X-RAY OBSERVATION AND ANALYSIS OF THE COMPOSITE SUPERNOVA REMNANT G327.1–1.1

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ABSTRACT

Based on the data from the observation of the supernova remnant (SNR) G327.1–1.1 by the Advanced Satellite for Cosmology and Astrophysics (ASCA) and ROSAT, we find that G327.1–1.1 is a composite remnant with both a nonthermal emission component and a diffuse thermal emission component. The nonthermal component is well fitted by a power-law model with photon index $\Gamma \sim 2.2$. This component is attributed to the emission from the synchrotron nebula powered by an undiscovered central pulsar. The thermal component has a temperature of about 0.4 keV. We attribute it to the emission from the shock-heat swept-up interstellar medium (ISM). Its age, explosion energy, and density of ambient medium are derived from the observed thermal component. Some characteristics of the synchrotron nebula are also derived. We have searched for the pulsed signal but have not found it. The soft X-ray (0.4–2 keV) and hard X-ray (2–10 keV) images are different, but they both elongate in the southeast-northwest direction. And this X-ray southeast-northwest elongation is in positional coincidence with the radio ridge in the Molonglo Observatory Synthesis Telescope (MOST) 843 MHz radio map. We present a possibility that the X-ray nonthermal emission mainly comes from the trail produced by a quickly moving undiscovered pulsar, and the long radio ridge is formed when the pulsar is moving out of the boundary of the plerionic structure.

Subject headings: ISM: individual (G327.1–1.1) — radiation mechanisms: nonthermal — shock waves — supernova remnants — X-rays: ISM

1. INTRODUCTION

Supernova remnants (SNRs) are usually classified as shell type, plerion type, or composite type (Weiler 1985). Composite type makes up the most complex class, with varying appearance. The differences in appearance in X-ray and radio morphology and in emission nature are due to different characteristics of the progenitors and different physical conditions of the interstellar medium (ISM) surrounding them. For composite SNRs it is important to investigate the emission nature of the center-brightened part. As to the nonthermal nature, it is usually believed to come from the synchrotron nebula powered by pulsar wind (e.g., Blanton & Helfand 1996; Tamura et al. 1996; Harrus, Hughes, & Slane 1998). In recent years, the ASCA (Tanaka, Inoue, & Holt 1994) observations have revealed more and more nonthermal nature in the central part of some SNRs, such as G11.2–0.3 (Vasisht et al. 1996), Kes 75 (Blanton & Helfand 1996), W44 (Harrus, Hughes, & Helfand 1996), MSH 15–52 (Tamura et al. 1996), CTA 1 (Slane et al. 1997), Kes 73 (Gotthelf & Vasisht 1997), and MSH 11–62 (Harrus et al. 1998). These findings will improve our knowledge in the evolution of massive stars, the evolution of the synchrotron nebula, and the occurring rates of two kinds of supernovae.

G327.1–1.1 was detected by Caswell et al. (1975) as a faint shell with a diameter about 14' in the radio band. Lamb & Markert (1981) found that it was located in the error box of the COS B source CG 327–0. Seward (1990), in his summary work on Einstein observation of SNRs, classified it as an "irregular" SNR, the image of which is somewhat elongated in the south and the east to south directions. Based on the ROSAT observation, Seward, Kearns, & Rhode (1996) used a simple blast-wave model to estimate its age at about 7000 yr, a low ISM density at about 0.065 electrons cm$^{-3}$, and the supernova explosion energy at about $10^{51}$ ergs under an assumed distance of 6.5 kpc. Whiteoak & Green (1996) found that this source was a composite SNR in 843 MHz with a faint shell and an unusual off-center plerionic component (Fig. 4), and the plerionic component has two peaks in the central part. They also noticed that a 2' long ridge extended northwest from the west side of the plerionic component. The contribution of the plerionic component is 2.0 Jy, while the total flux of G327.1–1.1 in 843 MHz is 7.6 Jy. No public radio spectral index of G327.1–1.1 is available. Since its flux in 408 MHz is 10.6 Jy and its flux in 5 GHz is 4.3 Jy (Clark, Caswell, & Green 1975), as an estimate, its radio spectral index for the whole SNR is about 0.4.

