A HALF-MEGASECOND CHANDRA OBSERVATION OF THE OXYGEN-RICH SUPERNOVA REMNANT G292.0+1.8
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ABSTRACT

We report on our initial analysis of a deep 510 ks observation of the Galactic oxygen-rich supernova remnant (SNR) G292.0+1.8 with the Chandra X-Ray Observatory. Our new Chandra ACIS-I observation has a larger field of view and an order of magnitude deeper exposure than that of the previous Chandra observation, which allows us to cover the entire SNR and to detect new metal-rich ejecta features. We find a highly nonuniform distribution of thermodynamic conditions of the X-ray–emitting hot gas that correlates well with the optical [O III] emission, suggesting the possibility that the originating supernova explosion of G292.0+1.8 was itself asymmetric. We also reveal spectacular substructures of a torus, a jet, and an extended central compact nebula, all associated with the embedded pulsar J1124−5916.

Subject headings: ISM: individual (G292.0+1.8) — pulsars: individual (J1124−5916) — supernova remnants — X-rays: ISM

1. INTRODUCTION

G292.0+1.8 is one of only three known “oxygen-rich” supernova remnants (SNRs) in the Galaxy (Goss et al. 1979; Murdin & Clark 1979), the others being Cassiopeia A and Puppis A. The optical emission from these SNRs contains fast-moving (v ≳ 1000 km s⁻¹) O-rich ejecta knots, which are generally taken as evidence of He-burning nucleosynthesis in the core of massive stars (>10 M☉; e.g., Blair et al. 2000). O-rich SNRs provide us with a rare opportunity to study core-collapse supernova (SN) nucleosynthesis and the subsequent evolution of the remnant, including, in particular, the interaction of ejecta fragments and the blast wave with a circumstellar medium (CSM) produced by massive stellar winds from the progenitor. G292.0+1.8 is especially intriguing because it exhibits all the characteristics of a textbook-example core-collapse SNR: a central pulsar and pulsar wind nebula (PWN), metal-rich ejecta, a shocked CSM, and a blast wave.

To facilitate a study of SNR G292.0+1.8 in unprecedented detail, we performed a deep AO7 Chandra observation during 2006 September 13–October 20, with the SNR centered on the I-array of the Advanced CCD Imaging Spectrometer (ACIS). Our ACIS-I observation takes advantage of a larger (17′ × 17′) field of view (FOV) and an order of magnitude deeper exposure (510 ks) than that of the previous Chandra ACIS-S3 observation (8′ × 8′ FOV and 43 ks exposure; Hughes et al. 2001). This new deep Chandra observation is an essential part of our multiwavelength campaign for G292.0+1.8, including new observations in the radio, infrared, optical, and X-ray bands. Here we report on first results from the new Chandra images: a large-scale overview of the SNR in § 2 and new insights into the nature of the PWN in § 3. A description of the observations, data reduction, and results from extensive spectral and imaging analyses of detailed substructures of the SNR and PWN will be presented elsewhere.

2. SUPERNOVA REMNANT

Figure 1 shows an X-ray color image of G292.0+1.8 created from our deep Chandra data. The outer boundary of the radio SNR is overlaid with a white contour. The energy bands displayed in each color were chosen to emphasize major atomic line emission that illustrates the distribution of electron temperatures and ionization states across the SNR (Table 1). We note that the line and the underlying continuum emission are included in each subband; e.g., the bright blue emission near the SNR’s center is dominated by synchrotron emission from the PWN (see the inset in Fig. 1; Hughes et al. 2001). Our deep ACIS-I exposure comprehensively images the entire SNR to its faint outermost edge, which matches well the extent of the radio remnant (Fig. 1) and traces the location of the blast wave. Ejecta knots (Park et al. 2004; Gonzalez & Safi-Harb 2003) appear brightly colored—yellow, green, or blue—in Figure 1. They extend closest to the rim in the west and south, and they are farthest away in the SE quadrant. Due to their red-orange color in Figure 1 and their positional coincidence with [O III] ejecta (Winkler & Long 2006), the southernmost X-ray knots are likely to be O-rich as well. The SNR’s full diameter is ∼9.6′ (N-S) and ∼8.4′ (E-W), corresponding to physical sizes of ∼(14.7–16.7)dₖ pc, where dₖ is the distance to G292.0+1.8 in units of 6 kpc—the distance that we assume throughout (Gaensler & Wallace 2003).

Our new image of G292.0+1.8 shows little evidence of the featureless, spectrally hard, and geometrically thin X-ray filaments that trace sites of efficient particle acceleration in other young SNRs, such as Cas A, Tycho, and SN 1006. Instead, the SNR’s rim is defined by spectrally soft emission that is faint and diffuse in places (e.g., the SE rim) and filamentary elsewhere. Particle acceleration is evidently occurring in G292.0+1.8 under rather different conditions than other young Galactic SNRs.

