THE EXPANSION OF G11.2−0.3, A RADIO COMPOSITE SUPERNOVA REMNANT

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ABSTRACT

We compare recent observations of the supernova remnant G11.2−0.3 taken with the Very Large Array (VLA) during 2001–2002 with images from VLA archives (1984–1985) to detect and measure the amount of expansion that has occurred during 17 years. The bright, circular outer shell shows a mean expansion of 0.71% ± 0.15% and 0.50% ± 0.17%, from 20 and 6 cm data, respectively, which corresponds to a rate of 0.057 ± 0.012 yr⁻¹ at 20 cm and 0.040 ± 0.013 yr⁻¹ at 6 cm. From this result, we estimate the age of the remnant to be roughly between 960 and 3400 yr old, according to theoretical models of supernova evolution. This is highly inconsistent with the 24,000 yr characteristic age of PSR J1811−1925, located at the remnant’s center, but rather is consistent with the time that has passed since the observation of the historical supernova of a.d. 386. We also predict that G11.2−0.3 is currently in a pre-Sedov evolutionary stage and set constraints on the distance to the remnant based on Chandra X-ray spectral results.

Subject headings: pulsars: individual (PSR J1811−1925) — supernova remnants — supernovae: individual (G11.2−0.3)

1. INTRODUCTION

The process of supernova remnant (SNR) expansion evolution has long been the subject of thorough investigation, and as a result we can be confident of a few well-established facts. In the initial free expansion stage, a tremendous amount of energy in the form of material ejected is thrown outward in a (assumed) spherically symmetric explosion, driving a shock wave into the ambient medium. Later, when the mass of the swept-up material considerably exceeds the ejected material mass, the SNR enters the Sedov stage (Sedov 1993), as a reverse shock reaches the center of the remnant and the forward shock undergoes significant deceleration. This simple picture is complicated by the presence of a pulsar wind nebula (PWN) expanding within, but separate from, the SNR bubble (Chevalier 1984; Reynolds & Chevalier 1984). It eventually encounters the reverse shock, which induces complicated radial reverberations, before relaxing into Sedov phase expansion (van der Swaluw et al. 2001; Blondin, Chevalier, & Frierson 2001). Each stage of evolution can be described by the expansion parameter $m$, defined by $R \propto t^m$, where $R$ is the linear radius and $t$ is the remnant age.

In G11.2−0.3, we find a textbook example of a composite SNR comprising an extremely circular radio and X-ray shell, a PWN contained within the SNR (Vasisht et al. 1996; Kothes & Reich 2001), and an X-ray pulsar PSR J1811−1925 (Torii et al. 1997) located at the center. Its high surface brightness and the extremely centralized position of the pulsar within the remnant imply that it is much younger than the pulsar’s characteristic age, $\tau = 24,000$ yr (Torii et al. 1999; Kaspi et al. 2001) and support the possible association with the historical supernova (SN) event of a.d. 386 (Clark & Stephenson 1977). Furthermore, this discrepancy suggests that the pulsar’s current spin period is very near its initial value and that its spin-down energy, $E = 6.4 \times 10^{36}$ ergs s⁻¹, has remained nearly constant since the supernova explosion.

G11.2−0.3 is an ideal SNR for detailed study because of the observability of emission from all of its components, at hard X-ray, thermal X-ray, or radio frequencies; for a description of its radio and X-ray properties, see Tam, Roberts, & Kaspi (2002) and Roberts et al. (2003). The purpose of performing an expansion measurement is to set unambiguous upper and lower limits on its age by examining the expected behavior of the outer shock during the free expansion (high velocity) and Sedov (low velocity) phases.

2. OBSERVATIONS

We obtained 20 and 6 cm data of G11.2−0.3 taken during 1984–1985 (epoch 1) from the Very Large Array (VLA) archival database. Details of these observations can be found in Table 1 of Tam et al. (2002); data from 1985 February were omitted from this analysis because of poor calibration. Our recent observations made during 2001–2002 (epoch 2) at 20 and 6 cm (1465 and 4860 MHz, respectively) are outlined in Table 1.

