VLBI IMAGING OF LUMINOUS INFRARED GALAXIES: STARBURSTS & AGN

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Abstract. As described by Colin Lonsdale in this Workshop, VLBI observations reveal the presence of both AGN and Starburst activity in Luminous Infrared Galaxies. We highlight new results on two classical LIGs which span the range of LIG radio activity: Arp 220, which reveals luminous radio supernovae (RSN) produced in an intense starburst, and Mrk231, which has a powerful compact, AGN radio core. Second epoch observations of the compact radio sources in Arp 220 confirm their nature as luminous Radio Supernovae, but indicate a lower luminous RSN frequency ($\nu_{LRSN} \lesssim 0.3\, yr^{-1}$) and consequent slower decay rate than previously suggested. We interpret this as due to the dense starburst medium into which the supernovae detonate. The compact radio morphology of Mrk231 places it among the Compact Symmetric Objects (CSOs) which are suggested to be young radio sources in which asymmetric lobes or hotspots reveal the working surface of a relativistic jet upon the ambient medium. Assuming that the lobes in Mrk 231 are confined by ram pressure, we estimate an age for the jet/compact source, $\tau \lesssim 10^6$ yr. We interpret Mrk 231 as a newly formed QSO emerging from a starburst.

1. Introduction

Lonsdale (1999) in this volume reviews the high-resolution radio observations of Luminous Infrared Galaxies demonstrating that milli-arcsecond scale emission, $T_b >> 10^7 K$, is common, perhaps universal in LIGs. Furthermore, the LIGs follow a common relationship between core radio power and bolometric luminosity with radio-quiet QSOs (Lonsdale, Smith & Lonsdale 1995). This supports the interpretation of LIGs as dust-enshrouded AGN. On the other hand, a recent detailed analysis of our VLBI survey data (Smith, Lonsdale & Lonsdale 1998) investigated a Starburst origin for LIGs in which the compact, high-T_b emission is produced by luminous radio supernovae (RSN). This analysis indicates that most, but not all, LIG VLBI-scale emission may be modelled with Starburst-generated RSN, provided the RSN are *extremely luminous* and, in most cases, clustered. These predictions were confirmed with the detection of luminous RSN in the nuclei of Arp 220, consistent with a Starburst origin for the infrared luminosity (Smith, *et al.* 1998), described in §2. The AGN view is shown in §3 where our images of Mrk 231 which indicate an AGN core which has ignited within the last $\sim 10^6$ years in the center of a Starburst disk.

2. Arp 220: An Intense Starburst

In previous 18cm radio studies we have showed that about 3% of the 18cm radio power in Arp 220 originates from compact, high-T_b regions associated with its merging nuclei (Lonsdale, Smith & Lonsdale 1993). First epoch images (1994 November) of Arp 220 at 3×8 mas angular resolution (Smith, *et al.* 1998), showed over a dozen unresolved sources, $S_{18cm} = 0.2 - 1.2$ mJy, within a $0.2 \times 0.4''$(75×150 pc) region centered on the NW nucleus and at least two additional sources in the SE nucleus. We interpreted these compact sources as luminous radio supernovae and presented a simple Starburst model for Arp 220 which has a star-formation rate of $50 - 100\, M_\odot yr^{-1}$ and a luminous radio supernova rate, $\nu_{LRSN} \sim 2\, yr^{-1}$.

Our second epoch observations in 1997 September show that most of the compact radio sources have declined in brightness, but no new compact sources have appeared. Data for the two epochs are shown in Table 1. Two of the compact sources are detected at 6cm; these sources have inverted 1.67–5.0 GHz radio spectra, suggesting large optical depths, $\tau_{ff}(18cm) \gtrsim 1.0$–$1.5$ and possibly young ages. These observations are consistent with the luminous RSN interpretation, but require a slower decline in the 18cm radio light-curve with a concommittantly lower luminous supernova rate, $\nu_{LRSN} \lesssim 0.3\, yr^{-1}$, as also required by the lack of new RSN. If Arp 220 is powered by an enormous Starburst, then the new data indicate that the majority of the supernovae must not be luminous enough to

