G7.7–3.7: A Young Supernova Remnant Probably Associated with the Guest Star in 386 CE (SN 386)

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Abstract

Although the Galactic supernova rate is about two per century, only few supernova remnants (SNRs) are associated with historical records. There are a few ancient Chinese records of “guest stars” that are probably sightings of supernovae for which the associated SNRs are not established. Here we present an X-ray study of the SNR G7.7–3.7, as observed by XMM-Newton, and discuss its probable association with the guest star of 386 CE. This guest star occurred in the ancient Chinese asterism Nan-Dou, which is part of Sagittarius. The X-ray morphology of G7.7–3.7 shows an arc-like feature in the SNR south, which is characterized by an under-ionized plasma with subsolar abundances, a temperature of 0.4–0.8 keV, and a density of ~0.5 (4 kpc)−0.5 cm−3. A small shock age of 1.2 ± 0.6 (4 kpc)0.5 kyr is inferred from the low ionization timescale of 2.4±1.3 × 1010 cm−3 s of the X-ray arc. The low foreground absorption (NH = 3.5 ± 0.5 × 1021 cm−2) of G7.7–3.7 made the supernova explosion visible to the naked eye on the Earth. The position of G7.7–3.7 is consistent with the event of 386 CE, and the X-ray properties suggest that its age is also consistent. Interestingly, the association between G7.7–3.7 and guest star 386 suggests that the supernova was a low-luminosity supernova, thus explaining the brief visibility (2–4 months) of the guest star.

Key words: ISM: individual objects (G7.7–3.7 – SN 386) – ISM: supernova remnants – supernovae: general

1. Introduction

The energetic explosions of supernovae (SNe) are among the brightest events in a galaxy, but have a short-lived brightness that quickly declines a few magnitudes within a year. An SN rate of about two per century (Reed 2005; Diehl & Statler 2006) indicates tens of Galactic SNe were exploded in the past two millennia. However, only a few nearby SNe were observed with the naked eye and recorded by ancient astronomers. The debris of these historical transient events are now among the youngest members of Galactic supernova remnant (SNR) population. Historical SNRs play an important role in the mutual understanding of SNR physics and ancient astronomy, and have received much attention. The well-recorded group of historical SNRs includes Type Ia SNRs such as Tycho’s (SN 1572) and Kepler’s SNRs (SN 1604), SN 1006, as well as Type II SNRs Crab (SN 1054, a.k.a. guest star “Tian-Guan”) and 3C58 (likely SN 1181, see Green & Stephenson 2003, and references therein).

The long-duration transients that occurred more than a thousand years ago, found mainly in Chinese records (Xi 1955; Hsi 1957; Xi & Bo 1965), may provide crucial clues for finding other young SNRs. It is more difficult to establish a clear association between SNRs and the records, given the uncertainties of derived SNR ages and the vague positions in ancient texts. Despite these difficulties, RCW 86 has been considered as a probable SNR of the guest star observed in 185 CE that was visible for 20 or 8 months (e.g., Westerlund 1969; Clark & Stephenson 1977; Vink et al. 2006). It has been suggested that RX J1713.7-3946 is the SNR of the guest star in 393 CE (e.g., Wang et al. 1997). Guest star 393 appeared during the Jin (晉) dynasty, when two other long-duration guest stars were reported in 386 CE (2–4 months) and 369 CE (7–9 months, see Xi 1955; Xi & Bo 1965, and references therein), respectively.

The earliest available record of guest star 386 was found in Song Shu (宋書): during the third month of the eleventh year of the Tai-Yuan reign-period of the Jin dynasty, there was a guest star at Nan-Dou (南斗) until the sixth month, when it was extinguished (see Hsi 1957; Clark & Stephenson 1977). The records are very similar to those in later text sources Jin Shu (晉書), Tong Zhi (通志), Wen Xian Tong Kao (文獻通考), but shortened, probably because they transcribed the earlier record. The ancient Chinese asterism Nan-Dou (a.k.a. Dou, Southern Dipper or Dipper), as part of Sagittarius, is composed of six stars in the Galactic coordinates range l = 6°9–10°7, b = −1°6 to −15°4. Nan-Dou or Dou can also refer to a lunar mansion that covers a range of R.A. and a few asterisms including the Nan-Dou asterism itself (R.A. = 17°15′ to 18°50′; see Stephenson & Green 2002). It is unknown whether or not Nan-Dou meant an asterism or a lunar mansion for guest star 386, but if a young remnant with a consistent age is detected in the Nan-Dou asterism, it would support the former meaning.

