G0.570-0.018: A YOUNG SUPERNOVA REMNANT? *INTEGRAL* AND VLA OBSERVATIONS

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ABSTRACT

We report *INTEGRAL* IBIS γ-ray and VLA radio observations of G0.570−0.018, a diffuse X-ray source recently discovered by *ASCA* and *Chandra* in the Galactic center region. Based on its spectrum and morphology, G0.570−0.018 has been proposed to be a very young supernova remnant. In this scenario, the presence of γ-ray lines coming from the short-lived radioactive nucleus ^{44}Ti and synchrotron radio continuum emission are expected. The first could provide information on nucleosynthesis environments in the interior of exploding stars, and the latter could probe the interaction between the supernova blast wave and the circumstellar/interstellar matter. We have not detected ^{44}Ti lines or any conspicuous radio feature associated with this source down to the achieved sensitivities. From the derived upper limits we set constraints on the nature of G0.570−0.018.

Subject headings: gamma rays: observations — radio continuum: ISM — ISM: individual (G0.570−0.018) — nuclear reactions, nucleosynthesis, abundances — supernova remnants

1. INTRODUCTION

The Galactic center region is one of the richest regions in sources of the Milky Way. Numerous X-ray binaries, massive stellar clusters, and supernova remnants (SNRs) lie in this complex region, immersed in an extended high-temperature plasma that heavily dominates the global soft X-ray emission (Koyama et al. 1996). Recently, a diffuse X-ray source, G0.570−0.018, was detected with the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) and confirmed with *Chandra X-Ray Observatory* observations. The X-ray source has a ringlike structure, about $10''$ in radius, with a spectrum that can be fitted by a thermal emission model with a temperature of about 6 keV (Senda et al. 2002). The high value derived for $N_{\rm H}$ ($\sim 10^{23}$ cm^{-2}) is consistent with a source located near the Galactic center, at a distance of about 8 kpc. Based on the detection of an iron line with a high equivalent width at 6.5 keV and a high Fe abundance (suggesting a recently shocked plasma), the authors concluded that the origin must be a very young SNR with an age of ~ 80 yr. However, based on the analysis in the *Chandra* image of a faint east-west X-ray tail possibly related to G0.570−0.018, they conclude that it could be about twice as old. In a SNR scenario, we might expect nonthermal radio continuum emission from shock-accelerated electrons and the presence of γ-ray lines associated with the decay of ^{44}Ti. This radioactive nucleus is thought to be exclusively produced in supernova (SN) explosions. It is primarily generated in the α-rich freeze-out from nuclear statistical equilibrium occurring in the explosive silicon burning stage of core-collapse SNe (e.g., Woosley & Weaver 1995), while a normal freeze-out Si burning is at play in Type Ia SNe (Thielemann et al. 1986). The radioactive decay chain ^{44}Ti $\longrightarrow$ ^{44}Sc $\longrightarrow$ ^{44}Ca, with a lifetime of about 87.5 yr (Wietfeldt et al. 1999), produces three γ-ray lines at 67.9 keV, 78.4 keV (from ^{44}Sc*), and 1157 keV (from ^{44}Ca*) with similar branching ratios. It has been shown that ^{44}Ti may reveal young Galactic SNRs that could be hidden from our view at optical wavelengths due to heavy extinction in the Galactic plane region. ^{44}Ti γ-ray lines have been observed in the young SNRs Cassiopeia A (Iyudin et al. 1994; Vink et al. 2001; Vink 2005) and RXJ 0856−4622 (Iyudin et al. 1998). Moreover, the radio data can provide information on the interaction of the blast wave with the circumstellar and local interstellar media. G0.570−0.018 is then an ideal case to search for specific signatures of young SNe such as the ^{44}Ti lines and the radio nonthermal radiation by combining both observations as early proposed by Silberberg et al. (1993).

In this paper, based on the *INTEGRAL* (IBIS *INTEGRAL* Soft Gamma-Ray Imager [ISGRI]; § 3.1) and VLA[5] (§ 3.2) data, we investigate whether G0.570−0.018 is indeed a young SNR. Its possible type and characteristics, if this is the case, are discussed in § 4 in the light of all available observational and theoretical material.

