compact 1667 MHz OH maser emission (LDSL), which we interpreted as being due to maser amplification of the compact continuum source reported in Paper I. We were therefore surprised to see no continuum emission coincident with the compact maser sources associated with the NW or SE nuclei of Arp 220, but rather a series of unresolved sources, associated principally with the NW nucleus, which account for most, if not all, of the correlated flux density on baselines longer than $10^6\lambda$, corresponding to spatial scales, $\theta \lesssim 0\overset{''}{.}1$.

In Figure 1*a*, centered on the NW nuclear region, there are approximately a dozen unresolved sources between $S_{1.67\,\rm GHz} \approx 1.2$ mJy and our detection limit of approximately 0.20 mJy. Figure 1*b* is centered on the SW nuclear region and displays two faint sources and one possible weaker source. Table 1 lists

TABLE 1
COMPACT SOURCES IN ARP 220

Source (1)	$\Delta\alpha$ (mas) (2)	$\Delta\delta$ (mas) (3)	$S_{1.67}$ (mJy) (4)	Notes (5)
Arp 220 NW				
1	207.2	−124.5	0.30	
2	162.8	−117.6	0.38	
3	160.3	−233.7	0.76	
4	85.7	−162.8	0.62	
5	−0.1	−133.7	0.46	
6	−3.8	−144.8	0.77	
7	−5.3	−118.5	0.36	
8	−10.7	−186.0	0.24	Possible
9	−28.7	−229.8	0.35	
10	−45.1	−266.3	1.05	
11	−60.3	−172.6	1.05	
12	−100.2	−180.4	1.17	
13	−166.8	−181.8	0.61	
Arp 220 SE				
1	899.8	−400.9	0.20	Possible
2	961.7	−339.0	0.35	
3	945.6	−355.1	0.23	

the positions and flux densities for 14 "certain" and two "possible" sources in Arp 220. Column (1) gives the source designation, while columns (2) and (3) give the relative offsets of the features from the NW compact maser source, W1, for which we derive a position of $\alpha_{2000} = 15^{\rm h}34^{\rm m}57^{\rm s}.22467 \pm 0^{\rm s}.00015$, $\delta_{2000} = 23^\circ30'11''.564 \pm 0''.008$. Relative positions have errors typically less than 1 mas. Column (4) gives the source flux density. All the sources are unresolved, with formal size limits of order 0.25 mas, corresponding to about 0.1 pc at the distance of Arp 220.

3. COMPACT RADIO SOURCES IN ARP 220

It is clear that there is not a single compact high-T_b *core* in Arp 220—rather, the high brightness temperature emission comes from multiple, compact, submillijansky sources, distributed through the twin nuclei of Arp 220. The areal density and location of these sources, well over 100 per square arcsecond precisely aligned with the twin nuclei of Arp 220, eliminates the possibility that these are background sources, or that they are gravitationally lensed images of unrelated sources. The high brightness temperatures indicate that the emission is nonthermal, and not from H II regions.

The observed structure is not characteristic of AGN activity but is precisely what would be expected from a compact starburst—point sources representing recently detonated radio supernovae from recently formed massive stars—with the proviso that normal RSNe, $\langle P_{\rm max}\rangle \approx 10^{20}$ W Hz^{-1}, are well below our detection threshold. There exists a class of luminous radio supernovae for which RSN 1986J, the well- studied luminous Type II RSN in NGC 891 (Weiler et al. 1990), is a prototype. RSN 1986J was one of the most luminous RSNe known with radio power at maximum, $P_{1.67\,{\rm GHz}}({\rm max}) = 1.4 \times 10^{21}$ W Hz^{-1}, corresponding to a flux density at maximum, $S_{1.67\,{\rm GHz}}({\rm max}) \approx 2$ mJy, at the distance of Arp 220—about twice as bright as the brighter compact sources observed in Arp 220. In Paper II, we estimate the *free-free* extinction appropriate to the diffuse radio emission in Arp 220 to be $\tau_{\rm ff} \approx 0.5$, reducing the flux density for RSNe similar to RSN 1986J to $S_{1.67}({\rm max}) \approx 1.2$ mJy. We emphasize that this is a *lower limit* to the extinction, since the optical depth to the nuclear core, where the RSNe probably reside, is likely to be much greater than that estimated from the diffuse radio emission.

