A candidate $\gamma$-ray pulsar in the supernova remnant CTA 1

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ABSTRACT

We present a detailed analysis of the high energy $\gamma$-ray source 2EG J0008+7307. The source has a steady flux and a hard spectrum, softening above 2 GeV. The properties of the gamma-ray source are suggestive of emission from a young pulsar in the spatially coincident CTA 1 supernova remnant, which has recently been found to have a non-thermal X-ray plerion. Our 95% uncertainty contour around the $>1$ GeV source position includes the point-like X-ray source at the centre of the plerion. We propose that this object is a young pulsar and is the most likely counterpart of 2EG J0008+7307.

1 THE EGRET SOURCE 2EG J0008+7307

The high-energy $\gamma$-ray source 2EG J0008+7307, announced in the First EGRET catalogue as a ‘high confidence’ detection (GRO J0004+73; Fichtel et al., 1994), and included as a $\sim 9\sigma$ source in the Second EGRET (2EG) catalogue of point sources (Thompson et al., 1995), is still unidentified. Nolan et al. (1996) found on the basis of EGRET data from observation phases 1 and 2 that the source had a spectral index of $-1.58 \pm 0.20$ and was variable ($>95\%$ confidence). In McLaughlin et al. (1996), however, the source was placed slightly above their variability threshold, but close to the range in which variability is uncertain. 2EG J0008+7307 is a well-defined, isolated source 10.5 degrees from the Galactic plane.

In this paper we attempt to identify 2EG J0008+7307. To date, primary candidates for EGRET sources have included blazars, pulsars, and more diffuse objects such as supernova remnants (SNRs) and OB associations, which may appear as EGRET point sources. Only blazars and pulsars have been unambiguously identified as EGRET sources (see e.g. von Montigny et al., 1995; Thompson et al., 1994). The two source types are theoretically easy to distinguish: blazars are highly variable, have power-law spectra of order $\sim 2$ or steeper and are spread uniformly across the sky; pulsars are persistent long-term sources, have harder spectra and are often associated with supernova remnants. A $\gamma$-ray flux from a known pulsar can be verified by the detection of pulsations, which make up close to 100% of the radiation at these energies. Historically, radio observations have provided the accurate pulse timing measurements used in this work, but such measurements are not available for either radio-quiet or unknown radio-loud pulsars. Distinguishing an unknown pulsar from possible SNR emission is difficult. The two may be spatially indistinguishable to EGRET and we must rely initially on spectral evidence and data from other wavelengths with higher angular resolution. Careful analysis of the primary $\gamma$-ray data is of course essential.

2 DETAILED ANALYSIS OF EGRET DATA

The EGRET database has now expanded beyond the two and three years’ data analysed by Nolan et al. (1996) and McLaughlin et al. (1996) respectively. Throughout this paper, we will use data from the first five years of EGRET operation (Phases 1–5). This large database has enabled us to complete a more detailed study of 2EG J0008+7307 than has previously been made.

Because this source is clearly visible above 1 GeV, we have been able to determine its position from likelihood analysis (Mattox et al., 1996) of data from these high energies alone, where the instrumental point spread function is much smaller than at lower energies. The $>1$ GeV position of $l=119.87, b=10.52$ is compatible with the positions listed in the 2EG catalogue ($l=119.77, b=10.52$) and in Nolan et al. ($l=119.81, b=10.65$). The improved statistics from the increased database, combined with the benefits of the $>1$ GeV analysis, reduce the positional error to 11 arcmin at the 95% contour and 8 arcmin at the 68% contour. The source position uncertainty is also small because 2EG J0008+7307 is well outside the Galactic plane and no other EGRET sources are detected nearby.