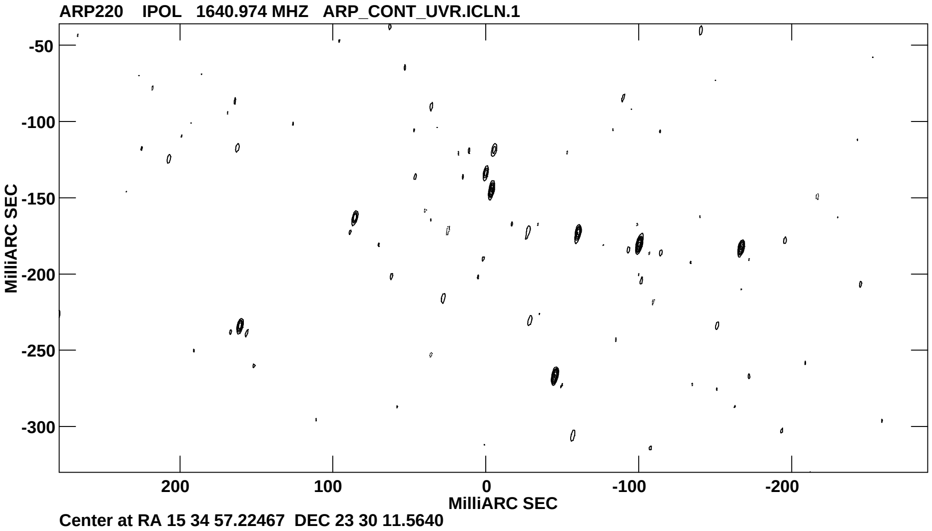

Figure 1. 18 cm VLBI image of the W Nucleus of Arp 220 from our second epoch observations, which may be compared with Smith, Lonsdale, Lonsdale & Diamond (1998). We interpret the twelve compact (unresolved) radio sources as luminous Radio Supernovae.

be detected individually by our experiment, either because luminous RSN only occur in the most extreme environments, or because only very massive stars ($M \gtrsim 20 M_{\odot}$) produce luminous RSN. We believe that it is likely that we are seeing only the upper part of the RSN luminosity function, formed in the densest molecular regions of the compact nuclear Starburst.

3. Mrk 231: A Nascent Quasar Emerging from A Starburst

Mrk 231 has long been recognized as a remarkable galaxy: it is the most luminous galaxy in the local ($z \lesssim 0.1$) Universe with properties that place it among classical AGN and also infrared galaxies.The luminosity of Mrk 231, $L_{bol} \gtrsim 10^{46} erg\, s^{-1}$, is comparable to other low-redshift radio-quiet QSOs and it falls in the midst of the radio power–luminosity relation for QSOs (and LIGs) constructed by Lonsdale, Smith & Lonsdale (1995). Mrk 231 shows a variety of characteristics in common with classical QSOs including: a strong, broad-emission-line spectrum with strong FeII emission (Boksenberg *et al.* 1977), variability at both optical (Hamilton & Keel 1987) and radio wavelengths (McCutcheon & Gregory 1978), as well as multiple broad absorption line systems (Rudy, Foltz & Stocke 1985). Although underluminous compared to "normal QSOs", its x-ray luminosity is comparable to other BAL QSOs, it is among the most luminous LIGs in the x-ray (Nak-

TABLE 1. Arp 220 RSN Flux Densities

SOURCE	$\Delta\alpha$ (mas)	$\Delta\delta$ (mas)	$S_{1.67}$ (mJy) 1994.11	$S_{1.67}$ (mJy) 1997.9	% change
(1)	(2)	(3)	(4)	(5)	(6)
Arp 220 NW 1	-207.2	-124.5	0.30	0.19	−37%
2	-162.8	-117.6	0.38	0.19	−50%
3	-160.3	-233.7	0.76	0.61	−20%
4	-85.7	-162.8	0.62	0.47	−24%
5	0.1	-133.7	0.46	0.45	0%
6	3.8	-144.8	0.77	0.76	0%
7	5.3	-118.5	0.36	0.32	−11%
8	10.7	-186.0	0.24	<0.09	
9	28.7	-229.8	0.35	0.22	−37%
10	45.1	-266.3	1.05	0.96	− 9%
11	60.3	-172.6	1.05	0.69	−34%
12	100.2	-180.4	1.17	1.08	− 8%
13	166.8	-181.8	0.61	0.71	+16%

agawa 1999), and it shows a QSO-like hard x-ray spectrum (Turner 1999).

With an infrared luminosity, $log\, L_{FIR} = 12.35(L_\odot)$, Mrk 231 is the most luminous infrared galaxy in the complete sample of Condon *et al.* (1991). Like other well-studied LIGs, the system is rich in molecular gas, $log\, M_{H_2} \approx 10.2(M_\odot)$ (Solomon *et al.* 1997) and it is one of the original OH megamaser systems (Baan 1985). Furthermore, Mrk 231 shows tidal tails and other evidence for merger or disturbance in the host galaxy, which is itself a luminous system with evidence for rapid star formation (Sanders, *et al.* 1988). Bryant & Scoville (1996) have interpreted the CO distribution as a molecular disk containing an estimated $M_{H_2} \approx 3 \times 10^9 M_\odot$ within $1''$(=840pc) with a scale height, $h \approx 30pc$. Carilli, Wrobel and Ulvestad (1998; CWU98) have detected HI *absorption* against the inner radio disk ($r \lesssim 160pc$) with $N_{HI} \approx 6 \times 10^{22}(T_s/1000K)cm^{-2}$, $< n_{HI} > \approx 250(T_s/1000K)\, cm^{-3}$, and $M_{HI} \approx 2 \times 10^7(T_s/1000)M_\odot$. Our OH maser observations show only extended 1667MHz emission within the central 100pc.