In this paper, we present the ASCA observation of G327.1–1.1 and the analyses combined with ROSAT observation and the Molonglo Observatory Synthesis Telescope (MOST) 843 MHz radio observation. ASCA and ROSAT observation and data reduction are described in §2. The analyses of its spectra, spatial structure, and temporal behavior are given in §3. The derived physical quantities and physical scenario are discussed in §4. Section 5 is a simple conclusion.

2. X-RAY OBSERVATION AND DATA REDUCTION

ASCA observed G327.1–1.1 on 1996 March 9, with two kinds of detectors, the gas scintillation spectrometer (GIS) and the solid state spectrometer (SIS). SIS profits from higher energy resolution ($E/\Delta E = 50$, at 6 keV) than GIS, but has poor time resolution (4 s for the 1 CCD mode), and its spatial resolution is limited by the wide point-spread function (PSF) of the X-ray telescope (XRT) with FWHM of about 3'. GIS has higher time resolution and detection efficiency above $\sim 3$ keV than GIS, so the two kinds of detectors are complementary. In this observation the SIS data are in 1 CCD mode. All data are screened using the

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standard REV2 processing, which includes removing photons with low cutoff rigidity (COR), correction for the South Atlantic Anomaly (SAA), grade selection, removing hot and flickering pixels, and so on. After screening we obtain about 22,000 events from each GIS detector, about 6000 events from SIS1 and about 7500 events from SIS0. Approximate exposure time is 37.1 ks for SIS-screened data and 39.5 ks for GIS-screened data. GIS data used non-standard mode (10 bits for time record) to increase time resolution. To achieve this high time resolution, the GIS rise-time information (RTI) was sacrificed. Without RTI, the background rejection based on the RTI cannot be done (ASCA Data Reduction Guide 1997), so the data will have more internal background than otherwise. Thus, in the spectral analysis, only SIS and the Position Sensitive Proportional Counter (PSPC) data are used, while GIS data are used to do temporal analysis. The standard software FTOOL4.0 (XSELECT1.3) are used to process the data.

ROSAT observed G327.1 – 1.1 during 1993 March 3–13 using the PSPC. After subtracting the background source and foreground source, a total about 1600 events (including background) are obtained in the region of G327.1 – 1.1. The ROSAT PSPC data have better spatial resolution and a larger field of view (FOV) than the ASCA data, so we use these profits as a supplement to the ASCA data.

3. ANALYSIS

3.1. Spectral Analysis

Since G327.1 – 1.1 is a faint source, it is necessary to get a good estimate of its background spectrum. The ASCA Data Reduction Guide (1997) provides two basic methods of obtaining background spectra. One is to subtract a source-free part from the same observation, and the other is to subtract suitable portions of blank-sky observations. In the case of G327.1 – 1.1, the first is not suitable because the observation was made in 1 CCD mode and the FOV is almost full of the source. In addition, the responses of SIS depend on position in the FOV, so background events should be extracted from the same part of the FOV as the source events. The second method is good for high-latitude sources. But for sources in the Galactic plane, like G327.1 – 1.1, the contribution of “Galactic ridge” emission (Warwick et al. 1985; Koyama et al. 1986; Valinia & Marshall 1998) to the observed spectra must be considered.

(Blanton & Helfand 1996). So the following method is applied to get the background spectrum. First, we select a small source-free region in the same observation, and estimate the photon flux in this region. We also find some observations from the ASCA archive data that are near G327.1 – 1.1, and in each of those observations we also select one or two small source-free regions and estimate the photon fluxes. If the X-ray background does not change significantly around G327.1 – 1.1, those photon fluxes that are estimated in the above regions give the approximate range of the background photon flux around G327.1 – 1.1.

Second, we consider the sequences of the public Galactic ridge data. The photon flux is estimated for each of them. Those sequences that have photon fluxes approximately in the range that we estimate above are selected. Finally the selected sequences are used to extract background spectrum.

Referring to the article of ROSAT observation on G327.1 – 1.1 (Seward et al. 1996), it is found that source 4 (Seward et al. 1996, Fig. 5 and Table 3) is just in the FOV of SIS. Although it is weak in the FOV of SIS, we subtract it in the analysis.