The smaller datasets used by Nolan et al. (1996) and McLaughlin et al. (1996) indicated some variability in 2EG J0008+7307. Using the $>1$ GeV source position, we have examined the viewing periods 018, 022, 034, 211, 303.2, 319, 319.5, 325, 401 and 530 in order to determine
the long term flux history of the source. This analysis included only observations in which the offset of the source from the EGRET axis was < 35 degrees. The lightcurve of 2EG J0008+7307 from these observations is shown in Fig. 1, in which fluxes are for photon energies above 100 MeV, from a source at the > 1 GeV position. Using the method described by McLaughlin et al., we find a variability index \[ V = -\log(Q) \] of 0.55, where \( V \geq 1 \) indicates variability. \( Q \) is defined as
\[ Q = 1 - P\left(\frac{N_{\text{obs}} - 1}{2}, \frac{\chi^2}{2}\right), \]
where \( P(a,b) \) is the incomplete gamma function, \( N_{\text{obs}} \) is the number of observations analysed and, as discussed in McLaughlin et al., 6.5% systematic errors in the fluxes were included. There is therefore no significant variability in the source. The apparent variability claimed by Nolan et al. in Phases 1 – 2 may have resulted from the inclusion of 2 observations in which 2EG J0008+7307 was > 35 degrees from the instrument axis, where the response is less well known and effective area is low. McLaughlin et al. used only three observations (Phases 1 – 3) with an off-angle < 30 degrees, of which one in their analysis did not result in detection of the source.

As the source flux is consistent with non-variability, we were able to construct a single spectrum from 30–10000 MeV (Fig. 2) using the four prime observations in which the source was within 20 degrees of the instrument axis. Each of these observations taken individually gives a significant detection of the source. The spectral index of \(-1.58 \pm 0.18\), obtained from a fit to the data between 70 and 2000 MeV, is consistent with the indices found by Nolan et al. (1996) and Thompson et al. (1995); the smaller uncertainty in the new spectral index results largely from replacing two upper limits (70-200 MeV) with detections from the larger dataset. The spectrum is extremely well determined between 200-2000 MeV, with index \(-1.58 \pm 0.09\). Above 2000 MeV the spectrum softens, falling below the extrapolated power law.

The total flux above 100 MeV implied by this spectrum is \(4.4 \pm 6.2 \times 10^{-8} \text{cm}^{-2} \text{s}^{-1}\) for Phases 1–5, compatible with the values of \((55.2 \pm 8.0, 56.8 \pm 8.2, 40.1 \pm 7.1) \times 10^{-8} \text{cm}^{-2} \text{s}^{-1}\) calculated by previous authors (Nolan et al., 1996; Thompson et al., 1995; McLaughlin et al., 1996).

3 IDENTIFICATION OF 2EG J0008+7307

The clear position of 2EG J0008+7307 makes it an excellent target for identification work. The source was discussed in Nolan et al. (1996) as an intermediate-latitude source and it was suggested that the most plausible counterpart was the brightest point-like X-ray source in the field, an AGN identified by Seward, Schmidt and Slane (1995, SSS). From Fig. 3 it is clear that this is now an unlikely candidate, since the AGN is not consistent with the refined EGRET position. Furthermore, the optical spectrum presented by SSS has broad emission lines and the object has a radio flux of less than roughly 20 mJy (cf. Pineault et al. 1993). We propose that the AGN is more likely to be a Seyfert unrelated to the EGRET source.

Mattox et al. (1997) assigned probabilities to the identification of EGRET sources with catalogued flat-spectrum radio sources. For 2EG J0008+7307 only a single, improbable counterpart was found (QSO B0016+731), which is about 1 degree from the EGRET source position. We can now definitively exclude QSO B0016+731, on the grounds of inconsistency with our EGRET source position. No other catalogued point-like object has been proposed as the source of the gamma-ray emission.