The RSNe will remain compact until they fade from view; thus, we would not expect them to be resolved. An expansion rate of the supernova shell, $v = 10{,}000$ km s^{-1} translates to about 0.01 pc yr^{-1} so that it takes over 10 years before the shell/remnant would be convincingly resolved, by which time the flux density will have decayed below our detection limit. If the star formation rate is constant, the VLBI-scale flux density from RSNe approaches an asymptotic maximum. The diffuse radio emission will have a small contribution from accumulated supernova remnants but will be dominated by cosmic rays accelerated in the ambient magnetic field of the interstellar medium. The observed sources are clearly consistent, both in size and flux density, with luminous RSNe in a compact nuclear starburst.

4. DISCUSSION

4.1. *A Starburst/Luminous RSN Model*

In Paper II, we discuss heuristic, constant star formation starburst models for our sample of luminous infrared galaxies, including Arp 220. These models (Scoville & Soifer 1991) use simple scaling law relationships to estimate luminous starburst characteristics in terms of the star formation rate, $\dot{m}$ ($M_\odot$ yr^{-1}), the lower and upper mass limits to the initial mass function (IMF), m_l and m_u, and the starburst timescale, Δt_{*B}:

$$L_{\rm fir} = 1.2 \times 10^{10}\, L_\odot \left(\frac{m_l}{1\ M_\odot}\right)^{0.23} \times \left(\frac{m_u}{45\ M_\odot}\right)^{0.37} \left(\frac{\Delta t_{*B}}{10^8\ {\rm yr}}\right)^{0.67} \dot{m}\ (M_\odot\ {\rm yr}^{-1}). \qquad (1)$$

Adopting $m_l = 1\ M_\odot$, $m_u = 45\ M_\odot$, and $\Delta t_{*B} = 10^8$ yr, we estimate the star formation rate (SFR), $\dot{m} \approx 109\ M_\odot$ yr^{-1} for $\log L_{\rm fir} = 12.11$ appropriate to Arp 220. The supernova rate is

$$\nu_{\rm sn} = \int_{m_{\rm sn}}^{m_u} \psi(m)\, dm \approx \frac{\dot{m}}{3} \frac{(m_{\rm sn}^{-1.5} - m_u^{-1.5})}{(m_l^{-0.5} - m_u^{-0.5})}. \qquad (2)$$

If the lower mass limit for Type II supernova is $m_{\rm sn} = 8\ M_\odot$, then $\nu_{\rm sn}$(Arp 220) $= 1.75$ yr^{-1}.

In the case of Arp 220, there are independent constraints on the starburst IMF. Scoville et al. (1991) and Armus et al. (1995) use the observed *free-free* emission at 2.6 mm and the Paβ flux, respectively, to place limits on the ionizing photon flux, which results in a limit of $m_u \lesssim 28\ M_\odot$. However, no attempt is made to correct for the dust absorption, which may destroy as much as 90% of the Lyman continuum flux (Voit 1992), considerably relaxing any constraint on the number of hot stars. Estimates of the dynamical mass in Arp 220's nuclear region place limits on the number of low-mass stars, which do not contribute appreciably to the starburst luminosity but which dominate the mass. Scoville, Yun, & Bryant (1997) infer a mass $M_{\rm dyn} \approx 5.4 \times 10^9\ M_\odot$ from the CO gas velocities, which they interpret as rotational velocities in a thin disk. About half the central mass must be in molecular gas and dust, which implies $M_* \lesssim 2.5 \times 10^9\ M_\odot$. This places a limit of

$m_l \gtrsim 5\ M_\odot$, depending upon the appropriateness of the CO disk model solution.

Adopting restrictive limits, $m_l \approx 5\ M_\odot$ and $m_u \approx 28\ M_\odot$, implies SFR $\approx 70\ M_\odot$ yr^{-1} (Scoville et al. 1997), and a supernova frequency, $\nu_{sn} = 3.4$ yr^{-1}. The supernova frequency is relatively insensitive to the assumptions about the starburst model, because the supernovae are produced by stars in the mid-range of the IMF. We adopt a supernova frequency, $\nu_{sn} = 2$ yr^{-1}, with an estimated uncertainty of approximately a factor of 2, noting that restricting the IMF will, in most circumstances (see eq. [3]), raise the supernova frequency. A radio supernova would thus appear approximately every 6 months, and several individual supernovae would be visible at any given time.

4.2. *RSN Characteristics*

Chevalier (1982) has modeled the radio emission from Type II RSNe in which an optically thick, thermal supernova shell expands into a dense circumstellar medium, presumed to be the stellar wind from the supergiant precursor, $\rho_{csm} \sim r^{-2}$. A fixed fraction of the supernova shock wave energy is transferred to a synchrotron plasma, which is in field/relativistic particle energy equipartition. The RSN has a characteristic light curve that rises to maximum as the *free-free* optical depth decreases in the expanding shell, then decays in power-law fashion. The post-maximum light curve has a form

$$S_\nu = \frac{P_\nu(\max)}{4\pi d^2}\left(\frac{t - t_0}{\tau}\right)^\beta , \qquad (3)$$

where $P(\max)$ is the power at maximum that occurs an interval τ after detonation, $t = t_0$.

