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THE POSITION OF PSR 0540−69[1]

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ABSTRACT

Using time-resolved two-dimensional photon counting techniques we have found an accurate position for the X-ray and optical pulsar PSR 0540−69. Our position using postexposure variable aperture photometry confirms the position suggested by Caraveo et al.

Subject headings: instrumentation: detectors — pulsars: individual: PSR 0540−69

1. INTRODUCTION

The young Crab-like pulsar, PSR 0540−69 was discovered as an X-ray pulsar (Seward et al. 1984) and has been observed to pulsate optically (Middleditch & Pennypacker 1985). Recently radio pulsations have been observed (Manchester et al. 1993). PSR 0540−69 is very similar to the Crab pulsar but differs in number of key areas. In particular, its pulse profile is almost sinusoidal in marked contrast to the Crab's. Like the Crab the object is associated with a synchrotron nebula. Its apparent magnitude is lower than the Crab due to its location within the LMC, and as a consequence it has been difficult to measure the optical position of the pulsar using conventional techniques. The pulsar has an integrated B magnitude of 23.2 and the surrounding nebula has an integrated B magnitude of 18.7 (Middleditch & Pennypacker). Conventional aperture photometry has had to rely upon large apertures ($>4''$) due to positional uncertainty, and long exposures ($>1^h$) due to the faintness of the pulsar relative to the nebula. These problems combined with the absence, until recently, of any radio detection has meant that no accurate position has been determined. Manchester & Peterson (1989), from optical timing, have derived a position within the X-ray error circle, reported by Seward et al., but outside the synchrotron nebula. Caraveo et al. (1992) observed the remnant using the ESO SUSI camera in B, V, and narrow-band filters and reported two maxima within the nebula which could correspond to the pulsar. They suggest that their "northern maximum" is the candidate because of its starlike appearance and central position to both the nebula and the Hα jetlike structure they observed. Our study using two-dimensional photon counting techniques enables us to measure directly the pulsar's position.

2. THE OBSERVATIONS

This work is based upon observations taken using the TRIFFID[5] Image Sharpening Camera (Redfern et al. 1994), mounted upon ESO's New Technology Telescope, during 1993 January. Two observations of the supernova remnant were made of length 65 minutes and 37 minutes (see Table 1). A 6 minute exposure was made of the Crab pulsar, for calibration purposes.

TRIFFID's normal mode of operation involves matching the telescope aperture to the prevalent seeing. TRIFFID uses $3.5R_0$ subpupils, R_0 is Fried's atmospheric scale parameter which can be considered to be the diameter of a telescope whose diffraction limit is equivalent to the seeing disk. In this way, improvements in resolution of up to 2 can routinely be achieved (Redfern et al. 1989) without frame selection. As the seeing was poor, $R_0 \approx 8$ cm, TRIFFID was operated at full aperture to maximize our signal-to-noise ratio.

In the present version TRIFFID uses two detectors simultaneously, the ESO MAMA[6] two-dimensional photon counting detector for unfiltered observations, simulating B, and the RAL-PCD[7] for V and R observations. The RAL-PCD is a framing detector with frames of length 7 ms and was not used for the time series analysis. The MAMA detector has an image format of 1023 × 256 25 μm pixels and a bi-alkali photocathode. Each detected photon generates a strobe pulse within 1 μs of the photon's arrival time and an x-y coordinate pair. These were processed by an array of Transputers and recorded on to an optical WORM disk. Our clocks were externally synchronized to UTC to better than 10 μsec using a GPS receiver. The final MAMA plate scale was 0."090 pixel^{-1}.

3. DATA REDUCTION

The images were sharpened using our normal procedures (Redfern 1991; Redfern et al. 1989). As expected, given the operation at $\approx 40R_0$, these were ineffective in reducing image motion due to atmospheric turbulence. However, small movements caused by telescope wobble on timescales less than those corrected for by the guide probe were removed.