2EG J0008+7307 is coincident with a supernova remnant, G119.5+10.2 (CTA 1). The radio remnant is an incomplete shell, approximately 100 arcmin in diameter, with a diffuse bar running across its centre from north to south. Pineault et al. (1993, 1997) propose that the missing north-west part of the shell can be explained by expansion of the remnant into a low density region of the interstellar medium. They also derive a kinematic distance of \(1.4 \pm 0.3\) kpc from neutral hydrogen observations. The age of the remnant is estimated from the \(\Sigma – D\) relationship to be \(10^{4}\) years but could be as low as \(5000\) years (Slane et al. 1997).
3.1 X-ray observations of CTA 1

As a high-latitude SNR, CTA 1 is relatively uncontaminated by foreground or background Galactic emission and has attracted observations in radio, infrared, optical and X-ray bands. Of particular interest to the purposes of this paper are the ROSAT and ASCA soft X-ray data, presented by SSS and Slane et al. (1997) respectively. Parts of the remnant were also observed by the Einstein satellite (Seward 1990).

The ROSAT PSPC data (Fig. 3) confirm that CTA 1 is dominated in X-rays by a patch of central, diffuse emission.
with the 1954 POSS image amounts to 1.5" over 43 years.

Stocke et al. (1991) produced distributions of the X-ray to optical flux ratios for stars, AGN, galaxy clusters and BL Lacs detected in the Einstein Medium Sensitivity Survey. This has been adapted for use with ROSAT by Bower et al. (1996), who defined the parameter $\alpha_{OX}$ to be

$$\alpha_{OX} = [11.88 - 0.4m_H - \log(F_{X(0.5-2.0)}/10^{-14})]/2.861,$$

where $m_I$ is the I-band magnitude and $F_{X(0.5-2.0)}$ is the X-ray 0.5–2.0 keV flux in units erg cm$^{-2}$ s$^{-1}$, derived from the ROSAT PSPC count rate by assuming a power law spectrum of photon index -2.

Using this spectral assumption and the $N_H$ measured by Slane et al., the X-ray flux of RX J0007.0+7302 is around $9 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. Our upper limit to an optical source within the ROSAT error circle in Fig. 4 is $m_I = 21.5$, implying $\alpha_{OX} < 0.82$. An AGN with this small relative optical luminosity is unlikely and a stellar source is ruled out. We require deeper optical and radio observations to address the possibility of a BL Lac.

If the K star is the counterpart to RX J0007.0+7302, then its $\alpha_{OX}$ is 1.5, making it extremely X-ray luminous among stellar sources. This seems unlikely for the spectral type; given the lack of emission lines and the positional offset, we reject the star as the source of the X-ray flux.

### 4 DISCUSSION

Through a detailed analysis of the EGRET data on 2EG J0008+7307, we have established that this gamma-ray source has combined properties found among identified sources only in pulsars: a hard spectrum ($\alpha = -1.58 \pm 0.18$) with steepening above $E_\gamma \sim 2$ GeV and a non-variable flux.

2EG J0008+7307 has been known for some time to be coincident with the supernova remnant CTA 1, which is at a distance of 1.4 kpc and has an estimated age of 10,000 years, similar to the age of the Vela pulsar. Our refined position estimate for the $\gamma$-ray source places it in the northeast quadrant of the SNR, which includes the maximum of the non-thermal X-ray emission described by SSS and Slane et al. (1997). Only a handful of X-ray synchrotron nebulae are known, including the nebulae around the Crab, Vela, PSR 1951+32 and PSR 1509-58: powerful particle acceleration in a pulsar magnetosphere supplies both the $\gamma$-rays and the synchrotron-emitting wind. Like Slane et al., we propose that the point-like X-ray source RX J0007.0+7302 at the heart of the CTA 1 emission is the pulsar that drives the diffuse X-radiation and we further propose that it is indeed the source of the gamma-rays.