2. *INTEGRAL* AND VLA OBSERVATIONS

The *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*; Winkler et al. 2003) is an ESA mission carrying two main telescopes based on a coded aperture imaging system: IBIS (Ubertini et al. 2003) and SPI (Vedrenne et al. 2003). IBIS, with its soft γ-ray (15 keV–1 MeV) imager ISGRI (Lebrun et al. 2003), provides the finest imaging ($13'$ FWHM) and the best line sensitivity up to a few hundred keV. It is therefore best suited for a search for the two low-energy ^{44}Ti lines, and we only analyzed data from this instrument. *INTEGRAL* is mainly devoted to the observation of Galactic sources and spends a considerable amount of time pointing toward the Galactic plane and the Galactic center regions. We performed an analysis of data from the Galactic Center Deep Exposure (GCDE) of the Core Program, acquired during the first 2 years of *INTEGRAL* operations. In a search for the radio counterpart for G0.570−0.018, we have reprocessed archival VLA data at $\lambda = 20$ and 6 cm from different pointings during which this source was within the field of view. We have

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also analyzed the 90 cm intermediate-resolution VLA image of the Galactic center from LaRosa et al. (2000).

3. ANALYSIS AND RESULTS

3.1. ^{44}Ti γ-Ray Lines

Both *ASCA* and *Chandra* observations of G0.570−0.018 present a thermal X-ray spectrum, without any evidence of synchrotron radiation. Therefore, detection of this source with IBIS in the hard X-ray continuum, above 15 keV, is highly improbable. Besides, as revealed by IBIS ISGRI, the Galactic center region is a crowded area at hard X-ray energies (Bélanger et al. 2006), making it more difficult to precisely distinguish the part of the emission that could be associated with this source. In fact, we did not find any evidence of such emission in the 20–40 keV mosaic presented in Bélanger et al. (2006). We analyzed pointings during which G0.570−0.018 lies within the field of view of IBIS ($\leq 15°$), in the 65–71 and 75–82 keV energy bands centered on the two low-energy ^{44}Ti γ-ray lines, using the Off-Line Scientific Analysis (OSA) software version 4.2 (Goldwurm et al. 2003). These narrow bandwidths take full advantage of the ISGRI energy resolution ($\sim$6 keV FWHM at 70 keV). The critical point in the analysis of the IBIS ISGRI data is the background subtraction: we have generated background shadowgrams (detector image containing the shadow of the coded mask onto the ISGRI detector) by analyzing and summing a large part of the high-latitude and empty field observations performed during the first 2 years of the mission in 256 energy bands. The high total exposure time ($\sim$2 Ms) warrants the best removal of structures in the detector images (Terrier et al. 2003), mainly around the Kα and Kβ fluorescence lines of the W (59 and 65 keV) and Pb (75 and 85 keV) located close to the two low-energy ^{44}Ti astrophysical lines. This method provides flat background-subtracted detector images in any desired energy band. Thus, the convolution of these shadowgrams with a decoding array derived from the spatial characteristics of the coded mask produces good-quality reconstructed sky images. We finally obtained two mosaic images in these two energy bands and combined both to increase the signal-to-noise ratio. The resulting mosaic
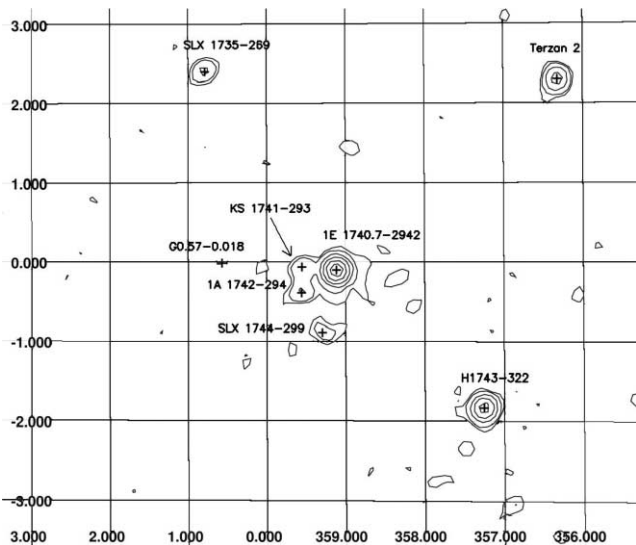

