A Starburst Revealed – Luminous Radio Supernovae in the Nuclei of Arp 220

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ABSTRACT

We report 18cm VLBI continuum imaging observations of Arp 220, the prototype Luminous Infrared Galaxy ($log L_{fir}$ = 12.1 $1 L_{\odot}$). In previous work we showed that Arp 220 has compact, high-T_b nuclear radio emission which might be interpreted as a dust-enshrouded AGN radio core, or, alternately, as multiple, very-luminous radio supernovae from a very active nuclear Starburst. In this work we present a new 18cm VLBI image, with 3 x 8 mas angular resolution, showing approximately a dozen unresolved sources, S_{18cm} = 0.2 — 1.2 mJy, within a 0.2 x 0.4'' (75 x 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 18cm radio emission associated with Arp 220 and for all the estimated radio flux density with $T_b > 10^6 K$. No other 18cm emission is detected on scales from 3-100 mas (1--30 pc). We interpret these compact radio sources as luminous radio supernovae of the class in which RSN1986J is a prototype. This interpretation is consistent with a simple Starburst model for the infrared luminosity of Arp 220 which has a star-formation rate of 50- 100 $M_{\odot} yr^{-1}$ and a luminous supernova rate, ν_{sn} = 1.75 – 3.5 yr^{-1}. *In* this model prescription virtually all supernova explosions in Arp 220 must result in luminous RSN, comparable to the most luminous RSN observed. We discuss briefly possible mechanisms for the origin of very luminous RSN in compact, luminous infrared galaxies. Although our observations do not rule out the presence of an AGN which 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.

1. Introduction

The discovery of infrared galaxies with qua.sar-like luminosity has stimulated considerable speculation regarding the nature of these systems, which represent the dominant population of luminous galaxies in the local Universe (see Sanders & Mirabel 1996 for an excellent review). At this luminosity virtually all Luminous Infrared Galaxies (LIGs) are merging or strongly interacting systems. LIGs are gas-rich, with large reservoirs of high-density molecular gas, $log\, M_{H_2}(M_\odot) \gtrsim 10$, (Sanders, Scoville & Soifer 1991, Solomon *et al.* 1992) so that it may be expected that they should be active star-forming galaxies. Recent work suggests that the molecular gas in some systems, notably Arp 220 and Mrk 231 (Bryant & Scoville 1996, Scoville, Yun & Bryant 1997), is concentrated in nuclear disk-like structures rather than in giant molecular clouds. It seems unlikely that these systems may be modelled *simply as* scaled-up analogs of star-forming regions in the Milky Way or nearby Starbursts such as M82. The LIGs, furthermore, exhibit high excitation spectra characteristic of AGN/LINER systems (Sanders *et al.* 1988) and uncomfortable constraints may be placed on Starburst models in individual cases. This has led to suggestions that the LIGs may harbor obscured AGN or perhaps may represent an intermediate stage in the formation of AGN from the collision of gas-rich spirals.

In an 18-cm VLBI survey of a complete sample of LIGs for compact, high-brightness-temperature emission commonly associated with AGN activity, Lonsdale, Smith, and Lonsdale (1993; Paper I) showed that milli-arcsecond scale emission with $T_b >> 10^7$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 AGN. On the other hand, in a recent detailed analysis of our VLBI survey data, Smith, Lonsdale and Lonsdale (1997; Paper 11) 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 *all extremely luminous,* and in many cases spatial clumping of the RSN is also required. In particular, the VLBI visibility data for Arp 220 could be modelled by a starburst with a supernova frequency, ν_{sn} = 2.7 yr^{-1}, in which the RSN all exhibit an 18cm radio power comparable to that of RSN1986J, the well studied luminous Type IIn radio supernova in NGC 891 (Weiler *et al.* 1990). Notably, the Arp 220 visibility data do *not* require spatial clumping of the RSN.