The EGRET source properties are consistent with emission from a pulsar associated with CTA 1. For an assumed 1 steradian beam, the observed 100 - 2000 MeV flux corresponds to a luminosity of $4 \times 10^{33}$ erg s$^{-1}$, within the range of $9 \times 10^{32}$ erg s$^{-1}$ (Geminga) – $4 \times 10^{34}$ erg s$^{-1}$ (Crab) seen in the six confirmed EGRET pulsars. Likewise, the ratio $F_\gamma/F_X$ is of order 5000, similar to the values seen in the Vela pulsar and Geminga. The spectrum of 2EG J0008+7307 is also consistent with a young pulsar at the distance and age of the SNR, assuming the empirical trend in EGRET spectral index with pulsar age (Thompson et al. 1994), although this trend is not tight enough for us to predict the proposed
The most likely alternative explanation for the \textit{EGRET} flux is that cosmic rays accelerated in the SNR shell produce the $\gamma$-rays in the surrounding interstellar medium. A detectable \textit{EGRET} flux from this mechanism requires that the SNR is adjacent to a high density cloud that forms the target for incident cosmic rays, or that it is breaking out of a dense cloud (Aharonian et al., 1994). CTA 1 is indeed thought to be breaking out on its northwest side into a rarer environment, although from a region of only average density (Pineault et al., 1997). Is this a good explanation for the observed $\gamma$-ray source? The \textit{EGRET} spectrum is much harder than that predicted by cosmic ray models (Drury et al. (1994)) and the flux is very high for a cloud that is not dense. In addition, the non-thermal X-ray nebula within the SNR argues in favour of a pulsar. The current data therefore do not support the cosmic ray origin of this $\gamma$-ray source.

To take the identification further, we must clearly confirm that RX J0007.0+7302 is a pulsar and not merely superimposed on the field by chance. To date, our optical observations have ruled out stellar and most AGN source categories. It is still possible that RX J0007.0+7302 is a BL Lac, a possibility to be tested by future observations, but with the X-ray, optical and radio fluxes already constrained to be very much fainter than the five BL Lacs seen by \textit{EGRET} (Lin et al., 1996), such an object would be an unlikely explanation for the \textit{EGRET} flux.

No radio pulsed source was detected in CTA 1 during recent surveys of SNRs and \textit{EGRET} sources (Biggs & Lyne, 1996; Nice & Sayer, 1997). These surveys yielded upper limits of 10 mJy (BL, 610 MHz) and $\sim$ 1 mJy (NS, 370 MHz). Targeted observations of RX J0007.0+7302 at the Jodrell Bank 76 m telescope have yielded a limit of 0.3 mJy at 1412 MHz (J. Bell & A.G. Lyne, private communication). Thus, if 2EG J0008+7307 and RX J0007.0+7302 are a pulsar, then it is extremely radio-weak. Completely radio-silent objects visible as gamma-ray pulsars are a prediction of some current pulsar models (e.g. Romani & Yadigaroglu, 1995) and may in fact form the majority of pulsars visible as gamma-ray sources. The current bias to radio-loud pulsars in the catalogue of \textit{EGRET} pulsars, with only Geminga radio-quiet, is (probably) due to the relative difficulty of detecting unknown pulsation frequencies in X-ray or gamma-ray data.

A pulsar in CTA 1 would not be a surprise, given the five radio pulsars and one radio-quiet pulsar that are the only galactic \textit{EGRET} sources identified so far (Thompson
et al., 1994), but its discovery is nonetheless important in the task of characterising both the $\gamma$-ray sky and the population of pulsars. A further \textit{EGRET} source, 2EG J2020+4026 has also been suggested as a candidate pulsar, probably radio-quiet (Brazier et al., 1996), and a number of papers have concluded that a large fraction of the unidentified \textit{EGRET} sources near the Galactic plane will probably be pulsars, some of them radio-quiet (e.g. Mattox et al., 1997; Yadigaroglu & Romani., 1997; Kanbach et al., 1996; Merck et al., 1996; Sturner & Dermer, 1995). If confirmed, the proposed pulsar in CTA 1 will strongly support this prediction.

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