The data processing was performed using standard procedures within the MIRIAD package (Sault & Killeen 1999), in mosaic and multifrequency synthesis mode. We performed calibration and editing on each data set individually, before combining all the data of a particular frequency band and epoch. The primary gains were determined using 3C 286 and 3C 48, and phase calibrations were made from observations of 1743−038, 1751−096, 1751−253, and 1820−254 (J2000.0). Imaging was performed with Robust weighting (Sault & Killeen 1999) as a compromise between maximized signal-to-noise ratio and resolution. We utilized the maximum entropy method algorithm for deconvolution (Cornwell, Braun, & Briggs 1999) and applied self-calibration iteratively to improve phase and amplitude calibrations.

3. ANALYSIS

The VLA and other radio interferometers have been used to measure the expansion of many SNRs such as G11.2−0.3. For a summary of remnants and the techniques used to study them,
The amount of expansion has occurred between epochs. Contours of the \( H_{21002} \) of 1.5, 2, 3.5, and photons cm\(^{-2}\) keV X-ray image, smoothed with a 5 pixel FWHM image, with no expansion applied. Positive (black) emission on the outer shell and negative (white) emission on the inner shell indicate that a noticeable amount of expansion has occurred between epochs. Counts of the Chandra 0.6–1.65 keV X-ray image, smoothed with a 5" Gaussian, are shown at levels of 1.5, 2, 3.5, and 5 \( \times 10^{-6} \) photons cm\(^{-2}\) s\(^{-1}\) pixel\(^{-1}\). The extended structure in the interior of the X-ray shell is thought to be the PWN forward shock; this is discussed in Roberts et al. (2003).

Rather than subtract our maps in the \( u-v \) plane as done by see Reynoso et al. (1997) and the references therein. Because it is not always possible to make new observations with the same \( u-v \) coverage as the archival data, it is important to match up as many of the properties that might affect the quality of our results as best possible, before attempting to directly compare the final images from each epoch. We used the final self-calibrated epoch 2 cleaned map, after correcting it for primary beam attenuation, as the model for self-calibrating epoch 1 data, as described by Masson (1986) in his cross-calibration method. The purpose of this step was to apply the same residual calibration errors to epoch 1 as existed in epoch 2, thereby minimizing the effects of self-calibration errors on the final subtracted map. In order to match the spatial scales of our images at both epochs, we used MIRIAD modeling procedures to spatially filter the \( u-v \) coverage of epoch 2 data to match that at epoch 1, thus creating an epoch 2 data set with degraded visibility coverage (Gaensler et al. 1999).

Rather than subtract our maps in the \( u-v \) plane as done by Masson (1986), we instead mimicked the direct approaches of Moffett, Goss, & Reynolds (1993) and Reynoso et al. (1997; used to measure the remnant expansions of SN 1006AD and Tycho’s SN [3C 10], respectively), who adopted procedures outlined by Strom, Goss, & Shaver (1982), Tan & Gull (1985), and Dickel et al. (1988). Using the MIRIAD task IMDIFF, we fitted the five parameters, described by the maximum likelihood algorithm of Tan & Gull (1985), between our final images: expansion, amplitude (the mean brightness ratio between epochs), \( x \)-shift (in the negative right ascension direction), \( y \)-shift (declination), and DC offset (the difference in background brightness levels). The best-fit geometrical center of the shell was found to be less than 0.5” from the position of PSR J1811-1925. We then fixed the amplitude, \( x \)-shift, \( y \)-shift, and offset at the fitted values, performed a series of image subtractions of epoch 1 from epoch 2, each time artificially scaling the epoch 1 image by an expansion factor between 0% and 1.5% in steps of 0.1%, and examined the radial profiles of each difference image for the best-fit expansion factor, or more specifically, the profile that most resembled a line of zero slope. It was evident when examining the difference images that 1.5% was a sufficiently large upper bound on the expansion factor. The difference images were convolved with Gaussians whose FWHM was the same as the synthesized beams’ (1973 \( \times \) 1573 at 20 cm, 873 \( \times \) 777 at 6 cm). Figure 1 shows a map of epoch 2 minus epoch 1 at 20 cm with zero expansion.

