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3C391**

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ROSAT PSPC OBSERVATION OF THE SUPERNOVA REMNANT 3C391

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Received 1995 March 3 Accepted 1996 March 1

ABSTRACT

The supernova remnant 3C391 (G31.9+0.0) was observed using the ROSAT PSPC. The PSPC image reveals centrally concentrated X-ray emission inside the radio shell, anticorrelated with the radio image. The northwestern half of the remnant has a strong radio shell and weak, centrally concentrated X-ray emission. In contrast, the southeastern half has strong central X-ray emission and weak radio emission. A spectral analysis combining PSPC and *Einstein* IPC data indicates that the X-ray emission arises from a thermal plasma that has not attained ionization equilibrium, though a non-thermal model can be rejected only with 90 percent confidence. There is evidence, at the 90% confidence level, of enhanced abundances of the intermediate α burning elements, Mg, Si, and S. The best fit N_H is $2.4 \times 10^{22} \text{ cm}^{-2}$ and kT is 0.5 keV ($T = 5.9 \times 10^6 \text{ K}$). The centrally concentrated morphology and the probable thermal origin of the X-ray emission along with the radio shell suggest 3C391 is similar to W44 and W28.

There are spectral variations between the northwestern and southeastern parts of the remnant: either the northwest has higher N_H or the southeastern part has lower temperature, the former being more consistent with the X-ray morphology. The difference in N_H is large enough to account for the reduced X-ray surface brightness in the northwest, and the density in the northwest is higher than in the southeastern shell. The X-ray data are consistent with the idea that the progenitor supernova has exploded just inside a molecular cloud but close to the edge. The northwestern structure is created by the propagation of the SN shock into the cloud, while the enhanced central X-ray emission arises from evaporation of clumps from the edge of the cloud trapped within the SNR. The southeastern radio and X-ray emission represent a "breakout" of the shock into low density, intercloud material.

Subject headings: ISM: individual (3C391) - shock waves - Supernova remnants - X-rays: ISM

1. Introduction

3C391 (G31.9+0.0) is one of the brightest supernova remnants in the radio (radio flux density ~ 20 Jy at 1446 MHz; Green 1988) while only moderately bright in X-rays. The radio observations (Becker & Kundu 1976; Goss *et al.* 1979; Reynolds & Moffett 1993, RM93 hereafter) have revealed a shell-like structure. The VLA high resolution (6'') radio map (RM93) resolved the remnant into two distinct regions. While the northwestern shell is bright and well defined, no shell has formed in the southeast. In addition, there are both a distinct brightness reduction and an elongation of the remnant from the northwest to southeast. RM93 interpret these as indicative of a breakout, which is due to expansion into a medium with a very strong density gradient. The radio spectrum is nonthermal, with index $\alpha = 0.55$, where $S(\nu) \propto \nu^{-\alpha}$ (Goss *et al.* 1979). No spectral index variation has been found across the remnant (Moffett & Reynolds 1994). Recombination lines have been detected in the direction of 3C391 and the low frequency turnover suggests the presence of an H II region in the line of sight. The distance to 3C391 is 7.2 -11.4 kpc (RM93); we have adopted 9 kpc, an intermediate value, for this work.

In the X-ray band, the *Einstein* IPC image (Wang & Seward 1984) is interpreted as showing a limb-brightened morphology, as in the radio, but with the X-ray peak displaced from the radio. Wang and Seward (1984) suggested that 3C391 is a middle aged SNR (5300 yrs) in the adiabatic phase.

While shell-like and Crab-like (plerions) SNR are commonly known and well studied, there is a recently identified category of remnants, called "composite" remnants, which fall morphologically between the shell-like and Crab-like SNR. While some transition objects simultaneously show central emission from a pulsar and a shell either in X-ray or radio (such as Vela and Kes 75), this category consists primarily of SNR for which the X-ray emission is brightest at the center and the radio morphology is shell-like. Members of this class are W44, W28 and 3C400.2. The existing X-ray spectral evidence suggests that the X-ray

emission is thermal and the center-filled X-ray morphology arises from the evaporation of clouds in the remnant interior (Long *et al.* 1991; Seward 1985; Rho *et al.* 1994). In this paper, we report on the basis of a ROSAT PSPC observation that 3C391 has a centrally concentrated X-ray morphology, rather than a limb brightened, shell-like one. 3C391 thus is probably a member of this composite SNR class. We present the PSPC X-ray image, as well as the results of mapping of the column density and temperature, from which spectral variations across the remnant have been found. The X-ray image and spectral properties support the existence of a breakout to the southeast from a dense region associated with a molecular cloud in which the progenitor exploded.

