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Pulsed Optical Emission from Geminga ^{*}

A. Shearer¹, A. Golden², S. Harfst², R. Butler², R. M. Redfern², C. M. M. O'Sullivan², G. M. Beskin³, S. I. Neizvestny³, V. V. Neustroev³, V. L. Plokhotnichenko³, M. Cullum⁴, A. Danks⁵

¹ Information Technology Centre, University of Galway, Galway, Ireland

² Department of Physics, University of Galway, Galway, Ireland

³ SAO, Nizhnij Arhyz, Karachai-Cherkessia, Russia

⁴ European Southern Observatory, Garching-bei-München, Germany

⁵ STX/Goddard Space Flight Centre, Greenbank, Maryland, USA

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Abstract. We present optical data which shows that G^o, the optical counterpart of the γ -ray pulsar Geminga, pulses in B with a period of 0.237 seconds. The similarity between the optical pulse shape and the γ -ray light curve indicates that a large fraction of the optical emission is non-thermal in origin - contrary to recent suggestions based upon the total optical flux. The derived magnitude of the pulsed emission is $m_B = 26.0 \pm 0.4$. Whilst it is not possible to give an accurate figure for the pulsed fraction (due to variations in the sky background) we can give an upper limit of $m_B \approx 27$ for the unpulsed fraction.

Key words: pulsars: individual (Geminga) techniques: 2-d photon-counting detectors

1. Introduction

The nature of the bright γ -ray source Geminga remained elusive from the first observations using SAS-B (Fichtel et al, 1975) until its recognition as a pulsar with a period of 0.237 seconds in γ rays (Bertsch et al, 1992 Bignami and Caraveo, 1992) and in X-rays (Halpern and Holt, 1992). Based upon colour considerations an optical candidate was proposed, G^o with a m_V of 25.5 (Halpern and Tytler, 1988). This star had a measurable proper motion (Bignami and Caraveo, 1993) indicating a probable distance of about 100 pc and thereby making a probable association with a neutron star. Subsequent Hubble Space Telescope observations have given a distance based upon parallax of 159^{+59}_{-34} pc (Caraveo et al., 1996).

Send offprint requests to: A Shearer, andy.shearer@ucg.ie

* Based on Observations taken at ESO, La Silla, Chile and SAO, Nizhnij Arhyz, Russia

Optical observations in B showed Geminga to be fainter than 26th magnitude (Bignami et al, 1988) - a result confirmed by HST observations (Bignami, 1997). In V Geminga is brighter at 25.4. This aspect of the spectrum has been explained by a proton cyclotron feature causing either preferential emission in V or absorption in B and I (Bignami et al, 1996) superimposed on a thermal continuum. However, re-analysis of the EUVE and ROSAT datasets highlight an error in this earlier work, indicating that the thermal continuum would not be expected to dominate in the optical regime, based on the observed flux (Halpern et al, 1996). Such an apparent absorption feature has been previously observed in the Crab spectrum (Nasuti et al 1996) although not confirmed by other observations (Komarova et al, 1996). Recent spectral studies of Geminga (Martin et al, 1998) show a continuous power-law from 3700 to 8000 (Å) with no such features consequently indicating that a predominantly magnetospheric origin is preferred over a thermal one. It should be noted that these spectroscopic studies were at the limit of the observational capabilities of the Keck and with a low signal-to-noise ratio.

Of crucial importance to the understanding of neutron star structure is the stellar radius. This can in principle be inferred once the distance and the black-body contribution has been measured (Walter and Matthews, 1997). However determining the black-body component of an isolated neutron star is complicated by magnetospheric and possible atmospheric effects (Pavlov et al. 1996). As Geminga is very nearby it is a prime candidate for measuring the thermal component - crucial to this will be the removal of the magnetospheric component of its emission. This is possible by determining what contribution of the optical emission is pulsed and whether it 'follows' the hard (magnetospheric) or soft (presumed thermal) X-ray emission profile. The faintness of the optical counterpart has precluded time-resolved observations using conventional

photometers. However by using 2-d photon counting detectors, the required astrometric analysis can be carried out off-line. Consequently photon arrival times can be measured from a reduced (seeing optimised) aperture diaphragm.

