

HIGH-RESOLUTION RADIO OBSERVATIONS OF THE SUPERNOVA REMNANT 3C 391: POSSIBLE BREAKOUT MORPHOLOGY

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Received 1992 June 25; revised 1993 February 17

ABSTRACT

We present radio observations of the bright, compact supernova remnant 3C 391 (G31.9+0.0), made with the Very Large Array² at 6'' resolution. The remnant's morphology suggests expansion into a medium with a very strong density gradient. We interpret radio and x-ray [Wang & Seward, *ApJ*, 279, 705 (1984)] morphologies as evidence for a breakout of the expanding material into a region of abruptly lower density. The CO survey of Sanders *et al.* [*ApJS*, 60, 1 (1986)], though not fully sampled, shows the presence of molecular gas at the position of the remnant, with a radial velocity of 90–110 km s⁻¹, similar to the highest velocity absorption features seen in H I toward 3C 391. This gas may thus be near the remnant, though direct evidence of interaction is lacking. More detailed CO observations, and searches for evidence of shocked molecular gas such as 2.12 μ emission from H₂, might confirm or refute the tantalizing possibility that 3C 391 is interacting with an observable molecular cloud.

1. INTRODUCTION

As part of a program to study small angular size, bright supernova remnants (SNRs) for information on electron acceleration, we observed several SNRs in the first galactic quadrant. 3C 391 has never been observed at resolutions greater than 1 arcmin, though its compactness (diameter roughly 6 arcmin; Goss *et al.* 1979) and relatively high radio flux density (~ 20 Jy at 1446 MHz; Green 1988) make it the tenth-highest surface-brightness remnant in the Galaxy at 1 GHz. Early, low-frequency observations (summarized in Kassim 1989) distinguished 3C 391 for its strong foreground thermal absorption, causing a low-frequency turnover in the integrated radio spectrum below about 100 MHz. The implied presence of large amounts of ionized gas along the line of sight has been confirmed by detections of radio recombination lines (Cesarsky & Cesarsky 1973; Chaisson 1974; Downes & Wilson 1974). Both the turnover and the recombination lines have been attributed by these authors to low-density foreground H II regions, rather than to any gas in the immediate vicinity of the remnant. Single-dish observations (Caswell *et al.* 1971; Radhakrishnan *et al.* 1972) show H I absorption against 3C 391 up to ~ 105 km s⁻¹, the tangent-point velocity in that direction, indicating a distance of at least 7.2 kpc (for a Galactocentric radius of 8.5 kpc). Emission without ab-

sorption is seen at velocities of 35–60 km s⁻¹, suggesting that 3C 391 is closer than 11.4 kpc (though the original authors used a Galactocentric radius of 10 kpc and obtained a distance range of 8.5–13.4 kpc). Aside from the low-frequency turnover, the spectrum is not unusual ($\alpha = -0.55$, where $S_\nu \propto \nu^\alpha$; Green 1988).

Wang & Seward (1984) describe x-ray emission detected by the IPC aboard the *Einstein Observatory*, showing a map with resolution of about 1'.5. They conclude that 3C 391 is a normal middle-aged remnant in the adiabatic stage of evolution, with an age of about 5300 yr, and interpret the x-ray morphology as indicative of a standard limb-brightened shell. We shall argue below that our new radio observations suggest a totally different picture relating x-ray and radio emission, which can be tested with further x-ray imaging observations and with molecular observations.

The radio morphology we observe suggests that the remnant is expanding into a region of greatly varying density. The presence of CO emission at the position of 3C 391 (Sanders *et al.* 1986) and at a velocity consistent with that of 3C 391, though possibly a coincidence in this confused region of the Galaxy, suggests that we contemplate the interesting possibility that 3C 391 is in fact the remnant of a supernova that occurred just inside a molecular cloud. If so, it would be quite unusual. While other associations between galactic supernova remnants (SNRs) and molecular clouds have been made based on positional coincidence (Huang & Thaddeus 1985, 1986), evidence for interaction of particular supernova remnants with molecular clouds remains fairly thin, except for a few well-studied