The SNR interior contains a complex network of knots and filaments with a variety of colors and morphologies. The overall color distribution of these features is highly asymmetric; the S-SE regions are dominated by red-orange emission, whereas the W-NW regions are bright in emission appearing green-blue in color. We are confident that these variations largely reflect
Fig. 1.—X-ray color image of G292.0–1.8. Red is the sum of the 0.58–0.71 and 0.88–0.95 keV bands (dominated by emission from O Ly$\alpha$ and Ne He$\alpha$), orange is the 0.98–1.10 keV band (Ne Ly$\alpha$), green is the 1.28–1.43 keV band (Mg He$\alpha$), and blue is the sum of the 1.81–2.05 and 2.40–2.62 keV bands (Si He$\alpha$ + S He$\alpha$). Each subband image has been exposure-corrected, binned with 2 × 2 pixels (~1”), and smoothed for the purposes of display. The radio SNR center (Gaensler & Wallace 2003) is marked with a black cross. The position of PSR J1124–5916 (Hughes et al. 2003) is marked with white bars near the SNR center. The lower left inset is the 3–7 keV band image (binned by pixel and smoothed by a Gaussian with pixels). The brightest central parts of the PWN are saturated to white. The lower right inset is the 2–7 keV band image of the PWN (FOV centered on the pulsar position). The image is unbinned and smoothed by a Gaussian with pixel, to emphasize the faint torus and jet. The upper left and upper right insets are the 60 μm images from the IRAS Galaxy Atlas (Cao et al. 1997) and archival ISO data, respectively. In all panels, except for the lower right, a boundary contour from the 20 cm radio image, taken by Australian Telescope Compact Array, is overlaid.

TABLE 1
ENERGY BANDS USED TO GENERATE THE X-RAY COLOR AND HR IMAGES

| Energy Band (keV) | Identification | Color |
|------------------|----------------|-------|
| 0.40–0.50        | Continuum      | …     |
| 0.58–0.71        | O Ly$\alpha$   | Red   |
| 0.75–0.84        | Continuum      | …     |
| 0.88–0.95        | Ne He$\alpha$  | Red   |
| 0.98–1.10        | Ne Ly$\alpha$  | Orange|
| 1.16–1.25        | Continuum      | …     |
| 1.28–1.43        | Mg He$\alpha$  | Green |
| 1.81–2.05        | Si He$\alpha$  | Blue  |
| 2.40–2.62        | S He$\alpha$   | Blue  |
served HR variation (Fig. 2b). We can draw on our previous work (i.e., fitting the spectra of individual knots) to relate HR values to plasma temperatures. Spectral region 3 from Park et al. (2004) lies in the hard “NW” region, and spectral analysis yields a best-fit $kT \sim 5$ keV, corresponding to HR $\sim 2.5$. We find that this HR value strongly traces the electron temperature rather than individual elemental abundances. Although we did not study knots in the soft “SE” region previously, our preliminary spectral modeling of the SE regions favors significantly lower temperatures ($kT \sim 0.7$ keV), corresponding to HR values of $\sim 1.0$. Thus, the observed HR distribution reveals a large-scale spatial variation of the thermal condition of metal-rich ejecta that could not be detected by previous low-resolution data (Hughes & Singh 1994); i.e., a significantly higher temperature of the hot gas ($kT \sim 5$ keV) is implied in the NW regions, whereas a relatively lower temperature plasma ($kT \lesssim 1$ keV) prevails in the SE regions of the SNR.

There is also a very similar and highly significant gradient in the optical properties of G292.0+1.8. The region with the lowest HR values is coincident with the bulk of the optical [O III] emission indicated by the “SE” region in Figure 2a (Ghavamian et al. 2005; Winkler & Long 2006). Across the projected middle of the SNR (within an $\sim 3'$-wide region aligned roughly N-S), there are dozens of isolated optical knots (generally uncorrelated with X-ray knots), whereas on the western edge, no optical emission appears at all. This high degree of correlation between the optical and X-ray properties suggests the possibility that radiative cooling in the ejecta is responsible for the SE-NW gradient in observed properties. In this picture, the SE ejecta would be undergoing significant, perhaps catastrophic, cooling. Across the projected middle of the SNR, cooling is probably just beginning to occur in isolated knots that happen to have the appropriate thermodynamic conditions, whereas the emission toward the NW remains fully nonradiative. Variation in the ambient density surrounding G292.0+1.8 could provide us with an explanation for the observed asymmetry in the ejecta properties. However, there is no evidence of a higher density in the SE regions (Braun et al. 1986), as would be expected. In fact, 60 $\mu$m images (see the upper right and upper left insets to Fig. 1) show that around the rim of the SNR, the SE region is a minimum in flux, whereas the SW is a maximum. Thus, albeit somewhat speculative at the current stage of the analysis, we raise the possibility that the ejecta asymmetry has its origin in some intrinsic asymmetry of the SN explosion itself, such as a variation in the density or velocity distribution from SE to NW. Further work is required to test this asymmetric explosion scenario, including a detailed X-ray spectral analysis of ejecta and hydrodynamic studies appropriate for G292.0+1.8.