Fig. 1.—IBIS ISGRI contour map in Galactic coordinates of the combined significance in the ranges of the two low energy ^{44}Ti lines. Contours are drawn from 3 to 100 using a square root scale. The continuum emission of several known bright sources is clearly detected, while there is no evidence of any emission coming from G0.570−0.018 above the 3 σ level.
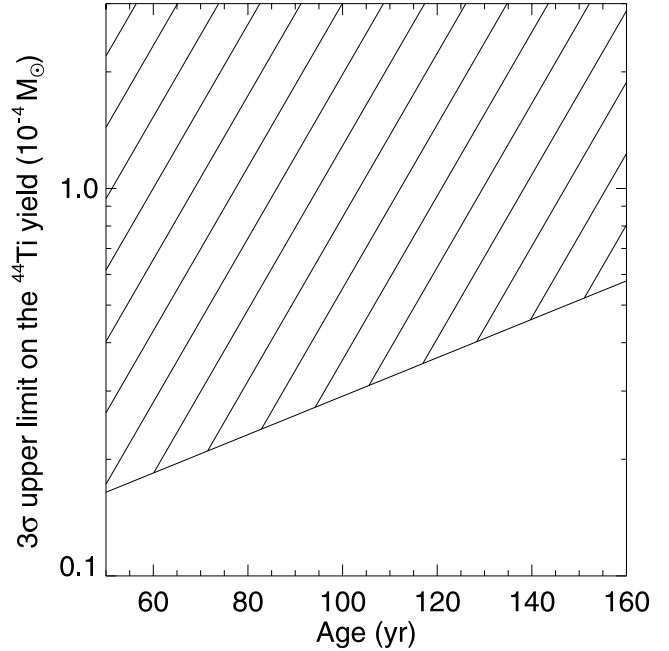

Fig. 2.—Plot shows 3 σ upper limit on the ^{44}Ti yield (in units of $10^{-4}\,M_\odot$) as a function of the age (in years). The hatched region corresponds to the range of parameters excluded at the 3 σ confidence level.

is shown in Figure 1, with a final exposure time toward the source of about 4.3 Ms.

We found no evidence for any emission above 3 σ from G0.570−0.018 in the ^{44}Ti γ-ray lines range and estimated an upper limit of 1.2×10^{-5} cm^{-2} s^{-1} at the 3 σ confidence level. This can be converted into an upper limit on the ^{44}Ti yield via

$$Y_{44} = 1.38 \left[\frac{F_\gamma}{\text{cm}^{-2}\,\text{s}^{-1}} \left(\frac{d}{1\,\text{kpc}} \right)^2 e^{t/\tau_{44}} \frac{\tau_{44}}{1\,\text{yr}} \right] \times 10^{-4}\,M_\odot, \quad (1)$$

where Y_{44} is the ^{44}Ti yield, F_γ the ^{44}Ti line flux, and τ_{44} the ^{44}Ti lifetime, $\sim$87.5 yr (Wietfeldt et al. 1999). Assuming that G0.570−0.018 is located near the Galactic center region, a distance of 8 kpc is adopted (Eisenhauer et al. 2003). Based on this assumption, we obtained the relation between the maximal ^{44}Ti yield and the age of this source presented in Figure 2.

For an age of 80 yr, our 3 σ upper limit on the ^{44}Ti ejected mass is $\sim$2 $\times 10^{-5}\,M_\odot$. One should notice that this value is $\sim$8 times lower than that of the youngest known SNR Cassiopeia A (Cas A) derived from the *Compton Gamma-Ray Observatory* (*CGRO*) COMPTEL (Iyudin et al. 1994), *BeppoSAX* PDS (Vink et al. 2001) and IBIS ISGRI (Vink 2005) observations. This result is discussed in detail in § 4.