This paper is organized as follows. In Section 2, we describe the PSPC observation. In Section 3, we present the X-ray image of 3C391, compare it with the radio map, and describe the analysis of the X-ray spectra. In Section 4, we discuss the inferred X-ray properties of 3C391 and the evolution of the remnant in an inhomogeneous medium. We also propose a scenario that can account for the X-ray properties, involving a SN explosion at the edge of a molecular cloud plus evaporation of cloudlets within the SNR interior.

2. Observations

3C391 was observed using the X-ray telescope on ROSAT with the Position Sensitive Proportional Counter (PSPC). The observation took place during Oct. 8-12, 1992; the net exposure time is 23,839 sec. The data presented here have been extracted from the ROSAT archive. This object happens to be in the field of another observation (sequence 900402). The pointing position was R.A. $18^h49^m43.2^s$ and Dec. $-0^\circ 49'48.00''$ (J2000). The remnant 3C391 appeared $8'$ away from the pointing center. The entire remnant ($\sim 8'$ diameter) is contained within the central, most sensitive region of the PSPC. The PSPC image is presented in epoch 2000 coordinates in Figs. 1 and 4; when it is compared with other images, it is precessed to epoch 1950. The PSPC response function has been corrected for vignetting, dependent on the location in the detector, and thus the spectrum from each region required a slightly different response function for the spectral fitting. We also used data from the *Einstein* IPC to cover the higher 2-4 keV energy band invisible to *ROSAT*.

The X-ray image data were reduced primarily using the Post-Reduction Off-line Software (PROS) in IRAF, supplemented by IDL has also been used. The X-ray spectra were fitted using XSPEC (Shafer *et al.* 1989).

3. Results

3.1. PSPC X-ray image

The smoothed PSPC image in Fig. 1 shows that X-ray emission is centrally concentrated. The deep *ROSAT* exposure has facilitated the first detection of diffuse emission in the southwest. The remnant thus shows a roughly circular shape. The highest surface brightness, concentrated in the center of the remnant, appears bar-like, running from east to west with approximate angular size $3' \times 1.6'$. The background-subtracted

PSPC count rate for all of 3C391 was 0.186 ± 0.004 cts s^{-1} , which can be compared with the *Einstein* IPC rate of 0.24 ± 0.03 cts s^{-1} . The central ellipse where most of the X-ray emission is concentrated has a surface brightness of 0.01 counts s^{-1} arcmin $^{-2}$; the average surface brightness excluding the central area is 0.0031 counts s^{-1} arcmin $^{-2}$. No X-ray flux below 0.5 keV has been detected, due to high column density in the line of sight.

The PSPC image is superposed on the high resolution radio map (RM93) in Fig. 2. The radio map shows a shell-like morphology, with a strong surface brightness gradient along the shell from the northwest to the southeast. The X-ray emission is sharply anticorrelated with the radio emission: the centrally peaked X-ray morphology contrasts strongly with the shell-like radio morphology. The X-ray emission is mostly confined within the radio shell.

To show more clearly the morphology difference between the radio and X-ray maps, we compare the X-ray and radio surface brightness profiles. We choose the X-ray center ($\alpha = 18^h 46^m 55^s$, $\delta = -01^\circ 00'$ (B1950) in Fig. 2) as the center for this analysis; this is also approximately the geometric center of the remnant. We divided the remnant into 4 sectors based on their different appearance in radio and X-ray images (see Fig. 2): NW, covering azimuth angles between $0^\circ - 75^\circ$ (where 0° is north, and azimuth increases clockwise); SW, covering $75^\circ - 180^\circ$; SE, covering $180^\circ - 310^\circ$; and NE, covering $310^\circ - 360^\circ$. The brightness profiles are shown in Fig. 3. All four X-ray profiles peak at the center, while the radio profiles show a shell in all but the southeast, where a shell has apparently not formed.

A spectral hardness ratio (SHR) map, defined here as the ratio of a high energy band map to a low energy band map, can reveal spectral variations due to absorption and/or temperature. A high SHR value indicates a locally high column density or temperature. We have created a PSPC hardness map, corresponding to the ratio between channels 151-250 (~ 1.5 - 2.2 keV) and 50-150 (~ 0.5 - 1.5 keV). The reason that we choose the energy boundary of 1.5 keV is that the spectral peak appears at this energy (see Fig. 6) and thus approximately equal numbers of counts will be contained in the two maps whose ratio yields the SHR. The hardness ratio map is shown in Fig. 4 superposed on the PSPC surface

brightness contours. The SHR anticorrelates with the surface brightness, with the hardest emission near the bright northwestern radio shell. This suggests that the surface brightness variation is produced at least partially by a column density gradient towards the northeast. In order to explore this possibility, as well as alternatives, we use the hardness map when defining regions for spectral fitting, as described in the next section.

