An X-Ray Proper-motion Study of the Large Magellanic Cloud Supernova Remnant 0509-67.5

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Abstract

We present a third epoch of Chandra observations of the Type Ia Large Magellanic Cloud Supernova remnant 0509-67.5. With these new observations from 2020, the baseline for proper-motion measurements of the expansion has grown to 20 yr (from the earliest Chandra observations in 2000). We report here the results of these new expansion measurements. The lack of nearby bright point sources renders absolute image alignment difficult. However, we are able to measure the average expansion of the diameter of the remnant along several projection directions. We find that the remnant is expanding with an average velocity of 6120 km s$^{-1}$. This high shock velocity is consistent with previous works, and also consistent with the inference that 0509-67.5 is expanding into a very low density surrounding medium. At the distance of the LMC, this velocity corresponds to an undecelerated age of 600 yr, with the real age somewhat smaller.

1. Introduction

The supernova remnant (SNR) 0509-67.5 was discovered in the Large Magellanic Cloud (LMC) by an X-ray survey using the Einstein observatory (Long et al. 1981). Follow-up optical observations (Tuohy et al. 1982) identified the remnant as the result of a Type Ia supernova. This was later supported by the Advanced Satellite for Cosmology and Astrophysics observations in X-ray (Hughes et al. 1995). The first Chandra observations were presented in Warren & Hughes (2004) who found a circular morphology with the bulk of the continuum emission coming from nonthermal origins. They support the earlier conclusion from Tuohy et al. (1982) that the remnant is expanding into a low-density environment. Further support for a low-density environment surrounding 0509-67.5 was provided by Spitzer infrared observations, where modeling of emission from warm dust grains in the postshock environment imply a preshock density of less than 1 cm$^{-3}$ (Borkowski et al. 2006; Williams et al. 2011).

A light echo was found by Rest et al. (2005) from which they estimate an age of 400 ± 120 yr. Ghavamian et al. (2007) used spectroscopic UV observations to detect significant broadening of the Lyα line, corresponding to a shock velocity of 5200–6300 km s$^{-1}$. An optical proper-motion study using HST Hα observations over a 1 yr baseline was presented by Hovey et al. (2015). They find a global shock speed of 6500 ± 200 km s$^{-1}$. Their accompanying hydrodynamic simulations predict an age of $310^{+10}_{-50}$ yr, consistent with that of Rest et al. (2005), and in agreement with the calculations of Seitzenzahl et al. (2019), which required an age of 310 yr and a sub-Chandrasekhar explosion mass in order to simultaneously match the observed broad optical coronal line emission of Fe XIV and Fe XV, and the position and speed of the forward shock. Roper et al. (2018) used Chandra observations over a 7 yr baseline (2000 and 2007) to perform an X-ray proper-motion study. They report an overall average expansion velocity of $7500 ± 1700$ km s$^{-1}$.

In this paper, we report results from a proper-motion study using a new epoch of Chandra X-ray observations from 2020. These observations extend the baseline of measurements to 20 yr following the initial observations in 2000. The paper is organized as follows. In Section 2, we detail the X-ray observations and data reduction, the unsuccessful attempts to align the two epochs to a common coordinate system, and the alternative methods we employed. We report our results in Section 3.

2. Observations

A new epoch of Chandra observations (PI: B. Williams) was acquired between April 11 and 2020 November 21 totaling 414 ks and spread over 14 individual segments ranging in length from 25 to 40 ks (Table 1). The initial Chandra observations from 2000 May 12 (PI: J. Hughes) consist of a single 49 ks pointing. Both observations place SNR 0509-67.5 on the S3 chip of the ACIS-S array close to the optical axis of the telescope.