3.2. Radio Emission

The image at 20 cm was obtained from archival data corresponding to observations carried out using the VLA in the hybrid CnB configuration for about 1.5 hr on 2004 February. The data were processed under the MIRIAD software package (Sault et al. 1995) following standard procedures. The resulting synthesized beam is $13'' \times 8''$, the P.A. = 54.6, and the average rms noise is on the order of 2.5 mJy beam^{-1}. The largest scale structure accessible to this array is of about $5'$. A field around G0.570−0.018 is shown in Figure 3b, with a few contours superposed representing the *Chandra* X-ray emission smoothed
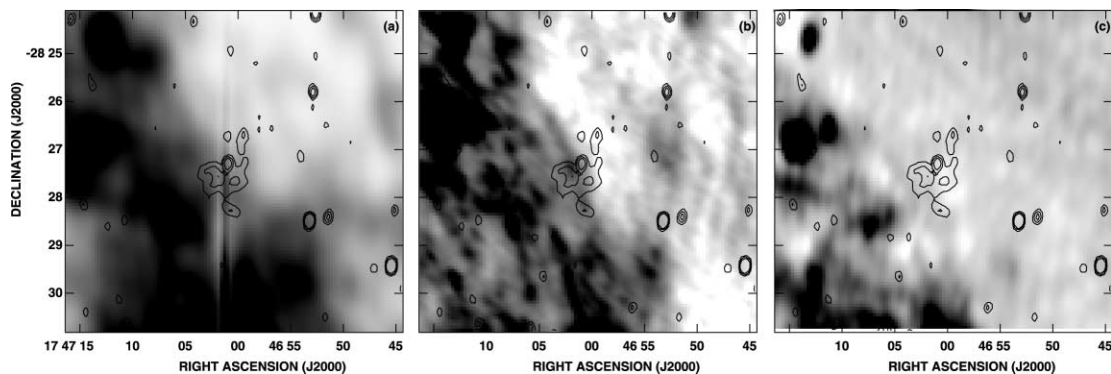
Fig. 3.—Radio images of a $\sim 7'$ field around G0.570−0.018 at (*a*) $\lambda = 90$ cm, (*b*) $\lambda = 20$ cm, and (*c*) $\lambda = 6$ cm. The contours represent X-ray emission convolved with a Gaussian beam of $13'' \times 8''$. The gray scale varies between 0 and 150 mJy beam^{-1} at 90 cm, between −5 and 10 mJy beam^{-1} at 20 cm, and between −10 and 40 mJy beam^{-1} at 6 cm.

to the same angular resolution as the radio image. Correction for primary beam attenuation was applied.

To produce the image at 6 cm we used archival data from observations carried out with the VLA-D array during 45 minutes on 2003 April 30. The synthesized beam is $27'' \times 11''$, the P.A. = −5.2, and the average rms noise in the field is about 2.2 mJy beam^{-1}. The resulting image is displayed in Figure 3*c*, again with *Chandra* X-ray contours overlapped.

The image shown in Figure 3*a* at 90 cm was extracted from the $4° \times 4°$ image of the center of the Galaxy obtained with the VLA B, C, and D configurations (LaRosa et al. 2000). The angular resolution of these data is $48'' \times 48''$, with rms sensitivity of 5.9 mJy beam^{-1}. The largest angular scale to which this image is sensitive is approximately $45'$.

From these images, it is apparent that G0.570−0.018 lies on a region with tenuous, smooth radio emission. Not any conspicuous radio feature can be associated with the X-ray source at any frequency up to the limit of the angular resolution and sensitivity of these images. An upper limit for the flux densities at 90 and 20 cm can be estimated by integrating the radio emission over a region with the size of the outer X-ray contour. From this integration we estimate $S_{90\,cm} \sim 0.23$ and $S_{20\,cm} \sim 0.066$ Jy. Although the flux contribution from large-scale structures was not added to these images, the flux density estimates are reliable within observational errors because the size of the studied structure is smaller than the largest well-imaged structure at the respective frequencies. This is not the case for the emission at 6 cm, and thus it was not possible to accurately estimate the flux density at this short wavelength.