After doing this, we extract G327.1 – 1.1 spectra with a 45' radius circle centered in R.A. 15°54′16'', decl. –55°03′57'' (J2000). The spectra are binned to 256 channels to contain enough photon counts for $\chi^2$ model fits. The inclusion of PSPC data would contribute to constrain the $N_H$. The Raymond & Smith (1977) thermal plasma model with cosmic abundances is used for the thermal component, the power-law model is used for the nonthermal component, and the model from Morrison & McCammon (1983) for absorption along the line of sight with an equivalent column density of hydrogen is also used. The standard software XSPEC (10.0) is used to fit the spectra. The result of the spectral fit is shown in Table 1. We can see that adding a thermal component significantly improves the fit of only a power-law model. The spectrum of G327.1 – 1.1 and the model are shown in Figures 1 and 2, respectively. It is obvious that the power-law component is dominant and the thermal component is distinct only below 2 keV. The residuals in Figure 1 show a weak sign for an emission line in 1.3–1.4 keV, which may be the Mg Kα emission line or the blend of Fe L lines.

Limited by the FOV of SIS, the region that we study in the above is mainly the central part. Therefore, ROSAT

| Parameter | Value$^b$ |
|-----------|-----------|
| $N_H$ (10$^{22}$ cm$^{-2}$) | 1.14$^{+0.12}_{-0.10}$ |
| Photon index | 2.01$^{+0.12}_{-0.10}$ |
| $kT$ (keV) | 2.2$^{+0.20}_{-0.12}$ |
| $F_X$ (observed nonthermal) (ergs cm$^{-2}$ s$^{-1}$) | 5.9 $\times$ 10$^{-12}$ |
| $F_X$ (observed thermal) (ergs cm$^{-2}$ s$^{-1}$) | 1.1 $\times$ 10$^{-11}$ |
| $\chi^2$ | 262.1/277(dof) |

Note.— We used data of SIS0, SIS1, and PSPC to do a joint fit.

a Cosmic abundances (Anders & Grevesse 1989).
b Single-parameter 2.706 $\sigma$ errors (90% confidence region).
c $F_X$ is the flux in the 0.5–10 keV band.

$^b$ Value$^b$
PSPC data are used to analyze the outer part of G327.1−1.1. The data are extracted from a circle of radius 7.5, deducting the part that we have studied above and the foreground and background sources. When spectral fitting is performed, $N_H$ is fixed to $1.8 \times 10^{22} \text{ cm}^{-2}$, according to our SIS and PSPC data joint fitting. The fitting result is listed in Table 2.

### 3.2. Spatial Analysis

The PSF of the *ASCA* X-ray telescopes has a relatively sharp core (FWHM ~ 50′), but broad wings (half-power diameter of 3′). So it is not trivial to do spatial analysis for extended sources. Here we use the Lucy-Richardson method to perform the deconvolution of SIS images (e.g., Jalota, Gotthelf, & Zoonematkermani 1993). First the raw soft X-ray (0.4−2 keV) image and hard X-ray (2−10 keV) image of G327.1−1.1 are obtained. Then we perform background subtraction, exposure correction, and vignetting correction on these raw images. In those processes, FTOOLS ASCAEFFMAP and ASCAEXPO are used, and the background images are obtained using a similar method to that in § 3.1. Second, we consider applying the Lucy-Richardson method. The signal-to-noise ratio of the two images are all larger than the lower limit of 5 $\sigma$. But the photon numbers of each image (about 3200 counts) are not good enough. So we perform only 18 iterations of the Lucy-Richardson deconvolution to these two images and smooth the deconvolved images with a Gaussian function of FWHM = 45′ to avoid the false overresolving. In the case of the PSPC image, owing to its better spatial resolution than *ASCA*, we only smooth it with a Gaussian function of FWHM = 30′. These images are shown in Figure 3. The peaks of X-ray emission in the soft and hard *ASCA* images and the PSPC images are all located in the same place: R.A. 15°54′25″ (±0′1), decl. −55° 04′04″ (±0′9) (J2000). And a similar

### TABLE 2

PROPERTIES OF THE THERMAL COMPONENT

| Property          | Value$^{a,b}$ |
|-------------------|---------------|
| $N_H$ ($10^{22} \text{ cm}^{-2}$) | (1.8)         |
| $kT$ (keV)        | 0.40 $^{+0.14}_{-0.13}$ |
| $F_X$ (0.5−2 keV) (ergs cm$^{-2}$ s$^{-1}$) | $7.5 \times 10^{-13}$ |
| Unabsorbed $F_X$ (0.5−2 keV) (ergs cm$^{-2}$ s$^{-1}$) | $6.2 \times 10^{-11}$ |

| Derived Properties$^{c,d}$ |
|-----------------------------|
| $D$ (kpc)                   | (9.0)         |
| $R$ (pc)                    | 17.0          |
| $n_0$ (cm$^{-3}$)           | 0.10          |
| $t_4$ (10$^6$ yr)           | 1.1           |
| $M_w$ ($M_\odot$)           | 49            |
| $E_u$ (10$^{51}$ ergs)      | 0.23          |
| $v_e$ (km s$^{-1}$)         | 600           |

$^a$ Values in parentheses are fixed.

