LA-UR -85-286

Conf-8410232--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG 36.

TITLE: THE OPTICAL PULSAR IN THE LARGE MAGELLANIC CLOUD REMNANT 0540-69.3

LA-UR--85-286

DE85 006707

AUTHOR(S): J. Middleditch and C. R. Pennypacker

SUBMITTED TO: Proc. Workshop on the Crab Nebula and Related Supernova Remnants
George Mason University
Washington, DC
October 11-12, 1984

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

THE OPTICAL PULSAR IN THE LARGE MAGELLANIC CLOUD REMNANT 0540-69.3

J. Middleditch
Earth and Space Sciences Division, ESS-9, MS D436
Los Alamos National Laboratory, Los Alamos, NM 87545

C. R. Pennypacker
Rm. ?32, Bldg. 50, Lawrence Berkeley Laboratory
and Space Sciences Laboratory
University of California, Berkeley, CA 94720

We have detected pulsed optical emission from the Large Magellanic Cloud (LMC) X-ray pulsar PSR 0540-693 (Seward et al. 1984). The pulsed emission has a time averaged magnitude of approximately 22.7.

The X-ray pulsar was discovered in the LMC remnant, 0540-69.3 as a pulse repetition period of ~50 milliseconds (ms) in Einstein Observatory data (Seward et al. 1984). Earlier, Clark et al. (1982) had noted that this remnant resembles the Crab Nebula because of the X-ray power law spectrum, and suggested that the nebular emission was synchrotron radiation powered by a central pulsar. After the announcement of X-ray pulsed emission, Chanan et al. (1984) measured the broad optical band properties of the nebula and found evidence for synchrotron emission. They reported that the 4.5 arc second continuum emission remnant has only a tenth the luminosity of the Crab Nebula.

We have recorded broad-band optical time-series data at 1 ms intervals with the 4-m and 1.5-m Cerro Tololo telescopes and have found strong pulsations, employing the usual Fourier transform methods (see Middleditch et al. 1983, and Middleditch & Kristian 1984). Table 1 gives a summary of the observations, including magnitudes, barycentric frequencies and times of arrival.

able 1 Log of time series obse[illegible]ations of PSR 0540-693-693

un number	1	2	3	4	5
T 1984 August	26.38182241(1)	27.36440074(1)	28.3595	30.36588796(2)	31.34988462(1)
uration (hours)	1.39	2.28	2.33	1.78	2.12
elescope	4-m	4-m	4-m	1.5-m	1.5-m
avelength (nm)	320-750	320-750	320-750	350-900	350-900
perture diam. "	4.6	4.6	6.6	7.0	7.0
ulse freq.$_{(b)}$ (Hz)	19.8881615(64)	19.8881420(26)	19.8881242(33)	19.888101(12)	19.8880695(73)
" period$_{(b)}$ (ms)	50.281168(16)	50.281218(7)	50.281263(8)	50.281322(30)	50.281401(18)
B+V)/2	22.75(0.06)	22.65(0.04)	22.75(0.05)	22.33(0.15)	22.34(0.10)