3.2. Spectral Observations

3.2.1. Entire Remnant

We have extracted PSPC and IPC spectra from the entire SNR, and PSPC spectra from the three regions indicated in Fig. 5. For the entire SNR, we performed fits to both the PSPC spectrum alone, jointly to the PSPC and IPC spectra. The spectra were fit using a coronal plasma model (Raymond & Smith 1977), a power law, and a time-dependent ionization (NEI) model (Hamilton, Sarazin, & Chevalier 1983, HSC hereafter). The best fit results are summarized in Table 1. The power law model provides the poorest fit to both data sets. A Raymond-Smith model with metal abundances fixed at solar provides a better fit, but one that is not formally acceptable. The fit is improved if the abundances of Mg, Si, and S are allowed to vary jointly. The best fit is obtained for both the PSPC alone and for the PSPC/IPC using an NEI model with Mg, Si, and S varying together. Addition of a second thermal component does not improve the fits. A description of the application of the Hamilton *et al.* models to PSPC data and the limitations on their use can be found in Rho *et al.* (1994).

The NEI fit to both data sets and the Raymond-Smith fit to the joint data are all formally acceptable. On the other hand, the power law model can be rejected with 90% confidence, but not rejected with 99% confidence (Bevington & Robinson 1969). Thus the interpretation of the spectrum as thermal is preferred, but not required. However, an *ASCA*

observation has detected line emission from this remnant (Tsunemi 1994), supporting our inference that the emission is predominantly thermal. The predominance of thermal emission indicates that 3C391 is similar to W44 and W28, not only possessing a center-filled X-ray morphology with a shell-like radio morphology, but also X-ray emission of thermal origin.

The best fit NEI model has $T = 10^{6.75}$ K and $N_H = 2.3 \times 10^{22} \text{ cm}^{-2}$; for the Raymond-Smith fit we find comparable values of the temperature and column density. The abundance of the intermediate α burning elements is larger than solar at the 90% confidence level in both thermal models. For the NEI model, best fit value of the ionization time scale τ is $1.4 \times 10^4 \text{ cm}^{-3} \text{ yr}$. This indicates that the X-ray emitting gas is near ionization equilibrium and explains the comparable results for the NEI and equilibrium fits. Given the similarity between these models, we can confidently perform our spectral mapping using a Raymond-Smith model with the expectation that the inferred parameter values are realistic.

3.2.2. Spectral Mapping

To study variations of temperature and column density across the remnant, we divided the PSPC image into three regions as shown in Fig. 5: region A in the northwest, where the X-rays are hardest; region B, representing the X-ray peak; and region C, comprising the remainder of the southeast. We use as a boundary between region A and the others the northeast-southwest line where the radio surface brightness varies abruptly (see Fig. 2). Since the IPC observation contains too few counts to split the data into subregions, they were not incorporated into the spatially resolved spectral fits. We have fit the spectra using a single-temperature Raymond-Smith model. As the inferred abundances for the entire remnant are only marginally inconsistent with solar, we chose to fix them at solar for this analysis. The best fit results for each region are listed in Table 2.

As suggested by the SHR map, there are spectral variations between the northwestern

and southeastern parts of the remnant. Fig. 6a shows the spectra of regions A (the northwest) and B (the southeast interior). The energies where the spectra peak are different, which is an indication of either different column density or different temperature. The fit results for the three regions are listed in the top half of Table 2, and the confidence contours for regions A and B are compared in Fig. 6b. The 90 percent confidence regions do not overlap, and the allowed ranges are more suggestive of a column density variation than a temperature difference. In the bottom half of Table 2, we show the fit results obtained from fixing kT at 0.5 keV, and from fixing N_H at $2.4 \times 10^{22} \text{ cm}^{-2}$, the best fit values from the PSPC/IPC fitting. These show that either a temperature or column density difference is allowed spectrally. While the anticorrelation between spectral hardness and surface brightness indicate that column density variations are the more likely case, we cannot rule out the alternative possibility using existing data. Table 2 shows that the assumption of constant temperature across the remnant requires N_H variations. However, if instead we assume constant N_H , the temperatures at the northwest ($kT = 0.83^{+0.90}_{-0.21} \text{ keV}$) and the center ($kT = 0.49^{+0.15}_{-0.12} \text{ keV}$) are marginally consistent with each other.

We use the best fit values from the three regions (top part of Table 2) to interpret the results. The observed surface brightness in region A (the northwest) is comparable to that in region C (the southeast), and 2.6 times smaller than that in region B (the center). The corresponding unabsorbed surface brightness in the northwest is 5 times larger than that in the southeast, but only half that of the northwest. Thus the low northwestern surface brightness is the result of variable line of sight absorption, and the true surface brightness contrast between the northwest and the southeastern shell is similar to that in the radio. This lends support to the suggestion by RM93 that a molecular cloud is located at the same distance as the SNR, and interacting with it. If the high N_H in the northwest is due to the molecular cloud, then some of the molecular cloud material is in the line of sight to the remnant. We also infer a substantially higher emission measure (n^2L) in the northwest than in the southeastern shell (see Table 2), despite comparable lines of sight through the remnant. Whether the X-ray emitting gas fills the entire remnant or only a shell, the

density in the northwest is 2-3 times higher than the southeast. Thus there are two effects in 3C391 that must be explained: the higher average density in the northwest than in the southeast, and the high central surface brightness and density. We interpret the former in the context of an explosion just inside a molecular cloud, and the latter as evaporation of cloudlets embedded within the remnant.