Arp 220 (= IC 4553/4 = UGC 9913 = IRAS 15327+2340) is the archetype LIG with $L_{fir} \approx 10^{12} L_\odot$ 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″(=370pc). The system has a reservoir of approximately 2 x $10^{10} M_\odot$ of molecular gas and Starburst models suggest a star-formation rate of order 100A4$_0$ yr^{-1} to produce the observed far-infrared luminosity, 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 ISO observations show that the mid-infrared spectrum is 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 *et al.* 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 1-10pc, with high amplification (Lonsdale *et* al. 1994; LDSL). At that time, a model in which the maser emission originates in a molecular torus surrounding a compact **AGN** core was suggested. In order to test this model by determining the morphology and kinematics of the compact maser emission, and to test the potential of using masers as probes of compact, luminous infrared galaxies, we carried out a major spectral VLBI imaging experiment on Arp 220 and the three other strongest OH megamasers accessible to northern VLBI arrays. The OH spectral data will be discussed in other papers (Diamond *et* al. 1997, Lonsdale *et* al. 1997). In this letter we discuss the 18cm continuum structure in Arp 220.

2. VLBI Observations and Results

The observations, conducted under project code GL 15 on 13 November 1994, involving 17 telescopes in Europe and the U. S., were designed to provide full imaging in line and continuum for the four brightest OH megamaser sources in the northern sky, including Arp 220. Arp 220 received a continuous 7-hour track, of which 4.2 hours was spent on-source, yielding excellent u-v coverage. After correlation in April 1996, standard techniques were used to reduce the observations as described in the accompanying paper (Lonsdale *et al.* 1997). The resulting continuum maps of the Arp 220 nuclei, with 3.1x 8.0 milliarcsec resolution (1.1 x 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, WI. The rms noise level on the images is approximately 30μJy/beam 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 due to maser amplification of the compact continuum source reported in Paper 1. We were therefore surprised to see no continuum emission coincident with the compact maser sources associated with either the NW or SE nuclei of Arp 220, but rather a series of unresolved sources, associated principally with the NW nucleus, which appear to account for most, if not all, of the correlated flux density on baselines longer than $10^6\lambda$, corresponding to spatial scales, $\theta \lesssim 0''.1$.

In Figure 1(a), centered on the NW nuclear region, there are approximately a dozen unresolved sources between $S_{1.67GHz} \approx$ 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 a small number of possible weaker unresolved sources. Table 1 lists the positions and flux densities for 14 '{certain" and 2 "possible" sources in Arp 220. Columns (1) gives the source designation, while columns (2) and (3) give the relative offsets of the features from the NW compact maser source, W 1, for which we derive a position of cr$_{2000}$ = 15^h34^m57 ! 22467 ± O : 00015, δ_{2000} = 23° 30' 11 $''.564 \pm$ O $''.008$. Relative positions have errors typically less than 1mas. Column (4) gives the source flux density. A careful examination of Figure 1 shows faint ghost images to the NE of the compact features due to a small undetermined phase error. These images contain about 15% of the flux in the features and the flux densities in Table 1 have been scaled upward by 15% to account for this flux. All the sources are unresolved, with formal size limits of order 0.25mas, corresponding to about 0.1pc at the distance of Arp 220.

3. The 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, sub-mJy 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 are gravitationally lensed images of unrelated sources. The high brightness temperatures indicate that the emission is non-thermal, and not from HII regions.

Although classical AGN exhibit a wide variety of structures on milliarcsecond scales, 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 single proviso that normal RSN, with $\langle P_{max} \rangle \approx 10^{20} W$ Hz^{-1}, are well below our detection threshold. There exists a class of radio supernovae with luminosities that may exceed this value by more than an order of magnitude, sometimes dubbed "hypernovae" (Wilkinson & de Bruyn 1990). In Paper II we used RSN1986J, the well studied luminous Type II RSN in NGC 891 (Weiler *et al.* 1990), as a template for luminous RSN in LIGs. It is one of the most luminous RSN known with 18cm radio power at maximum,

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	

$P_{1.67GHz}(max) = 1.4 \times 10^{21} W\,Hz^{-1}$. Luminous RSN like RSN1986J will have a flux density at maximum, $S_{1.67GHz}(max) \approx 2$ mJy, about twice as bright as the brighter compact sources observed in Arp 220.