$^b$ Single-parameter 2.706 $\sigma$ errors (90% confidence region).

$^c$ These properties are the best fit of *ROSAT* data to mainly the outer part of G327.1−1.1.

$^d$ We synthesize the fitting results from *ASCA* data and *ROSAT* to calculate these properties.
southeast-northwest elongated structure can be seen in all of the three images, especially in the hard X-ray image. But compared to the hard ASCA image, in which the emission mainly comes from the places close to the common peak, the soft ASCA image and the PSPC image are more extended. From the best fit the thermal flux is estimated at 30% of the total observed flux in the soft X-ray band (0.4–2 keV), and we can see some clumps in the PSPC image, which are beyond the hard contours but within the soft contours. Thus, it may be natural to attribute some parts of the soft extension to the contribution of the thermal component. From § 3.1 it is known that almost all the emission above 2 keV is nonthermal. Therefore, the southeast-northwest elongation in the hard X-ray image indicates the southeast-northwest elongation of the synchrotron nebula. When we overlay the ROSAT image on the MOST 843 MHz radio contour (Fig. 4), it is surprising to find that the X-ray elongation is in very good positional coincidence with the radio long ridge. This phenomenon helps to confirm the reality of the southeast-northwest elongation. If we prolong the elongation (or radio ridge) to the inner part of the plerion, it will not pass through the brightest central part. But we notice that there is some weak emission to the southwest of the plerion (Fig. 4), and if these are also taken as parts of the plerion, the elongation will be roughly in the diameter direction of the plerion, so we suggest that an undiscovered pulsar (see § 4.3) may be located just in the head of the radio ridge and the X-ray elongation, and the X-ray emission may come mainly from the trail caused by the quick movement of the assumed pulsar (e.g., Wang, Li, & Begelman 1993; Frail et al. 1996; Wang & Gotthelf 1998). This is just a possible interpretation.

3.3. Temporal Analysis

Since the X-ray emission of G327.1—1.1 comes mainly from the power-law component, it is interesting to know whether a pulsed signal could be found in the ASCA data. After barycenter correction of the photon times of arrival (using FTOOL TIMECONV), we extract GIS2 (GIS3) light curves from a 5′ radius circle centered on the peak of the X-ray emission. Both medium bit-rate mode (resolution ~0.5 ms) and high bit-rate mode (resolution ~0.06 ms) data are used. The combination of high and medium bit-rate mode limits the overall accuracy to 5 ms. First we set the time bins as 1, 2, and 10 minutes; no evidence for significant variations on these timescales is found. Then we extract only high-energy photons (2–10 keV) and use several time bins: 5 ms, 16 ms, 0.1s, 1 s. A 220 point fast Fourier transform was applied to the light curves using different Newbin time to search a period down to 10 ms, but no significant pulsations are detected.

4. DISCUSSION

4.1. Distance

The following methods are used to estimate the distance of G327.1—1.1. Ryter, Cesarsky, & Audouze (1975)
obtained the following statistical relation: \( N_X/E(B - V) = (6.8 \pm 1.6) \times 10^{31} \text{ equivalent H atoms cm}^{-2} \text{ mag}^{-1} \), where \( N_X \) refers to equivalent H column density observed in the X-ray band. From the contour diagrams given by Lucke (1978), it is found that \( E(B - V)/d \sim 0.3 \text{ mag kpc}^{-1} \) in the direction of G327.1–1.1. Combining these two relations and the fitting result of \( N_X \), we get the result that the distance of G327.1–1.1 is about 9 kpc.

It is known that the SNR MSH 15–56 is only about 1.5 kpc from G327.1–1.1, and the kinematic distance of MSH 15–56 is 4.1 ± 0.7 kpc (Rasado et al. 1996). From the ROSAT data analysis, Kassim, Hertz, & Weiler (1993) obtained \( N_H = (8.9 \pm 0.3) \times 10^{21} \text{ cm}^{-2} \) for MSH 15–56. Since the measured X-ray absorbing column density of G327.1–1.1 is about twice that measured for MSH 15–56, it is reasonable to assign a distance of about 8–9 kpc to G327.1–1.1.