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²The Very Large Array is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

examples, and no remnant actually inside a cloud has been confirmed. The older remnant IC443 has been observed in many molecular species (e.g., Wang & Scoville 1992; Turner & Lubowich 1991; Ziurys *et al.* 1989; etc.). Several remnants have been observed in CO (CTB 109 [G109.1–1.0], Tatematsu *et al.* 1990a; HB 21, Tatematsu *et al.* 1990b; Puppis A, Dubner & Arnal 1988) and in shocked OH (G33.6+0.1 and G84.2–0.8; Green 1989); and the Cygnus Loop has been observed in shocked H₂ (Graham *et al.* 1991). More examples will clearly aid the study of SN environments and of shocked molecular chemistry. The possibility that 3C 391 may fall in this class should motivate some observational attention.

2. OBSERVATIONS

We observed 3C 391 at various times during 1988–1991 with the Very Large Array in all four configurations at 333, 1446, and 4865 MHz. The multiwavelength information and polarimetry are described elsewhere (Moffett 1990; Moffett & Reynolds, in preparation); here we describe the best total-intensity image, that at 1446 MHz, using the B, C, and D configurations (projected antenna spacings from 25 m to 9.7 km). We detected all the single-dish flux of the remnant on the shortest baselines; in fact, we obtained 23.5 Jy as our best estimate of the flux of the remnant at 1443 MHz. (Less than 1 Jy of this can be attributed to background sources in the field.) The resolution obtained was 6", after a moderate Gaussian taper (correlated amplitudes decreased by 1/*e* at baselines of 8.3 km) was applied to the visibility data, to decrease sidelobes and improve the beam shape for deconvolution. Standard calibration, mapping, and deconvolution procedures were used to obtain the image shown in Fig. 1. (Plate 102) The AIPS task MX (using the CLEAN algorithm; Clark 1980) was used for the deconvolution, though we also deconvolved the image using the maximum-entropy task VTESS to check for consistency of features. All significant structures visible in Fig. 1 were also reproduced by the maximum entropy deconvolution and are quite reliable.

Above an intensity level of about 8 mJy/beam the remnant shows a very regular shell structure. About two thirds of a quite round shell is apparent, with diameter about 5 arcmin and thickness of order 1 arcmin. The intensity along the shell ridge line is fairly uniform, except where it drops rapidly as the shell vanishes to the SE, and where it rises rapidly in the bright NW "filament." However, at lower flux levels, the shell is seen to sit on a much larger, faint, fairly uniform plateau extending mainly to the SE but also protruding to the west beyond the brightest, most bounded portion of the shell, in an interesting loop-like structure. This plateau brings the maximum angular extent of the remnant along the NW–SE axis to about 8 arcmin, considerably larger than previously thought. A well-defined step in intensity can be observed across the open mouth of the shell; in the shell interior, faint linear filamentary structure can be made out. The bright NW filament of the shell reaches intensity levels of about 80 mJy/beam (about 1.6 mJy/arcsec²), comparable to the peak

intensity of Tycho's remnant (Dickel *et al.* 1991). The flux of the shell alone is about 16 Jy, neglecting any contribution of the fainter plateau beneath. Considered alone, the shell would have a mean surface brightness of 1.6 Jy/arcmin², which would put it in ninth place among Galactic shell supernova remnants.

3. DISCUSSION

The radio morphology of 3C 391 can be separated into two components: the fairly normal-looking bright shell, and the faint extension to the SE. We first find that the discovery of this faint extension considerably improves the correspondence between the radio and x-ray (Wang & Seward 1984) images. Figure 2 (Plate 103) shows the *Einstein* image as greyscale superposed on a contour representation of the radio emission. The x-ray peak in fact lies over the fainter radio extension, a fact we interpret below. The strong gradient in radio brightness around the shell, from its peak to the NW to its disappearance directly opposite, can be well reproduced by models invoking a substantial density gradient, density increasing along the SE to NW axis (Reynolds & Fulbright 1990). Figure 1 indicates that at least an order of magnitude in intensity separates the brightest portion of the shell from the intensity opposite. In fact a gradient in ambient magnetic field alone can also reproduce this morphology, but requires that the external magnetic field increase by almost an order of magnitude over only 10 pc or so, which seems somewhat implausible.