The compact nature of the LIGs and the fact that the LIGs have a FIR-to-radio parameter, $q \approx 2.48$ (Condon *et* al. 1991a; CHYT), somewhat larger than that for "normal" Starburst Galaxies, $q = 2.34$ (Condon *et al.* 1991 b), suggests that the LIGs have a small but significant free-free optical depth at 18cm. In order to estimate the extinction and derive corrected 1.67GHz flux densities, we follow CHYT by assuming that the VLA-scale radio structure in Arp 220 has a nominal spectral index $\alpha_{1.49}^{8.44} = 0.7$ between 1.49GHz and 8.44GHz and is optically thin to *f-f* extinction at 8.44GHz. The 1.67GHz optical depth is then:

$$\tau_{ff} \approx 2.3\ (\alpha_0 - \alpha_{1.49}^{8.44}). \qquad (1)$$

This implies an 18cm optical depth for Arp 220, $\tau_{ff} \approx 0.5$, and a flux density for RSN similar to RSN1986J at maximum, $S_{1.67}(max) \approx 1.2$ mJy. We emphasize that this is a *lower limit* to the extinction, since the optical depth to the nuclear core, where the RSN probably reside, is likely to be much greater than that estimated from the diffuse radio emission, which dominates the tot al flux density.

The RSN 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 would take well over 10 years before the shell/remnant would be convincingly resolved by our experiment, by which time the flux density will have decayed below our detection lit nit. If the star-formation rate is constant, the VLBI-scale flux-density from RSN 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 ISM.

The observed sources are clearly consistent, both in size and flux density, with luminous RSN in a compact nuclear Starburst. It is not yet certain what conditions give rise to such luminous RSN, but the extreme, compact star-forming regions inferred for the LIGs (CHYT) might seem likely sites. In particular, the RSN radio power is a strong function of the density of the medium into which the supernova shock expands (Chevalier 1982) so high densities either in the ambient molecular medium or in the precursor wind would be a prime candidate (see below).

4. Discussion

4.1, A Starburst/Luminous RSN Model

In Paper II we discuss heuristic, constant star-formation Starburst models (Scoville & Soifer 1991, Leitherer & Heckman 1995) for our sample of Luminous Infrared Galaxies, including Arp 220, and attempt to fit the 18cm survey visibility functions with multiple radio supernovae. The models of Scoville & Soifer, which we employ here, adopt a Miller-Scalo (1979) Initial Mass Function to derive simple scaling-law relationships among observable characteristics in terms of the star-formation rate, m $(M_\odot yr^{-1})$, the lower and upper mass limits to the IMF, m_l and mu, and the Starburst timescale, Δt_{*B}. For similar input parameters, the more sophisticated models of Leitherer & Heckman yield virtually identical global characteristics. The star-formation rate (SFR) is:

$$L_{fir} = 1.2 \times 10^{10} L_\odot \left(\frac{m_l}{1M_\odot}\right)^{0.23} \left(\frac{m_u}{45M_\odot}\right)^{0.37} \left(\frac{\Delta t_{*B}}{10^8 yr}\right)^{0.67} \dot{m}(M_\odot yr^{-1}) \tag{2}$$

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

$$\nu_{sn} = \int_{m_{sn}}^{m_u} \psi(m)dm \approx \frac{\dot{m}}{3} \cdot \frac{(m_{sn}^{-1.5} - m_u^{-1.5})}{(m_l^{-0.5} - m_u^{-0.5})} \tag{3}$$

for $m_l \geq 1.0 M_\odot$. Adopting a lower mass limit for Type II supernova detonation, $m_{sn} = 8M_\odot$, yields $\nu_{sn}(Arp\ 220) = 1.75\ yr^{-1}$.

In the case of Arp 220, observations at other wavelengths may substantially constrain the IMF for Starburst models. Scoville *et* al. (1991) have placed a limit on the *free-free* emission at 2.6mm, while Armus *et* al. (1995) have observed Paschen-β in Arp 220, both of which, under certain assumptions, place stringent limits on the ionizing photon flux from the upper end of the IMF, and which result in a constraint *mu* $\lesssim 28 M_\odot$. However, no attempt is made in either study to estimate the fraction of UV photons destroyed by absorption onto dust grains. Since dust within the ionized region may destroy as much as 90% of the emitted ionizing flux (Voit 1992), the limit on Lyman photons may be a significant underestimate, relaxing any constraint on the number of hot stars.

