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Time-Resolved Optical Observations of PSR 1509-58 ⋆

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Abstract. Using time resolved 2-dimensional aperture photometry we have established that the optical candidate for PSR 1509-58 does not pulse. Our pulsed upper limits ($m_V = 24.3$ and $m_B = 25.7$) put severe constraints on this being the optical counterpart. Furthermore the colours of the candidate star are consistent with a main sequence star at a distance of 2-4 kpc. The probability of a chance coincidence with a normal star and the difficulty of explaining the lack of pulsed emission leads us to conclude that this object is an intermediate field star.

Key words: – **pulsars: individual:** PSR 1509-58

1. Introduction

Interest in the optical emission from isolated neutron stars (INSs) has been growing, as recent improvements in detector sensitivity have enabled these faint sources to be observed. Optical observations of neutron stars are important for providing an understanding of pulsar emission mechanisms and allowing direct observations of the energy spectrum of the electron pair plasma. To date 6 INSs have been detected in the optical. Evidence suggests that it is the age and/or the period derivative of the INS, rather than its period, that determines the optical, and indeed multiwavelength, emission from an INS (Caraveo et al. 1994a, Goldoni et al. 1995).

PSR 1509-58 was initially identified by its X-ray emission (Seward & Harnden 1982) and shortly afterwards a radio signal, with a period of 150ms, was detected (Manchester et al. 1982). Later studies showed that it had a large $\dot{P}$ (1.5 x 10^{-12} ss^{-1}), in fact the largest known. The pulsar has had its second period derivative measured giving a breaking index ($n = \omega\ddot{\omega}/\dot{\omega}^2$) of 2.83 $\pm$0.03 (Manchester et al. 1985) in close agreement with the expectations of a radiating dipole (n=3). Its magnetic field ($\propto$ $(P\dot{P})^{1/2}$) is the largest known and its age 1,600, second only to the Crab pulsar in youth. Its age and location make its association with SNR MSH 15-52 (Seward et al. 1984) at a distance of 4.2 kpc (Caswell et al. 1975) likely, although this position has been challenged by Strom (1994), who has proposed a greater distance, 5.9 kpc, based upon radio dispersion and x-ray spectra of the extended emission around the pulsar. It has also been observed in soft gamma-rays (Gunji et al 1994) and a tentative optical counterpart has been proposed with $m_V \approx 22$ (Caraveo et al. 1994b). When taken at a distance of 4.2 kpc the optical observations indicate an absolute magnitude of $M_V \approx$ 4.9 (including the effects of interstellar extinction), fainter than the Crab pulsar. However, it is much brighter than would be expected from phenomenological models which have been successful in describing the X-ray emission from PSR 1509-58 (Pacini and Savati 1987). This overluminosity makes its behaviour similar to the older optical pulsars, PSR0656+14 (Shearer et al. 1997a) and Geminga (Shearer et al. 1997b). Observations of any pulsed optical component will be crucial in determining what fraction of the emission is thermal and what is magnetospheric. Only the magnetospheric emission would be expected to scale in a manner analogous to that described by Pacini and Savati. Indeed, by considering plausible emission mechanisms (Lu et al 1994) and high energy observations (Goldoni et al. 1995), it would be reasonable to expect that most of the emission would be non-thermal.

Given the importance of a correct determination of the optical emision from PSR1509-58, we have made time-resolved observations in an attempt to confirm its identification and determine the optical pulsed fraction.

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⋆ Based on observations taken at the European Southern Observatory, La Silla, Chile

2. Observations

The observations were made on 1995 February 24–25th using University College Galway's TRIFFID camera mounted at the Nasmyth focus of the ESO 3.5m New Technology Telescope (NTT) at La Silla, Chile. Both nights were photometric. The TRIFFID system consists of a multianode microchannel array (MAMA) 2-dimensional photon counting detector with a B extended S-20 photocathode (Timothy & Bybee 1985) and a fast data collection system (Redfern et al. 1993). The position and time-of-arrival of each photon are recorded to a precision of 25μm and 1μs, respectively. Absolute timing is achieved using a GPS receiver and an ovened 10-MHz crystal. On the NTT the 1024×256-pixel array had an equivalent spatial resolution of $0''.13$ pixel^{-1}. Observations were made with standard B and V filters. The Crab pulsar and photometric standard stars were observed each night for calibration purposes and to ensure that the system was working correctly. The pulsar observations are summarised in Table 1.

