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Letter to the Editor

Possible pulsed optical emission from Geminga*

A. Shearer[1], A. Golden[2], S. Harfst[2], R. Butler[2], R.M. Redfern[2], C.M.M. O'Sullivan[2], G.M. Beskin[3], S.I. Neizvestny[3], V.V. Neustroev[3], V.L. Plokhotnichenko[3], M. Cullum[4], and A. Danks[5]

[1] Information Technology Centre, National University of Ireland, Galway, Galway City, Ireland
[2] Department of Physics, National University of Ireland, Galway, Galway City, 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 suggests that G", the optical counterpart of the γ-ray pulsar Geminga, possibly 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 1 σ 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 discovery as a pulsar with a period of 0.237 seconds in X-rays (Halpern and Holt, 1992) and subsequently in γ rays (Bertsch et al, 1992, Bignami and Caraveo, 1992). Based upon colour considerations an optical candidate was proposed, G", with a m_V of 25.5 (Bignami et al, 1987 Bignami et al, 1988 Halpern and Tytler, 1988). Later studies indicated that this star had a measurable proper motion (Bignami and Caraveo, 1993) indicating a probable distance of about 100 pc and thereby making a strong association with a neutron star. Subsequent Hubble Space Telescope observations have yielded a distance based upon parallax of 159^{+59}_{-34} pc (Caraveo et al., 1996). Optical observations in B showed Geminga to be fainter than 26th magnitude (Bignami et al, 1988) – a result confirmed by HST observations (Bignami, 1997 Mignani et al, 1998). In V Geminga is somewhat brighter at 25.4. This aspect of the spectrum was initially 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. A re-analysis of the EUVE and ROSAT datasets suggested that the thermal continuum would not be expected to dominate in the optical regime, based on the observed flux (Halpern et al, 1996). Recent spectral studies of Geminga (Martin et al, 1998) show a continuous power-law ($\nu^{-0.8}$) from 3700 to 8000 Å with a broad absorption feature over 6300–6500 Å with suggestions of a modulation peaking in V. Such power-law behaviour is markedly similar to that of PSR 0656+14 (Pavlov et al. 1997), which has been shown to have a dominant nonthermal synchrotron component (Shearer et al, 1997). Martin et al's results are explicable in terms of electron synchrotron emission and ion cyclotron absorption within the magnetosphere or the alternative thermal-cyclotron scenario. However, Mignani et al. (Mignani et al, 1998) have presented further HST/FOC broad-band photometric data which strongly confirms the earlier hypothesis of enhanced V emission superimposed upon the thermal continuum. These analyses are critically dependent upon the interpretation of the ROSAT/EUVE datasets, and the possibility of variable X-ray emission from the pulsar (Mignani et al, 1998 Halpern et al, 1996). This variation in X-ray flux is sufficient to account for differences of up to 1 magnitude in the optical flux which is observed to be steady.

Of crucial importance to the understanding of neutron star structure and the equation of state 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, the determination of the black-body component of an isolated neutron star may very well be 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 optically – crucial to this will be the removal of the possible magnetospheric or surface anistropic components of its emission. This is possible by determining what

Send offprint requests to: A. Shearer (e-mail: andy.shearer@ucg.ie)

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

Table 1. Summary of total observations

Date	Duration (s)	Detector/ Telescope	Filter	Seeing (″)
1995 Feb 26	12629	GSFC/NTT	V	1.4
1995 Feb 27	5884	ESO/NTT	B	1.4
1996 Jan 12-14	29307	ESO/BTA	B	1.5
1996 Jan 12	6829	ESO/BTA	V	1.4

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 diaphram.

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 (GSFC, Timothy and Bybee, 1986) and the other a bialkali (ESO, Cullum, 1990) photocathode. The National University of Ireland, Galway TRIFFID camera (Redfern et al, 1993) was used to record the data. The arrival time and position of each photon was recorded to a precision of 1 μsecond 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 accurate to < 1 μsecond 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 μseconds over the whole period. Table 1 shows a log of the total 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, incorporating the pulsar's measured proper motion (Bignami and Caraveo, 1993, Caraveo et al., 1998). After coaddition of all the B and V images from January 1996, a faint star could be seen at the expected position of Geminga. A subsequent analysis of the each colour band indicated the candidate was evident in B, not so in V. This is explicable in terms of the overall deeper B observation, and enhanced V sky brightness at the BTA observing site. No such object could be seen in the February 1995 data. The reason for this is two fold: firstly the exposure time-telescope aperture product was 5 times greater in 1996 compared to 1995 and secondly the flat-fields were more accurate, photometrically, in the later observations.