The exposure on the Crab was used to consolidate our procedures. During this process it was found that the times and photon addresses had become separated due to a subtle effect in the recording system. Analysis of the effect has allowed 70% of the Crab times to be realigned with their addresses. We have estimated, based upon the different fluxes from the Crab field and from the field surrounding PSR 0540−69, that the same procedure will realign ~40% of the times from PSR 0540−69.

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[5] Transputer Instrument For Fast Image Deconvolution.
[6] Multi-Anode Microchannel Array (Timothy & Bybee 1985; Cullum 1990).
[7] Rutherford-Appleton Laboratory Photon Counting Detector (Carter et al. 1990).

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TABLE 1

SUMMARY OF OBSERVATIONS

Date (1993)	UTC	Object	Duration (s)	Seeing	$3.5R_0$ (cm)
Jan 16.........	07:01	0540 − 69	3898	1″.4	28
Jan 17.........	01:33	0540 − 69	2215	1.6	24.5
Jan 17.........	02:12	Crab	383	1.6	24.5

The realigned photon arrival times were extracted from a grid of nonoverlapping apertures across the field of view. Once extracted, the times were reduced to the Solar System Barycenter using the JPL DE200 Ephemeris. The procedure is equivalent to making a number of independent aperture photometry measurements. At the time of the observations, based upon normal spin down, the pulsar was expected to have a frequency of 19.838083 Hz, derived from Manchester et al. The arrival times were analyzed using Fourier techniques and the significance of the expected 19.838 Hz peak in the power spectrum was determined for each aperture. Each box had sides of 40 × 40 pixels, corresponding to ≈3″.5 on the sky. In both images the nebula region had significant pulses. A smaller circular window, of radius 15 pixels, was then moved in 5 pixel steps around the nebula. Finally the same window was moved in 3 (0″.25) pixel steps centered upon the peak of the previous distribution. The final width was chosen to maximize the signal-to-noise ratio from an assumed point source given the poor seeing. The final peaks had a SNR of 4.1 on night 1 and 2.4 on night 2. The SNR was calculated as the ratio between the power spectrum peak height at the barycentric pulsar period and the 1 σ noise level taken from the surrounding 19–20 Hz band.

Figure 1 shows the nebula with the position of the peaks on the two nights. Also marked is the position of the northern maximum described by Caraveo et al. Our spatial errors, at the 2 σ level derived from fitting a Gaussian profile, were ±4 pixels for the first night and ±3.2 pixels on the second, corresponding to ±0″.35 and ±0″.28, respectively. The relative astrometry, using IRAF, was based on five stars observed in both our night 2 and in the Caraveo image. This was accurate to ±1 pixel (0″.09).

Monte Carlo simulations of our procedures show that this peak corresponds to ∼0.6 photons s^{-1} from the pulsar. The expected flux from the pulsar was 1.9 photons s^{-1} given our observed nebula flux and the fluxes observed by Middleditch & Pennypacker and Caraveo et al. The measurement 0.6 photons s^{-1} should be compared with our estimate of 0.8 photons s^{-1} assuming that realignment recovers 40% of the pulsed photons from PSR 0540−69. Our figure is therefore not inconsistent with the expected flux, but due to the timing problem no more definitive statement can be made.