SNR G11.2–0.3 was initially regarded as the prime candidate remnant of the guest star (Clark & Stephenson 1977; Green & Stephenson 2003), but was recently ruled out as it cannot have been visible to the naked eye, given its distance and large extinction (A_V = 16 ± 2, Borkowski et al. 2016). Another candidate SNR, G7.7–3.7, is located in the Nan-Dou asterism (Stephenson & Green 2002). However, its age is
unclear, as there have been very few studies and observations of the SNR. It has a shell-like morphology in the radio band (Milne et al. 1986; Milne 1987; Dubner et al. 1996). The empirical $\Sigma-D$ (radio surface-brightness–distance) relation, which has considerable scatter, provides a very rough SNR distance of $\sim3.2-6$ kpc (Milne et al. 1986; Pavlovic et al. 2014). The distance was suggested to be closer than 6 kpc; otherwise, the SNR would be unusually far out of the Galactic plane (Milne et al. 1986). An X-ray imaging study with short-exposure XMM-Newton data in 2005 (partially covering the SNR) showed that G7.7−3.7 contains an X-ray feature in the south and a point-like source in the northeast (Giacani et al. 2010).

Motivated by the need to link young SNRs with early historical records, and the uncertain association of the SNR with the guest star of 386 CE, we performed an analysis of the SNR G7.7−3.7. We report here that G7.7−3.7 is indeed a young SNR in Nan-Dou, and suggest that it is the remnant of the guest star 386 (SN 386), according our X-ray imaging and spectroscopic analysis of this remnant.

2. Data

G7.7−3.7 was observed with XMM-Newton in 2005 (OBSID: 0304220401, PI: E. Gotthelf) and 2012 (OBSID: 0671170101, PI: M. Smith). The whole SNR was covered by the pn and MOS cameras of the 2012 observation, which were operating in full frame mode with a thin filter. The 2005 observation was targeted to the nearby point source AX J1817.6−2401, and pn/MOS cameras were in full frame/small window mode with a medium filter. For this observation, the X-ray emitting region of G7.7−3.7 was fully covered by MOS2 camera at an off-axis region, partially covered by MOS1 camera, but were missed by the pn camera. Therefore, we use the MOS2 data in 2005 and all of the MOS and pn data in 2012. The total exposure times were 13 and 40 ks, respectively, and both observations suffered soft proton flares in most of the observation time. After removing the high background periods from the events, the screened exposure time in 2012 is 6.3, 7.5, and 6.6 ks for pn, MOS1 and MOS2, respectively, and the net exposure time of the MOS2 data in 2005 is only 2.9 ks.

The XMM-Newton data were reduced using the Science Analysis System software (SAS, vers. 16.1.0). We used XSPEC (vers. 12.10.0c) with AtomDB 3.0.9 and and SPEX (vers. 3.0.4) with SPEXACT 3.04 atomic tables (Kaastra et al. 1996) for a comparative spectral analysis. The fitting statistics method employed was C-statistics (Cash 1979).

We also retrieved the 1.4 GHz radio continuum data from NRAO Very Large Array (VLA) Sky Survey (Condon et al. 1998) for a comparison with the X-ray data.

3. X-Ray Analysis of G7.7−3.7

The X-ray image of G7.7−3.7 in 0.3−3 keV reveals an arc-like feature in the south (see Figure 1), which is unlike the radio emission that delineates the SNR’s boundary (see Dubner et al. 1996, for a study in radio band). There seems to be an anti-correlation of the brightness between X-ray and radio emission along the arc: the radio emission is brightest in the arc center, where the X-ray emission is fainter. Although the southern arc is the only bright X-ray feature in G7.7−3.7, very dim, diffuse X-ray emission is detected inside the eastern radio boundary.