We divided the remnant into 24 wedge-shaped regions of 15” azimuthally and found the average flux of each difference image in annular ring sections as a function of radius between 1’ and 3’, recalling that the radius of G11.2–0.3 is \( \sim 2.25 \) (Tam et al. 2002). The purpose of averaging over wedges, as opposed to simply taking radial cuts, was to smooth out small fluctuations that might have corrupted our data (Strom et al. 1982). The next task was to determine which of these profiles of average residual flux versus radius most resembled a flat line. A straightforward \( \chi^2 \) analysis was not possible because of our lacking measured uncertainties \( \sigma \) on the residual profile data points. Therefore, we chose to take a modified approach to \( \chi^2 \)-fitting in the hopes of obtaining somewhat legitimate error bars. We weighted each profile data point according to the total intensity in that region at that radius, in lieu of \( \sigma \), and calculated \( \chi^2 \) at each expansion value using a flat line as the expected difference profile. To find the best expansion and uncertainties for a particular region, we divided the \( \chi^2 \)-values by the minimum \( \chi^2 \) of that region; therefore, when we fitted the values to a parabola, its minimum was forced to be near 1. The best expansion was determined by the location of the minima and the 1 \( \sigma \) errors from the location of \( \chi^2 = 2 \). It should be noted that although these error bars do not represent 1 \( \sigma \) in the traditional sense, they do provide a rough indication of each measurement’s precision.

### Table 1: VLA Observing Parameters for Epoch 2

| Observing Date       | Array Configuration | Frequencies (MHz) | Bandwidth (MHz) | Time on Source (minutes) |
|----------------------|---------------------|-------------------|-----------------|--------------------------|
| 2001 Jun 26 .......... | CnB                 | 1465              | 25              | 63                       |
| 2001 Aug 03 .......... | CnB                 | 4835, 4885        | 25              | 81                       |
| 2001 Sep 24 .......... | C                   | 1465              | 25              | 60                       |
| 2001 Sep 24 .......... | C                   | 4835, 4885        | 25              | 66                       |
| 2002 May 24 .......... | BnA                 | 1465              | 25              | 92                       |
| 2002 May 24 .......... | BnA                 | 4835, 4885        | 25              | 99                       |

**Fig. 1.—** The 20 cm difference map of epoch 1 image subtracted from epoch 2 image, with no expansion applied. Positive (white) emission on the outer shell and negative (black) emission on the inner shell indicate that a noticeable amount of expansion has occurred between epochs. Contours of the Chandra 0.6–1.65 keV X-ray image, smoothed with a 5" Gaussian, are shown at levels of 1.5, 2, 3.5, and 5 \( \times 10^{-6} \) photons cm\(^{-2}\) s\(^{-1}\) pixel\(^{-1}\). The extended structure in the interior of the X-ray shell is thought to be the PWN forward shock; this is discussed in Roberts et al. (2003).
4. RESULTS

Figure 2 contains a plot of the best expansion rate estimates as a function of azimuthal angle. As expected, the largest uncertainties correspond to the regions of the shell that are most diffuse, specifically the southwestern quadrant (between 90° and 180° west of north). We calculate the weighted mean expansion rate for the entire shell and find the overall expansion during the ~17 yr period separating the epochs to be 0.71% ± 0.15% from 20 cm data and 0.50% ± 0.17% from 6 cm data. This corresponds to a rate of 0.057 ± 0.012 yr⁻¹ and 0.040 ± 0.013 yr⁻¹ (from 20 and 6 cm data, respectively). The uncertainties represent the rms deviation about the weighted mean. The expansion parameter \( m = (ΔR/R)/(Δt/t) \) will later be used to constrain a rough estimate of the age of G11.2−0.3; here, we assume that the age is equivalent to the time, since SN 386AD, \( t = 1616 \) yr, and calculate \( m = 0.68 ± 0.14 \) (20 cm) and 0.48 ± 0.16 (6 cm).

We do not know why there exists a general trend in the difference between the two sets of results, making the expansion at 20 cm appear consistently greater than that at 6 cm; however, we note that the 6 cm data are more susceptible to errors in primary beam correction and incomplete u-v coverage. Even so, the error bars on our data points overlap significantly, and the calculated mean expansion values agree within our scatter-based uncertainties.

As an independent check, we compare our measured expansion with the general overall expansion for the entire remnant as fit by IMDIFF. Our results agree with the fit values of 0.7% and 0.5% at 20 and 6 cm, respectively.