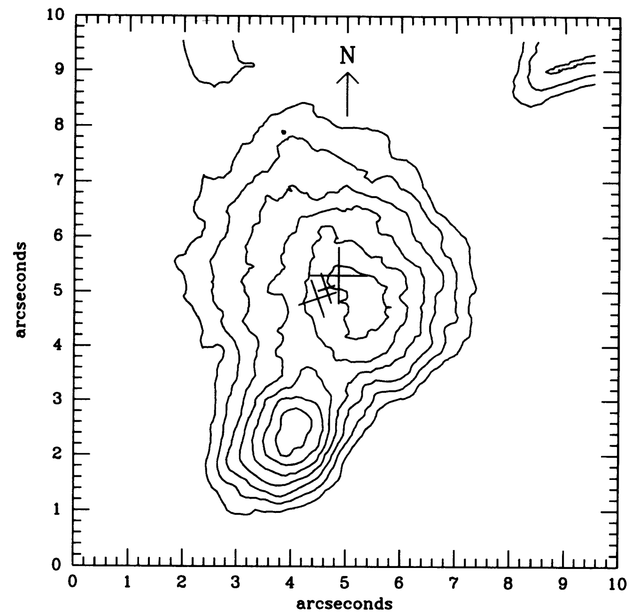

FIG. 1.—The positions corresponding to the maximum in the 19.838 Hz signal plotted over the nebula contours for the data taken on night 2. Also shown is the position of the Caraveo northern maximum. Our error bars correspond to the 95% confidence level.

4. DISCUSSION

The spatial coincidence between our peaks at the expected frequency and the Caraveo position gives us confidence that the Caraveo et al. northern maximum, at $\alpha_{(1950)} = 5^h40^m33^s.84$ (±0″.5), $\delta_{(1950)} = -69°21'20''.9$(±0″.5), is the pulsar. Its central location to the synchrotron nebula corroborates the similarity between this system and the Crab.

The significance level of the 19.838 Hz pulse (99%), combined with significance of the overlap of our positions on the two nights (92%), give us a combined confidence at the 99.5% level. This is before we considered the coincidence of the flux and the spatial coincidence with the Caraveo et al. peak, which are not quantifiable in a straightforward manner, but must increase the significance. It is important to note that although our two points are coincident on the sky they come from different parts of the MAMA's photocathode and anode structure ruling out any instrumental cause of the spatial coincidence. Our position is within the X-ray error circle, but away from the Manchester & Peterson position derived from optical timing considerations. Their position has been criticized by Nagase et al. (1990) and lies outside the synchrotron nebula. We do, however, agree with the approximate position described by Middleditch & Pennypacker in their discovery paper.

The X-ray error circle of diameter 2″ produces an annual 5 ms barycentric timing error (Nagase et al. 1990). Consequently an improved position would enable a more accurate $\ddot{p}$ and hence braking index to be determined. *Hubble Space Telescope* observations using this refined position should produce a better measurement of the pulse profile, which differs markedly from the Crab pulsar, to be made. We have also demonstated the power of two-dimensional photon counting detectors compared to conventional aperture photometers.

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REFERENCES

Caraveo, P. A., Bignami, G. F., Mereghetti, S., & Mombelli, M. 1992, ApJ, 395, L103
Carter, M. K., Cutler, R., Patchett, B. E., Read, P. D., Waltham, N., & van Breda, I. G. 1990, Proc. SPIE, Vol. 1235, Instrumentation in Astronomy VII, 644
Cullum, M. 1990, The MAMA Detector Users' Manual (Garching: ESO)
Manchester, R. N., Mar, D. P., Lyne, A. G., Kaspi, V. M., & Johnson, S. 1993, ApJ, 403, L29
Manchester, R. N., & Peterson, B. A. 1989, ApJ, 342, L23
Middleditch, J., & Pennypacker, C. 1985, Nature, 313, 659
Nagase, F., Deeter, J., Lewis, W., Dotani, T., Makino, F., & Dotani, K. 1990, ApJ, 351, L13
Redfern, R. M. 1991, Vistas in Astron., 34, 201
Redfern, M., Devaney, N., O'Kane, P., Ballesteros Ramirez, E., Gomez Renasco, R., & Rosa, F. 1989, MNRAS, 238, 791
Redfern, R. M., Shearer, A., O'Kane, P., O'Byrne, C., & Butler, R. 1994, in preparation
Timothy, J. G., & Bybee, R. L. 1985, Proc. SPIE, 687, 1090

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