4. DISCUSSION

The X-ray morphology and spectra of G0.570−0.018 show a hot-temperature plasma distributed in a ringlike structure, two characteristic features of young ejecta-dominated SNRs. In this context, we attempted to shed further light on the nature of this source searching for ^{44}Ti γ-ray lines and radio continuum emission. However, to our surprise neither the ^{44}Ti γ-ray lines observations nor the radio continuum maps reveal any feature that can be ascribed to G0.570−0.018 at the levels of sensitivity presented above.

Concerning SNe nucleosynthesis products such as ^{44}Ti, pre-supernova evolutions and calculations of explosive yields have a long history. Recently, core-collapse SNe have been studied by Woosley & Weaver (1995), Thielemann et al. (1996), Rauscher et al. (2002), and Limongi & Chieffi (2003), while nucleosynthesis

in Chandrasekhar mass models for Type Ia SNe can be found in Iwamoto et al. (1999). The ^{44}Ti yields used in this paper were extracted from those obtained by Rauscher et al. and Limongi & Chieffi since their calculations include several improvements in stellar physics and revised nuclear reaction rates. Figure 4 shows these ^{44}Ti yields as a function of the energy of the explosion, for different masses of the progenitor with our $3\,\sigma$ upper limit for the two possible ages of G0.570−0.018.

Explosive yields are sensitive to many details of the explosion and in the case of core-collapse SNe, ^{44}Ti is thought to be created close to the mass-cut (the mass above which the matter falls back onto the compact remnant). From Figure 4 it can be seen that for each track of constant progenitor mass, the higher the energy of the explosion is, the larger the ejected mass of ^{44}Ti is. For an age of 80 yr, our $3\,\sigma$ upper limit is only a compatible with few models of core-collapse SNe, where the energy
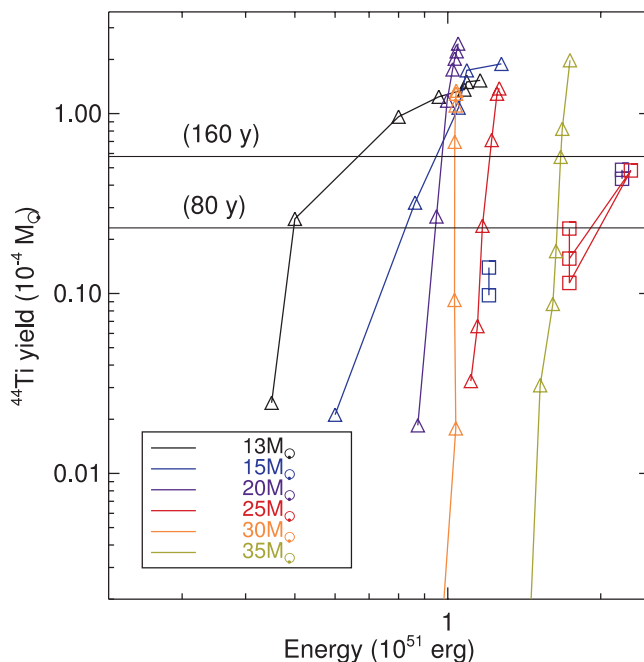

Fig. 4.—^{44}Ti yield (in units of $10^{-4}\,M_\odot$) vs. the energy of the explosion (in units of 10^{51} ergs) for two sets of nucleosynthesis calculations in Type II SNe: triangles represent those of Limongi & Chieffi (2003), and squares those of Rauscher et al. (2002). Each color is related to the mass of the progenitor. Horizontal lines represent our $3\,\sigma$ upper limit for two different ages of G0.570−0.018.