To study the properties of the X-ray arc of G7.7−3.7, we extracted spectra from the region surrounding the arc (see the dashed region in Figure 1). The background is subtracted from a nearby source-free region. Four groups of spectra are extracted, from the pn/MOS1/MOS2 observation in 2012, and the MOS2 observation in 2005. The left panel of Figure 2 shows the spectra optimally binned (Kaastra & Bleeker 2016) using the Obin command in SPEX. The detected X-ray photons mainly have an energy below 2 keV. An He-like Mg line is clearly detected at 1.33 keV and an He-like Si bump is shown at ~1.85 keV, indicating a thermal origin of the emission. We therefore applied an absorbed non-equilibrium ionization (NEI) model (vnei in XSPEC and neij in SPEX) to jointly fit the four spectra above 0.3 keV. For the analysis with SPEX, we applied the absorption model hot and solar abundances from Lodders et al. (2009). For XSPEC, we used the absorption model tbabs (Wilms et al. 2000) and the solar abundances from Asplund et al. (2009). Each individual spectrum used in XSPEC is adaptively binned to achieve a background-subtracted signal-to-noise ratio (S/N) of three.

The absorbed NEI models well describe the spectra, as shown in the left panel of Figure 2 (SPEX model). In spite of differences in the two spectral fitting packages and binning methods, we found that the best-fit results are similar to each other, except that the XSPEC analysis provides tighter constraints on the parameters, as summarized in Table 1. Hereafter, we conservatively use the results obtained with SPEX, considering that it provides uncertainty ranges mostly covering those from XSPEC. The low foreground absorption $N_H = 3.5 \pm 0.5 \times 10^{21}$ cm$^{-2}$ implies that G7.7−3.7 is not
much absorbed compared to many other SNRs toward the Galactic center. The spectra are characterized by an under-ionized thermal component with an electron temperature $kT = 0.5^{+0.3}_{-0.1}$ keV and subsolar abundances. The low abundances suggest that the X-ray emission is from shocked interstellar medium rather than from the ejecta. The electron temperature $kT$ and ionization timescale $\tau$ show a degeneracy in spectral fit as shown in the right panel of Figure 2, with higher fitted $kT$ values accompanied with lower fitted $\tau$.

The density of the gas, $n_H$, is calculated using the best-fit X-ray volume emission measure (from the parameter norm $= 10^{-14} / (4\pi d^2) \int n_e n_H dV$),\(^{10}\) where $d$ is the SNR distance, $n_e$ and $n_H$ are the electron and H densities in a volume $V$, and $n_e$ is the fully ionized plasma. As the spectra are selected from an arc-like region with a thickness of $2'$, we assume that the geometry of the X-ray-emitting region is a thin cap with an apex angle of $52 \pm 8$ (length is $8'$) and a radius the same as the SNR’s radius $R = 9'$. We adopt one-twelfth of $R$ as the thickness of the cap, which is the expected thickness of the shell for a uniform density $\rho_0$ and a shock compression ratio of four ($4\pi R^2 \Delta R (4\rho_0) = 4\pi/3R^2\rho_0$). The thickness of $1/12R$ is found to be a good approximation, because the projection effect of the cap can result in a visual thickness of $1/6$. The larger point spread function at an off-axis region of XMM-Newton and our adaptive smoothing procedure can further smooth the arc to reach the thickness of $\sim 2'$. As a result, the plasma density is estimated to be $n_H = 0.53^{+0.18}_{-0.08} d^{-0.5}_{4}$ cm$^{-3}$, where $d = d/(4 \text{kpc})$ is the distance scaled to 4 kpc.

An SNR age can be inferred from the ionization timescale $\tau$ if its plasma has not reached ionization equilibrium. For under-ionized plasma, $\tau$ is defined as a product of the electron density and the time elapsed since the gas is shock heated ($\tau = n_e t_H$). The shock age $t$ of G7.7−3.7 is estimated to be $1.2 \pm 0.6 d^{-5}_{4}$ kyr, given the low ionization timescale $\tau = 2.4^{+1.3}_{-0.7} \times 10^{-3}$ s and the best-fit H density. The small shock age implies that G7.7−3.7 is a young SNR that could possibly have been observed by ancient astronomers.

G7.7−3.7 does not show evidence of synchrotron X-ray emission or bright thermal emission with enhanced metal abundances in the hard X-ray band, which is unlike other young/historical SNRs. Nevertheless, if this hard component is very faint, it could not be easily detected with the $<10$ ks observations. Note that the SNR is likely expanding into a low-density ($<0.1$ cm$^{-3}$) environment, which explains its low X-ray brightness. The ambient density is likely non-uniform, as indicated by the not-so-spherical radio morphology and the enhanced X-ray emission in the south.