Therefore, a distance of 9 kpc is used in the following discussion.

4.2. The Thermal Component

As stated in § 3.1, the region in which we do the joint spectral fit of the SIS and PSPC data is mainly the inner part, while the PSPC data are also used to study the other parts of G327.1–1.1. As shown in Tables 1 and 2, the thermal temperatures obtained for the two regions are very similar and the difference between their thermal fluxes can be explained well by the difference between their emission volumes. Such consistency suggests that the thermal component is almost all over the source, and should be diffuse as implied by little condensation in the outer part of the image and its low-flux nature. The large radius of the radio shell of G327.1–1.1 implies its old age. Therefore, it is natural to think that the SNR is in the adiabatic expansion phase. For simplicity, and following Seward et al. (1996), we also assume a complete shell, and attribute the incompleteness of the shell to the inhomogeneities in the ISM. A simple Sedov (1959) relation is the following:

\[
\begin{align*}
    t_s & = 9.2 \times 10^2(T/\text{keV})^{1/2}(0.6/\mu)^{1/2}, \\
    t_4 & = (T/\text{keV})^{-1/2}(R_s/25 \text{ pc}) , \\
    E_{51} & = 1.16 \times 10^{-3}(n_0/1 \text{ cm}^{-3})(T/\text{keV})(R_s/\text{pc})^3 , \\
    M_{su}(\odot) & \approx 0.10(n_0/1 \text{ cm}^{-3})(R_s/\text{pc})^3 ,
\end{align*}
\]

where \( v_s \) is the shock speed in units of km s\(^{-1}\), \( t_4 \) is the time since the supernova explosion in units of 10\(^4\) yr, \( n_0 \) is the mean ambient particle density, \( E_{51} \) is the explosion energy in units of 10\(^{51}\) ergs, \( R_s \) is the radius of the supernova shock front, \( M_{su} \) is the swept-up mass in units of the mass of the Sun, and \( \mu = 0.6 \) for cosmic abundances.

The instantaneous power radiated from a shell is \( L_s(t) = (16\pi/3)R_s^2(t)n_0^2 \Lambda(T) \), where \( \Lambda(T) = 1.0 \times 10^{-22}T_6^{-0.7} + 2.3 \times 10^{-24}T_6^{0.5} \text{ ergs cm}^3\text{ s}^{-1} \) is the radiative cooling function (McCray 1987). Here \( T_6 \) is the postshock temperature in units of 10\(^6\) K. We synthesize the fitting results.
Fig. 4.—ROSAT gray image (smoothed with a Gaussian function with FWHM = 30") overlie the radio contour map in 843 MHz. The two brightest sources in the ROSAT image were attributed to foreground or background sources by Seward et al. (1996). The radio shell is nearly complete except in the northeast and northwest. The radio plerionic structure is off center and has two peaks. The radio long ridge is well in positional coincidence with the main part of the ROSAT X-ray emission. We add some levels into the original linear scale levels to show the plerionic structure and the shell more clearly, so radio contour levels are 0.02, 0.05, 0.15, 0.3, 0.45, 0.6, 0.75, 0.9, and 0.95 of the maximum.

from ASCA data and ROSAT data to calculate the properties and list the results in Table 2. The value of $M_{\infty}$ is greater than any reasonable estimate of the initial ejected mass and serves as a self-consistency check to ensure that G327.1−1.1 has reached the adiabatic phase as assumed. The explosion energy and the mean ambient particle density are a little low, and these results are consistent with the result of Seward et al. (1996).

The presence of a dominant power-law component in the ASCA spectra of G327.1−1.1 clearly suggests the existence of an undiscovered pulsar and a pulsar-driven synchrotron nebula. Based on the observed quantities, some properties of the pulsar and its surrounding synchrotron nebula are discussed as follows.