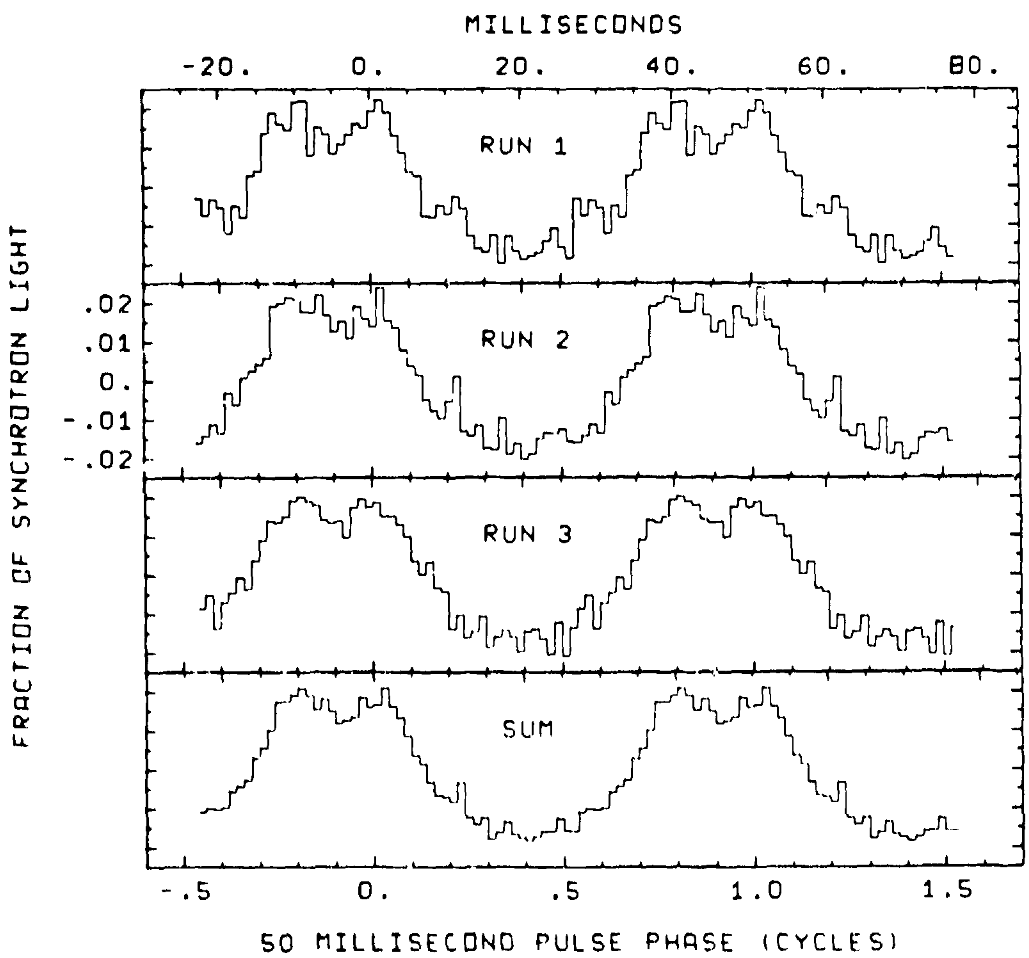
ean epoch (1984 August) 28.8659

ean frequency$_{(b)}$ 19.8881152(16) Hz = 50.2812856(40) ms

ean $\partial f/\partial t$ $-2.05(0.11)\cdot 10^{-10}$ Hz/s = 44.8(2.4) ns/day

The pulse profile is predominantly sinusoidal with a 10-20% dip in the intensity maximum (see Figure 1).

Fig. 1 The optical pulse profiles of the LMC PSR 0540-693 from runs 1-3 (see Table 1) and the average pulse profile of these runs are shown repeated over two whole cycles. The profiles have been co-aligned according to the phase of the 20 Hz fundamental structure.



Although this dip persists in the three most sensitive time series, the amplitudes of the next highest harmonics (60 Hz and 80 Hz) correspond to only 12% and 14% of the amplitude at the fundamental 20 Hz frequency (see Table 2). However, the average pulse profile for these runs (Fig. 1 bottom) shows that the duty cycle of the pulse is ~44%, not 50%. No significant 10 Hz structure (at half the fundamental frequency) was found in the time series data, the corresponding amplitude having a 90% probability of being less than 10% of the 20 Hz amplitude.

The integrated broad-band pulsed light intensity (~(B+V)/2), is approximately equivalent to $(22^{m}.7)\times\sin(2\pi\cdot 20\cdot t)$, corresponding to just under 2% of the nebular light included in the 4.6 arc second circular aperture used in runs 1 and 2. This circular aperture was centered by count rate on the bright knot of the synchrotron emission, one or two arc seconds west of the center of the OIII emission ring surrounding the nebula (Chanan et al. 1984). The centering was achieved by adjusting the offsets of a star-tracking autoguider probe which controlled the telescope motion during the data recording interval. The lack of erratic modulation of the pulse amplitude and the consistency of the magnitudes derived in runs 1-3 imply that the pulsing source coincides with the bright peak of the continuum emission (Chanan et al. 1984) to within 1.5 arc seconds.

The intrinsic optical luminosity of the LMC pulsar (~10^{34} erg s^{-1}) is about the same as that of the Crab Pulsar (see Table 3), taking into account the larger distance to the LMC (55 kpc vs. 2 kpc) and the smaller visual extinction (A_V) toward the LMC (0.6 magnitudes vs. 1.6 magnitudes, Miller 1973). Here we have used a 0.13 magnitude color excess in the LMC from Savage et al. (1983) and have applied an extra 0.07 magnitudes due to the Milky Way foreground, as suggested by Kirshner (1984), along with his estimated probable error of 0.05. Our rough estimate shows the pulsar to be significantly red when compared to the Crab Pulsar (see Table 3), with the intrinsic colors of $(B-V)_o$ ~ 0.7, vs. $(B-V)_o$ ~ -0.03 for the Crab Pulsar (Kristian et al. 1970; Miller 1973). Standard stars were observed in addition to the Crab Pulsar and the central LMC remnant to establish the flux calibrations.