A more robust limit on the lower-mass cutoff may be placed by the dynamical mass in the core of Arp 220; over the course of its lifetime, the Starburst cannot have produced stars and remnants whose mass exceeds the dynamical mass in Arp 220's nuclear region. In a recent CO imaging study of Arp 220, Scoville, Yun, and Bryant (1997) infer a mass $M_{dyn} \approx 5.4 \times 10^9 M_\odot$ 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 on the number of low mass stars which do not contribute appreciably to the luminosity, but which dominate the mass, $ml \gtrsim 5 M_\odot$. The validity of this restriction depends upon the appropriateness of the disk model solution to the central CO distribution.

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, Yun & Bryant 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, For the following discussion we adopt a supernova frequency, $\nu_{sn} = 2 yr^{-1}$ with an estimated uncertainty of approximately a factor of two, noting that restricting the IMF will, in most circumstances (see Eqn. 3), raise the supernova frequency.

A radio supernova would thus be expected to appear approximately every six months and several individual supernovae would be visible at any given time, with a background radio emission produced by more extended remnants and cosmic-ray-generated synchrotrons emission in the ISM.

4.2, **RSN Characteristics**

Chevalier (1982) has modelled the radio emission from Type II RSN 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 synchrotrons plasma, which is in field/relativistic particle energy equipartition. The RSN has a characteristic light curve which 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:

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

where $P(max)$ is the power at maximum light, which occurs an interval τ after detonation at t = to,

Weiler and collaborators (1986, 1990) have demonstrated that these models provide a good fit to observations of Type 11 RSN. Luminous RSN reach a later maximum than normal RSN, $\tau \approx$ 3 yrs, and decay at a steeper rate, $\beta \approx -1.3$, although the best studied cases do not decay monotonically (Weiler *et* al. 1990). Taking 1.2 mJy as $S_{1.67}(max)$ and $\beta = -1.3$, τ = 3yr for luminous RSN, we predict 17 RSN visible between 0,23-1 .2mJy, 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.

Nevertheless, these calculations are subject to substantial uncertainty due to our lack of knowledge about the unusual conditions responsible for the ubiquity of high-luminosity RSN in Arp 220, and the manner in which these conditions may influence the shape of the RSN radio light curves. Among the possibilities are 1) extremely massive stars with high mass-loss rates, 2) high density coccoons surrounding the supernova precursor in the dense molecular regions in which the stars are forming, and 3) unusually strong magnetic fields in the star-forming regions.

The radio power scales with the density of the circumstellar medium in the Chevalier (1982) models, $P \sim \rho^{15/4}$. Stellar mass-loss rates are a fairly steep function of mass (Conti 1982) and radio power is a steep function of mass-loss rate (density), in this case $P \sim (\frac{\dot{M}}{v_{wind}})^{15/4}$, so that massive stars may give rise to more luminous RSN. There is some support for this view in the observations of luminous RSN in nearby galaxies (Weiler *et* al. 1997). Our result then requires a high *luminous RSN rate* with either (a) an even larger number of RSN below the detection limit of this experiment, or (b) a very high lower mass cutoff to suppress lower luminosity RSN. In either case, our starburst model would require substantial modification.

Alternately, if the high densities in the molecular medium in compact LIGs provide a denser circumstellar environment, luminous RSN might arise quite naturally in LIGs regardless of the stellar mass. The mean molecular density in the central 0.5 kpc of Arp 220 is $< n_{H_2} > \approx 2$ x 10^4 c m^{-3} (Scoville, Yun & Bryant 1997) and it is likely that the densities in the regions where star-formation is occurring may be considerably higher. If the ambient molecular medium inhibits the progenitor wind, or in itself provides a dense circumstellar medium, then the radio power will, according to the Chevalier prescription, scale with the density to a high power. 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 the $\beta = -1.3$ assumed in the discussion above, sharply reducing the required luminous RSN rate and modifying the starburst model parameters.

Finally, if the magnetic field in the molecular gas is anomalously strong compared to the environments of normal supernovae, it is possible this seed field will lead to equipartition at higher radio luminosity. Little is known about field strengths in LIGs, except for upper limits of $B \lesssim 3$–5mG 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 energetic of Arp 220, the prototype LIG. A simple model calculation indicates that the characteristics of Arp 220 may be fully explained without recourse to AGN activity.

