XMM-NEWTON DETECTION OF THE SUPERNOVA REMNANT G337.2+0.1

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ABSTRACT

We report the first XMM-Newton detection of the SNR candidate G337.2+0.1 (= AX J1635.9−4719). The object shows centrally filled and diffuse X-ray emission. The emission peaks in the hard 3.0−10.0 keV band. A spatially resolved spectral study confirms that the column density of the central part of the SNR is about N_H ∼ 5.9(±1.5) × 10^{22} cm^{-2} and its X-ray spectrum is well represented by a single power law with a photon index Γ = 0.96 ± 0.56. The nondetection of line emission in the central spectrum is consistent with synchrotron radiation from a population of relativistic electrons. Detailed spectral analysis indicates that the outer region is highly absorbed and quite softer than the inner region, with N_H ∼ 16.2(±5.2) × 10^{22} cm^{-2} and kT = 4.4(±2.8) keV. Such characteristics are already observed in other X-ray plerions. On the basis of the morphological and spectral X-ray information, we confirm the SNR nature of G337.2+0.1 and suggest that the central region of the source is a pulsar wind nebula, originated by an energetic although yet undetected pulsar, that is currently losing energy at a rate of ∼10^{-8} ergs s^{-1}.

Subject headings: ISM: individual (G337.2+0.1) — radiation mechanisms: nonthermal — supernova remnants — X-rays: individual (AX J1635.9−4719) — X-rays: ISM

1. INTRODUCTION

Supernova remnants (SNRs) of the Crab-like or plerionic class are objects characterized in the radio band by a compact, filled-center morphology with a relatively flat spectral index (Slane et al. 2000). In the X-ray band they present nonthermal spectra, characteristic of synchrotron emission. The nonthermal spectrum, in some cases, can even reach the very high energy gammaray region, like in MSH 15-52, G18.0−07, and Vela X (see Aharonian et al. 2005, 2006a). It is widely believed that plerions are powered by the loss of rotational energy from energetic pulsars, although clear evidence of the presence of these objects is often lacking. The pulsar wind forms a nebula inside the SNR (the pulsar wind nebula [PWN]), where relativistic particles can be efficiently accelerated producing synchrotron radiation that yields the typical morphologies observed at radio and X-rays.

The new generation of X-ray instruments with improved sensitivity and spatial/spectral resolution like ASCA, XMM-Newton, Chandra, and the International Gamma-Ray Astrophysics Laboratory allows us to detect and study not only distant energetic objects with these characteristics but also those located in regions of high density.

Recently, Combi et al. 2005 have presented evidence supporting a SNR origin for the radio source G337.2+0.1. The object was discovered by the Molonglo Observatory Synthesis Telescope Galactic plane survey at 843 MHz toward the Norma spiral arm (Whiteoak & Green 1996), and later, detected with the ASCA telescope during a survey of part of the Galactic plane (Sugizaki et al. 2001). Its integrated flux was reported to be ∼1.2 × 10^{-12} ergs cm^{-2} s^{-1} in the 0.7−10 keV energy band. The photon index is poorly constrained: Γ = 2.8^{+1.6}_{-1.0}, and the absorption column density of the best-fit model yielded N_H = 15^{+30}_{-18} × 10^{22} cm^{-2} (Combi et al. 2005). A thorough study of its radio (continuum and line) and X-ray properties shows that the emission from the source is consistent with what is expected for a young SNR located at a distance d ∼ 14 kpc (Combi et al. 2005). More recently, G337.2+0.1 has been suggested as the potential counterpart of the high-energy gamma-ray source HESS J1634−472 (Aharonian et al. 2006b): this possibility needs further confirmation. Throughout this Letter, we adopt 14 kpc as the distance to G337.2+0.1 (hence, 1′ corresponds to 4 pc).

In this Letter, we present the first XMM-Newton observations of the SNR candidate G337.2+0.1. On the basis of its X-ray properties, we are able to confirm that this object is a nonthermal SNR with a hard, featureless power-law spectrum and, possibly, a PWN originated by a nondetected energetic pulsar. In § 2, we present the X-ray observations and data reduction. X-ray analysis and results are presented in § 3, and in § 4 we provide a brief discussion and a summary.

