Constraints on the Parameters of the Unseen Pulsar in the PWN G0.9+0.1 from Radio, X-Ray, and VHE Gamma-Ray Observations

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Abstract. Radio, X-ray, and H.E.S.S. gamma-ray observations of the Galactic Center (GC) composite supernova remnant SNR G0.9+0.1 are used to constrain a time-dependent injection model of the downstream electron spectrum responsible for the total multiwavelength spectrum. The effect of spindown power evolution as well as nebular field evolution is employed to reproduce the present-day multiwavelength spectrum. Assuming a nebular magnetic field decay model of typical H.E.S.S.-type pulsar wind nebulae (PWN), ending with a present-day field strength of 6 µG, we obtain an initial spindown power of ∼ 10^38 ergs/s if we assume a birth period and age of 43 ms and 6,500 yr respectively to reproduce the properties of the SNR shell. This gives a present-day spindown power of ∼ 10^37 ergs/s, which agrees well with the present-day spindown power derived from X-ray observations.

1. Introduction

The H.E.S.S. Collaboration recently reported the detection of the composite supernova remnant SNR G0.9+0.1 in very high energy (VHE) gamma-rays [Aharonian et al. 2005] with a significance of ≈ 13σ, after 50 hours of observations of the Galactic Center (GC) region during March-April 2003 with the full telescope system (see also [Aharonian et al. 2006]). The unresolved gamma-ray radiation, which appears to be associated with the plerionic remnant core, corresponds to a photon flux above 200 GeV of (5.7 ± 0.7_{stat} ± 1.2_{sys}) × 10^{-12}/cm²/s and luminosity of ∼ 2 × 10^{34} ergs/s, making this one of the faintest VHE gamma-ray sources. For a radially symmetric Gaussian emission region, a 95% confidence limit of 1.3′ ∼ 3.2 pc on the source radius is obtained, and similarly for emission from a uniform thin shell, with extension < 2.2′ ∼ 5.4 pc. This is the first time that SNR G0.9+0.1 has been detected at gamma-ray energies [1], subsequent to the earlier unconstraining upper limit given by HEGRA [Aharonian et al. 2002], and H.E.S.S. observations in 2003 (resulting in a 4σ detection) [Aharonian et al. 2004]. MAGIC also detected a small excess from G0.9+0.1 [Albert et al. 2006], but it is however not statistically significant yet due to limited observation time.

Helfand and Becker [8] observed G0.9+0.1 in 1984 for 45 minute integrations at 20 cm and 6 cm with the VLA in their search for further examples of composite objects, despite its omission from Green’s first catalogue [7]. This led to the discovery of the composite nature of this bright, extended source near the GC in the radio band, with the flat radio core, corresponding to the pulsar wind nebula (PWN), and steeper shell components clearly distinguishable. (Shortly afterwards, Reich, Sofue & Fuerst [12] confirmed G0.9+0.1’s non-thermal nature and its identification as an SNR by detailed comparison of radio continuum and infrared emission from the GC). Using various previous observations, Helfand and Becker assigned spectral indices of α_c ≈ 0.1 (typical of Crab-like remnants) and α_s ≈ 0.6 to the core and shell components, and also constructed a broad band spectrum (radio – X-ray) of this source, as well as an upper limit of 3 Jy on the 25 µm infrared flux. (Recent VLA measurements at 90 cm [9] revealed similar indices of 0.12 and 0.77 for the core and shell components, confirming this SNR’s composite classification [26]; see [3] for a recent review).

Helfand and Becker [8] furthermore indicated a core-to-shell diameter ratio of ∼ 0.25. Assuming a distance of 10 kpc, they obtained radio luminosities of L_{R,c} = 7.0 × 10^{34} ergs/s and L_{R,s} = 2.8 × 10^{34} ergs/s for the core and shell components, and an X-ray luminosity (0.5–4.5 keV) of ∼ (1–5) × 10^{34} ergs/s for this remnant, setting the X-ray-to-radio flux ratio for the core to ≲ 0.6. Other cited luminosity ratios are L_{R,c}/L_{R,s} ∼ 2.5 and L_{X,c}/L_{X,s} ∼ 0.5. These authors also argued for an initial spin period of a few ms for the putative pulsar, but further VLA observations at 6 cm and 20 cm did not reveal any point source above 6σ (0.45 mJy) [4]. Observations during a continuum GC survey at 843 MHz by MOST [6] confirmed a core and shell component, with respective flux densities in close agreement with the spectra given by [8]. Owing to G0.9+0.1’s structure being similar to that of SNR 0540-693 (in the Large Magellanic Cloud) which contains a pulsar, G0.9+0.1 was identified as a likely candidate for being
a pulsar host. High dispersion measures and interstellar scattering may however inhibit detection of pulsed emission from G0.9+0.1 [6].