3. PULSAR WIND NEBULA

Previous Chandra observations of G292.0+1.8 (Hughes et al. 2001) revealed a point source, which is now known to be the pulsar J1124–5916 (Camilo et al. 2002; Hughes et al. 2003), powering an extended synchrotron nebula (Torii et al. 1998; see the lower left inset to Fig. 1). The emission from the pulsar itself was observed to be surrounded by a compact elliptical structure roughly 1.8$''$ × 1$''$ in size. Our deep ACIS-I observation confirms this structure and reveals additional faint emission suggestive of a jet/torus structure (5$''$ in jet length and torus radius, respectively; see the lower right inset to Fig. 1) similar to those observed to form just outside the pulsar wind termination shock region in a number of other young PWNe (e.g., Gaensler & Slane 2006 and references therein).

Our preliminary spectral analysis indicates that these features...
show a power-law spectrum with photon index $\Gamma \sim 1.5$–1.8, supporting the idea that these features are composed of synchrotron emission associated with the PWN. The ratio between the N-S and E-W sizes of the torus implies an inclination of the axis of the torus (with respect to the line of sight) of \sim 20\degree. Physical sizes are then \sim 0.4d_{6} pc for the jet and a radius of \sim 0.15d_{6} pc for the torus. This is similar to the size of the jet/torus structure observed in 3C 58 (Slane et al. 2002), although we note that there is large variation in the size and relative brightness of such structures from system to system.

Since the E-W “belt” of the SNR (Tuohy et al. 1982) appears to be a relic feature of the progenitor star’s equatorial winds (Park et al. 2002), the pulsar spin axis, defined by the N-S orientation of the jet, is generally aligned with the progenitor’s rotation axis, at least in projection. If the pulsar position that is offset to the SE of the radio center of the SNR represents the direction of the pulsar velocity, then a misalignment of $\theta \sim 70\degree$ between the projected velocity and the spin-axis vectors is implied.

This is in contrast to the strong tendency toward spin-kick alignment claimed by Ng & Romani (2007), although it is important to note that many of their estimated velocity vectors are, like ours, based on pulsar offsets from the geometric centers of their host SNRs—a technique that is quite sensitive to the ambient density because the SNRs will expand more rapidly in the direction of lower density, thus creating a shell that is not centered on the explosion point. Without a proper-motion measurement, our results for J1124 – 5916 are inconclusive, although the density distribution that is inferred from the 60 $\mu$m data—and that is enhanced in the NW-W-SW direction—is difficult to reconcile with the current pulsar position if the observed spin axis is aligned with the velocity vector. Finally, we note that our results are even consistent with possible orthogonality between the spin and kick directions, as might be suggested for some pulsars on the basis of polarization measurements (Johnston et al. 2005; Rankin 2007).

4. SUMMARY

Our deep Chandra observation of SNR G292.0+1.8 detects the entire outer boundary of the blast wave and reveals metal-rich ejecta knots reaching the shock front. We find no evidence of strong particle acceleration sites in X-rays. The initial large-scale analysis reveals a highly nonuniform distribution of X-ray-emitting hot gas. This overall structure is caused by an asymmetric distribution of the gas temperatures, rather than variable foreground absorption. The expected properties of the ambient medium that are required to explain this asymmetry are inconsistent with observations, which leads us to the supposition that the SN explosion itself was asymmetric. A detailed X-ray spectral analysis of the metal-rich ejecta and hydrodynamical simulations will be required to test this scenario.

Proper-motion measurements of the blast wave with the new radio data and detailed IR/optical studies of thermal states of cooling ejecta will also be important tests.

We discover a torus and a jet associated with the PWN of the embedded pulsar J1124 – 5916, similar to a growing number of such structures observed in other young pulsar-driven systems. Assuming that the pulsar’s birthplace was at the geometric center of the radio SNR and that the jet defines the direction of the pulsar spin axis, we find a large misalignment of \sim 70\degree between the spin and kick velocity directions, in apparent contrast to suggestions of spin-kick alignments in other systems.

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