2.1. Image Alignment and Reprojection

The standard procedure for aligning observations requires the matching of known sources from external catalogs with point sources detected in the image, or aligning common point sources detected in the image, or aligning common point sources detected in the image, or aligning common point sources detected in the image.
sources within images from each epoch. We used the CIAO tool wavdetect to search for point sources in the reprocessed event files. The found point sources were then filtered by eye to exclude false positives and a transformation matrix file was created using the tool wcs_match, and wcs_update to align the 2000 observation and all 2020 segments to the longest observation from the new epoch (ObsID 24637). This method was used in the analysis of Roper et al. (2018) using the 2000 and 2007 data. However, we find that the results of this alignment were not accurate for a robust measurement at the subpixel level. The point-source brightnesses in the individual segments did not yield enough counts to achieve convincing fits to the point-spread function.

Without the necessary point sources to allow for a robust alignment between epochs we return to the method employed in our previous work (Williams et al. 2018) and measure the diameter of the remnant such that perfect alignment is unnecessary.

3. Measurements and Discussion

The low energy sensitivity of Chandra has been significantly affected by a buildup of contaminants (Marshall et al. 2004). In order to achieve a fair comparison between epochs we filter the observations to energies between 1.7 and 7 keV (Figure 1).

We measured the diameter of the remnant using radial profiles along 6 regions which all cross the geometric center of the remnant and are spaced by rotations of 30° (Figure 2). Each region is 7 pixels wide, where 1 pixel is the native Chandra pixel size of 0.0492. The measurements were made individually for the six longest 2020 observation segments (Table 1) each paired with the 2000 observation. The forward shock front is assumed to be the location in the profile where the brightness rises sharply. Profiles are normalized to align the tops of these rise peaks (Figure 3). We then shift epoch 1 with respect to epoch 2 on a grid of 0.0048 resolution elements corresponding to 0.01 Chandra pixels and minimize the chi-squared value resulting from the difference between the two profiles over small few pixel windows. The best-fit shift depends on the choice of fitting window, which is impossible to state with absolute certainty. To account for this uncertainty, for each measurement several window values were chosen spanning between roughly 4–10 pixels depending on the specific profile shape, beginning where the profile rises from the background and ending at the outermost peak. For each individual measurement, we change the window by 1 pixel on each end and average the results from repeating this process three times. For each projection angle we then have a set of required shifts from each of the six longest 2020 observations paired with the 2000 observation. The diameter

![Figure 1. Spectrum taken from the 2000 observation (black) and the longest individual 2020 observation ObsID 24637 (red) showing the decrease in low energy sensitivity. The dotted line is at 1.7 keV, above which the observations may be compared fairly.](image1)

| obsID | year | Exp (ks) |
|-------|------|----------|
| 776   | 2000 | 48.99    |
| 7635  | 2007 | 32.74    |
| 8554  | 2007 | 29.47    |
| 22442 | 2020 | 34.6     |
| 22443 | 2020 | 36.58    |
| 22444 | 2020 | 24.74    |
| 23020 | 2020 | 24.77    |
| 23021 | 2020 | 27.7     |
| 23022 | 2020 | 24.74    |
| 23023 | 2020 | 24.59    |
| 23024 | 2020 | 24.47    |
| 24635 | 2020 | 32.48    |
| 24636 | 2020 | 32.17    |
| 24637 | 2020 | 39.54    |
| 24638 | 2020 | 24.8     |
| 24858 | 2020 | 35.6     |
| 24867 | 2020 | 27.17    |

Note. Those in bold were used in this work.
expansion is then determined by the difference between the required shifts for each pair of shock fronts on opposite sides of the remnant. In this method, the absolute position of either shock is irrelevant, and our results are independent from the choice of alignment. We report the average radial expansion among the six pairs of 2000–2020 observations and the associated standard deviation and expansion velocity in km s$^{-1}$ in Table 2 using a distance of 50 kpc to the LMC (Pietrzyński et al. 2013). The standard deviation column is calculated from the expansion results from each of the six observation pairs. The velocity we measure results from the expansion of the diameter of the remnant. Since this expansion may be happening asymmetrically, reporting an average velocity with an error calculated by assuming all of the measurements are corresponding to the same true inherent value is not correct. Here we choose to report the average velocity with an error calculated from the deviation of the individual velocity measurements.