While performing a survey of the GC, BeppoSAX serendipitously detected SNR G0.9+0.1 [10]. This detection represented the first firm evidence of X-ray emission from G0.9+0.1, in addition to an earlier marginal detection by the Einstein Observatory [8] and a nondetection by ROSAT [11][21]. Follow-up observations of the GC and on-axis observations of G0.9+0.1 [19, 20, 23, 24] confirmed the non-thermal nature of X-rays from its radio core, and thus the composite nature of this remnant, and also found marginal indications of a diffuse character. Only an upper limit for X-ray emission from the SNR shell could be given, probably due to line-of-sight absorption [10]. Although no flux variations or pulsations were found, Sidoli et al. [24] argued for the existence of a young central neutron star based on the broad band (radio & X-ray) properties of the SNR.

The ASCA GC survey also detected significant X-ray emission from G0.9+0.1 in the 3 – 10 keV band, but no significant emission in the softer energy band [18]. The emitting region was compact, in accordance with the radio core, but unresolved, and no line-like feature was observed. Similar updated results for the 0.7 – 10 keV band, as well as an upper limit of 1.5’ for the apparent X-ray size, are given in [15].

A higher resolution 35 ksec observation of this source in October 2000 with Chandra X-Ray Observatory [5] revealed a clear axial symmetry for the PWN, which matched the morphology of the radio nebula, as well as a faint X-ray point source along the symmetry axis (CXOU J174722.8-280915) which is considered to be the best candidate for emission from a central pulsar (although no pulsations were detected). A bright elliptical 5’’ x 8’’ clump, which may be an intermediate-latitude feature in the pulsar wind, was also observed. An equatorial torus and axial jet morphology provides a natural explanation for the data and lends support to the idea that this type of morphology might be ubiquitous within the pulsar population.

SNR G0.9+0.1 was also easily identified in the hard energy band when a wide-angle XMM-Newton survey of the CG Region was conducted during 2000-2001 (11 pointings of 10 – 25 ksec exposures) [16][17]. On-axis observations during September 2000 (~ 29 ksec) [11] revealed a large scale X-ray morphology in good correspondence with the 20 cm VLA radio contours [8], with the X-ray core matching the eastern radio peak, and the western side of the X-ray arc-like feature corresponding to the western radio peak. Diffuse emission from the radio shell was also detected in X-rays for the first time (of either thermal or non-thermal origin), in good agreement with the earlier upper limit of Sidoli et al. [24]. Both an absorbed power-law and a thermal bremsstrahlung model provide good fits for the data in the region of the PWN. Evidence for spectral steepening with increasing radius supports a scenario where high-energy electrons undergo synchrotron losses as they diffuse through the nebula. The spectral steepening is stronger than in other PWN (e.g. 3C58 & G21.5-0.9) and the core is harder. Small-scale structure resembled that detected by Chandra, having less detail but double the extent of the emission. Spectra of the various structures were derived for the first time, indicating that the eastern part of the arc-like feature exhibited harder X-ray emission than the western part. This may be explained in terms of relativistic beaming or Doppler boosting effects. The jet-like feature also had distinct spectral indices for its northern and southern part. Furthermore, the central pulsar candidate CXOU J174722.8-280915 was visible above 6 keV, and magnetospheric emission seems to be preferred to a black-body model, implying a luminosity of ~ 10^{33}d_{10}^{2} ergs/s for this source (d_{10} = d/10 kpc). The deepest X-ray observation ever performed on this SNR [22] confirms the spectral softening at larger radial distances from the PWN peak as well as X-ray emission from a region spatially coincident with the radio shell.

During 2003-2004, INTEGRAL observed the GC in the 20 – 100 keV energy range for an effective exposure time of 4.7 × 10^6 sec [Belanger et al. 2006]. Emission from a region with centroid label IGR J17475-2822, a source associated with Sgr B2, was clearly observed [13]. The extension of this source toward the north was tentatively associated with G0.9+0.1 and interpreted as a detection of VHE synchrotron radiation.

In this paper we use radio, X-ray, and gamma-ray data to constrain both a time-dependent injection model of the downstream electron spectrum (responsible for the total multiwavelength spectrum), and the evolutionary history of the spindown power.

2. The Model

We assume that the central pulsar’s spindown power has the following functional form:

\[ L = I \omega \dot{\omega} = -K \omega^{n+1} \quad (1) \]

with \( I \) the moment of inertia, \( \omega \) the angular frequency, \( \dot{\omega} \) its time-derivative, and \( n = \omega \dot{\omega} / \omega^2 \) the braking index. We next assume that \( n \) is a constant (see, however, Chen & Li 2006) and that the neutron star’s crustal magnetic field does not decay. This leads to the condition

\[ \dot{P} P^{n-2} = \dot{P}_0 P_0^{n-2} \quad (2) \]

with \( P = 2\pi / \omega \) the pulsar period, \( \dot{P} \) its time-derivative, and the subscript ‘0’ indicating quantities at pulsar birth. Upon integration of \( \dot{\omega} \) from eq. (1), and using eq. (2), one finds the following general expression for the evolution of \( L(t) \) (see also [14]):

