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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 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 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 PWN, ending with a present-day field strength of $\sim 6\mu$G, we obtain an initial spindown power of $\sim 10^{38}$ ergs/s if we assume a birth period and age of 43 ms and $\sim 6,500$ yr respectively to reproduce the properties of the SNR shell. This gives a present-day spindown power of $\sim 10^{37}$ ergs/s, which agrees well with the present-day spindown power derived from X-ray observations.

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 gamma-rays [1] with a significance of $\approx 13\sigma$, which makes this one of the faintest VHE gamma-ray sources. Helfand and Becker [5] reported the discovery of this bright, extended source near the Galactic center in radio. The flat-spectrum ($\alpha \sim 0$), highly polarized core is $\sim 2'$ across and is embedded within a steep-spectrum ($\alpha \sim -0.7$) shell of emission which is $\sim 8'$ across [6], which confirms this SNR's composite classification [13] (see [3] for a recent review). SNR G0.9+0.1 has also been observed in X-rays by *XMM-Newton* [8,11], *Chandra* [4], and *BeppoSAX* [7,10], in addition to an earlier marginal detection by the *Einstein Observatory* [5]. In this paper we use radio, X-ray, and gamma-ray observations to constrain both a time-dependent injection model of the downstream electron spectrum (responsible for the total multiwavelength spectrum), as well as the evolutionary history of the spindown power.

The Model

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

$$L = I\omega\dot{\omega} = -K\omega^{n+1}, \tag{1}$$

with I the moment of inertia, ω the angular frequency, $\dot{\omega}$ its time-derivative, and $n = \omega\ddot{\omega}/\dot{\omega}^2$ the braking index. We next assume that n is a constant and that the neutron star's crustal magnetic field does not decay. This leads to the condition

$$\dot{P}P^{n-2} = \dot{P}_0 P_0^{n-2}, \tag{2}$$

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 [9]):

$$L(t) = L_0\left[1 + \frac{(n-1)P_0^2 L_0 t}{4\pi^2 I}\right]^{-\frac{n+1}{n-1}}. \tag{3}$$

In what follows, we assume $P_0 = 0.043$ s [12]. We model the effect of a time-changing nebular field by

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

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 α_1 and α_2, and break energy $E_{\rm break}$. We normalise Q by requiring that