A surprising consequence of our work is the implication that virtually all supernovae in the compact nuclear starbursting regions inhabit the extreme upper end of the currently known radio luminosity function of radio supernovae. While plausible explanations for this characteristic exist, involving high ambient medium densities or magnetic field strengths, or perhaps unusually massive progenitor stars, more information is needed. New, more sensitive experiments are planned which will provide a direct measure of the RSN rate without recourse to models of radio light curves, as well as constraints upon the radio luminosity function. Provided these experiments reveal no large population of lower-luminosity RSN, nor a RSN rate greatly exceeding that estimated here, the simple starburst model for the luminosity of Arp 220 described here should remain on firm ground.

Nevertheless, we cannot rule out the presence of an AGN, nor are the model parameters sufficiently secure to eliminate the possibility that AGN activity is energetically important in Arp 220. Furthermore, the OH maser characteristics of Arp 220 (Lonsdale et al. 1997) show intriguing hints of AGN activity, though not necessarily at an energetically significant level. The presence of bona-fide AGN in our LIG sample (Paper II) is an additional factor motivating continued investigation into possible relationships between compact luminous Starbursts and AGN.

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Fig. l.—- VLBI continuum images of the NW nucleus (Panel a) and SE nucleus (Panel b) of Arp 220 at 1659.35 MHz. Angular resolution is 3.1 x 8.0 milliarcsec (1.1 x 2.9pc). The zero point for positions is the peak of the stronger compact maser complex W1(Lonsdale *et* al. 1997) at $\alpha_{2000} = 15^h 34^m 57$! 2246, δ_{2000} = 23”30’ 11! ’564. Contour levels are -2, -1, 1, 2, 3, 4, . . . times 0.12 mJy/beam. A phase error of unknown origin is responsible for faint ghost images, comprising about 15% of the flux density, visible to the ENE of the brighter sources.