\[ L(t) = L_0 \left[ 1 + \frac{(n-1)P^2_0 L_0 t}{4\pi^2 I} \right]^{-\frac{n+1}{n+2}}. \quad (3) \]
| Model Parameter   | Symbol | Value/Range |
|-------------------|--------|-------------|
| Braking index     | $n$    | 3           |
| B-field parameter | $\alpha$ | 0.5         |
| Present-day B-field | $B(T)$ | $6 \mu G$   |
| Conversion efficiency | $\epsilon$ | 0.1       |
| Age              | $T$    | 6,500 yr    |
| Characteristic time scale | $\tau_0$ | 500 yr     |
| Distance         | $d$    | 8.5 kpc     |
| Magnetization parameter | $\sigma$ | 0.2       |
| Moment of inertia | $I$    | $10^{45}$ g.cm$^2$ |
| Q break energy   | $E_b$  | $10^{-8}$ − $10$ ergs   |
| Q index 1        | $\alpha_1$ | -1.0       |
| Q index 2        | $\alpha_2$ | -2.2       |
| Initial spindown power | $L_0$ | $10^{36}$ − $10^{40}$ ergs/s |
| Birth period     | $P_0$  | 0.043 s     |

Table 1. Values of parameters used for the model (see text for details).

In what follows, we assume $P_0 = 0.043$ s, as inferred by Van der Swaluw and Wu [25] using the ratio of the PWN and shell radii. We model the effect of a time-changing nebular field by

$$B(t) = \frac{B_0}{1 + (t/\tau_0)^\alpha}. \quad (4)$$

For the electron injection spectrum $Q(E,t)$ (number of electrons per second per energy at the shock radius $r_S$), we assume a broken power law with indices $\alpha_1$ and $\alpha_2$, and break energy $E_b$:

$$Q(E,t) = \begin{cases} Q_0(t) \left( \frac{E}{E_b} \right)^{\alpha_1} & E < E_b \\ Q_0(t) \left( \frac{E}{E_b} \right)^{\alpha_2} & E \geq E_b \end{cases}.$$  

We normalise $Q$ by requiring that

$$\int Q(E,t)EdE = \epsilon L(t), \quad (5)$$

with $\epsilon \sim 0.1$ a conversion efficiency of spindown power into particle luminosity. This leads to

$$Q_0(t) = \frac{\epsilon L(t)}{E_b^2} \left[ \frac{(\alpha_1 + 2)(\alpha_2 + 2)}{(\alpha_2 - \alpha_1)} \right], \quad (6)$$

for $\alpha_2 < -2$.

We next impose two boundary conditions. The first is that $r_L \lesssim 0.5 r_S$, with $r_L$ the electron’s Larmor radius [2]. This ensures particle confinement within the PWN, and leads to a condition on the particle energy:

$$E(t) < \frac{\epsilon}{2} \frac{\sigma L(t)}{(1 + \sigma)c}, \quad (7)$$

with $\sigma \equiv L_{EB}/L_E$ the ratio of the electromagnetic energy flux to the particle energy flux. The second energy condition is required to ensure that the particles radiating synchrotron emission will survive until time $t = T$ (with $T$ the PWN’s age):

$$E(t) < \frac{422}{B(t)B(T)(T-t)} \text{ ergs.} \quad (8)$$

We lastly calculate the leptonic spectrum $dN/dE$ subject to eq. (7) and eq. (8) by integrating $Q$ over time from $t = 0$ to $t = 6,500$ yr (see [10]), where an age of $\sim 6,800$ yr is derived assuming that G09.+0.1 is expanding adiabatically. Table 1 summarizes the values adopted for certain model parameters.

3. Results and Conclusions

Using this time-dependent model for the nebular averaged leptonic spectrum, we add the contributions from all epochs which survive to the present-day to give the net present-day photon spectra as calculated for synchrotron and inverse Compton emission. In the latter case the target photon fields are the CMBR, as well as galactic target photon fields from the 25K dust and starlight photon fields, assuming associated energy densities of $\sim 1$ eV/cm$^3$ for each component.

From Figure 1 we find an optimum fit of initial spindown luminosity $L_0 \sim 2.5 \times 10^{38}$ ergs/s and a spectral break energy of $E_b \sim 8 \times 10^{-3}$ ergs. Note that we obtain different optimum values when we fit the radio, X-ray and VHE gamma-ray data individually. The resulting...
fits (and multiwavelength observations) are shown in Figure 2 and Table 2, where we also show the corresponding total energy output $E_{\text{tot}} = \int L(t)dt$, integral X-ray flux $F_X (2 - 10 \text{ keV})$ in ergs/cm$^2$/s, and integral $\gamma$-ray flux above 0.2 TeV, $F_\gamma (> 0.2)$, in ergs/cm$^2$/s. A distance of $d = 8.5$ kpc is assumed [Aharonian et al. 2005]. These values correspond quite well to inferred values given in [Aharonian et al. 2005, 11]. Column units are log$_{10}$ of ergs, ergs/s, /cm$^2$/s, ergs, and log$_{10}$ of a dimensionless test statistic. (See text for details).

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