As a sanity check, we calculated the average expansion from the area of contours for each epoch. This is a completely independent method. To examine the effect of the differing response of the detector particularly at low energies, we first equate the number of detected 0.5–7 keV counts in the 2000 observation counts image and the longest 2020 observation segment by filtering the 2000 observation exposure time to a brief period, which resulted in an effective exposure time of 6.9 ks. We then drew a single contour in DS9 around the remnant defining a contour level of 0.25 with a smoothing level of 4. The contours were then converted to region files from which the areas were read. The 2000 contour encompassed 704.2 square arcseconds while the 2020 contour covered 771.0. The area increases as the square of the diameter, meaning that on average, the diameter of the remnant increased by 1.4 or 2.8 pixels. This is larger than the diameter increase we measure with the projection method. The brief effective exposure time however leads to a systematically smaller area since the leading edge of the remnant appears to be dominated by harder emission which would not have been able to build up to the same degree as the longer 2nd epoch. We then restricted the energy range to the 1.7–7 keV band, where the change in response is much less significant. We again filter the exposure time of the 2000 observation in order to match the total number of counts in the longest 2020 observation segment. This both accounts for the small change in response visible in the differing heights of the Si line in Figure 1 and the different exposure times which affect the number of background counts to which the contour method is sensitive. The resulting contours are shown in Figure 4. Here we required an effective exposure of 31 ks. The resulting contour areas increased from 713.1 square arcseconds as measured in the 2000 epoch to 757.7 square arcseconds in 2020. This corresponds to a diameter expansion of 1.9 pixels and is consistent with the result we found using the projection method, supporting our result.

As an additional test, we attempt to align the 2020 observations using the method of Carlton et al. (2011). We smooth one counts image constructed from a single observation segment filtered to 0.4–8 keV, and fit the unsmoothed images from the other observations binned to 1/4 of an acis pixel to this smoothed image using only translations and no expansion.
We merged the aligned 2020 observations using the CIAO tool merge_obs and repeated our analysis using the diameter measurement method. We find results consistent with our unaligned individual measurements indicating that we have achieved a reasonable alignment of the 2020 observations. We attempted to align with the 2000 observation using the added counts in the few point sources yielded by the merging. A resulting difference image is shown in Figure 5. While expansion is clearly visible in the difference image, there also appears to be a systematic shift between epochs suggesting the alignment is not sufficient to perform localized velocity measurements.

The high shock velocity we find supports SNR 0509-67.5’s status as a young SNR. The average velocity we calculate corresponds to an undecelerated free expansion age of 600 yr with the true age somewhat lower. The velocity we measure is
consistent with the results of Hovey et al. (2015) who then used hydrodynamic simulations to calculate an age of 310 yr. Our method, which measures the change in the diameter of the remnant, does not allow for detailed inferences on whether one area of the remnant is expanding more quickly than another. The difference in brightness of the south western limb of the remnant may suggest a local increase in density in this direction. However, our diameter measurement normal to this direction does not yield systematically different results than the others. This is not unexpected since the measurement includes the motion in the opposite direction from the opposing shock, which would offset any difference in velocity. We list the velocity and age we infer along with the X-ray proper-motion results from comparable Type Ia remnants in Table 3. We find a comparable velocity to Tycho’s remnant and the nonthermal rims of SN 1006, both of which are expanding into low-density media similar to SNR 0509-67.5.