The dominant feature of the overall morphology of 3C 391 is the strong contrast between the brighter (NW) and much fainter (SE) halves of the radio emission. We suggest that 3C 391 resulted from a supernova explosion at the center of the circular portion of the shell, approximate position (1950) (RA, δ) = (18^h46^m48^s, –00°59'). We hypothesize that the remnant expanded into a roughly uniform, relatively dense medium (the "cloud") until the SE edge met a sharp drop in the external density. The considerably lower radio surface brightness in the southeast supports the idea of a lower ambient density, which might be expected to mean both a smaller ambient magnetic-field strength and lower immediate post-shock pressure ρv_s^2 , which may mean less efficient shock acceleration of electrons. If we adopt an intermediate distance estimate of 9 kpc, 1' = 2.6 pc, so the shell radius is about 6.4 pc now. The open "jaw" of the shell defines a chord approaching within about 1' (2.6 pc) of the putative explosion center, in projection; we shall take that distance to be the depth inside the cloud at which the explosion took place. We assume for the time being that the object is cylindrically symmetric about a SE–NW axis lying in the plane of the sky; the image certainly seems roughly consistent with this assumption. The maximum extent of emission to the NW of the putative explosion center is about 2.5', including the faint plateau; that in the other direction, about 5.5', or 7 and 14 pc, respectively. If a "breakout" occurred when the explosion reached a sharp density drop at 2.6 pc from the explosion center, since that time the shell, in the higher-

density region, has expanded an additional 4 pc, while the breakout has traveled 11 pc, three times as far.

While the scenario laid out so far is speculative, it can aid in the interpretation of several puzzling features of 3C 391. The observations of Wang & Seward (1984) indicated an absorbing column density of $2.3 \times 10^{22} \text{ cm}^{-2}$, considerably higher than the $6 \times 10^{21} \text{ cm}^{-2}$ indicated by H I observations (Caswell *et al.* 1971). The IPC instrument on the *Einstein Observatory* has limited spectral response, so the x-ray value is somewhat uncertain; but the difference between these two results could also be due to part of the remnant being behind a much greater depth of molecular hydrogen than the rest. Since the photoionization cross section for H_2 at 1 keV, per H atom, is about eight times that for atomic hydrogen (Brown & Gould 1970), to supply the equivalent of the extra $N_{\text{H}} = 1.7 \times 10^{22} \text{ cm}^{-2}$, one would need only $N(\text{H}_2) \sim 1 \times 10^{21} \text{ molecules cm}^{-2}$, or a density $n(\text{H}_2) \sim 300 l_{\text{pc}}^{-1}$, where l_{pc} is the depth in pc of the molecular layer. For the simple geometry outlined here, this layer would obscure only the NW half of the remnant; but the total x-ray spectrum would reflect a larger column density for photoabsorption than would be seen in H I observations.

Additional evidence for such an increase in x-ray absorption for the “buried” half of the remnant comes from the x-ray morphology. Figure 2 shows that, as mentioned above, the x-ray morphology poorly reflects the radio; the two peaks are in the interior of the radio image, and the brighter one coincides with the faint SE extension of the remnant, so that the ratio of x-ray-to-radio brightness varies by an order of magnitude across the remnant. Significant extra photoabsorption in front of the shell could plausibly hide what would otherwise be a simpler x-ray structure, with a maximum in the region of the shell interior. (If the shell has become cool and dense, it could contribute “limb darkening” to the x-ray structure, particularly in the westernmost part of the shell.) The relatively low column density may indicate that the remnant is near the front edge of the cloud as well; the faint extensions of synchrotron emission beyond the well-defined shell might then be material expanding into a much lower-density region toward us, seen in projection in front of the shell inside the denser cloud. If this is true, the total column depth through the cloud on the near side would be expected to be of order the remnant radius of a few pc, implying a mean molecular density of order 100 cm^{-3} . This is low for a molecular cloud, but perhaps reasonable for the mean density in the outermost few pc of a cloud. We note that this hypothesis requires molecular hydrogen, not just denser atomic hydrogen, in front of part of the remnant. Furthermore, we cannot exclude an inhomogeneous distribution of H_2 in front of 3C 391, with denser regions absorbing virtually all of the *Einstein* band x-rays, leaving only the observed x-ray morphology preferentially indicating regions of the lowest molecular density.