4. Discussion

4.1. X-ray emitting gas

The physical parameters we estimate from the fit results using the Raymond-Smith model are listed in Table 3. The observed flux (0.5-2.4 keV) is $f_x = 3.9 \times 10^{-12}$ ergs s⁻¹ cm⁻². Correction for absorption yields an absolute flux $f_x^{corr} = 1.9 \times 10^{-10}$ ergs s⁻¹ cm⁻² and a 0.5-2.4 keV luminosity of $1.7_{-1.3}^{+5.9} \times 10^{36}$ erg s⁻¹, using 9 kpc as the distance to 3C391. If we assume the X-ray emission arises from a uniformly-filled sphere, then the electron density $n_e = 0.63$ cm⁻³, and the X-ray emitting mass $M_x \sim 74 M_\odot$.

We have also estimated the mass ratio of X-ray emitting gas and swept up mass (M_s) to compare with those of other middle-aged shell remnants such as Puppis A (Canizares & Winkler 1981) and IC 443 (Petre *et al.* 1988), where $M_x/M_s \sim 0.1$. If we assume an initially uniform density ISM, then the preshock density would have been $n_o \sim 0.2$ cm⁻³, and the total swept up mass M_s would be $20 M_\odot$. The high mass ratio of M_x/M_s (>1) for 3C391 is unphysical, indicating that a simple model of a uniform ISM is clearly inadequate to explain the amount of X-ray emitting material. As we discuss in section 4.4 below, an additional reservoir of material is probably supplied in the form of clouds within the SNR shell. The pressure in 3C391 is $\sim 2n_e T = 6-9 \times 10^6$ K cm⁻³, which is 2 orders of magnitude higher than that of the interstellar medium.

4.2. SN explosion at the edge of a molecular cloud

The radio morphology of 3C391 has been interpreted as evidence for a breakout of the shock into a region of abruptly lower density from a region with a density as high as 100 cm^{-3} (RM93). The higher density and N_H in the northwest inferred from the X-ray observation support this idea. Here we examine what the X-ray data can tell us about the environment in which 3C391 is located.

For a supernova exploding in a uniform density medium, we can express its temperature as a function of the initial explosion energy E_{51} (in units of 10^{51} ergs), the density of the ambient medium n_o (cm^{-3}), and the shock radius R_s (pc) using the following formula (Gorenstein & Tucker 1976):

$$T = 8 \times 10^9 \left(\frac{E_{51}}{n_o} \right) R_s^{-3} \text{ K}$$

If we use the observed shock radius 10_{-2}^{+3} pc , the canonical value of the energy E_{51} ($=1$), and the density $n_o \sim 100 \text{ cm}^{-3}$ suggested by RM93, we estimate $T \sim 2.5 \times 10^5 \text{ K}$. This is clearly inconsistent with the presence of any X-ray emission. The highest density of a uniform medium consistent with the X-ray data is $\sim 10 \text{ cm}^{-3}$, too low to reconcile with the radio results.

However, in practice, molecular clouds do not have uniform density distributions (Arquilla & Goldsmith 1985). The behavior of a supernova shock propagating through a cloud will depend on the density gradients it encounters. Self-similar solutions for an adiabatic blast wave propagating through a density gradient have been constructed by Wheeler *et al.* (1980) and Chevalier (1976). The preshock density profile assumed for the molecular cloud is $n(r) \propto r^{-\omega}$, where r is the radius of molecular cloud (see Fig. 7a). For $\omega = 2$ as expected for an isothermal, self-gravitating sphere, the shock radius (R_{sh}), temperature (T_{sh}), and velocity (V_{sh}), and the density of the swept up material (n_{sh}), can

be expressed in terms of the remnant energy (E_{51}), the mass of the ejecta (M_{eject}), the radius (R_o) and ambient density (n_o) at the end of the free expansion phase (Wheeler *et al.* 1980):

$$\begin{aligned} n_{sh} &= 4n_o \left(\frac{R_{sh}}{R_o} \right)^{-2} \text{ cm}^{-3} \\ R_{sh} &= 6.3 \times 10^{-3} E_{51}^{1/3} n_{4,0}^{-1/3} R_o^{-2/3} t^{2/3} \text{ pc} \\ T_{sh} &= 2.0 \times 10^6 E_{51} n_{4,0}^{-1} R_{sh}^{-1} R_o^{-2} \text{ K} \\ V_{sh} &= 4.0 \times 10^7 E_{51}^{1/2} n_{4,0}^{-1/2} R_{sh}^{-1/2} R_o^{-1} \text{ cm s}^{-1} \\ \text{where } R_o &= 0.3 (M_{\text{eject}}/100 M_\odot)^{1/3} n_{4,0}^{-1/3} \text{ pc} \end{aligned}$$