### Table 2

| Region | Expansion (pixels) | Standard deviation (pixels) | Expansion Velocity (km s\(^{-1}\)) | Standard deviation (km s\(^{-1}\)) |
|--------|------------------|-----------------------------|------------------------------------|------------------------------------|
| 1      | 1.47             | 0.32                        | 4350                               | 960                                |
| 2      | 2.60             | 0.82                        | 7710                               | 2440                               |
| 3      | 1.88             | 0.66                        | 5580                               | 1970                               |
| 4      | 2.31             | 0.54                        | 6840                               | 1590                               |
| 5      | 2.32             | 0.47                        | 6880                               | 1390                               |
| 6      | 1.81             | 0.69                        | 5380                               | 2060                               |
| Avg    | 2.07             |                             | 6120                               | 1200                               |

**Note.** The six velocities are not considered the true velocity since the remnant may be expanding asymmetrically. We therefore consider the deviation of the individual velocity results as a method to estimate our errors.

### Figure 4

Contours containing the full remnant with a level of 0.25 created from the filtered 1.7–7 keV event files. The green contour is from the 2000 observation while the longest 2020 observation is magenta. The 2000 observation was filtered to a shorter exposure time to equate the number of counts with the 2020 segment. The contours use the native coordinates for each epoch and the offset highlights the difficulty with alignment.

### Figure 5

Difference image showing the aligned and merged 2020 observations minus the 2000 observation. Each image was filtered to 1.7–7 keV, smoothed with a 2 pixel Gaussian, and the merged image was normalized to the number of counts in the filtered 2000 observation. Expansion is clearly visible, but the true alignment between epochs is not trusted.

### Table 3

| Remnant     | Velocity (km s\(^{-1}\)) | Age (yr) |
|-------------|--------------------------|----------|
| 0509-67.5   | 6120                     | 620\(^a\) |
| N103B\(^b\) | 4170                     | 850\(^a\) |
| Tycho\(^c\) | 5300                     | 450      |
| Kepler\(^d\)| 1780                     | 418      |
| SN 1006\(^e\)| 3000–5000               | 1016     |

**Notes.** The ages inferred from the measured velocity assuming free expansion represent the upper limit on the age of SNRs 0509-67.5 and N103B, while the age of Tycho, Kepler, and SN 1006 are from historical record (e.g., Baade 1943; Hanbury Brown & Hazard 1952; Gardner & Milne 1965).

\(^a\) Free expansion.

\(^b\) Williams et al. (2018).

\(^c\) Williams et al. (2016).

\(^d\) Coffin et al. (2022).

\(^e\) Katsuda et al. (2013), Winkler et al. (2014).

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**Figure 4.** Contours containing the full remnant with a level of 0.25 created from the filtered 1.7–7 keV event files. The green contour is from the 2000 observation while the longest 2020 observation is magenta. The 2000 observation was filtered to a shorter exposure time to equate the number of counts with the 2020 segment. The contours use the native coordinates for each epoch and the offset highlights the difficulty with alignment.

**Figure 5.** Difference image showing the aligned and merged 2020 observations minus the 2000 observation. Each image was filtered to 1.7–7 keV, smoothed with a 2 pixel Gaussian, and the merged image was normalized to the number of counts in the filtered 2000 observation. Expansion is clearly visible, but the true alignment between epochs is not trusted.

### 4. Conclusions

We have observed the LMC SNR 0509-67.5, 20 yr after its initial Chandra observation with the goal of measuring the expansion of the remnant. The lack of strong point sources in the field made the absolute astrometric alignment impossible. We measure instead the change in the diameter of the remnant in six directions, yielding an average expansion velocity of just over 6100 km s\(^{-1}\). This corresponds to an undecelerated age of 600 yr, making the true age even lower. Our results are broadly consistent with previous Chandra X-ray measurements, as well
as those made in Hα with HST. Continued monitoring of young SNRs in the Galaxy and the LMC is critical for understanding the early stage of their development, the stage most closely related to the explosion of the progenitor system. We encourage future observations of this remnant and others like it with HST and LUVOIR in optical bands and Chandra, AXIS, and Lynx at X-ray wavelengths.

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