Given this suggestion of the presence of molecular gas, we consulted the CO survey of the first galactic quadrant made with the FCRAO 14 m telescope (Sanders *et al.* 1986), which reveals at the position of 3C 391 fairly ex-

tensive emission at a velocity of $90\text{--}110 \text{ km s}^{-1}$, consistent with velocities in H I absorption seen against 3C 391 (Caswell 1971; Radhakrishnan *et al.* 1972). That is, if 3C 391 is in the nearer half of the allowed distance interval, it could be at the same distance as the observed CO. The CO emission is to the NW of the position of the remnant, where denser gas is expected according to the above scenario, with a steep gradient in the required sense; the lowest contour of CO emission cuts directly across the middle of 3C 391. Thus the currently available CO observations allow the possibility that 3C 391 has in fact been expanding into molecular gas and has recently broken out. The NW edge of 3C 391 runs almost exactly parallel to the galactic plane, at a galactic latitude of $00^\circ 04'$. At that location Sanders *et al.* (1986) report antenna temperatures of about 4 K over a range of about 10 km s^{-1} centered on a velocity of 100 km s^{-1} . These values imply a total estimated column density $N(\text{H}) \equiv N(\text{H I}) + 2N(\text{H}_2) \sim 3 \times 10^{22} \text{ cm}^{-2}$, consistent with the estimates above, using the calibration of Scoville *et al.* (1987): $N(\text{H}_2) \sim 4 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$. Of course, the presence of large amounts of CO in the galactic plane in the first quadrant near the tangent point (the “molecular ring”) means that more evidence than simple spatial coincidence is necessary to claim interaction, though the additional velocity information raises the likelihood that this is the case. We note that the FCRAO survey sampled on a $3'$ grid, with a beamwidth of $45''$, so that fully sampled observations may help confirm, or exclude, a physical association. As far as we know, no other CO observations in this direction have been published, and this remnant has not been previously searched for CO.

If we assume that the well-defined radio shell marks the main SNR blast wave moving into a much denser medium, and attribute the faint emission beyond it in the NW to projection effects as discussed above, we can estimate the remnant age from Sedov relations. This portion of the discussion does not require that the denser gas we hypothesize be molecular. We obtain

$$t = 17\,000 \left(\frac{R}{6.4 \text{ pc}} \right)^{5/2} E_{51}^{-1} \left(\frac{n}{100 \text{ cm}^{-3}} \right)^{1/2} \text{ yr},$$

where n is the effective density of H I [$n = 2n(\text{H}_2)$] in the cloud, and E_{51} is the supernova explosion energy in units of 10^{51} erg . The actual age is likely to be larger than this, since the “blowout” into the lower-density region can be expected to decrease the interior pressure and slow the expansion. The remnant would have reached the cloud edge, at $R = 2.6 \text{ pc}$, after only 1600 yr, so that the “blowout” is almost as old as the shell. The current blast-wave velocity corresponding to the above age estimate is

$$v_s = 0.4R/t$$

$$= 150 \left(\frac{R}{6.4 \text{ pc}} \right)^{-3/2} E_{51} \left(\frac{n}{100 \text{ cm}^{-3}} \right)^{-1/2} \text{ km s}^{-1},$$

and may again be an overestimate. We guess that a factor of three uncertainty in the above estimate is reasonable, implying a velocity somewhere in the range of $50\text{--}500$

km s^{-1} . Thus the remnant may be dominantly in the radiative phase (which begins when shock velocities drop to about 200 km s^{-1} ; Woltjer 1972). Even if the overall blast wave velocity is above 200 km s^{-1} , regions of somewhat higher density run over by the shock would currently be radiative. The shock velocity in the “blowout” region would be expected to be about three times as large, then, or $150\text{--}1500 \text{ km s}^{-1}$. A crude guide to the density contrast inside and outside the cloud can be obtained by assuming that the relative sizes of shell and “blowout” reflect only differences in the external density, as if they were independent Sedov blast waves with the same age. Then, since for the same age $n \propto R^5$, and taking the blowout “radius” to be the distance to the chord across the shell “jaw” of about 11 pc, we find $n(\text{in})/n(\text{out}) \sim 15$. This is probably an overestimate, since the interior pressure where the shell meets the “blowout,” at the cloud edge, will be smaller than the Sedov pressure for the shell, but larger than the Sedov pressure for a sphere with the radius of the “blowout.”