Here n_o expressed in units of 10^4 cm^{-3} as $n_{4,0}$. Because the calculation is sensitive to R_o , one should estimate the values with caution. We adopt $10 M_\odot$ as a reasonable canonical mass ejected by the supernova. The inferred parameter values are summarized in Table 4. We have chosen the density $n_o = 100$ (1000) cm^{-3} , which is low for a molecular cloud, but perhaps reasonable for the mean density in the outermost few pc (RM93). For $n_o = 100 \text{ cm}^{-3}$ (1000 cm^{-3}), R_o is 0.66 pc (0.33 pc), and E_{51} is 0.1 (0.22). The density n_{sh} is 1.6 (3.3) cm^{-3} , which is much more comparable to the density we obtained from the X-ray observation than 100 cm^{-3} . Using $R_{sh} = 10 \text{ pc}$, and the X-ray temperature $5.9 \times 10^6 \text{ K}$, we find $V_{sh} = 650$ (690) km s^{-1} , and τ_{sh} (the shock time $= R_{sh}/V_{sh}$) $= 1.64 \times 10^4$ (1.56×10^4) yrs. In this calculation, since the radius of the SNR is proportional to $t^{2/3}$, the age is $t = 2R_s/3v_s$, which is different from the Sedov value, $t = 2R_s/5v_s$. Therefore, the age of 1.2×10^4 (1.1×10^4) yrs is higher than the age estimated from Sedov or evaporation model (see Table 4 and the following section for detail). The consistency between the values inferred here and those measured using the X-ray data strongly suggests that the 3C391 progenitor exploded within a molecular cloud, but close to the edge. The CO survey with the FCRAO 14 m telescope (Sanders *et al.* 1986) reveals extensive emission at the position of 3C391 with a velocity of $90\text{-}110 \text{ km s}^{-1}$ and shows the CO emission is higher at the northwestern

position of 3C391 than that at the southeast. In addition, most recent CO mapping shows a pronounced surface brightness drop across the northwest/southeast line demarcating regions A and C (Wilner 1995), which indeed confirms the progenitor explosion of 3C391 at the edge of a molecular cloud.

If an appreciable fraction of all supernovae explode buried in molecular clouds, then the rate of such events within the Galaxy could be of the order of one per 100 yr. A supernova explosion within a molecular cloud may have important indirect consequences. Clouds or portions of clouds could be entirely disrupted by the momentum of the supernova, even if most of the energy is radiated away. Even if the cloud is too massive to be disrupted, such an internal source of kinetic energy may provide an important input to the cloud, extending its lifetime against dynamical collapse (Wheeler *et al.* 1980). 3C391 is one of a few examples where we observe the remnant of supernova which exploded within a molecular cloud.

4.3. Breakout morphology and center-filled X-ray emission

The existence of a breakout, suggested by the radio and X-ray morphologies, offers in itself no explanation for the centrally concentrated X-ray surface brightness. A smoothly varying density distribution is, however, an idealization of the boundary of a molecular cloud. Between the cloud itself and the intercloud medium is thought to exist a warm, partially-ionized boundary region (McKee & Ostriker 1977). More importantly for this discussion, the molecular cloud is thought to be clumpy, and small, dense clumps are expected to exist in the warm surrounding region and the nearby intercloud medium. All these clumps are thought to arise from the larger molecular gas structures (Gonzalez-Alfonso & Cernicharo 1994). In the Rosette Nebula, there are numerous small ($R \sim 0.01$ pc), teardrop-shaped globules which are aligned radially toward the star cluster (Herbig 1974). These globules are formed either through Rayleigh-Taylor instability or clumping in the ambient medium. Similar teardrop-shaped globules, with sizes 0.01-0.2

pc and masses $0.02\text{--}0.5\ M_{\odot}$, are observed in the bright background of some H II regions, normally surrounding large gas and dust condensations. The existence of these clumps complicates the interaction of a shock front with the surrounding medium, but offers a potential explanation for the central brightness of 3C 391.