$$\int Q(E,t)E\,dE = \epsilon L(t), \tag{5}$$

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

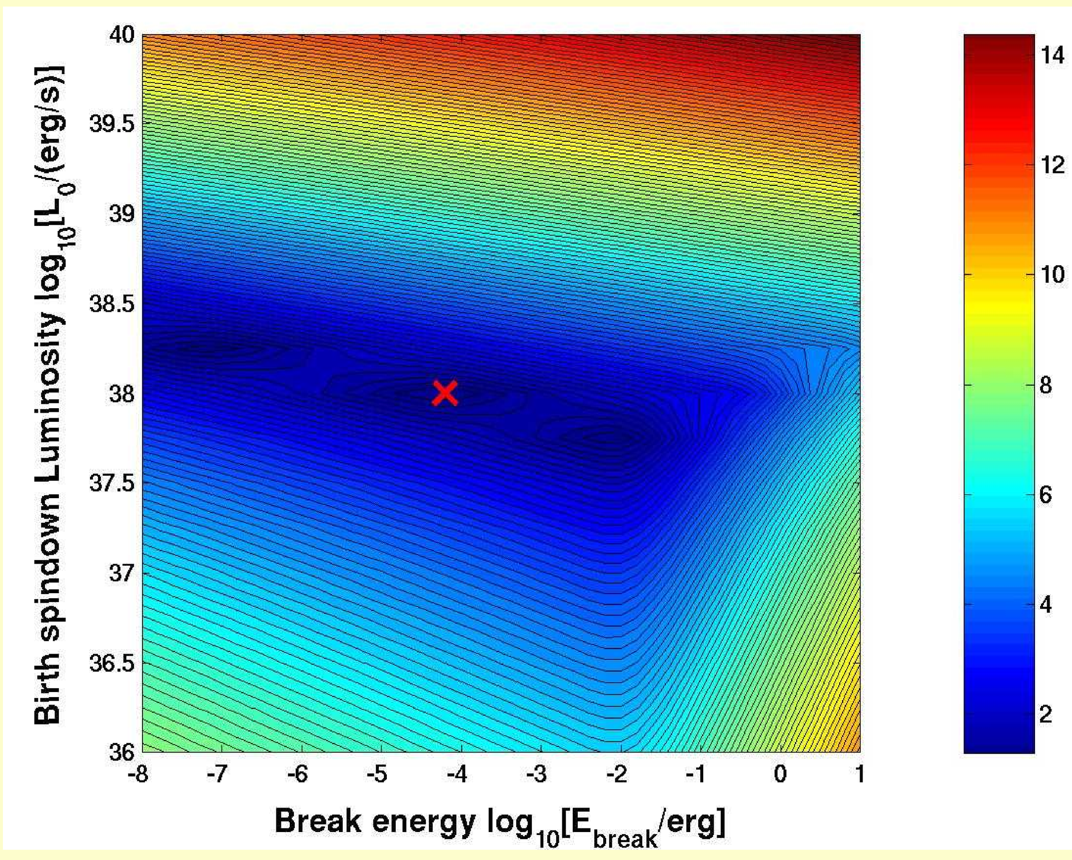

Fig. 1: Plot of a test statistic (rms-total for radio, X-rays, gamma-rays) vs. L_0 and $E_{\rm break}$ in order to find the 'best fit' (at red cross) for L_0 and $E_{\rm break}$ (at a fixed age T = 6,500 yr and birth period $P_0 = 0.043$ s).

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 leads to a condition on the particle energy:

$$E(t) < \frac{e}{2}\sqrt{\frac{\sigma L(t)}{(1+\sigma)c}}, \tag{6}$$

with $\sigma \equiv L_{\rm EB}/L_{\rm E}$ 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:

$$E(t) < \frac{422}{B(t)B(T)(T-t)}\quad \text{erg}, \tag{7}$$

with T the PWN's age. We calculate the photon spectrum $dN/dE(E)$ subject to eq. (6) and eq. (7) by integrating Q over time up until T = 6,500 yr (see [7]). (Table 1 summarizes the values adopted for certain parameters).

Results and Conclusions

Using this time-dependent model for the nebular averaged particle spectrum, we add the contribution 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 densities of ~ 1 eV/cm^3 for each component. From Figure 1 we find an optimum fit of $L_0 \sim 10^{38}$ ergs/s and a spectral break energy of $E_{\rm break} \sim 6\times10^{-5}$ erg. Note that we obtain different optimum values when we fit the radio, X-rays and VHE gamma-rays individually (see Table 2, where we also show the corresponding total energy

Model Parameter	Symbol	Value/Range
Braking index	n	3
B-field parameter	α	0.5
Present B-field	$B(T)$	6 μG
Conversion efficiency	ϵ	0.1
Age	T	6,500 yr
Characteristic time scale	τ_0	500 yr
Distance	d	8.5 kpc
Magnetization parameter	σ	0.2
Moment of inertia	I	10^{45} g.cm^2
Q break energy	$E_{\rm break}$	$10^{-8} - 10$ erg
Q index 1	α_1	-1.0
Q index 2	α_2	-2.2
Initial spindown power	L_0	$10^{36} - 10^{40}$ erg.s^{-1}
Birth period	P_0	0.043 s

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

Data	$E_{\rm break}$	L_0	$F_\gamma(>0.2)$	$F_{\rm X}$	$E_{\rm tot}$	χ
γ-rays	–	37.3	-11.43	–	48.7	-0.62
X-rays	–	38.0	–	-11.41	49.9	-1.78
Radio	–	38.3	–	–	50.5	-2.11
All	-4.20	38.0	-11.02	-10.81	49.9	1.19

Table 2: Table of 'best fit' parameters. Column units are $\log_{10}$ of erg, erg/s, cm^{-2}s^{-1}, erg.cm^{-2}s^{-1} and erg. (Last column: $\log_{10}$ of a dimensionless test statistic).

output $E_{\rm tot} = \int L(t)dt$, integral X-ray flux (2-10 keV) $F_{\rm X}$ in erg/s/cm^{-1} and integral γ-ray flux above 0.2 TeV $F_\gamma(>0.2)$. A distance of d = 8.5 kpc is assumed [1]. These values correspond quite well with inferred values given in [1,7,10,11]). Eq.(3) now implies a value of present-day spindown power of $L(T) = 1.2\times10^{37}$ ergs/s, which agrees within 25% of the inferred value of $L(T) \sim 1.5\times10^{37}$ ergs/s from *BeppoSAX* observations [10]. Note however that we are yet not satisfied with the quality of the fit. Future investigations will relax the initial spin period P_0 and age T (keeping them free) to see if we can obtain better quality fits.

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