Hydrodynamic simulations of a supernova just inside a dense cloud were performed by Tenorio-Tagle *et al.* (1985), for explosion energies of 10^{51} erg in a cloud of density $10^3 \text{ H atoms cm}^{-3}$, varying distances from a region of density 1 H atom cm^{-3} , with and without cooling. They plot contours of density at various times for each simulation. Given the reasonable assumption that radio emission fills the much lower-density cavities inside and outside the cloud, our image of 3C 391 bears considerable resemblance to several of their models. Both adiabatic and cooling models can produce morphologies resembling 3C 391, apparently; the adiabatic model Z-5 (outburst 5 pc inside a plane-bounded molecular cloud) for ages between 1.2×10^5 and 2.6×10^5 yr has outer density contours resembling the outer synchrotron boundary of our image. We might expect electrons to be accelerated at strong shock waves, which occur at the strongest density gradients in the simulations; thereafter, the energy densities in both relativistic electrons and magnetic field should track the thermal gas density to some power near 1. Thus it is reasonable to expect a strong resemblance between contours of gas density and of synchrotron brightness. A rarefaction wave moves into the cloud as the breakout proceeds; we note that our image of 3C 391 shows a faint but distinct step in synchrotron brightness across the open end of the shell, significantly inside the chord of the “jaw” taken to indicate the cloud edge. This structure might be identified as the density drop due to that rarefaction.

Clearly, the first step in searching for firmer evidence of interaction of 3C 391 with the observed molecular gas will be fully sampled ^{12}CO , ^{13}CO , and perhaps C^{18}O mapping of 3C 391 and its immediate environs. Purely morphological evidence of interaction may not be very convincing, however. Shock velocities above $50\text{--}55 \text{ km s}^{-1}$ are expected to dissociate all molecules (McKee & Hollenbach

1980), but it is possible that the shock velocities in 3C 391 are this low, and shocked molecular emission should definitely be searched for, either in the form of high-velocity CO, or high-excitation transitions such as the infrared lines of shocked H_2 . Even if the shock is totally dissociative, it may be radiative, so that high-velocity molecular gas formed in the post-shock cooling flow may be observable. If further study of the molecular cloud emission supports an interaction with 3C 391, such observations hold the prospect of learning directly about the material outside the SNR shell. A column density of $2 \times 10^{22} \text{ cm}^{-2}$ implies an optical extinction A_V of about 10^m (Bohlin *et al.* 1978). Detailed study of this CO emission and emission from other molecules could then provide important information on the interaction of SNRs with dense molecular clouds, on the nature of the molecular environment of supernovae, and on the chemistry of these environments.

Our scenario also makes predictions for x-ray studies of 3C 391. X-ray spectral observations with arcminute resolution should find a gradient in n_{H} , as discussed; at high energies, the faintness and absence of limb-brightening in the “breakout” portion of the remnant might indicate lack of a strong shock, and a higher x-ray temperature in the shell region. The infrared emission (Arendt 1989) plausibly associated with 3C 391 might also give information on the interaction of the remnant with its surroundings. If properties of the immediate molecular environment can be plausibly deduced from CO observations, the observed synchrotron brightness contrast between the high and low density environments can provide useful information on shock acceleration of electrons in SNRs.