5. DISCUSSION

In the first phase of SN evolution, the outer shock wave freely expands into the surrounding medium such that \( R \propto t \), and the mass of the ejected material \( M_\text{ej} \) is much greater than the mass of swept-up material \( M_\text{swe} \). As the forward shock begins to decelerate, a reverse shock is driven toward the center of the SNR, where it interacts with the PWN, if present (Reynolds & Chevalier 1984; Blondin et al. 2001; van der Swaluw et al. 2001). Eventually these interactions dissipate as the SNR enters the Sedov phase. At this stage, \( M_\text{ej} \ll M_\text{swe} \) and the expansion is described by the Sedov solution \( R \propto t^{0.4} \) (Sedov 1993). Interactions between the SN shock front and its ambient medium, which has a density profile thought to be affected by a circumstellar wind produced by presupernova mass loss of Type II SNe, are currently the subject of extensive investigations (Chevalier 1982; Chevalier & Fransson 1994; Truelove & McKee 1999). The \( m \)-values predicted for such an environment tend to lie between the extreme values of free expansion and the classical Sedov solution for a constant density medium. Therefore, we consider these classical definitions for now.

Assuming that G11.2−0.3 is likely 1616 yr old, we adopt the expansion parameters that we find corresponding to this age and estimate roughly that the SNR reverse-shock radius is currently between 0.5 and 0.8 times the forward blast wave shock radius, assuming a typical ejecta mass for Type II SNe of \( 3−5 M_\odot \). The ratio of PWN to SNR diameter is \( \sim 0.28 \), so the reverse shock would not be expected to have reached the PWN yet. This agrees with what we observe in Figure 1, as well as conclusions outlined in Tam et al. (2002) based on the hydrodynamical simulations of van der Swaluw et al. (2001). Furthermore, we refer to Chevalier (1982), who predicts that the initial expansion phase of a SNR with a red supergiant progenitor can be described by a self-similar solution with a value of \( m = 0.9 \), as long as both the circumstellar material and the stellar envelope density distributions are power laws in radius. This is considerably
higher than our $m$ estimates, based on $t = 1616$ yr, of roughly 0.48–0.68, which suggests that the transition from the initial phase to the Sedov phase is well underway.

5.1. Distance Estimate

The distance to G11.2–0.3 is estimated by considering its expansion and angular size. Given the relations $v = mR/t$ and $R = \theta d$, where $v$ is the shell’s spatial velocity, $\theta$ is the angular radius, and $d$ is the distance to the remnant, it can be seen that

$$d = v \frac{\Delta r}{\theta \Delta R/R}.$$ 

To find the velocity of the shell, we consider the Mach number of the SNR shock front $M = \gamma/c_s$, where $c_s = (\gamma p/\rho)^{1/2}$ is the sound velocity (Longair 1994). Here, $\gamma = 5/3$, and the ratio of pressure to particle mass density is given by $p/\rho = kT/p\mu_m$, where $T_i$ is the temperature of the surrounding material and $\mu_m$ is the mean mass per particle ($\mu = 0.6$ for cosmic abundances, $m_p$ is proton mass; Reynolds et al. 1994). Longair (1997) quotes $T_i/T_x = 5M^2/16$ for a strong shock in an ideal gas. We measure the temperature behind the shock $T_x = 7 \times 10^4$ K from X-ray spectral fits (Roberts et al. 2003); however, $T_i$ is the ion temperature and if the electrons are not in full thermal equilibrium with the ions, the observed spectrum may underestimate the shock temperature, and our distance estimate will be too small by a factor of $(T_i/T_x)^{1/2}$ (Borkowski, Lyerly, & Reynolds 2001). Combining the above information we find

$$\frac{T_i}{T_x} = \frac{5}{16} \frac{\Delta v^2}{5kT/p\mu_m}.$$ 

which gives a lower bound on the distance estimate,

$$d = \left(\frac{16kT_i}{3\mu_m}\right)^{1/2} \frac{\Delta r}{\theta \Delta R/R} \geq 3 \sqrt{\frac{T_i}{T_x}} \frac{0.0071}{\Delta R/R} \text{kpc}.$$ 

Green et al. (1988) previously estimated a minimum distance of $\sim 5$ kpc to the remnant based on its H i spectrum. Fits to the X-ray spectrum with the XSPEC model NPSHOCK (Borkowski et al. 2001) suggest that the electrons are near equilibrium; therefore, the distance derived assuming total equilibrium should be very close to that at near equilibrium and, hence, not much greater than the minimum H i distance.