2. X-RAY OBSERVATIONS AND DATA REDUCTION

The SNR candidate G337.2+0.1 was marginally observed in 2004 February by the XMM-Newton X-ray satellite in two separate observations (ObsID 0204500201 and 0204500301). Both observations were centered toward the source IGR J16358−4726 (α_2000.0 = 16^h 35^m 53.820, δ_2000.0 = −47^°25′41.10″ and were acquired with the European Photon Imaging Camera (EPIC) MOS (Turner et al. 2001) and EPIC PN (Strüder et al. 2001) cameras. Observations were taken with a “thin” filter and in the full-frame (FF) imaging mode. Temporal resolution is 2.5 s and...
local background level of the smoothed image is \( \sim 0.94 (\pm 0.17) \) counts pixel\(^{-1}\). Contours show the level of 1.6 (\( \sim 1 \sigma \)), 3.2 (\( \sim 2 \sigma \)), 4.7 (\( \sim 3 \sigma \)), and 6.3 (\( \sim 4 \sigma \)) photons pixel\(^{-1}\), from outer to inner curves, respectively.

200 ms for the MOS and PN CCDs, respectively.\(^5\) Observations were obtained from the XMM-Newton Science Archive.\(^6\) and raw EPIC data were calibrated using the last version of the Standard Analysis System (SAS).\(^7\) To create images, spectra, and light curves, we selected events with FLAG \( \leq 10^{-15} \) keV energy band, which leads to a reduction of intervals by the accumulation of background light curves in the is unaffected by background fluctuations. We derive good time

The off-angle of G337.2\,+0.1 with respect to the center of the observation is about \( \sim 6.67 \), which implies a reduction of the XMM-Newton effective area of about 12%. The net exposure times of the observations are 34.7 (ObsID 0204500201) and 32.6 (ObsID 0204500301) ks. Unfortunately, the first observation was affected by a high and variable soft proton background level (Lumb et al. 2002), whereas the second one (ObsID 0204500301) is unaffected by background fluctuations. We derive good time intervals by the accumulation of background light curves in the 10–15 keV energy band, which leads to a reduction of \( \sim 87\% \) in the net exposure time of the ObsID 0204500201. In order to avoid contamination for high background patterns, hereafter our analysis concerns only the observation 0204500301. The number of detected counts in the 0.5–2.5 and 2.5–10.0 keV energy bands are 117/121/315 and 431/403/1154 for the MOS1, MOS2, and PN cameras, respectively. Finally, at the SNR G337.2\,+0.1 EPIC-PN position, there is a CCD gap in the X-ray image, leading us to ignore these data only for the X-ray image analysis section, but they are included for the rest of our study.

3. X-RAY ANALYSIS OF G337.2\,+0.1

3.1. Image

The coordinates of the SNR G337.2\,+0.1 were defined at the position where X-ray emission peaks (\( \alpha_{2000.0} = 16^h35^m54^s95, \delta_{2000.0} = -47^\circ 19'02''2 \)), being the errors in right ascension and declination of \( \epsilon_\alpha = \pm 2'1 \) and \( \epsilon_\delta = \pm 3'3 \), respectively (at the 90% level of confidence). This position agrees well with the previous estimate of the radio position (Combi et al. 2005) but differs in \( \sim 50' \) from the ASCA coordinates. Because of the poor spatial resolution (\( \sim 2'9 \)), the ASCA telescope alone is not conclusive in resolving the SNR G337.2\,+0.1. Fortunately, the avail-

ability of the 0.5–10.0 keV X-ray observations from XMM-Newton, the largest X-ray telescope so far (1480 cm\(^2\) at 1.5 keV), allows us to investigate with success the X-ray nature of this source. In fact, XMM-Newton has \( \sim 40 \) times more spatial resolution than ASCA, whereas the sensitivity limit is at least \( \sim 3 \) times better.

Figure 1 shows the X-ray image of the SNR G337.2\,+0.1 in the 0.5–10.0 keV energy band. The image does not reveal a typical rim-brightened outer SNR shell, so the overall size of the diffuse X-ray emission is uncertain.