We suggest the following scenario for the evolution of 3C391, illustrated in Fig. 7, which can account for all its observed X-ray morphological features. As shown in Fig. 7a, the progenitor star exploded within a molecular cloud, near its edge (RM93 proposed the explosion site is 2.5 pc inside the edge). The portion of the shock front propagating into the cloud encounters increasingly higher average density and decelerates, while the outwardly propagating portion encounters increasingly lower average density, and eventually breaks out into the intercloud medium (Fig. 7b). Density enhancements (clumps or cloudlets) encountered by the shock will either be dissipated or, if they are sufficiently large or dense, overrun and compressed by the shock (Klein, McKee & Colella 1994). These clumps, now embedded in a hot, tenuous medium, evaporate, increasing the density of X-ray emitting gas within the remnant (Fig. 7c). This scenario has been explored theoretically by White & Long (1991), and is thought to explain the centrally-filled X-ray morphologies of W44 (Rho *et al.* 1994), W28 and 3C400.2, among others.

The evaporation model (White & Long 1991) assumes that the clouds are numerous and that they have much higher density than the tenuous phase of the ISM (and thus a small filling factor). The value of C , the mass ratio between the clouds and the intercloud medium, should be high, about 100 (see WL for details). The range of τ , the ratio between the cloud evaporation time and the SNR age, becomes a crucial factor in creating a centrally peaked X-ray morphology: only when $\tau = 20 - 30$ is the X-ray morphology centrally peaked. Under these conditions the temperature distribution is more uniform than a Sedov SNR. Using $C/\tau = 3\text{--}5$, we can infer values for the intercloud density, remnant age and X-ray emitting gas mass. These are listed in Table 4. The intercloud density $n_f = 0.07\text{--}0.23\ \text{cm}^{-3}$, the age is 6000 - 7500 yr, and X-ray emitting mass is 85 - 95 $M_{\odot}$. Using the inferred values

of n_f and $C = 100$, we find that the total interclump mass swept up by the remnant is 8 - 27 $M_\odot$ and the clump mass is 800 - 2750 $M_\odot$. Therefore, the X-ray emitting mass is 3 - 11 percent of the swept-up mass, more consistent with results in other middle-aged remnants such as Puppis A (Canizares & Winkler 1981) and IC443 (Petre *et al.* 1988).

Since the intercloud density estimated in White & Long (1991) depends on Λ (the cooling coefficient), which in turn is a function of $n_e t$ (relaxation rate of ionization), we should consider the entire range of allowable $n_e t$, $1 - 10^5 \text{ yr cm}^{-3}$. If the remnant is in ionization equilibrium, the intercloud density can be as high as 0.6 cm^{-3} . The corresponding age estimate is 12,000 years, and the emitting mass becomes 250 $M_\odot$.

We have estimated the cloud size required for saturated conduction using the density and temperature of the X-ray emitting gas. Cowie & McKee (1977) define a saturation parameter σ_o , the ratio of the classical heat flux to the saturated heat flux, which allows a determination of whether the conduction is classical or saturated :

$$\sigma_o = \left(\frac{T}{1.54 \times 10^7 K} \right)^2 \left(\frac{1}{n_f r_{pc} \phi_s} \right)$$

where n_f is intercloud density (cm^{-3}), r_{pc} is cloud size (pc), and ϕ_s is saturated heat flux parameter (of order unity). For conduction to be saturated, the value of σ_o must be larger than 1. Using the values of T and n_f we have inferred for 3C391, saturated conduction requires cloud sizes smaller than 0.4 pc ($n_{ICM} = 0.23 \text{ cm}^{-3}$) or 1.3 pc ($n_{ICM} = 0.07 \text{ cm}^{-3}$), consistent with the evaporation model assumptions (White & Long 1991) that the clouds should be cold and dense, with a small filling factor.

While the PSPC spectra support the idea that the SN of 3C391 exploded at the edge of a molecular cloud with a large N_H variation across the remnant, it is important to confirm using high resolution spectroscopy ASCA data. In particular, the detailed analysis of the spectral variations in the northwestern and southeastern parts of the remnant will help us to understand SNR evolution in a medium with a density discontinuity, and the evolution

of X-ray center-filled remnants.

5. Summary

We report the results of the analysis of a 24 ks ROSAT PSPC observation of the supernova remnant 3C391 (G31.9+0.0).

1. The PSPC image reveals centrally concentrated X-ray emission inside the radio shell. The X-ray surface brightness is anticorrelated with the radio. The northwestern half of the remnant has a radio shell and weak central X-ray emission. In contrast, the southeastern half has strong central X-ray emission and weak radio emission.

2. A spectral analysis combining PSPC and *Einstein* IPC data indicates that the X-ray emission arises from a thermal plasma that has not attained ionization equilibrium, though a non-thermal model can be rejected only with 90 percent confidence. A single temperature thermal model gives the fit parameters $N_H = 2.4 \times 10^{22} \text{ cm}^{-2}$ and $kT = 0.5 \text{ keV}$ with enhanced abundances of Mg, Si and S, using either PSPC data alone or jointly with the *Einstein* IPC data.