2. Observations

Observations were made on 25th and 26th February 1995 using the 3.55m New Technology Telescope (NTT) at La Silla. Follow up observations were taken in January 1996, using the 6m telescope (BTA) of the Special Astrophysical Observatory over three nights. Two MAMA detectors were used; one a B extended S-20 (Timothy and Bybee, 1986) and the other a bialkali (Cullum, 1990) photocathode. By using the UCG TRIFFID camera (Redfern et al, 1993) to record the data. The arrival time and position of each photon was recorded to a precision of $1 \mu\text{second}$ and 25 microns. The spatial resolution was equivalent to $0''.13$ on the NTT and $0''.25$ on the BTA. Absolute timing was achieved using a combination of a GPS receiver, which gave UTC to a precision of 400nsec every 10 seconds, and an ovened 10MHz crystal which was accurate to $< 1 \mu\text{second}$ per 10 second interval. On each night the Crab pulsar was observed for calibration purposes. Using a Crab timing ephemeris (Lyne and Pritchard, 1996) the barycentric phase of the Crab pulse was determined; phase was maintained to within 10 $\mu\text{seconds}$ over the whole period. Table 1 shows a log of the observations.

Photon positions were binned to produce an image after each exposure was made. By using the TRIFFID image processing software, the images could be marginally improved by removing the effects of telescope movement (Shearer et al, 1996). These images were compared with HST/WFPC2 archival images to determine the position of Geminga at these epochs. After coaddition of all the B and V images from January 1996, a faint star could be seen at the expected position of Geminga. No such object could be seen in the February 1995 data. The reason for this was two fold: firstly the exposure time-telescope aperture product was 5 times greater in 1996 compared to 1995 and secondly the flat-fields were deeper in the later observations.

Once the position of Geminga was established, the photon times were extracted from a window, centred on Geminga, with a diameter corresponding to the average seeing widths for each exposure. This was chosen to maximise the signal to noise ratio. These extracted times were then translated to the solar system barycentre using the JPL DE200 ephemeris. The Geminga arrival times were folded in phase using the EGRET ephemeris (Mattox et al, 1996) for each colour and for each observing run.

Figure 1 shows the light curve in B for each night of January 1996 and Figure 2 shows the combined light curve. Figure 3 shows the time resolved images in B for

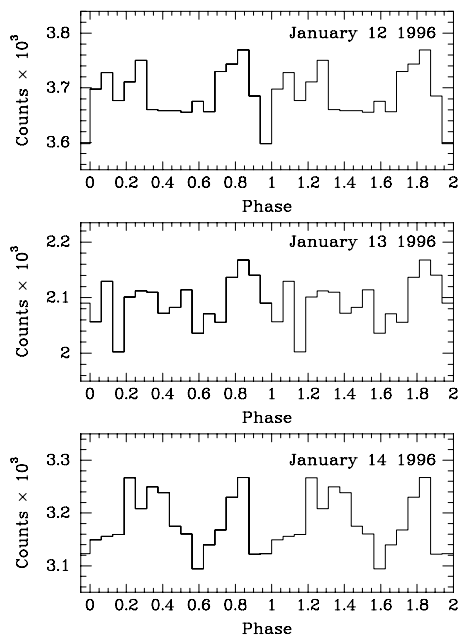


Fig. 1. Phase plot for the three individual nights observed in January 1996. Two phases are shown for clarity.

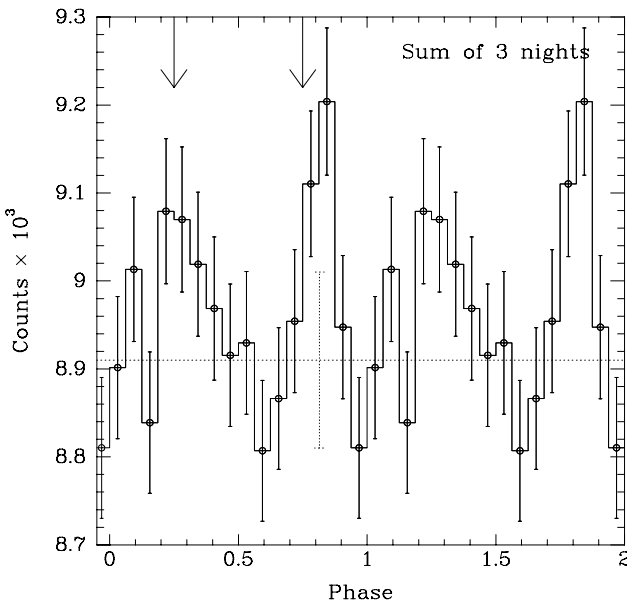


Fig. 2. Total phase plot for January 1996 in B. The error bars represent the Poissonian fluctuations of the original data set. Also marked are the phases of the peaks of the EGRET light curve. The dotted line indicates the background level with its associated error based upon counting statistics (± 25) and systematic errors including flat field errors (± 75).