We feel that the radio morphology of 3C 391, and the spatial coincidence with CO in the appropriate velocity range, make 3C 391 a strong candidate for further study for confirming evidence of interaction with molecular gas. The supporting evidence we have set out for this picture, the difference between x-ray and radio absorption column densities, the x-ray morphology, and the resemblance of the synchrotron images to model calculations, is far from conclusive, but adds weight to the idea that further observations of 3C 391 may be very productive. We note that certain portions of this picture, the radio morphology and its resemblance to theoretical calculations, require only a strong density contrast in surrounding material, while the absorption column discrepancy specifically requires molecular gas covering part of the remnant. Though this region of the galactic plane is complex and confused, efforts to unravel the environment of 3C 391 could help our understanding of supernova remnants as probes of the interstellar medium.

We would like to thank H. Liszt, B. Turner, and J. Black for helpful discussions. S.P.R. acknowledges support from NSF and NASA.

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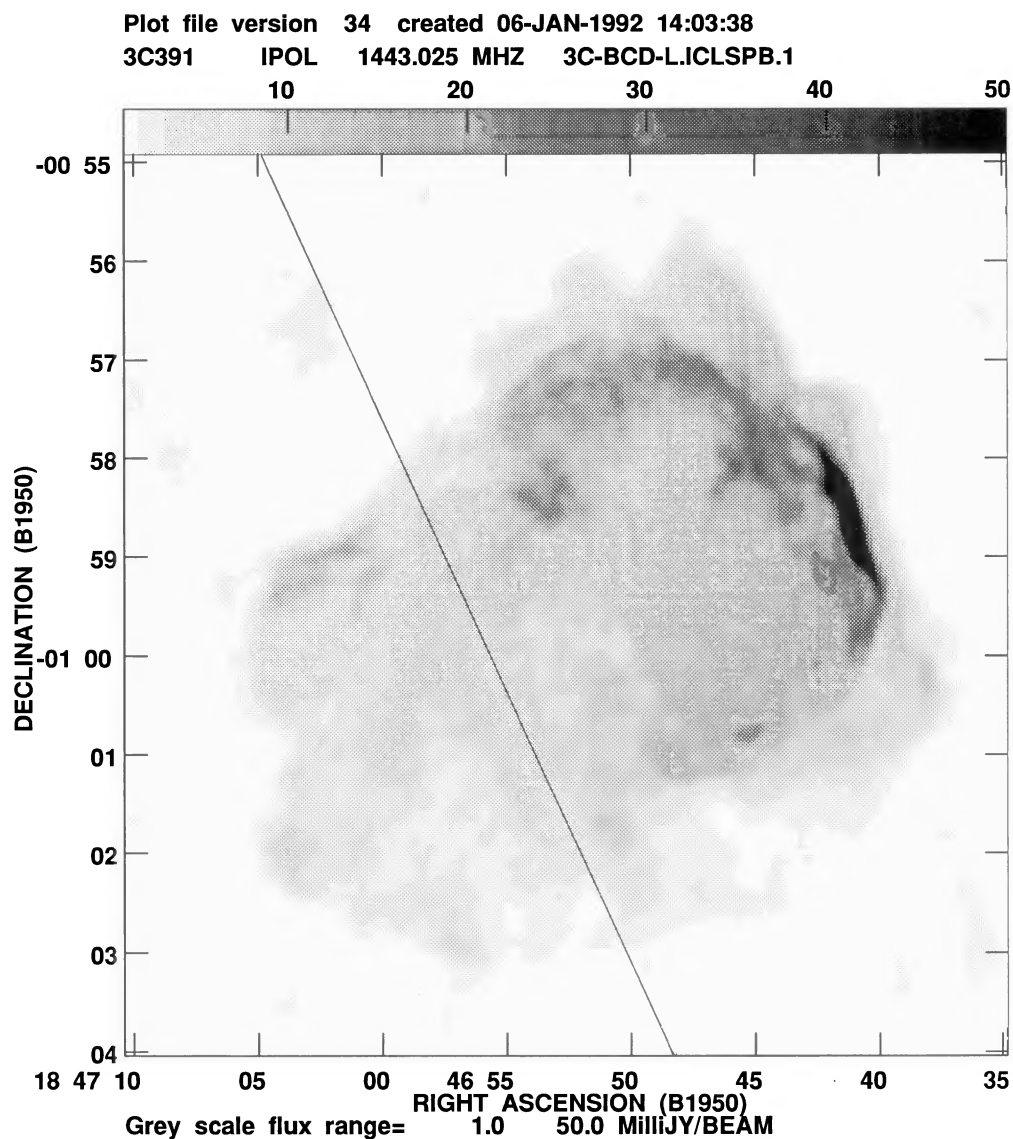


FIG. 1. 1446 MHz image of 3C 391, with a resolution of 6". The noise level (map rms away from sources) is 0.7 mJy/beam. The galactic plane is indicated.