is unsufficient to eject an amount of ^{44}Ti above 2×10^{-5} $M_\odot$. We also considered the expected ^{44}Ti yields in various Chandrasekhar mass models for SN Ia explosions (Iwamoto et al. 1999 and references therein). In these models, explosive nucleosynthesis is calculated for a variety of deflagration speeds and ignition densities. We find that "standard" models (Nomoto et al. 1984; Thielemann et al. 1986) predict ^{44}Ti yields clearly below our $3\,\sigma$ upper limit, while delayed-detonation models with highly energetic explosions ($>1.4 \times 10^{51}$ ergs) predict ^{44}Ti yields between $\sim 3 \times 10^{-5}$ and 4.5×10^{-5} $M_\odot$, which could be compatible only in the case where G0.570−0.018 is at least 2 times older (>160 yr). The situation is worse in the case of sub-Chandrasekhar SN Ia explosions, in which helium burns in a detonation wave, causing a detonation also in the interior of the white dwarf (Woosley et al. 1986; Woosley & Weaver 1994). In such systems, substantial overproductions of ^{44}Ti from several 10^{-4} $M_\odot$ up to 4×10^{-3} $M_\odot$ are expected and then well above our sensitivity. In summary, comparing our upper limits with various models, we conclude that only few subenergetic core-collapse or standard thermonuclear explosions predict ^{44}Ti yields that explain our nondetection at the IBIS ISGRI sensitivity.

From an observational point of view, the 1.157 MeV ^{44}Ti γ-ray line was detected for the first time in Cas A with *CGRO* COMPTEL (Iyudin et al. 1994). Later, Vink et al. (2001) reported the detection with *BeppoSAX* PDS of the two low-energy ^{44}Ti lines in this SNR implying an initial ^{44}Ti mass of $(0.8-2.5) \times 10^{-4}$ $M_\odot$. Preliminary analysis of the IBIS ISGRI data on Cas A yielded a detection of the 68 keV ^{44}Ti line with a flux consistent with the *BeppoSAX* detections (Vink 2005). Moreover, it is suspected that the late-time light curve of SN 1987A (≥ 2000 days) is dominated by the ^{44}Ti decay. From time-dependent models for the light curve in combination with broadband photometry, Fransson & Kozma (2001) estimated a ^{44}Ti mass of $(0.5-2.0) \times 10^{-4}$ $M_\odot$. On the other hand, Senda et al. (2002) noticed similarities between the X-ray structure of the ring of G0.570−0.018 and that of SN 1987A, where strong stellar winds might produce a gas ring being heated by SN ejecta. However, one can see from Figure 2 that G0.570−0.018 should have been detected in the ^{44}Ti γ-ray lines range if it had emitted yields comparable to those measured from Cas A or those inferred from SN 1987A, even in the worst case of considering the lower limits of ^{44}Ti yields, and the oldest age of 160 yr.

Concerning the radio observations, one can expect synchrotron emission coming from either initially accelerated or shock-accelerated electrons, and the nonobservation at any radio frequency of G0.570−0.018 is then surprising. If G0.570−0.018 has an age of 80 yr, it should be considered an "intermediate-age" supernova (see Eck et al. 2002 and references therein) evolving from an SN into an SNR. G0.570−0.018, however, could be as old as 160 yr. With such an upper limit on the age, we cannot exclude that G0.570−0.018 is in the SNR phase, where the electrons responsible for the radio synchroton emission are accelerated at the shock front. The main difficulty of the studies of radio emission from SNe/SNRs is that between the observed extragalactic radio SNe (RSNe) and the youngest known Galactic SNR (Cas A), there is an observational gap of about 300 yr, and thus the evolution from RSN to SNR is poorly understood. Type II SNe seem to be well described by Chevalier's models (Chevalier 1982a, 1982b, 1984), where the radio emission is related to the circumstellar matter, while that of older SNe, entering the SNR phase (predicted to take at least 100 yr), can be related to the amount of interstellar matter (Gull 1973; Cowsik & Sarkar 1984). The emission mechanisms in both cases are in any case identical. Thus, we have divided our discussion in two parts,

one considering that G0.570−0.018 is still a SN and an other assuming that it could be a very young SNR.