We use the clean event files to generate MOS1 and MOS2 images in the energy band 0.5–10 keV with a spatial binning of 4.35 pixel\(^{-1}\). In order to increase the signal-to-noise ratio (S/N), we use the emosaic SAS task to merge together the two images. The corresponding set of exposure maps for each camera has been prepared to account for spatial quantum efficiency and mirror vignetting by running the SAS task eextrap. Exposure vignetting corrections were performed by dividing the superposed count image by the corresponding superposed exposure maps. We adaptively smoothed this image to a S/N of 10 using the SAS task asmooth (see Fig. 1). Plotted contours correspond to 1, 2, 3, and 4 \( \sigma \) levels over the mean background flux of the image (\( \sim 6 \times 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\)).

Finally, we are able to investigate the spatial extent of G337.2\,+0.1. Initially, this was performed by Combi et al. (2005) using ASCA data. However, the low resolution of this image led these authors to consider a radial analysis at large angular distance (\( \sim 10' \)). Thanks to the high-resolution XMM-Newton image, we found at least 19 weak pointlike X-ray sources inside this radius, making the ASCA studies of G337.2\,+0.1 to be hardly biased by source contamination effects. According to the image presented in Figure 1, G337.2\,+0.1 does not extend farther than 1.5 from the central peak. We also compare the G337.2\,+0.1 spatial extent with that produced by a point source placed at a similar off-axis (\( \sim 6' \)) position. In Figure 2, we show that the SNR G337.2\,+0.1 has an extension \( \sim 3.5 \) times larger than what is expected for a pointlike source.

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\(^5\) See http://xmm.vilspa.esa.es/external/xmm_user_support/documentation.

\(^6\) See http://xmm.vilspa.esa.es/xsa.

\(^7\) See http://xmm.vilspa.esa.es/external/xmm_sw_cal/sas.shtml.
3.2. Spectral Analysis

For the spectral analysis, we used MOS and PN data. It was performed using the XSPEC package (Arnaud 1996). Since the statistics of the source is not complete enough to perform a spatial-spectral analysis, we extracted X-ray photon events from only three different regions: (1) a circular region of 50'', (2) a circular region of only 12'' that accounts for the central source observed in the image, and (3) an annulus for the extended emission of inner-outside radii of 12''–50''. The background region was taken from a nearby blank region in the neighborhood of the source. Ancillary response files and redistribution matrix files were calculated. All spectra are grouped with a minimum of 16 counts binnings.

The distribution matrix files were calculated. All spectra are grouped with a minimum of 16 counts bin-1. The background-subtracted spectra of the MOS and PN data are shown in Figure 3 (upper line). We checked for possible background contamination in our spectra, inconsistency in the extraction of local backgrounds, and differences in background-corrected spectra of SNR G337.2+0.1. We note excesses in spectra, essentially at energies between 7.5 and 8 keV. However, such features have a low statistical significance (∼1–1.5σ) and are related to fluorescence lines in the background spectrum of XMM-Newton (e.g., De Luca & Molendi 2004).

Our analysis of the XMM-Newton EPIC spectra was essentially performed using a simple nonthermal model, described by a basic power-law emission model. We also fit the spectra by a thermal emission model (APEC; Brickhouse 2003). Both models were affected by an absorption interstellar medium component (WABS; Morrison & McCammon 1983). The goodness of the model fit was derived according to the χ²-test statistics. The best-fitting parameters of the models are shown in Table 1, and the errors quoted are 90% confidence limits.

According to the results presented in Table 1, the central part of the SNR appears quite harder (Γ ~ 0.96) than the outer one (Γ ~ 2.38). We suggest that the most reasonable interpretation of the observed emission from the central part of the SNR is synchrotron radiation from relativistic electrons accelerated in the vicinity of the central source of the SNR.

The softening of the spectrum toward the outer regions of the nebula is a well-known effect that has been seen in other X-ray plerions (e.g., G0.9+0.1: Porquet et al. 2003; 3C 58: Torii et al. 2000; G21.5–0.9: Slane et al. 2000).