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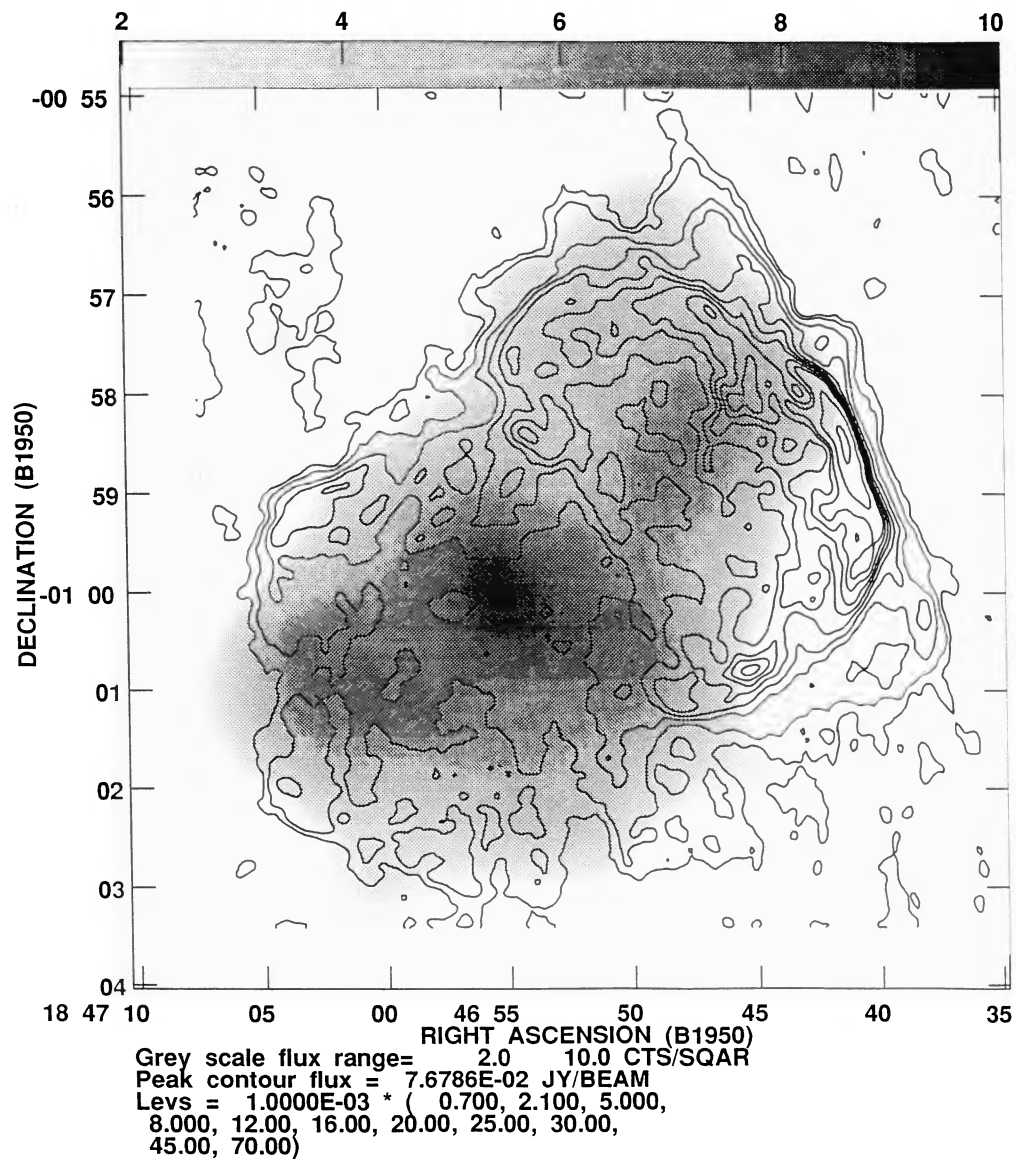