In the first case, according to the Chevalier's model (Chevalier 1982b), the flux of RSNe drastically depends on the ratio between the mass-loss rate of the pre-SN progenitor and the wind speed. For small values, no strong radio emission is expected, thus explaining why despite several searches (e.g., Eck et al. 1995), no Type Ia SNe have been detected in radio and why most of the extragalactic SNe seen at radio wavelengths (Weiler et al. 2002) have progenitors with dense winds. Massive stars are thought to experience strong mass losses during the final stages of their evolution implying that they would be bright radio sources. Our nondetection in radio therefore points to the lower progenitor masses. Figure 4 shows that for these lower masses, our upper limit on the production of ^{44}Ti favours rather low energetic events. On the other hand, G0.57−0.018 could be similar to the Type Ia SN 1885A in M31, the first extragalactic SN identified, where no radio emission has been found (Crane et al. 1992).

Now if we assume that G0.57−0.018 has an age of 160 yr, it can be considered as a very young SNR (Cowsik & Sarkar 1984). Recently, Asvarov (2000) developed a model based on the diffusive shock acceleration mechanism to explain the radio emission of adiabatic SNRs and compared its modeled surface-brightness–diameter (Σ-D) evolutionary tracks with the empirical Σ-D diagram. He found that adiabatic SNRs evolve at nearly constant surface brightness: $\Sigma \propto D^{-0.5}$. We have used this relation and compared the surface brightness of the historical SNRs Kepler, Tycho, Cas A, and SN 1006 (we exclude the Crab Nebula and 3C 58 because they are continuously fed by relativistic electrons from a central neutron star) as given by Green (2005) and scaled to an age of 160 yr, with our upper limit at 20 cm, $\Sigma \sim 2 \times 10^{-20}$ W m^{-2} Hz^{-1} sr^{-1}. The only concordance found is with SN 1006, suggesting that G0.570−0.018 might be a Type Ia SNR evolving in a low-density medium. This is consistent with our upper limit on the ^{44}Ti yield, since standard Type Ia SNe produce on average less ^{44}Ti than core-collapse SNe, and with its very low radio flux density. Although SNIa can be found at any location in spiral galaxies like the Milky Way, the location of G0.570−0.018 within the disk and close to the Galactic center, which is known to host abundant molecular material and young stars (Figer 2004), makes the scenario of a core-collapse event more likely. In any case, G0.570−0.018 must be located in a region that has been depleted, probably by a succession of strong stellar winds of massive stars and/or previous SN explosions.

In any scenario of a SN/SNR, a possible explanation for the lack of radio emission is that G0.570−0.018 appears to be evolving in a low-density hot plasma. In such medium-high Mach numbers shocks may not be formed, even if velocities are high, as the sound speed in a hot plasma is also high. Such SNR shocks will not give rise to high compression ratios, and also shock acceleration may be less efficient. Therefore, the radio emission may not be very strong. In addition, if the SNR shock expands within a bubble blown out by the wind of the precursor star, the possibility of creating a radio synchrotron shell is even lower.

5. CONCLUSION

In conclusion, the present γ-ray and radio observations have not solved the basic question of whether G0.57−0.018 is a genuine SN/SNR. If it is, then our upper limits on the ejected ^{44}Ti mass and radio emission from G0.57−0.018 help to constrain its characteristics: the weak production of ^{44}Ti rules out all the sub-Chandrasekhar Type Ia SN scenarios and can be explained if G0.57−0.018 is a subenergetic core-collapse supernova from

a moderate mass progenitor or a standard thermonuclear explosion. Since no Type Ia SNe in radio have been detected, the second scenario looks more likely, although the location of G0.57−0.018, very close to the Galactic center, might suggest a massive star progenitor. According to Chevalier's model, the very weak radio surface brightness is probably due to the low-density surrounding medium. If the SN/SNR nature of G0.57−0.018 is questioned, then the X-ray morphology, the high Fe abundance, and the position and width of the Fe line observed by Senda et al. (2002) remain to be explained. In any scenario of a young SN/SNR, G0.57−0.018 seems to be unusual, and only the next generation of hard X-ray/soft γ-ray focusing telescopes, such as *SIMBOL-X* (Ferrando et al. 2004), will be in the position to disentangle its nature.

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