Table 1. Summary of Observations

Date	UTC	Duration (s)	Detector	Telescope	Filter	Seeing (")
1995 Feb 26	01:14:37	4580	GSFC	NTT	V	1.3
1995 Feb 26	02:36:37	4387	GSFC	NTT	V	1.4
1995 Feb 26	03:50:49	3662	GSFC	NTT	V	1.4
1995 Feb 27	01:58:20	788	ESO	NTT	B	1.3
1995 Feb 27	02:42:23	2096	ESO	NTT	B	1.2
1995 Feb 27	03:19:28	3000	ESO	NTT	B	1.7
1996 Jan 12	18:07:15	4397	ESO	BTA	B	1.6
1996 Jan 12	19:21:14	6409	ESO	BTA	B	1.5
1996 Jan 12	21:36:04	884	ESO	BTA	V	1.5
1996 Jan 12	21:52:02	413	ESO	BTA	V	1.5
1996 Jan 12	22:23:56	2914	ESO	BTA	V	1.3
1996 Jan 12	23:13:26	2618	ESO	BTA	V	1.4
1996 Jan 13	19:28:34	7509	ESO	BTA	B	2.2
1996 Jan 14	16:59:25	8182	ESO	BTA	B	1.2
1996 Jan 14	19:18:44	2810	ESO	BTA	B	1.2

4 phase bands as indicated. Clearly Geminga can be seen during the two 'on' phases; star G is to the top right. We note that background fluctuations are consistent with the expectations of Poissonian statistics. Table 2 shows the determined pulsed magnitude or 1 sigma upper limits where appropriate. This type of light curve is best analysed using the Z_n^2 statistic (Buccheri et al 1989). Only the January 1996 B data shows significant pulsations - the Z_2^2 statistic for this data set (of 20.6) has a significance of 99.96%. In the January 1996 V data a weak signal, with a similar form, can also be observed.

Table 2. Fluxes

Data Set	Pulsed 3σ Upper Limits	Flux μJy
95V	24.0	0.95
95B	23.8	1.3
96V	25.5	0.24
96B	26.0 ± 0.4	$0.17^{+0.07}_{-0.05}$

This can be understood from the length of the V observation being about a fifth of the B, the sky brightness in V was about 1.5 magnitudes higher than in B and the detector used in 1996 had a bi-alkali photocathode with a B DQE higher than V (Cullum, 1990). No significant signal was observed in February 1995 - mainly due to the smaller telescope aperture. Given these considerations the upper limits of our data are consistent with the level of pulsations remaining constant. In order to estimate the pulsed fraction the background level had to be measured. For each data

set the background was determined as the mean of the signal in a small annulus, of radius $2''.5$ and width $0''.25$ around the position of Geminga. The magnitude calibration was achieved using the star G (Bignami et al, 1988) which was always in the field of view. Our measured pulse fraction is consistent with 100%, but, we should stress that there is a large error in this value, due to uncertainties in measuring the sky background, as seen in figure 2. We can however give a 1σ upper limit to the unpulsed component of 30%.

