Multi-wavelength Studies of the Gamma-ray Pulsar PSR J1907+0602
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Abstract. PSR J1907+0602 is a radio-faint, 107-ms GeV gamma-ray pulsar that was discovered with the Fermi LAT in a blind pulsar search. PSR J1907+0602 is located near the bright, extended TeV gamma-ray source MGRO J1908+06 which may be an associated pulsar wind nebula. We present an analysis of XMM-Newton X-ray data and EVLA radio data of the pulsar. We detect a faint X-ray source coincident with the gamma-ray pulsar and investigate its spectral and timing properties. We also find marginal evidence for a bow shock in the X-ray images. The pulsar was not detected with the EVLA, and we derive upper limits on the time-averaged radio flux in multiple frequency bands.

Keywords: Pulsar, Pulsar Wind Nebula, X-rays, Radio, PSR J1907+0602, MGRO J1908+06

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INTRODUCTION

MGRO J1908+06 (HESS J1908+063) is one of the brightest TeV gamma-ray sources in the Galactic disk with a flux of \(\sim 80\%\) that of the Crab nebula at 20 TeV. It was discovered with Milagro [1] and later confirmed with H.E.S.S. [2] and VERITAS [3] as an extended TeV source with a radius of \(\sim 0.3^\circ\) [4]. Even though MGRO J1908+06 is very bright in TeV gamma rays, no extended emission from the source has so far been detected at other wavelengths.

In a blind pulsar search, the Fermi LAT collaboration later discovered a 107-ms GeV gamma-ray pulsar, PSR J1907+0602, at a position \(\sim 0.23^\circ\) offset from the center of MGRO J1908+06 [5]. The close proximity of the TeV source to the pulsar suggests that MGRO J1908+06 may be an extended pulsar wind nebula of PSR J1907+0602. Using a time differencing technique, the position of the gamma-ray pulsar was determined with arcsecond accuracy, which allowed the detection of a faint X-ray counterpart with Chandra as well as faint, pulsed radio emission with the Arecibo 305-m telescope [6]. PSR J1907+0602 has a characteristic age of 19.5 kyr and a spin-down power of \(2.8 \times 10^{36}\) erg s\(^{-1}\). We present an analysis of X-ray data from a deep XMM-Newton observation of PSR J1907+0602 and of radio data obtained with the Expanded Very Large Array (EVLA).

X-RAY OBSERVATIONS

PSR J1907+0602 was observed with XMM-Newton [7] on 2010 April 26 (Obs. ID 0605700201) in one continuous 52 ks observation. We analyzed the data from the EPIC
FIGURE 1. X-ray images of the region around PSR J1907+0602. Shown are the combined XMM-Newton data from the three EPIC cameras in the 1–10 keV energy range. The images have been binned at 2′′ and have a size of 3′ and 0.75′ respectively. The ellipse shows the uncertainty of the pulsar position determined with the Fermi LAT [6]. Note that the images have not been background subtracted or exposure corrected, causing the CCD boundary of the EPIC PN to be visible in the left image.

MOS [8] and EPIC PN [9] cameras with the XMM-Newton Science Analysis Software (SAS) to create X-ray images, spectra, and light curves. Figure 1 shows X-ray images of the region around PSR J1907+0602. Shown are the combined XMM-Newton data from the three EPIC cameras in the 1–10 keV energy range. A faint X-ray source is detected at RA = 19h07m54s.7 and Decl. = 06°02′14″.9 with a statistical uncertainty of 0.8″. This is consistent with the position of the gamma-ray pulsar determined with the Fermi LAT and the position of the X-ray counterpart detected with Chandra [6]. The apparent size of the X-ray counterpart in the image is consistent with a point-like source when the angular resolution of XMM-Newton is taken into account. However, the image appears to show a marginal excess 7″ to the lower left of the pulsar which may indicate an extended morphology. This excess could be interpreted as a bow shock in front of the pulsar as it is moving away from MGRO J1908+06 (located ∼0.2° to the north). As noted by [6], a bow shock would be expected if the pulsar was born at the center of MGRO J1908+06 and has moved to its current location during its 19.5 kyr characteristic lifetime.