Table 2 Harmonic content of the PSR 0540-693 pulse profile

Run number	1	2	3	(mean)
2nd harmonic (40 Hz)	<0.07	0.08(0.04)	<0.07	...
3rd harmonic (60 Hz)	0.11(0.06)	0.13(0.04)	0.14(0.05)	0.12(0.03)
4th harmonic	0.23(0.06)	0.13(0.04)	0.06(0.05)	0.14(0.03)
5th harmonic	0.07(0.06)	0.06(0.04)	<0.08	0.06(0.03)
6th harmonic	0.06(0.06)	<0.06	<0.07	...
7th harmonic	<0.07	0.06(0.04)	<0.07	...

The Crab-like luminosity of the (slower) LMC pulsar (Table 3) may be due in part to beaming effects (a five times larger duty cycle than that of the Crab -- ~50% vs. ~10%), or possibly to a higher efficiency of conversion of mechanical energy into pulsed radiant energy. The nominal magnetic field for this pulsar would be about 1.3 times the Crab Pulsar's field (or $\sim 5 \cdot 10^{12}$ gauss), all other parameters being the same and using standard arguments (Manchester & Taylor 1977). The coincidence of the absolute luminosity of this pulsar and that of the Crab Pulsar, even though this pulsar is 33% slower, argues against emission models predicting optical luminosity as a high power of rotation (see, e.g., Pacini 1973, and Pacini & Salvati 1983), unless beaming effects can be invoked to account for an extra luminosity factor of ~20 in the LMC pulsar. Determination of the <u>unpulsed</u> flux from the LMC pulsar will be difficult at best due to the strong central condensation of the nebular synchrotron emission (Chanan *et al.* 1984).

The optical and X-ray pulsed fluxes of the LMC pulsar do not have the same ratio as the corresponding nebular fluxes (which interpolate as, and are both internally consistent with, $\nu^{-0.8}$ -- Clark *et al.* 1982; Chanan *et al.* 1984) but instead interpolate as $\nu^{-0.3}$. Since the optical and X-ray pulse profiles of the LMC pulsar are identical within statistics (Seward *et al.* 1984, and this work), the $\nu^{-0.3}$ relationship is particularly suggestive. This power law would result from the same electron injection spectrum which produces the synchrotron

Table 3 Pulsed fluxes of PSR 0540-693

Measured parameters		
(B+V)/2 (4-m)	22.70(0.07)	
(B+V)/2 (1.5-m)	22.34(0.07) + (0.39(0.10))(B-V)	
	Magnitude	Flux
Derived parameters		
(B-V)	0.89(0.35)	...
B	23.15(0.20)	2.0(0.4) μJy
V	22.26(0.20)	4.5(0.9) μJy
Correcting for absorption, E(B-V) = 0.20(0.05)		
$(B-V)_o$	0.69(0.35)	...
B_o	22.35(0.28)	4.2(1.2) μJy
V_o	21.66(0.25)	7.9(2.0) μJy
L_{B_o}	$0.5L_\odot$	$0.8L_{B\ Crab}$
L_{V_o}	$0.7L_\odot$	$1.6L_{V\ Crab}$

loss-dominated nebular emission spectrum of $\nu^{-0.8}$, except that the electrons producing the optical and X-ray pulses would not have had time to become loss-dominated, but instead have an electron number distribution of $n(E)dE \propto E^{-1.6}$. Such a curve also extrapolates to 0.4 mJy at 400 MHz -- a factor of ~2 below below the current upper limit (Manchester 1984) and perhaps measurable with further effort. Although the spectrum for the pulsed X-radiation, corresponding to $\nu^{-0.5}$ from 0.2 to 4 KeV (Seward 1984), is nearly consistent with the interpolated optical-to-X-ray spectrum, the estimated optical spectrum from B to V, corresponding to $\nu^{-2.8(1.4)}$, is not. The nebular and pulsed fluxes of the Crab also do not each follow a single power law, instead the pattern is much more complex. Although a $\nu^{-0.9}$ interpolation fits the nebular spectrum well from optical to γ-ray energies, a slope change occurs in the corresponding pulsar spectrum, and other slope changes occur in both the nebular and pulsar spectra at longer wavelengths (Manchester & Taylor 1977).