The luminosity of the nonthermal component and the current spin-down energy loss rate of the pulsar were found to follow an empirical relationship (Seward & Wang 1988) for the Einstein energy band. A similar relationship for the ASCA band (1−10 keV) is $\log L_X = 1.27 \log \dot{E} - 12.3$ (Kawai, Tamura, & Shibata 1997). If we take the observed unabsorbed value of $L_X$, we obtain $\dot{E} = 1.5 \times 10^{37} d_{10}^{-6}$ ergs s$^{-1}$. Under the assumption that a pulsar’s current spin period is much larger than its initial spin period and its moment of inertia, $I = 10^{45}$ g cm$^2$, we will get the current spin period (Seward & Wang 1988),

$$P = 0.25 [t(10^3 \text{ yr})^{-1/2} [\dot{E}(10^{37} \text{ ergs s}^{-1})]^{-1/2} \text{ s}$$

$$= 62 d_{10}^{-1.3} \text{ ms}, \quad (5)$$

the period derivative,

$$\dot{P} = 1.58 \times 10^{-11} [P(s)][t(10^3 \text{ yr})]^{-1} \text{ s s}^{-1}$$

$$= 8.9 \times 10^{-14} d_{10}^{-2.3} \text{ s s}^{-1}, \quad (6)$$

the surface magnetic field,

$$B_0 = [P(s)]^{1/2} \times 10^{12} \text{ G}$$

$$= 2.3 \times 10^{12} d_{10}^{-1.8} \text{ G}, \quad (7)$$

Although the radio spectral index of the plerion is unknown, the break frequency $v_B$ can also be estimated in the two extreme cases. In case I, the plerion has a flat spectrum in the radio band, $S_v \sim 2 \text{ Jy}$. Since $S_v \approx 0.3 \mu\text{Jy}$ at 5 keV is known from the above X-ray spectral fit, it is easy to use the derived X-ray spectral index to extrapolate and obtain $v_B \sim 2.5 \times 10^8 \text{ GHz}$. In case II, assuming a radio spectral index of about 0.4 (as mentioned in § 1 for the whole source), then the derived $v_B$ would be about $1.3 \times 10^5 \text{ GHz}$; or, assuming the steepest spectral index 0.3 for pure
The radio luminosity of ergs s\(^{-1}\) is about \(2.5 \times 10^4\) GHz. Hence, \(v_B\) may be in the infrared range: \(2.5 \times 10^3\)–\(1.3 \times 10^4\) GHz (or \(3.5 \times 10^4\) GHz), which is comparable to the break frequency of the Crab Nebula, \(\sim 10^4\) GHz, and the derived break frequency of Kes 75, \(\sim 10^4\) GHz (Blanton & Helfand 1996). In the two extreme cases, integrating the spectrum from \(10^7\) to \(10^{11}\) Hz, we derive the radio luminosity \(L_R\) of 1.9 \(\times 10^{33} d_2^2\) ergs s\(^{-1}\) or 4.8 \(\times 10^{33} d_2^2\) ergs s\(^{-1}\), respectively, while as a comparison the unabsorbed X-ray luminosity \(L_X\) is \(1.2 \times 10^{33} d_2^2\) ergs s\(^{-1}\). If we take a \(v_B\) value of \(10^4\) GHz, from the relationship \(v_B \approx 3.6B^{-2}(t/10^4\) yr\(^{-1}\)) (Lozinskaya 1992) we get \(B \sim 0.7 \times 10^{-4}\) G. If we assume that the reverse shock has passed the boundary of the plerion, and the equilibrium between the plerion magnetic pressure and the ambient thermal pressure \(P_0\) has been approached, we can obtain another estimate about \(B\). According to the Sedov solution, the central pressure should be \(P_0 = 0.31P\) (postshock) = 0.0372\(P_0/(R_p/\theta)\)\(^2\) (Reynolds & Chevalier 1984), then we obtained \(P_0 = 1.4 \times 10^{-10}\) dyn cm\(^{-2}\), \(B \sim 0.6 \times 10^{-4}\) G. These two estimated values of field strength are similar and are typical for synchrotron nebulae, such as W44 (Fralil et al. 1996).

The X-ray emission lifetime of relativistic particle \(\tau_R\) is about \(50\)\(\times 10^2\), while the radio emission lifetime of relativistic particle \(\tau_R\) is about \(9 \times 10^2\) yr (1 GHz)\(^{-1}\). Where \(\epsilon\) is the characteristic synchrotron photon energy in units of keV, and \(B_{22} = B/(10^{-4}\) G). Because \(\tau_R > \tau_X\), the X-ray synchrotron nebula should be significantly smaller than the radio one and should be located close to the pulsar. Therefore, the undiscoversed pulsar should be located close to the hard X-ray emission.