FIG. 2. X-ray greyscale image from the IPC instrument,² angular resolution about 1'.5, superposed on a contoured version of Fig. 1. (The full-resolution radio map has been used for clarity. For the numerical x-ray/radio brightness ratios mentioned in the text, the radio map was convolved to the same resolution as the x-ray map.)

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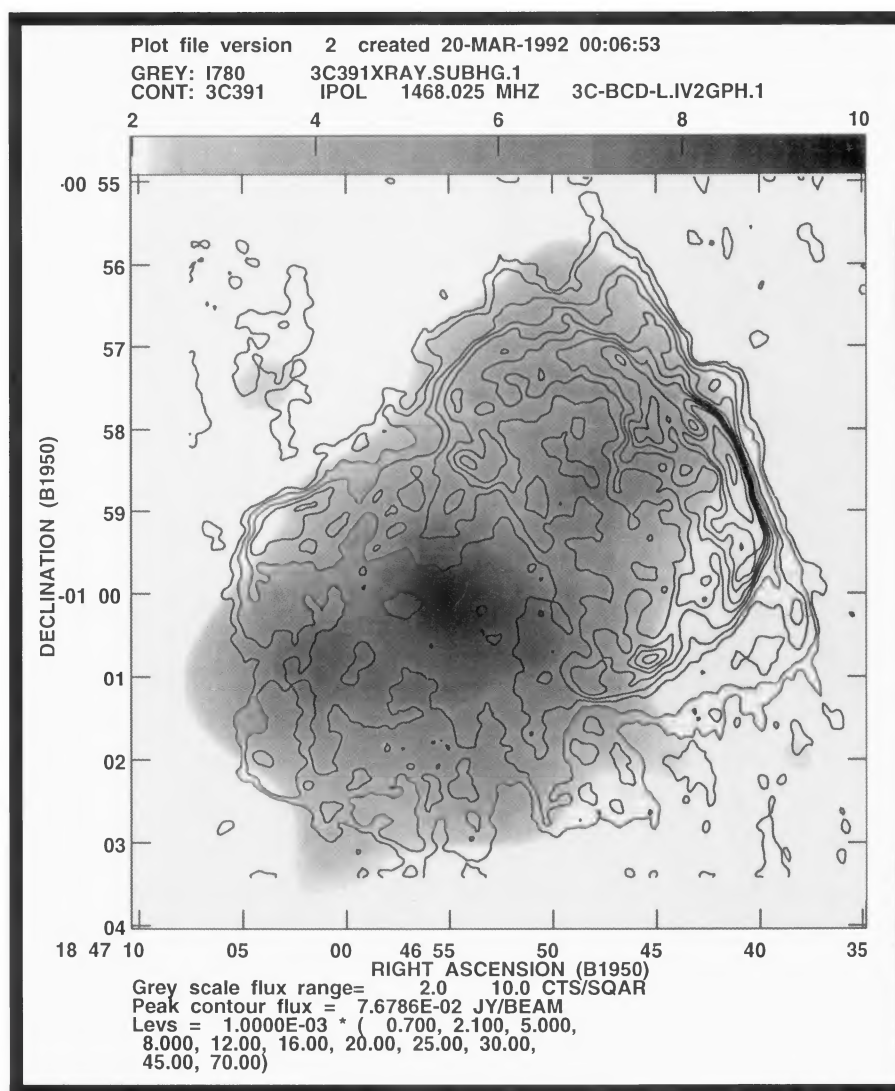
JUN 01 1993

VOLUME 105

June 1993 ~ No. 1649

HARTFORD, CONN.

NUMBER 6



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Published for the
AMERICAN ASTRONOMICAL SOCIETY
 by the

AMERICAN INSTITUTE OF PHYSICS

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