Because of timing uncertainties, we could not connect phase reliably between the five nights of data. No satisfactory cycle number assignment was found which agreed with the mean $\partial P/\partial t$ value for 1979-1984 (Seward et al. 1984, and this work) of 41.395 ns/day. The mean frequency quoted in Table 1 is consistent with the mean of the individual frequencies, but also can be used to count the cycles between runs 2 and 4, and 1 and 5. However, the resulting $\partial P/\partial t$ is 45.9(0.3) ns/day and is inconsistent with the nominal value of 41.4 ns/day. If this behavior is confirmed by future observations, then PSR 0540-693 would have to be subject to starquakes as large as those found in the Vela Pulsar (Downs 1981), namely $\Delta f/f \sim 10^{-6}$, where f is the pulse repetition frequency. In this situation, any hope of measuring the braking index, n, in $\partial f/\partial t \propto -Cf^n$, would be lost. An index of 3 corresponds to magnetic dipole braking; the Crab Pulsar has an index of 2.5 (Groth 1975). However, we must defer judgement on this matter until more accurately timed data becomes available.

In conclusion, the broad pulse profile and the intrinsically red color render the LMC pulsar distinct from the Crab Pulsar. The relatively high pulsed optical luminosity of PSR 0540-693 will facilitate measurements of polarization and colors and, consequently, the refinement of models of pulsed emission. The interpolated $\nu^{-0.3}$ pulsed optical-to-X-ray spectrum suggests a simplifying assumption regarding the electron number distribution may be valid for such models -- an assumption which can be tested by slightly more sensitive pulsation limits in radio frequency bands.

ACKNOWLEDGEMENTS

We thank the staff of CTIO for their support. We are grateful to Dr. Myles Standish of the NASA Jet Propulsion Laboratory for providing us a copy of JPL ephemeris DE96. Carl Pennypacker acknowledges the continual support and encouragement of Richard Muller and thanks Costas Papaliolios for pulsar tutelage. This work was performed under the auspices of the Department of Energy, in part through Internal Supporting Research funds at Los Alamos, and in part through the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics, under contract Number DE-AC03-76SD00098.

REFERENCES

Chanan, G. A., Helfand, D. J. & Reynolds, S. P. (1985). Astrophys. J. Lett: (in press).

Clark, D. H., Tuohy, I. R., Long, K. S., Szymkowiak, A. E., Dopita, M. A., Mathewson, D. S. & Culhane, J. L. (1982). Astrophys. J., 255, 440-6.

Downs, G. S. (1981). Astrophys. J., 249, 687-97.

Groth, E. J. (1975). Astrophys. J. Suppl., 29, 453-65.

Kirshner, R. P. (1984). private communication.

Kristian, J., Visvananthan, N., Westphal, J. A. & Snellen, G. H. (1970). Astrophys. J., 162, 475-83.

Manchester, R. N. & Taylor, J. H. (1977). Pulsars. San Francisco: Freeman.

Manchester, R. N. (1984). In Proc. Workshop on Birth & Evolution of Neutron Stars (Number 8): Issues Raised by Millisecond Pulsars, ed. S. P. Reynolds & D. R. Stinebring. June, NRAO, Greenbank, WV: NRAO Publications.

Middleditch, J., Cudaback, D., Oliver, B., Pennypacker, C., Lebofsky, M. J., Rieke, G. H., McGraw, J. T., Dearborn, D., Wisniewski, W. & Chini, R. (1983). Nature, 306, 163-4.

Middleditch, J. & Kristian, J. (1984). Astrophys. J., 279, 157-61.

Miller, J. S. (1973). Astrophys. J. Lett., 180, L83-7.

Pacini, F. (1971). Astrophys. J. Lett., 163, L17-20.

Pacini, F. & Salvati, M. (1983). Astrophys. J., 274, 369-71.

Savage, B. D., Fitzpatrick, E. L., Cassinelli, J. P. & Ebbets, D. C. (1983). Astrophys. J., 273, 597-623.

Seward, F. D., Harnden, F. R. & Helfand, D. J. (1984). Astrophys. J. Lett: (in press).

Seward, F. D. (1984). In Proc. Workshop on the Crab Nebula and Related Supernova Remnants, ed. M. C. Kafatos & R. C. B. Henry. Oct. 11-12, George Mason University, Fairfax, VA: Cambridge University Press.

F. C. Michel: It looks as if there are significant pulse-shape changes for this object, unlike the Crab pulsar.

J. Middleditch: The evidence for such changes is not strong, the problem is the higher harmonics were not detected at high levels of significance. So far we have a feeling that the strongest higher harmonic -- the 4th harmonic -- may be somewhat variable in amplitude and may not follow the fundamental frequency well in one case. More significant observations may give us a definite answer.

C. Jarrett: Is there no evidence of any interpulse and is this attributable to the absence of higher harmonics?

J. Middleditch: Yes -- there is no evidence of an interpulse in the [illegible] pulse structure and the X-ray evidence for an interpulse is [illegible]y significant.

END

DATE FILMED

04/03/85