3. There are spectral variations between the northwestern and southeastern parts of the remnant: either the northwestern part has higher N_H or the southeastern part has lower temperature. The PSPC spectra indicate the former to be more likely, and the difference in N_H is large enough to state that the low X-ray surface brightness in the northwest is due primarily to absorption. The higher N_H at the northwest is consistent with the results of CO observations.

4. The higher N_H toward the northwest and the higher density at the northwestern part inside the remnant suggest that the progenitor of 3C391 exploded near the edge of a molecular cloud and subsequently the shock broke out into the lower density intercloud medium. This is consistent with the distinct breakout morphology in the radio map.

Evaporation of small clouds left behind the shock could then be responsible for the centrally concentrated X-ray emission. Thus the X-ray morphology of 3C391 is the result of the combination of two very different effects.

Acknowledgements

The authors would like to thank S. P. Reynolds for providing the radio image and helpful discussions, H. Tsunemi and D. Wilne for sharing ASCA results and the CO observation, respectively, on 3C391 before publication. We are grateful to the people who have made the ROSAT mission successful.

Table 1: Spectral fit results for 3C391

data	Model	χ^2/ν^a	N_H (10^{22} cm^{-2})	kT_{low} or Γ (keV)	z^b
PSPC	1T ($Z \equiv 1$) + N_H	28.06/19~1.48	$3^{+0.2}_{-0.8}$	$0.4^{+0.5}_{-0.2}$	1
PSPC	1T (Mg, Si, S^c) + N_H	24.3/18~1.35	$2.5^{+0.7}_{-0.6}$	$0.5^{+0.25}_{-0.10}$	$2.6^{+6.3}_{-1.4}, 1^d$
PSPC	power law + N_H	33.7/19~1.78	1.8 ± 0.6	2.9 ± 1.0	—
PSPC	NEI (Mg, Si, S^c) + N_H	22.6/18~1.18	2.3	$10^{6.75 \pm 0.50} \text{ K}$	$3.3, 1^d$
PSPC/IPC	1T + N_H	30.58/27~1.13	$3.0^{+0.1}_{-0.7}$	$0.4^{+0.5}_{-0.1}$	3
PSPC/IPC	1T (Mg, Si, S^c) + N_H	27.5/28~0.97	2.4 ± 0.6	$0.5^{+0.2}_{-0.1}$	$3^{+5.7}_{-1.8}, 1^d$
PSPC/IPC	power law + N_H	38.7/28 ~ 1.38	1.9 ± 0.4	3.0 ± 0.9	—
PSPC/IPC	NEI (Mg, Si, S^c) + N_H	26.15/28~0.93	2.3	$10^{6.75 \pm 0.50} \text{ K}$	$3.5^{+3.0}_{-2.1}, 1^d$

^a ν is numbers of degrees of freedom.

^b abundance compared with solar.

^c Mg, Si, and S abundances allowed to vary jointly

^d The first number indicates Mg, Si, and S abundances relative to solar, and the second indicates the other metal abundances

*90% confidence error bars.

Table 2: Spectral fit results from each region of 3C391

Region		χ^2/ν	$N_H(10^{22}\text{cm}^{-2})$	kT (keV)	n_e^2L (cm^{-6}pc)
A	NW	20.0/25	$3.6^{+0.4}_{-1.6}$	$0.37^{+(2)}_{-0.1}$	49^{+130}_{-37}
B	center	17.6/25	$3.0^{+0.2}_{-0.4}$	$0.34^{+0.2}_{-0.1}$	91^{+290}_{-64}
C	SE shell	22.0/25	$2.7^{+0.2}_{-1.0}$	$0.5^{+(2)}_{-0.1}$	10.3^{+8}_{-4}
Region		$kT \equiv 0.5 \text{ keV}$		$N_H \equiv 2.4 \times 10^{22} \text{ cm}^{-2}$	
		χ^2/ν	$N_H (10^{22}\text{cm}^{-2})$	χ^2/ν	kT (keV)
A	NW	10.3/19	$3.45^{+0.25}_{-0.35}$	10.0/19	$0.83^{+0.9}_{-0.21}$
B	center	15.2/19	$2.8^{+0.2}_{-0.3}$	16.8/19	$0.48^{+0.15}_{-0.12}$
C	SE shell	16.3/19	2.8 ± 0.15	14.8/19	$0.6^{+0.19}_{-0.13}$