Our image of the center of Mrk 231 shows a compact double-lobed source classified as a Compact Symmetric Object (CSO; Readhead, *et al.* 1996). The CSOs are believed to be young objects (age $\lesssim 10^4$yr) which evolve into FRII radio sources. Our analysis supports this view for Mrk 231. The radio component properties are shown in Table 2. Simple optically-thin synchrotron modelling of the dominant (southern) radio lobe, which

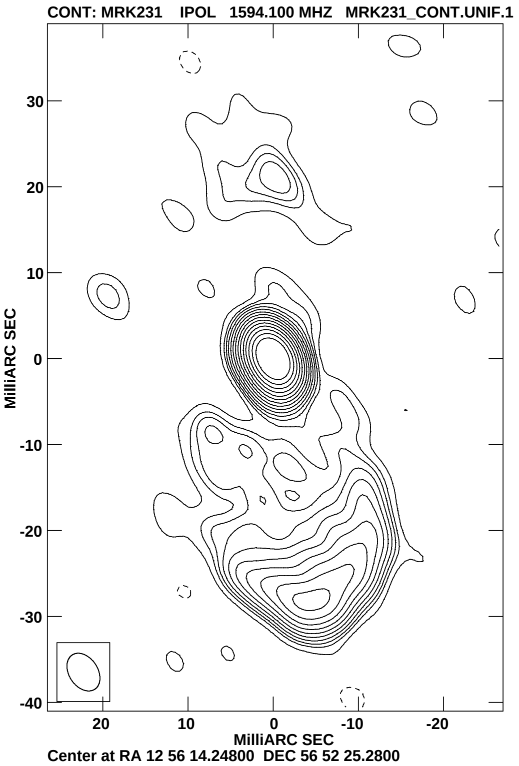

Figure 2. 18 cm VLBI image of the central 100pc of Mrk 231 at 5×8mas resolution. The radio structure of Mrk 231 places it among the Compact Symmetric Objects in which the radio lobes represent the working surface of a nuclear jet upon the ambient medium.

is almost certainly the working surface of a relativistic jet upon the ambient medium, produces an estimate of the pressure in particles and field, $P_{rel} \approx 4 \times 10^{-7} dyn\, cm^{-2}$. Equating this pressure to the ram pressure, $P_{ram} \sim \rho v^2$, provides an estimate of the advance speed of the south lobe, provided we have an estimate of the ambient density. A limit on the density of the medium surrounding the south lobe may be made from spectral index distribution around the S lobe, and by inference the distribution of τ_{ff}, from our map combined with the 21cm map of CWU98, suggesting $< n > \lesssim 10^4 cm^{-3}$. This provides a *lower limit*, $v_{adv} \gtrsim 10^{-4} c$, with a resulting *upper limit* on the timescale for the onset of activity, $\tau_{AGN} \lesssim 10^6 yr$. We suggest that Mrk 231 is a young quasar; the estimate of the age of the compact source is substantially less than the inferred age of the Starburst, $\tau_{*B} \sim 10^8 yr$. There is some evidence for previous activity on a scale of several tens of parsecs, however (de Bruyn & Wilson 1976, Ulvestad, *et al. 1998*) The extended radio emission from the molecular/Starburst disk implies a continuing star-formation rate of order 60 $M_{\odot}\mathrm{yr}^{-1}$, suggesting that

TABLE 2. Mrk 231 RADIO COMPONENTS

Component	Scale		$S_{1.6GHz}$ (mJy)	Reference
(1)	(2)	(3)	(4)	(5)
Extended	$> 1''$	Galaxy Disk?	80	CWU(1998)
	$0.''1 - 1.''0$	Starburst/Molecular Disk	130	CWU(1998)
Core	$< 0.''005$	AGN Core	49	This work
South Lobe		Jet Interaction Region	31	This work
North Lobe		Jet Interaction Region	3	This work

starburst emission provides up to about 2/3 of the FIR luminosity.

4. Summary

The VLBI characteristics of many Luminous Infrared Galaxies, like Arp 220, may be explained by Starburst-generated luminous RSN, but some LIGs, like Mrk 231, must harbor AGN cores. The scenario of Sanders *et al.* (1988) from merger $\longrightarrow$ luminous Starburst $\longrightarrow$ QSO remains an attractive picture for the interpretation of LIGs.

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