4. Is G7.7−3.7 the Remnant from Guest Star 386?

G7.7−3.7 is located near the stars Nan-Dou V ($\lambda$ Sgr) and Nan-Dou VI ($\mu$ Sgr) in the ancient Chinese asterism Nan-Dou. Figure 3 shows Nan-Dou and other three nearby asterisms, where the known SNRs (Ferrand & Safi-Harb 2012; Green 2014) are over-plotted for comparison. G7.7−3.7 and G8.7−5.0 are the known SNRs nearest to the center of Nan-Dou. There are very limited studies of the latter SNR. It has a diameter of 26’ in the radio band (Reich et al. 1988, 1990), slightly larger than G7.7−3.7. We did not find any information for the age of G8.7−5.0. Moreover, checking the X-ray archival data from ROSAT, Swift, and XMM-Newton, we did not find evidence for X-ray emission from this object. This suggests that G8.7−5.0 is an old remnant, and therefore it is unlikely to be the remnant of 386 CE. The youth ($<2000$ years) of G7.7−3.7 indicates that it is the more probable remnant of the guest star 386 that appeared at Nan-Dou.

The record of guest star 386 is the only historical record matching G7.7−3.7, given the SNR’s age ($0.6\pm1.8 d^{-5}_{4}$ kyr for 1-$\sigma$ uncertainty), the position, and expected SN brightness.

\(^{10}\) https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/node190.html

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**Figure 2.** Left panel: the XMM-Newton spectra of the southern arc fitted with an absorbed neij model. The residuals = (data-model)/model. Right panel: the correlation between the best-fit ionization timescale $\tau$ and post-shock temperature $kT$, overlayed with the 1-, 2-, and 3-$\sigma$ confidence levels (SPEX results).
Guest star 386 appeared more than two months in Nan-Dou, while other guest stars in the same asterism had short-term visibility. The relatively long duration is more probable for the guest star of G7.7−3.7, as its SN explosion should be bright enough to be observed with the naked eye on Earth (see Section 5).

It is unlikely that G7.7−3.7 is associated with another guest star in that part of the sky, one that was recorded to appear near Kui of Nan-Dou (the four southern stars in Figure 3) on 1011 February 8 (Song Shi; 宋史; Wen Xian Tong Kao; Xi 1955). The position does not agree with that of G7.7−3.7 and the time is too short to be considered an SN. We can also rule out another short-term transient event called Xing-Bo (星孛; brushy star) that appeared in Nan-Dou in November, 1375 (Guang Dong Tong Zhi; 广东通志; Xi & Bo 1965). Moreover, there is no other matching record for G7.7−3.7 from the SN/novae-like events recorded during 532 BC and 386 CE (Hsi 1957; Clark & Stephenson 1977). Therefore, we suggest that guest star 386 is an SN that resulted in G7.7−3.7, given the consistent age and position. Vice versa, if we accept that G7.7−3.7 is less than 2000 years old, there is no other historical record of the SN event than SN 386.

5. On the Relatively Short Visibility of the Guest Star

Guest star 386 was only visible with the naked eye for 2–4 months (386 April 15/May 14–July 13/August 10; Xi & Bo 1965), which is shorter than the duration of all of the other well-studied historical SNe with visibilities from a half a year to three years. Because Nan-Dou was visible in the night sky from 386 February to September at Jiankang (currently Nanjing; the capital of Jin at that time), the 2–4 month duration of the guest star is likely intrinsic to the guest star, and not due to the visibility of that part of the sky before April or after August. The asterism was visible from January to October, but in January it was only visible near dawn and October only early in the evening. Once a guest star has been detected one can keep following it, so its disappearance in August means the guest star was too faint to see with the naked eye. However, we cannot completely rule out the possibility that the guest star may have escaped attention when the asterism first became visible during the night in January or February, and was only noticed in April. However, for the present discussion we adopt the more likely possibility that the guest star was only visible for 2–4 months.