Table 1. Summary of Observations

Date (1995)	UTC	Filter	Duration (s)	Seeing
Feb 24	07:25:43	V	2600	1".2
Feb 24	08:51:46	V	5100	1".2
Feb 25	07:39:49	B	6250	1".0

3. Data Reduction

The data were first binned into 1 ms frames and divided by a deep flatfield taken during the observations. A post-exposure shift-and-add sharpening technique was applied to produce an integrated image (Shearer et al. 1996). Because of the large telescope aperture ($> 15r_0$, where r_0 is Fried's parameter), this does not produce any significant improvement in the image above the seeing limit, but corrects for effects such as telescope wobble. The optical candidate was identified in both the integrated B and V images. Photometry was carried out using the IRAF daophot package, with the background level being determined as the mean of the signal in an annulus of radius $1''.5$ and width $0''.25$ centred on the candidate position.

Photon times were extracted from a window with a diameter equal to the seeing width centred on the pulsar candidate. This choice of window diameter maximises the signal to noise. The time series was translated to the solar-system barycentre using the JPL DE200 ephemeris and then folded in phase using the PSR 1509-58 ephemeris of (Taylor et al. 1993) (Table 2). The resulting light curves were analysed using the Z_n^2 statistic (Buccheri & de Jager 1989).

Table 2. PSR1509-58 Ephemeris

Parameter	Value
ν	6.6375697299830 Hz
$\dot{\nu}$	-6.76954×10^{-11} Hz s^{-1}
$\ddot{\nu}$	1.96×10^{-21} Hz s^{-2}
Epoch	2448355.5

4. Results

The optical counterpart ($\alpha_{J2000} = 15^h13^m55^s.52, \delta_{J2000} = -59°8'8''.8$) proposed by Caraveo et al. (1994b) can clearly be seen in V (14σ) and, with less significance, in B(4σ).

We find the pulsar candidate has magnitudes $m_v = 22.4 \pm 0.4$, $m_b = 24.5 \pm 0.5$. This is to be compared with previous estimates $m_v = 22.0 \pm 0.2$, $m_b > 23$ (Caraveo et al. 1994b). The uncertainties in the measurements were calculated from a combination of the counting statistics as well as any systematic error in the flatfielding. Figures 1 and 2 show contour plots of the pulsar candidate.

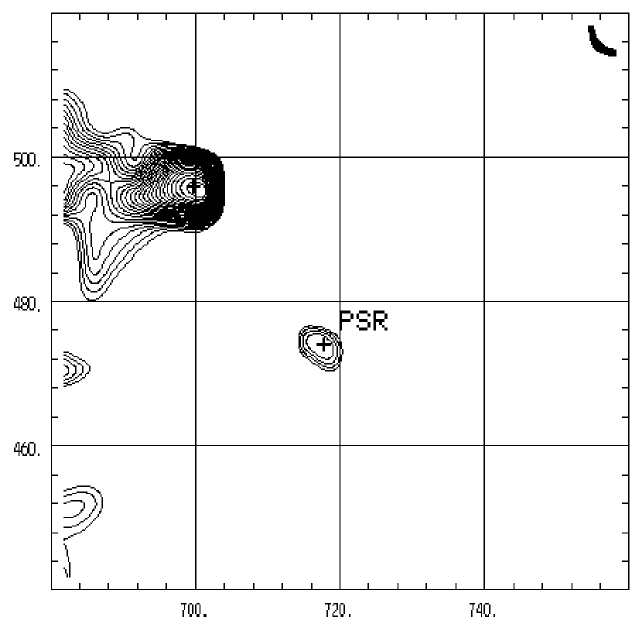

Fig. 1. 128-minute V-band image of the pulsar candidate, labelled PSR. (1 pixel = $0''.13$)