Table 3: The physical and inferred parameters for 3C391

θ (arcmin)	$8' \times 7' (R_s = 3.8')$
Distance	9 ± 2 (kpc)
Physical radius	10 ± 2 pc ($1' \sim 2.6$ pc)
count rate	0.186 ± 0.004 (counts s ⁻¹)
N_H	2.4 ± 0.6 (10^{22} cm ⁻²)
kT	$0.5^{+0.2}_{-0.1}$ (keV) ($T \sim 5.9 \times 10^6$ K)
flux	$3.9^{+1.3}_{-0.7} \times 10^{-12}$ (ergs sec ⁻¹ cm ⁻²)
unabsorbed flux (0.5-2.4 keV)	$1.9^{+6.5}_{-1.4} \times 10^{-10}$ (ergs sec ⁻¹ cm ⁻²)
L_x (0.5-2.4 keV)	$1.7^{+5.9}_{-1.3} \times 10^{36} d_{9kpc}^2$ (ergs sec ⁻¹)
Volume emission measure	$5.5^{+4.2}_{-1.4} \times 10^{58}$ (cm ⁻³)
n_e	0.63 ± 0.15 (cm ⁻³)
m_x	74 ± 20 (M _⊙)

^aThis count rate is background subtracted.

Table 4: Derived parameters for various models

Parameter	^a Explosion in MC	^b Evaporation model($C/\tau \sim 5.3$)
density	$n_o = *100$ (1000)	$n_{ICM} = 0.07-0.23$ (0.6)
n_{sh} (cm^{-3})	1.6 (3.3)	-
age (yr)	1.2×10^4 (1.1×10^4)	6000 - 7500 (12,000)
V_{sh} (km s^{-1})	650 (690)	-
E_o (10^{50} ergs)	1 (2.2)	3
m_x ($M_\odot$)	-	85 - 95 (250)

^a This model assumes SN explosion inside a molecular cloud based on Wheeler et al. (1980). The progenitor is assumed to be a massive star and the ejecta mass is assumed to be $10M_\odot$.

^bThe evaporation model is based on White & Long (1991). In this model n_{ICM} implies the intercloud density. The values in parenthesis are estimated accounting for the high limit of plausible ionization age ($n_o t$).

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Fig. 1.— The ROSAT PSPC image of 3C391. The image has been smoothed using a gaussian function with $\sigma = 7.5''$, to reduce the Poisson noise variations from pixel to pixel. The contours range from 0.8 to 5.2 photons per $7.5''$ pixel. The difference between adjacent contours is a multiplicative factor of 1.27.

Fig. 2.— The grey-scale PSPC image superposed on 1446 MHz radio continuum contours (Moffett & Reynolds 1994).

Fig. 3.— X-ray and radio surface brightness profiles in NW, SW, SE, and NE sectors. The X-ray surface brightness has units of counts per $7.5''$ pixel. and the background level is $0.29 \text{ counts } (7.5'' \text{ pixel})^{-1}$. The radio surface brightness unit is Jy/beam and the resolution is $6''$. The profiles are integrated clockwise from the north. NW, NE, SE and SW profiles cover azimuths 0° - 70° , 70° - 190° , 190° - 290° , and 290° - 360° , respectively.

Fig. 4.— The grey-scale PSPC spectral hardness ratio map (1.5 - $2.2 \text{ keV}/0.1$ - 1.5 keV) with a range of 0.3 - 2 , superposed on PSPC contours (J2000). A darker color indicates a larger hardness ratio.

Fig. 5.— The column density distribution of 3C391 region by region in units of 10^{22} cm^{-2} . The regions are marked 'A' (NW), 'B' (center), and 'C' (SE shell), corresponding with the spectral fits in Table 2.

Fig. 6.— Spectra (a) and confidence contours (b) of northeastern and central regions of 3C391. The spectral peak for the northwestern spectrum appears at higher energy than that of the central spectrum, indicating that the northwestern part has higher column density or temperature. The confidence levels are 67%, 90% and 99%.

Fig. 7.— Schematic diagram showing three stages in the evolution of 3C 391. (a) The progenitor explodes within a molecular cloud but close to the edge. The cloud has a density gradient, and surrounding it is a warm, partially-ionized medium with a density $\sim 1 \text{ cm}^3$. (b) Breakout occurs when the shock reaches the cloud boundary. For 3C 391, this is thought to happen when the shock radius reaches 2.5 pc. (c) The portion of the remnant that has broken out grows substantially faster than that propagating into the cloud. In the remnant interior, cloudlets from the edge of the cloud and the warm medium that were compressed and left behind by the passing shock evaporate in the hot remnant interior, enhancing the central X-ray surface brightness.

7
40
2

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6a

Fig. 66

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(a) $t=0$ SN explosion

$E = 3 \times 10^{50}$ ergs
Warm Medium
 $n = 1 \text{ cm}^{-3}$

Fig. 7

(b) $t=700$ yrs, breakout

$E = 3 \times 10^{50}$ ergs
Warm Medium
 $n = 1 \text{ cm}^{-3}$

(c) $t=11,000$ yrs, present

$E = 3 \times 10^{50}$ ergs
Warm Medium
 $n = 1 \text{ cm}^{-3}$