To get a statistical assessment of the X-ray variability of the SNR G337.2+0.1, we use the 43.6 ks EPIC-PN observation to compare the time arrival distribution of source photons by means of the Kolmogorov-Smirnov test (Press et al. 1992). We use an extraction region centered in the SNR with a radii of 50''. The total number of photons is 1470. We see no significant pulsed signal with a period greater than twice the readout time of the EPIC-PN camera in the FF mode, which corresponds to a Nyquist limit of 400 ms.

4. Discussion

The X-ray morphology of G337.2+0.1 shows a centrally peaked emission, surrounded by a diffuse X-ray nebula. The light curve of the object does not show any significant flux variability above 400 ms, implying that at first glance, a pulsar origin for the central contribution could be ruled out. However, a detailed spectral analysis indicates that the outer region is softer than the inner region, a phenomenon observed previously in several X-ray plerions with PWNs (e.g., IC 443; Bocchino & Bykov 2001). A spectral analysis of the central component of the SNR shows that the X-ray spectrum is well represented by a single power law with a photon index Γ = 0.96 ± 0.56, a value similar to that of objects powered by an energetic pulsar (Gotthelf 2003). Moreover, the nondetection of line emission in this spectrum is consistent with synchrotron radiation from a population of relativistic electrons. These facts suggest a nonthermal origin for the X-ray emission. We therefore con-

| Parameter | All | Inner Region | Outer Region |
|-----------|-----|--------------|--------------|
|            | Power Law | APEC | Power Law | APEC | Power Law | APEC |
| \( N_e (10^{22} \text{cm}^{-2}) \) | 11.49 ± 2.73 | 11.17 ± 2.18 | 5.9 ± 1.52 | 6.45 ± 2.31 | 16.21 ± 5.62 | 16.26 ± 5.25 |
| \( \Gamma \times \Delta \) (keV) | 1.82 ± 0.45 | 10.01 ± 6.49 | 0.96 ± 0.56 | 64 ± 64 | 2.38 ± 0.78 | 4.38 ± 2.79 |
| Abundance | ... | <0.05 | ... | <0.05 | ... | <0.05 |
| Normalization (10^{-5}) | 4.91 ± 1.93 | 8.28 ± 2.83 | 0.55 ± 0.51 | 0.83 ± 2.4 | 4.01 ± 1.44 | 6.7 ± 2.81 |
| Flux (ergs s^{-1} cm^{-2}) | 11.7 ± 0.8 | 9.81 ± 0.62 | 1.3 ± 0.2 | 1.1 ± 0.09 | 8.2 ± 0.7 | 7.4 ± 0.3 |
| Reduced \( \chi^2 \) | 1.13 | 1.14 | 1.10 | 1.25 | 1.09 | 1.06 |

Notes.—Flux is absorption-corrected in units of \( 10^{-14} \) ergs s^{-1} cm^{-2}, calculated in the 0.5–10 keV energy range. Normalization was calculated according to \( 10^{-14} \text{ergs s}^{-1} \text{cm}^{-2} (1+z)^2 \times n_e n_p dV \).

The APEC thermal model could not fit the spectra in a consistent way, yielding very ill-constrained parameters as a solution.

The nonthermal (power-law) fit seems to be the most representative emission model for the central part of the SNR.

The abundance was adopted from Anders & Grevesse (1989) and left as free parameter along all our fits, but its value is hardly affected by the low statistic of the spectra.
clude that the system G337.2+0.1/AX J1635.9−4719 is a non-
thermal SNR with, possibly, a nondetected pulsar.