This brief duration suggests that the event was fainter than other known historical SNe, due to either large visual extinction, large distance, or low intrinsic luminosity. The two former possibilities can be ruled out. G7.7−3.7 is at high Galactic latitude where visual extinction $A_V$ is only 1.2 ± 0.2, as obtained from the fitted $N_H$ and the $N_H$–$A_V$ relation ($N_H/A_V = 2.87 \times 10^{21}$ cm$^{-2}$; Foight et al. 2016). If we assume that G7.7−3.7 was a normal SN with a peak absolute magnitude $M_V = -17$ to $-19$ at a distance of 3–6 kpc, the peak apparent magnitude would be $m_V = M_V + 5 \log(d/10 \text{ pc}) + A_V = -1.7$ to $-5.6$ mag. This $m_V$ value, based on the assumption of a normal SN, would put the event among the brightest objects on the night sky at that time and visible for much longer than 4 months, which conflicts with the record of the guest star.

The absolute magnitude $M_V$ of the guest star shortly before it disappeared should be around $-9$ to $-8$ mag, given that a limiting magnitude for the naked eye is 5–6 mag. This brightness is exceptionally low compared to normal SNe, but may be consistent with some low-luminosity SNe (see Figure 4). A class of low-luminosity Type IIP SNe has a peak $M_V$ in the range $-14$ to $-16$ mag, and are very faint after 3–5 month’s optical plateau (e.g., as faint as $\sim -9$ mag for SN 1999eu, Pastorello et al. 2004). Another small class of very low-luminosity SNe belongs to Type Ia. An extremely sub-luminous case is Type Ia SN 2009ha, which has a peak $M_V$ as faint as $-14$ mag, very low photospheric velocity, and small explosion energy ($2 \times 10^{46}$ erg, Foley et al. 2009). The relatively high Galactic latitude of G7.7−3.7 might prefer a lower mass progenitor. However, the explosion kinetic energy of G7.7−3.7 is estimated to be $E \sim 2.0 \times 10^{51}$ erg (d/4 kpc)$^{4.5}$ s$^{-1}$, assuming that the SNR is in Sedov phase, has an age of 1632 yr, where $\chi$ is the deviation of the mean ambient density from the arc’s preshock density ($\chi < 1$ means that the arc is at a density-enhanced region). This rules out the possibility of a weak explosion, low-luminosity Type Ia SN. The distance of G7.7−3.7 is likely close to the lower limit of the 3–6 kpc range (with a smaller $E$ of...
\(\sim 5.5 \times 10^{50} \text{ erg s}^{-1} \text{ at } 3 \text{ kpc}\) and/or the mean ambient density is much lower than near the arc, as the low-luminosity Type IIP SNe are thought to have a relatively low explosion energy \((1-9) \times 10^{50} \text{ erg}\); see Table 5 in Lisakov et al. 2018, and references therein. In addition to the explanation of a very low-luminosity Type IIP SN, there is a possibility that the extinction of the explosion site is much higher than at the X-ray arc, which could be tested with future observations.

Our last remark is about the intriguing properties of G7.7–3.7. If the SNR is indeed the debris of the guest star 386 as we suggested, it would be the faintest historical SNR in the X-ray band, with an X-ray flux of \(2.3 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}\) in 0.3–2 keV. Moreover, G7.7–3.7 might be the only known historical SNR resulted from a very low-luminosity SN, and, therefore, of particular value for studying the evolution and origin of this small group of SNe (<4%–5% of all Type II SNe, Pastorello et al. 2004).

6. Conclusion

We report that G7.7–3.7 is a 1.2 ± 0.6d_{0.5} kyr young SNR probably associated with the guest star of 386 CE, given the consistent age and position, and given that there are no other compatible historical records that could be associated with this SNR. The SNR has a non-uniform X-ray distribution, with the X-ray emission only bright in the southern arc. The spectroscopic analysis shows that the shocked plasma is under-ionized \((2.4^{+1.3}_{-1.1} \times 10^{10} \text{ cm}^{-3} \text{ s})\) with subsolar abundances. The association between G7.7–3.7 and guest star 386 would suggest the supernova to be a low-luminosity supernova, possibly a low-luminosity Type IIP, in order to explain the not very long visibility (2–4 months) of the guest star. So far only limited observations and studies exist for G7.7–3.7. Given the peculiar properties of the SNR, and its probable association with the guest star of 386 CE, we hope that this situation will improve in the near future.

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\[\text{Software: XSPEC (Arnaud 1996), SPEX (Kaastra et al. 1996), SAS, DS9, Stellarium (vers. 0.18.0).}\]

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