6. Conclusions

On the basis of radio interferometric images of SNR G11.2–0.3, we have made a simple measurement of the outer shell expansion and find a mean rate of $0.057 \pm 0.012$ yr$^{-1}$ from 20 cm data and $0.040 \pm 0.013$ yr$^{-1}$ from 6 cm data. If we compare the expected age of G11.2–0.3, determined by our measurements, with the characteristic age of its associated pulsar PSR J1811–1925, we find an order of magnitude discrepancy; our result further strengthens the growing body of evidence linking G11.2–0.3 with the historical SN of A.D. 386. The evolutionary status of this SNR appears to be pre-Sedov, a conclusion that agrees with other observational evidence as well as theoretical arguments. We also estimate the distance to the remnant based on its X-ray shock velocity to be $\geq 3$ kpc and find it consistent with previously published results.

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### References

Blondin, J. M., Chevalier, R. A., &Frierson, D. M. 2001, ApJ, 563, 806
Borkowski, K. J., Lyerly, W. J., & Reynolds, S. P. 2001, ApJ, 548, 820
Chevalier, R. A. 1982, ApJ, 258, 790
Chevalier, R. A., & Fransson, C. 1994, ApJ, 420, 268
Clark, D. H., & Stephenson, F. R. 1977, The Historical Supernovae (Oxford: Pergamon)
Cornwell, T. Braun, R., & Briggs, D. S. 1999, in ASP Conf. Ser. 180, Synthesis Imaging in Radio Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley (San Francisco: ASP), 151
Dyck, D. R., Sault, R., Arent, R. G., Korista, K. T., & Matsui, Y. 1988, ApJ, 330, 254
Gaensler, B. M., Brazier, K. T. S., Manchester, R. N., Johnston, S., & Green, A. J. 1999, MNARS, 305, 724
Green, D. A., Gull, S. F., Tan, S. M., & Simon, A. J. B. 1988, MNARS, 231, 735
Kaspi, V. M., Roberts, M. E., Vasisht, G., Gotthelf, E. V., Pivovaroff, M., & Kawai, N. 2001, ApJ, 560, 371
Kothes, R., & Reich, W. 2001, A&A, 372, 627
Longair, M. S. 1994, High Energy Astrophysics, Vol. 2 (2d ed.; Cambridge: Cambridge Univ. Press)
Longair, M. S. 1997, High Energy Astrophysics, Vol. 1 (2d ed.; Cambridge: Cambridge Univ. Press)
Masson, C. R. 1986, ApJ, 302, L27
Moffett, D. A., Goss, W. M., & Reynolds, S. P. 1993, AJ, 106, 1566
Reynolds, S. P., & Chevalier, R. A. 1984, ApJ, 278, 630
Reynolds, S. P., Lyutikov, M., Blandford, R. D., & Seward, F. D. 1994, MNARS, 271, L1
Reynoso, E. M., Moffett, D. A., Goss, W. M., Dubner, G. M., Dickel, J. R., Reynolds, S. P., & Giacani, E. B. 1997, ApJ, 491, 816
Roberts, M. S. E., Tam, C. R., Kaspi, V. M., Lyutikov, M., Vasisht, G., Piovavoff, M., Gotthelf, E. V., & Kawai, N. 2003, ApJ, 588, 992
Sault, R. J., & Killeen, N. E. B. 1999, The MIRIAD User’s Guide (Sydney: ATNF)
Sedov, L. I. 1993, Similarity and Dimensional Methods in Mechanics (10th ed.; Boca Raton: CRC Press)
Strom, R. G., Goss, W. M., & Shaver, P. A. 1982, MNARS, 200, 473
Tari, C., Roberts, M. S. E., & Kaspi, V. M. 2002, ApJ, 572, 202
Tan, S. M., & Gull, S. F. 1985, MNARS, 216, 949
Torii, K., Tsunami, H., Dotani, T., & Mitsuda, K. 1997, ApJ, 489, L145
Torii, K., Tsunami, H., Dotani, T., Mitsuda, K., Kawai, N., Kinugasa, K., Saito, Y., & Shibata, S. 1999, ApJ, 523, L69
Truelove, J. K., & McKee, C. F. 1999, ApJS, 120, 299
van der Swaluw, E., Achterberg, A., Gallant, Y. A., & Töth, G. 2001, A&A, 380, 309
Vasisht, G., Aoki, T., Dotani, T., Kulkarni, S. R., & Nagase, F. 1996, ApJ, 456, L59