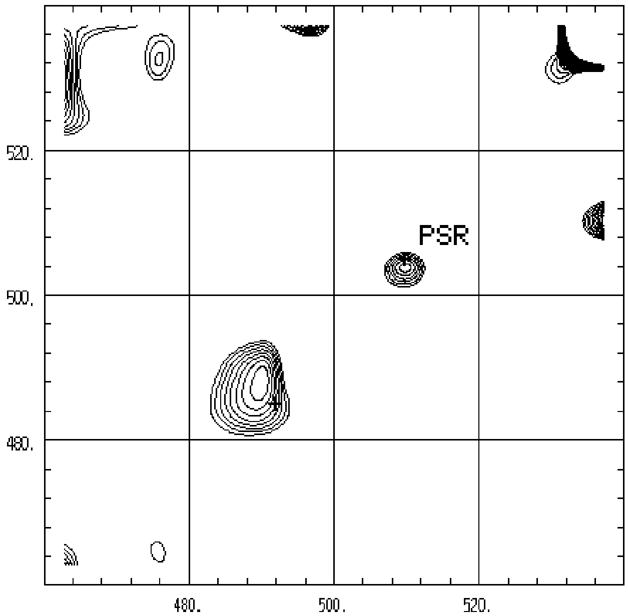

Fig. 2. 104-minute B-band image of the pulsar candidate, labelled PSR. The crosses correspond to the centres of the stars in the V-band image which is rotated with respect to this one. (1 pixel = $0''.13$)

No pulsations were seen (to the 1% significance level) in any of the time-series data sets. An upper limit for the pulsed fraction was calculated for the B and V emission assuming, conservatively, a duty cycle in the optical of 50%. The 3σ upper limits were found to be $m_{v,\mathrm{pulsed}} > 24.3 \pm 0.2$, $m_{b,\mathrm{pulsed}} > 25.7 \pm 0.2$. These correspond to pulsed fractions $< 18\%$ in V and $< 33\%$ in B. For comparison the Crab pulsar has a pulsed fraction of $> 99\%$ and Vela $> 77\%$. At the reported pulsar distance of 4.2 kpc ($A_V = 4, E_{B-V} = 1.3$), the measured B-V of 2.1 is equivalent to an intrinsic colour (B-V)$_o$ = 0.8 and absolute magnitude $M_v = 5.3$, somewhat redder and fainter than the Crab pulsar. At 4.2 kpc this would be equivalent to a G type main sequence star.

5. Conclusions

Our dervived magnitudes and colours, when combined with the lack of optical pulsations, cast doubt on the Caraveo et al (1994b) candidate being the optical counterpart of PSR 1509-58. Our data is consistent with an M type main sequence star at a distance of about 2 kpc. Alternatively, if it is the pulsar then the pulsed fraction must be anomolously low (lower than any other optical pulsar) and most of the radiation thermal. This is contrast with higher energy observations (dominated by non-thermal emission), where the pulsed fraction increases with decreasing energy (Greiveldinger et al 1995). However if the optical emission represents the Rayleigh-Jeans tail of the neutron star's black body spectrum, then with tabulated values for extinction towards MSH15-52, the distance would have to be ~ 1 kpc assuming a surface temperature of 3 10^6 K in contrast to the expected distance of at least 4.2 kpc. The presence of a neutron star atmosphere (Pavlov et al. 1996) would not change this distance sufficiently to explain the optical excess. If the radiation is non-thermal then it is difficult to imagine a geometry and a mechanism which would give such an anomolously low pulsed fraction and still be consistent with high energy observations. Even at the distance derived from radio dispersion (5.9 kpc) the star is still too red to be explained by a thermal extrapolation alone. A final answer to the nature of this star will come from spectroscopy - its magnitude is well within the capabilities of the VLT.

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