Possible reasons for the nondetection of a pulsar inside the
SNR are a short rotation period (less than 400 ms) or unfavorable
geometrical conditions. The presence of a pulsar is suggested by
the central X-ray peak found inside G337.2+0.1. In what fol-
low, we explore the possibility that there exists a hidden pulsar-
powered component (plerion) within the SNR. Using the
empirical formula derived by Seward & Wang (1988),
log \( L_X (\text{ergs s}^{-1}) \) = 1.39 log \( E - 16.6 \), where \( L_X \) is the X-ray
luminosity of the plerion in the 0.2–4 keV band, we can make
an estimate of the spin-down luminosity of the pulsar (see also
Becker & Trümper 1997). Using the X-ray flux of the compact
source and its nebula, \( F_X (0.2–4 \text{ keV}) = (4.9 \pm 1.7) \times 10^{-13} \)
ergs cm\(^{-2}\) s\(^{-1}\), we get \( L_X = 1.1 \times 10^{34} \text{ ergs s}^{-1} \) (unabsorbed).
This implies a spin-down luminosity of \( E \sim 2.5 \times 10^{38} \text{ ergs s}^{-1} \) and a period of \( P \geq 0.08 t_\text{rot}^{3/2} (\text{s}) \), where \( t_\text{rot} \) is the spin-down
luminosity in units of \( 10^{38} \text{ ergs s}^{-1} \) and \( t_\text{rot} \) is the pulsar
age in units of 10\(^3\) yr. In order to compare this result with those obtained with other empirical relations between the X-ray luminosity and the rate of the spin-down energy loss, we have used the Becker
& Trümper (1997) and Possenti et al. (2002) equations. In the first case (taking into account only the X-ray flux of the point
source in the 0.1–2.4 keV band), the spin-down luminosity is
\( E \sim 3 \times 10^{35} \text{ ergs s}^{-1} \), a factor of 9 lower than the value obtained with the Seward & Wang (1988) relation. In the second case (using the X-ray flux of the compact source and its nebula in the 2–10 keV band), we get \( E \sim 8 \times 10^{36} \text{ ergs s}^{-1} \), a value that is a factor of 3 higher than the value obtained with the Seward
& Wang (1988) relation. On average, a value of \( \sim 10^{36} \text{ ergs s}^{-1} \)
seems to be reasonable. If we assume a pulsar period of less
than 0.4 s, we obtain an upper limit for the age of the pulsar of
\( t \leq 1000 \text{ yr} \).

We have seen that G337.2+0.1 does not show a rim-bright-
ened outer SNR shell. This could be the result of the absorption of the soft thermal emission from the forward shock by the very
high absorbing column density. Other sources like Crab, G21.5−0.9 (Slane et al. 2000), and 3C 58 (Torii et al. 2000)
have weak or absent X-ray rims and all are powered by young X-ray pulsars (Murray et al. 2002; Camilo et al. 2006).

It could be interesting to compare the characteristics of G337.2+0.1 with 3C 58. The X-ray luminosities, between 0.5
and 10.0 keV, are \( \sim 4.8 \times 10^{34} \) and \( \sim 2.4 \times 10^{34} \text{ ergs s}^{-1} \), re-
spectively. The radio luminosities, at 1 GHz, are \( \sim 3 \times 10^{22} \) and
\( \sim 4 \times 10^{22} \text{ ergs s}^{-1} \). We see, then, that both sources are quite similar. We notice that the estimated age of 3C 58 is \( \sim 800 \text{ yr} \), a value based on the association of the SNR with SN 1181
(Stephenson & Green 2002). The nature of this SNR is discussed by Camilo et al. (2006), who, however, argue against the association with this historical SN (Bietenholz et al. 2001). The most significant difference seems to be the absence of any thermal
component in the case of G337.2+0.1. If we compare with the Crab, on the contrary, we see that the Crab pulsar is injecting
around 2 orders of magnitude more energy per unit time in the
nebula than G337.2+0.1. The spin-down luminosity inferred for the pulsar from the new X-ray data sets an upper limit to the
energy available for high-energy cooling channels like inverse
Compton scattering and proton-proton interactions. The lumin-
osity of the nearby HESS source J1634−472 (\( E \geq 1 \text{ TeV} \)), if it is located at the same distance inferred for G337.2+0.1, would be \( L_X \sim 7 \times 10^{36} \text{ ergs s}^{-1} \). So, a physical association would be possible only if \( \sim 7\% \) of the spin-down luminosity is converted in high-energy gamma rays.

Complementary studies of the PWN scenario will involve high-resolution X-ray observations with the Chandra satellite, and radio observations with ATCA, to allow the comparison of the X-ray spectrum and morphology with those at the radio band. Gamma-Ray Large Area Space Telescope observations could reveal a GeV gamma-ray source if the proposed asso-
ciation with HESS J1634−472 is correct.

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