To create X-ray spectra of the pulsar, we extracted events from a circular region with a radius of 12″. The spectrum for the EPIC PN is shown in Figure 2a. Significant flux is visible at high energies, suggesting a non-thermal emission mechanism. We fitted the spectra from the three EPIC cameras simultaneously with an absorbed power-law model. The best-fit parameters are shown in Table 1. The photon index of 0.9 ± 0.4 is somewhat lower than the typical values for young pulsars or pulsar wind nebulae. However, given the characteristic age (19.5 kyr) and spin-down power of the pulsar, the photon index is consistent with the correlation suggested by [10]. The neutral hydrogen column density obtained from the fit indicates a distance of several kiloparsec, which is consistent with
FIGURE 2. (a) Background-subtracted X-ray spectrum of PSR J1907+0602 from the EPIC PN data. The solid line shows the best fit with an absorbed power law model. (b) X-ray light curve of PSR J1907+0602 in the 1–10 keV energy range folded on the 106.6-ms pulsar spin period. The light curve has not been background subtracted.

| Neutral Hydrogen Column Density $N_H$ (cm$^{-2}$) | $(0.9 \pm 0.6) \times 10^{22}$ |
|-------------------------------------------------|---------------------------------|
| Photon Index                                    | $0.9 \pm 0.4$                  |
| Absorbed Flux (0.5–10 keV) (erg cm$^{-2}$ s$^{-1}$) | $(5.1 \pm 1.1) \times 10^{-14}$ |
| Unabsorbed Flux (0.5–10 keV) (erg cm$^{-2}$ s$^{-1}$) | $(5.7 \pm 1.0) \times 10^{-14}$ |

TABLE 1. Spectral parameters obtained from fitting an absorbed power law model to the XMM-Newton data of PSR J1907+0602. Uncertainties are given at a 90% confidence level.

the 3.2 kpc distance estimate from radio DM measurements [6]. The spectral fit does not require a thermal component from the neutron star surface. However, such a component is likely hidden by the strong absorption below 1.5 keV.

The pulsar was observed with the EPIC PN in small window mode which has a sufficiently small timing resolution (6 ms) for detecting pulsations at the 106.6-ms pulsar spin period. We searched the X-ray data in the 1–10 keV energy range for periodic oscillations but did not find significant pulsations at the spin frequency or any other frequency. A phase-folded X-ray light curve of PSR J1907+0602 is shown in Figure 1b.

The spectral and timing properties of the source indicate that most of the X-ray emission originates from a compact pulsar wind nebula that is not resolved in the images.

The close proximity of PSR J1907+0602 to MGRO J1908+06 suggests a likely association between the two objects. The 0.23° offset of the pulsar from the center of the TeV source may be due to a large transverse velocity of the pulsar, and MGRO J1908+06 may be a relic pulsar wind nebula from the early life of the pulsar. Future observations may help to confirm this hypothesis if a bow shock can be clearly identified and used to determine the birthplace of the pulsar.
TABLE 2. Upper limits on the time-averaged radio flux of PSR J1907+0602 obtained from the EVLA observations. Limits are given at a 84% confidence level.

| Band (GHz) | C Band (4.0–8.0 GHz) | X Band (8.0–12.0 GHz) | K Band (18.0–26.5 GHz) |
|------------|----------------------|-----------------------|------------------------|
|            | 5.9 µJy              | 38 µJy                | 36 µJy                 |

RADIO OBSERVATIONS

We have analyzed radio data of PSR J1907+0602 obtained with the EVLA [11] in the frequency bands C, X, and K. The observations were carried out on 2010 April 30 when the array was in the D configuration. We analyzed the EVLA data using the Common Astronomy Software Applications (CASA) package to create radio maps in the three frequency bands. We detect no radio source at the location of the pulsar or in its vicinity. Upper limits on the time-averaged radio flux in the three bands derived from the RMS noise level are shown in Table 2. We note that narrow radio pulses have previously been detected at 1.4 GHz with the Arecibo 305-m telescope [6]. The limited timing resolution of the EVLA does not allow the detection of pulsations at the spin frequency. The non-detection of a radio counterpart with the EVLA places strong constraints on the radio emission from any compact pulsar wind nebula surrounding the pulsar.

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