3. Discussion

Our results agree qualitatively with the previously observed optical flux, but the form of the optical light curve resembles the γ and hard X-ray rather than the soft X-ray signature, implying a magnetospheric origin. In γ -rays the spectrum is double peaked with maxima at phases 0.25 and 0.75 (Mattox et al, 1996). The soft X-ray is characterized by a sinusoidal modulation consistent with thermal emission with two temperatures ($5.2 \cdot 10^5$ and $3.0 \cdot 10^6\text{K}$) or from a single thermal source and a power spectrum (Halpern and Ruderman, 1993, Halpern and Wang, 1997). EUVE satellite observations, albeit with low significance, indicate that the extreme UV timing profile is similar in shape to the soft X-ray light curve. Recent reported detections of radio emission (Kuz'min and Losovskii, 1997, Malofeev and Malov, 1997) do not show a consistent pulse profile pattern and Geminga's radio emission is still a topic of some debate. However the phase agreement of the γ -ray light curve with the radio profile of Kuz'min and Losovskii, using the EGRET ephemeris, would suggest that peak 2 corresponds to direct polar emission as reported in their

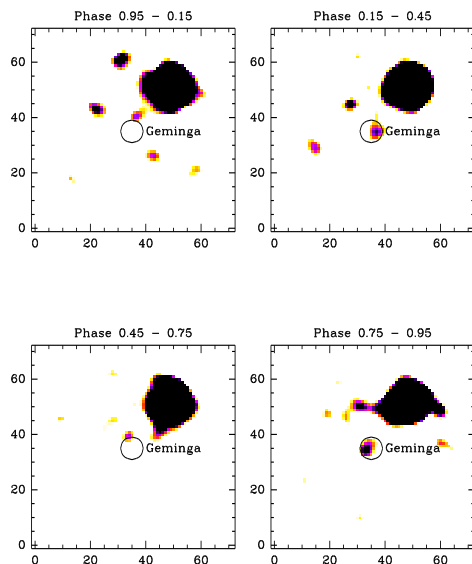


Fig. 3. Phase resolved images of Geminga. The pixel scale is $0''.22$ / pixel. Star G is to the top right in all images and Geminga is marked.

paper. When this is combined with the doubled pulsed optical, hard X-ray and γ -ray profile we can attempt to constrain models for the high energy emission. The high energy pulses are about 0.5 phase apart which rules out a geometry similar to the Crab pulsar. It would seem that Geminga has a magnetic axis at about 90° to the rotation axis, with the emission sites situated close to the neutron star surface. Interestingly when we fold our data, using the Malofeev and Malov ephemeris, one of the optical pulse peaks arrives at phase zero - expected from most emission models where phase zero generally corresponds to the radio peak. What is not clear is why the Malofeev and Malov pulse is delayed to phase 0.4.

From Figure 2 we can see that the signal shows two peaks with a phase separation of ≈ 0.5 . We can understand this in terms of the extrapolation of the pulsed γ emission to optical wavelengths, which is valid for the Crab pulsar. γ -ray emission from Geminga has been suggested to be variable (Ramanamurthy, 1995) in both total intensity and spectral index. Our optical observations are within the spread of variation and wide dispersion from the higher energy points (Mayer-Hasselwander et al., 1994). Halpern & Wang's more recent analysis fitted the x-ray and hard UV data to a black-body spectrum ($T \approx 6 \cdot 10^5$ K) with a power law. The low energy extrapolation of their black-body fit would produce an optical flux 2 magnitudes fainter than we observe, whilst the power law would produce a flux > 5 magnitudes brighter. As with the Crab pulsar this points to a probable flattening of the spectrum in the UV region. We should also note this extension

from the X-ray to the optical does not require a proton cyclotron feature (Bignami et al, 1996) to explain the V data but it might imply that there is preferential absorption in I. This could be due to a number of processes including electron cyclotron resonance scattering or synchrotron self-absorption (unlikely in this instance). Such a turnoff has been observed spectroscopically in Geminga (Martin et al, 1998) albeit with low significance. As similar I attenuation is observed in both the Crab and Vela pulsars' spectra we are beginning to develop an understanding whereby the high energy emission from these objects comes from a similar process. Our results when taken in conjunction with the spectroscopy studies favour an electron synchrotron origin for the radiation at least up to the edge of the B band. Differences can be understood in terms of the viewing geometry and path length over which the electrons are radiated. Deep, phase resolved observations in V, R, I and H will be crucial in determining whether there is a continuum infra-red turnover or whether there is an absorption line. Such observations, including a determination of the pulse fraction, will adequately separate the thermal and non-thermal components with important ramifications for models of pulsar emission. Indeed, the unpulsed components would constrain Geminga's thermal continuum, which in conjunction with EUVE and X-ray data and the known distance would provide definitive estimates, rather than upper limits (Walter and Matthews, 1997), on the neutron star's size.

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