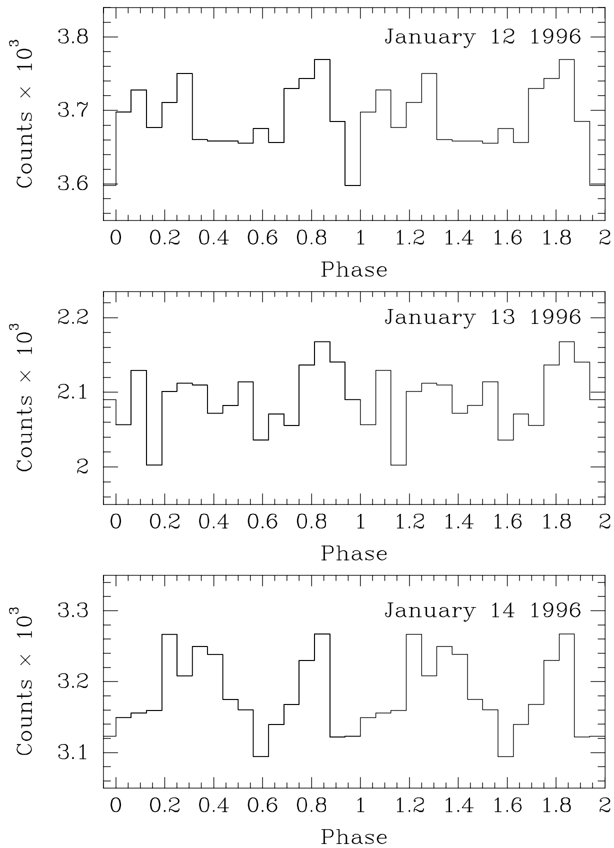

Fig. 1. Phase plot for the three individual nights observed in January 1996. Two phases are shown for clarity.

Photometry and astrometry was carried out using the IRAF DAOPHOT and GASP packages respectively. The background level was taken to be the mean of the signal in an annulus of radius $2\rlap{.}{''}0$ and width $0\rlap{.}{''}5$ centred on the object position. Photometric calibrations were achieved using the star G (Bignami et al, 1988) which was always in the field of view, in addition to other standard stars. In terms of astrometry, the candidate star was coincident with the expected Geminga position at this observing epoch, and it was determined to have a magnitude of 26 ± 0.4 in B, in agreement with previous photometric observations (Bignami et al, 1988, Bignami, 1997). Once the position and identity of this candidate star was established, the individual photon topocentric arrival times were extracted from a window, centred on Geminga, with a diameter corresponding to the average seeing widths for each exposure (see Table 1.). 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, 1996a; Mattox et al, 1998) for each colour and for each observing run.

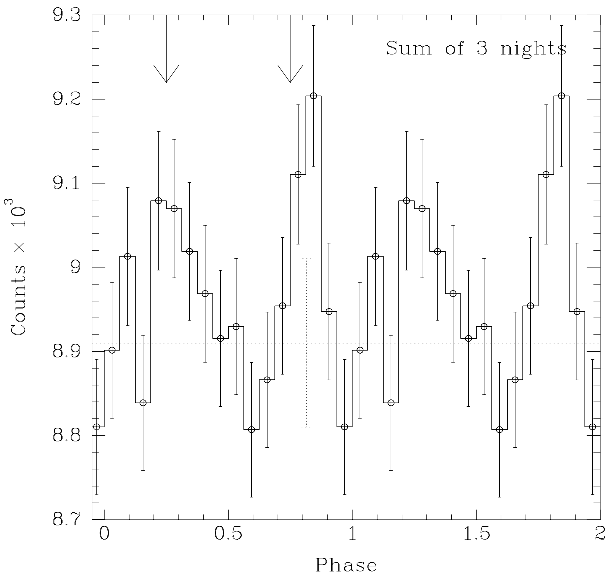

Fig. 2. Total phase plot for January 1996 in B. The error bars represent the Poissonian fluctuations of the original data set. Also marked are the phases of the peaks of the EGRET light curve. The dotted line indicates the background level with its associated error based upon counting statistics (± 25)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

Table 2. Fluxes

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

Fig. 1 shows the light curve in B for each night of January 1996 and Fig. 2 the combined light curve for each night of January 1996. 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. 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 that had been measured earlier was used. 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 Fig. 2. We can however give a 1σ upper limit to the unpulsed component of 30%.

3. Discussion

We have detected Geminga on our deep integrated images in B, and have a 99.96% significant detection of pulsations from the pulsar in B. The significance of our result is further enhanced by the phase agreement between our data and the γ and hard X-ray light curves.

As the form of the optical light curve resembles the γ and hard X-ray rather than the soft X-ray signature it suggests a magnetospheric origin. In γ-rays the spectrum is double peaked with maxima at phases 0.25 and 0.75 (Mattox et al, 1996a). The soft X-ray is characterized by a sinusoidal modulation consistent with thermal emission with two temperatures ($5.2\ 10^5$ and $3.0\ 10^6$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 phase agreement of the γ-ray and optical light curves with the radio profile using the EGRET ephemeris would suggest that peak 2 corresponds to direct polar emission. It would seem that Geminga has a magnetic axis at about 90^o to the rotation axis, with the emission sites situated close to the neutron star surface.

From Fig. 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 analysis fitted the X-ray and EUV data to a black-body spectrum (T $\approx$ $6\ 10^5$ 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 flattening of the spectrum in the UV region. The question remains how does our phase-resolved result compare with other optical studies? We have, at a reasonable significance, a pulsed signal in phase with higher energy emission. This is to first order 100% pulsed although it is possible for us to fix upper limits to an unpulsed component. If we restrict ourselves to the various attempts to determine the origin of Geminga's optical emission, we note that our pulse structure favours a predominantly magenetospheric origin (Halpern et al, 1996) over a thermal one (Bignami et al, 1996). Our determined unpulsed magnitude, albeit at a very low signifigance, would reproduce the required differences in pulsed, unpulsed and total fluxes that would fit the Rayleigh-Jeans component indicated in Martin et al. (Martin et al, 1998). However our observations do not rule out V band emission features as suggested by Mignani et al. Deep phase resolved observations in V, R, I and H are now required to adequately separate the thermal and non-thermal components with important ramifications for models of pulsar emission. It is not unreasonable to assume that such a definitive model of Geminga's thermal continuum in conjunction with it's known distance could provide definitive estimates, rather than upper limits (Walter and Matthews, 1997), on the neutron star's size.

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