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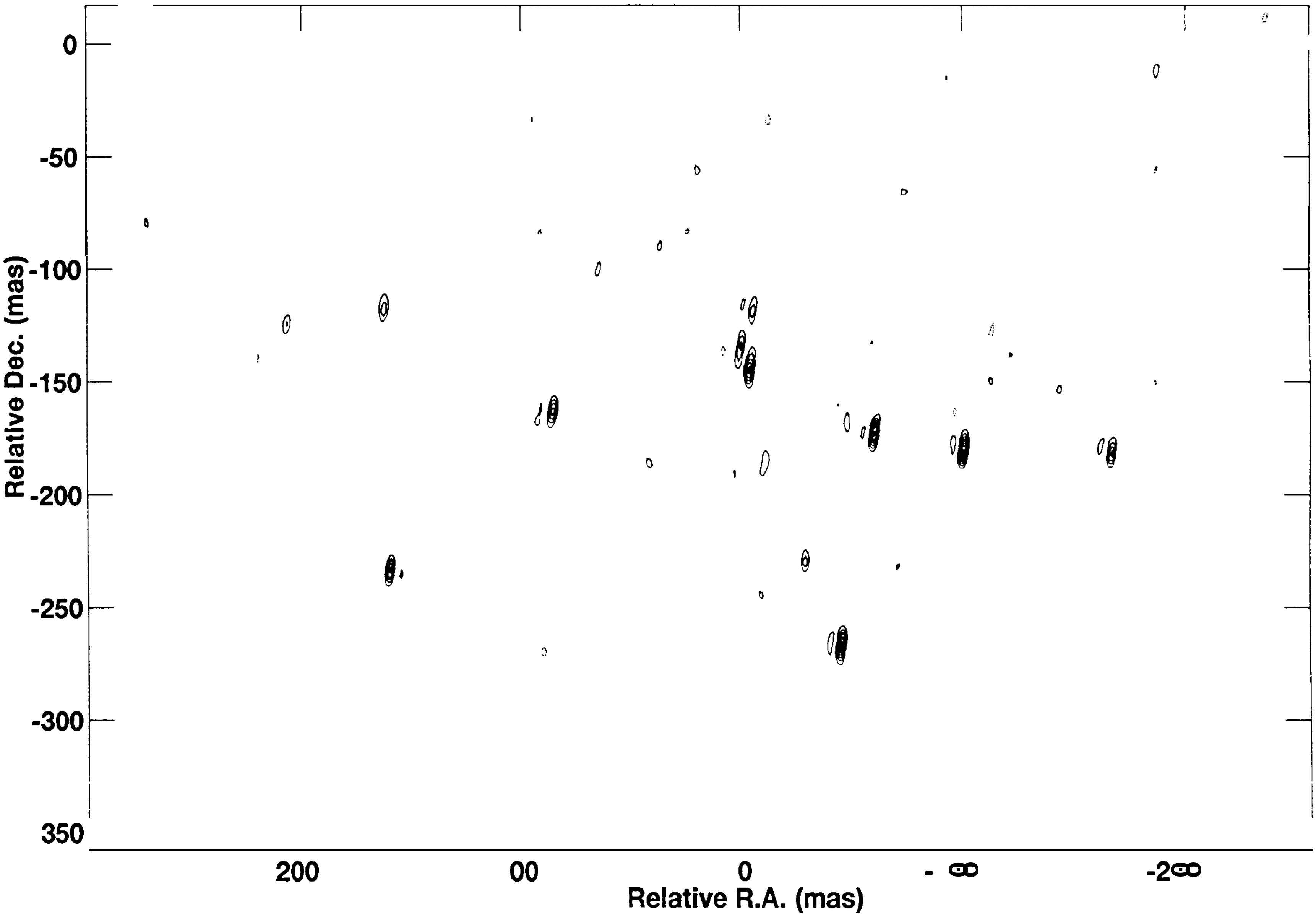
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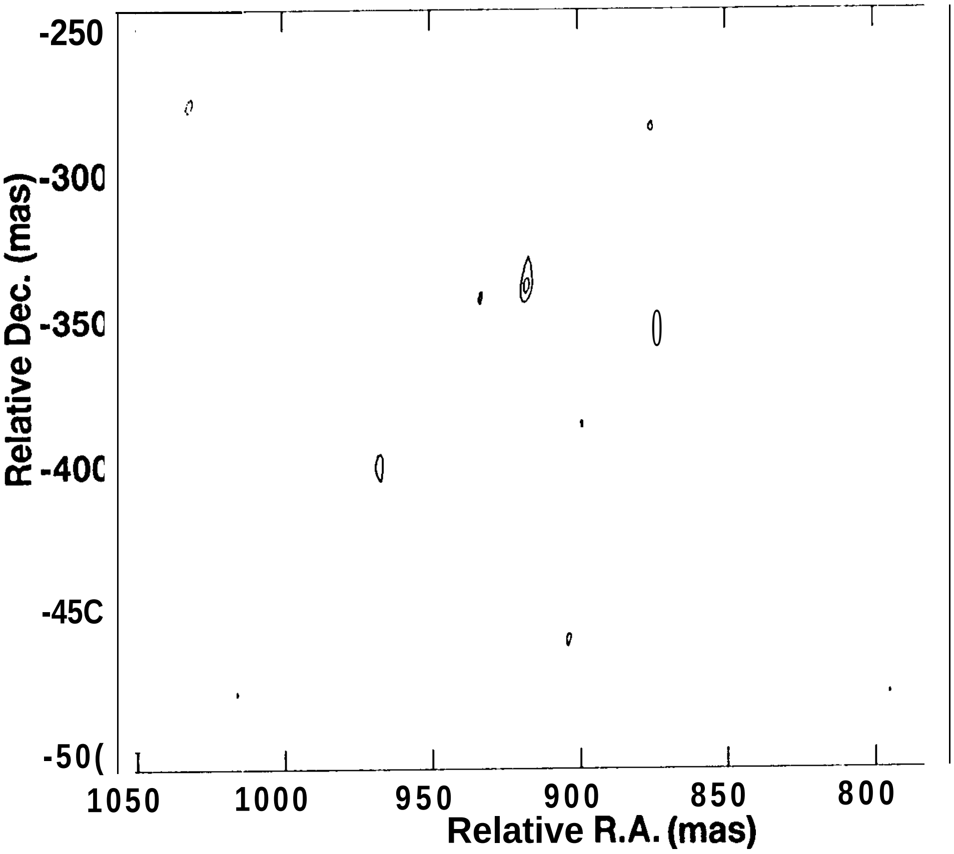
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