### 4.4. The X-Ray Trail-like Configuration and the Morphology of the Plerion

An interesting phenomenon of this source is the unusual X-ray trail-like morphology that we have mentioned above. As a possible explanation, we attribute this trail-like morphology to the trail confined by a bow shock which is caused by a quickly moving undiscovered pulsar. The X-ray emission might come mainly from the shocked pulsar wind, which flows gradually from the head portion of the bow shock to the trail along the thick layer of the reverse shock. Assuming the pulsar was “kicked out” at the moment of supernova explosion and the birthplace is the geometric center of the plerion, the projectional displacement of the pulsar is about 7 pc and the derived velocity of the pulsar would be \(v_p \sim 600(\sin \theta)^{-1}\) km s\(^{-1}\), where \(\theta\) is the angle between the line of sight and the real direction of the trail. This derived velocity is a reasonable velocity for pulsars (Lyne & Lorimer 1994). The ram pressure balance condition, \(n_0 m_u v_p^2 = E/(4\pi r_c^2 c)\), yields the standoff distance of the apex of the bow shock, \(r_a \sim 0.082 (n_0/0.1\) cm\(^{-3}\)\(^{-1/2}\) sin \(\theta\) pc. This distance corresponds to the observed separation of about \(1\)‘9 and obviously cannot be resolved by ASCA or ROSAT. The situation here seems like that in PSR 1929+10 (Wang et al. 1993), where the X-ray radiation arise from relativistic flows inside a narrow tunnel. For estimating the length of the trail, a quantitative analysis yields a bulk velocity \(\sim 0.5–0.6\) c in the layer of the shocked pulsar wind in most of the tunnel, based on the algorithm given by Chen, Bandiera, & Wang (1996). With such a bulk velocity, in the X-ray-emitting lifetime, the X-ray synchrotron-emitting flow (typified by 1 keV) will go through a length of about 7.5–9 pc. This is essentially in agreement with the measured projected length, about 6 pc, when considering the factor \(\sin \theta\) and the uncertainty in the value of \(B\).

G327.1–1.1 is clearly a composite SNR in the radio band. The plerion is nearly in the center of the SNR, and the little eastward displacement may be explained by the inhomogeneities in the ISM. The ridge may be created by the drag of the quickly moving pulsar. Certainly further observations are necessary to obtain more information about this source, such as the spatial distribution of the radio spectral index, the information about polarization, etc.

If a quickly moving pulsar does exist in G327.1–1.1, it will be interesting to examine its relationship to the COS B source CG 327–0. However, CG 327–0 has not been confirmed in the recent and more sensitive 100 MeV gamma-ray catalogs of EGRET. Further investigation may be needed.

### 5. Conclusion

The morphological and spectral analyses of the ASCA, ROSAT, and MOST radio data reveal that G327.1–1.1 is obviously a composite SNR. The X-ray synchrotron nebula may be powered by an undiscovered pulsar, which may now be located near the X-ray common peak, or the head of the radio ridge. The X-ray spectrum of G327.1–1.1 is well fitted by two components, a power-law component with photon index of \(\sim 2.2\) and a thermal component with temperature \(\sim 0.4\) keV. From the best fit of the thermal component, the explosion energy of the supernova, the ISM density, the shock velocity, and the age of G327.1–1.1 are derived as shown in Table 2. From the best fit of the non-thermal component, we predict the period, the period derivative of the pulsar, and the strength of its surface magnetic field as shown in § 4.3. These quantities are all in the range of reasonable values for a typical pulsar. The magnetic field of the synchrotron nebula is also estimated. The positional coincidence between the unusual X-ray elongation and the radio ridge may imply the existence of a trailing configuration produced by a runaway pulsar at a velocity of more than 600 km s\(^{-1}\). The emission from the ridge (or the trail) is assumed to arise from the synchrotron nebula confined by a bow shock. We expect that, with the development of the X-ray satellite, more and more composite SNRs will be found. And for this source, we hope that further observations will be carried out by XMM or AXAF to provide more detailed information.

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Note added in proof.—After acceptance of our paper, P. Slane and R. Bandiera provided us with a preprint that notes the presence of the pointlike source 1WGA J1544.4 – 5503 detected at the tip of the radio finger by the ROSAT PSPC. The source position is in good agreement with the peak of the ASCA hard X-ray image (Fig. 3). The ~ 1.6% flux ratio between this source and the X-ray plerion is typical of other pulsar/plerion associations. Further observations of this region are thus of considerable interest.