Weiler et al. (1990) have demonstrated that these models provide a good fit to observations of Type II RSNe. Luminous RSNe reach a later maximum than normal RSNe, $\tau \approx 3$ yr, and decay at a steeper rate, $\beta \approx -1.3$, although the best studied cases do not decay monotonically. Adopting 1.2 mJy as $S_{1.67}(\max)$ and $\beta = -1.3$, $\tau = 3$ yr for luminous RSNe, we predict 17 RSNe visible between 0.23 and 1.2 mJy, in rather remarkable agreement with the 16 sources listed in Table 1. This agreement lends considerable support to the validity of a simple starburst model for the bulk of the far-IR luminosity of Arp 220.

These calculations are subject to substantial uncertainty because of our lack of knowledge about the unusual conditions responsible for the ubiquity of high-luminosity RSNe in Arp 220 and the nature of the light curves in these circumstances. The possibilities for the extreme RSN luminosities are as follows: (1) high-density cocoons surrounding the supernova precursor in the dense molecular regions in which the stars are forming, (2) extremely massive stars with high mass-loss rates, and (3) unusually strong magnetic fields.

The radio power scales with the density in the Chevalier models, $P \sim \rho^{15/4}$. If the ambient molecular medium inhibits the progenitor wind, or in itself provides a dense circumstellar medium, then luminous RSNe might arise quite naturally in LIGs. The mean molecular density in the central 0.5 kpc of Arp 220 is $\langle n_{H_2} \rangle \approx 2 \times 10^4$ cm^{-3} (Scoville et al. 1997), and it is likely that the densities in the active star-forming regions are considerably higher. In this case, the circumstellar density is unlikely to follow the $\rho \sim r^{-2}$ profile, and it is probable that the radio light curve will decay more slowly than $\beta = -1.3$, sharply reducing the required luminous RSN rate and modifying the starburst model.

Alternately, if stellar mass-loss rates of RSN precursors are a strong function of mass, then the dependence of radio power on density translates into a relationship between radio power and mass-loss rate, $P \sim (\dot{M}/v_{\rm wind})^{15/4}$, so that more massive stars may give rise to more luminous RSNe. There is some support for this view in the observations of luminous RSNe in nearby galaxies (Weiler et al. 1997). However, the observational evidence suggests that mass-loss rates for the Wolf-Rayet progenitors are independent of spectral type, and thus probably of mass (Leitherer, Chapman, & Koribalski 1997). Furthermore, our result then requires a high *luminous RSN rate* with either (*a*) an even larger number of RSNe below the detection limit of this experiment or (*b*) a very high lower mass cutoff to suppress lower luminosity RSNe. In either case, our starburst model would require substantial modification.

Finally, if the magnetic field in the molecular gas is anomalously strong compared with the environments of normal supernovae, it is possible that this seed field will lead to equipartition at higher radio luminosity. Little is known about field strengths in LIGs, except for upper limits of $B \lesssim 3$–5 mG in the OH-emitting regions of four OH megamaser galaxies from Zeeman splitting measurements (Killeen et al. 1996), but high ambient densities and indications of disklike structure in the gas lend this idea some plausibility.

5. SUMMARY

These observations reveal the presence of multiple, luminous radio supernovae in the nuclei of Arp 220 and firmly establish the importance of star formation to the current energetics of Arp 220. A simple model suggests that the characteristics of Arp 220 may be fully explained without recourse to AGN activity. A surprising conclusion is that virtually all supernovae in the compact nuclear starburst inhabit the extreme upper end of the radio supernova luminosity function. While plausible explanations exist, involving high ambient densities, unusually massive progenitors, or high magnetic field strengths, more information is needed. New, more sensitive, experiments are planned that will provide a direct measure of the RSN rate and radio luminosity function. Provided these experiments reveal no large population of lower luminosity RSNe, nor a RSN rate greatly exceeding that estimated here, the simple starburst model for Arp 220 should remain on firm ground.

Nevertheless, we cannot rule out the presence of an AGN, nor are the models sufficiently secure to eliminate AGN activity as energetically important in Arp 220. Furthermore, the OH maser characteristics of Arp 220 (Lonsdale et al. 1998) show intriguing hints of AGN activity, although not necessarily at an energetically significant level. The presence of bona fide AGNs in our LIG sample (Paper II) is additional motivation for continued investigation into the relationship between compact luminous starbursts and AGNs.

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