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The optical pulsar B0540-69

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The high speed photometer Iqueye has been used at the NTT in January and December 2009, obtaining a series of data on the Crab, LMC and Vela pulsars. This paper describes in particular the data obtained on PSR B0540-69 (the second brightest optical pulsar) and the derived light curve. Conclusions are then drawn about the braking index and other characteristics.

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1. Introduction

PSR B0540-69 is the second brightest in the optical band after the Crab pulsar. It is located in the Large Magellanic Cloud and it has been observed in recent years with a variety of imaging and spectroscopic instruments on ground telescopes (e.g. [29, 7, 33]; and references therein). We observed this pulsar at the ESO NTT with our very-high-speed photometer Iqueye (the prototype of a 'quantum' photometer for the European Extremely Large Telescope E-ELT, [10]) in January and December 2009. From these observations we obtained an optical light curve, the first derived from data acquired since 1996.

PSR B0540-69 was first discovered in the X-rays by the Einstein Observatory [34]. Soon after its discovery, optical pulsations were detected by Middleditch et al. (1985) [26]. In radio, the pulsar was undetectable for a long time and finally its pulsations were detected from Parkes [25]. The optical light curve of this pulsar [27, 13, 3, 28, 9, 40] is characterized by a single broad peak. All those optical pulse shapes are consistent with the radio one [25] and with those observed in the X and Gamma-ray domains (e.g. [30, 9, 8, 5]).

2. Observations and analysis

The first published light curve was obtained by Middleditch et al. (1985, 1987) [26, 27] using the 4-m and 1.5-m telescopes at Cerro Tololo. Then, Gouiffes et al. (1992) [13] derived a second light curve from data taken with the ESO 3.6-m telescope. Boyd et al. (1995) [3] obtained a third light curve with the High Speed Photometer (HSP) on board the HST. The HSP light curve was consistent with the shape seen by Middleditch et al. (1987) [27] and Gouiffes et al. (1992) [13], and showed with clarity a double peak structure. A fourth curve, from data obtained in May 1994 at the ESO 3.6-m telescope, was inserted by Mignani et al. (1998) [28] in a paper about the pulsar PSR B1509-58. Subsequently, Deeter et al. (1999) [9] published a light curve based on data originally taken by Manchester et al. (1989) [24] at the 4-m Anglo Australian Telescope over the period 1986 14 July to 1988 16 June. Finally, Ulmer et al. (1999) [40] published a light curve obtained at CTIO in Nov. 1996, and suspected a strong phase difference between optical and X-ray data. Figure 1 shows all these light curves.

We observed PSR B0540-69 in January and December 2009 with Iqueye, a fixed aperture photometer that collects light within a field of view of few arcseconds around the target object. It divides the light beam into four equal parts and focuses each sub-beam on an independent single photon-counting diode (SPAD, Single Photon Avalanche Diode). Its data acquisition system allowed us to time tag the detected photons with a final absolute UTC referenced rms time accuracy superior to 0.5 ns over one hour of observation (see [1] and [31] for a more detailed description of the instrument).

The observations were obtained through 3.5 or 5.2 arcsec diaphragms, without filters (maximum sensitivity around 550 nm, bandwidth at half maximum approximately 300 nm). The observation log is provided in Table 1. The columns UTC and MJD = Modified Julian Date = JD - 2 400 000.5 provide values of time and date at mid counting period referred to the barycentre of the solar system in TCB units.

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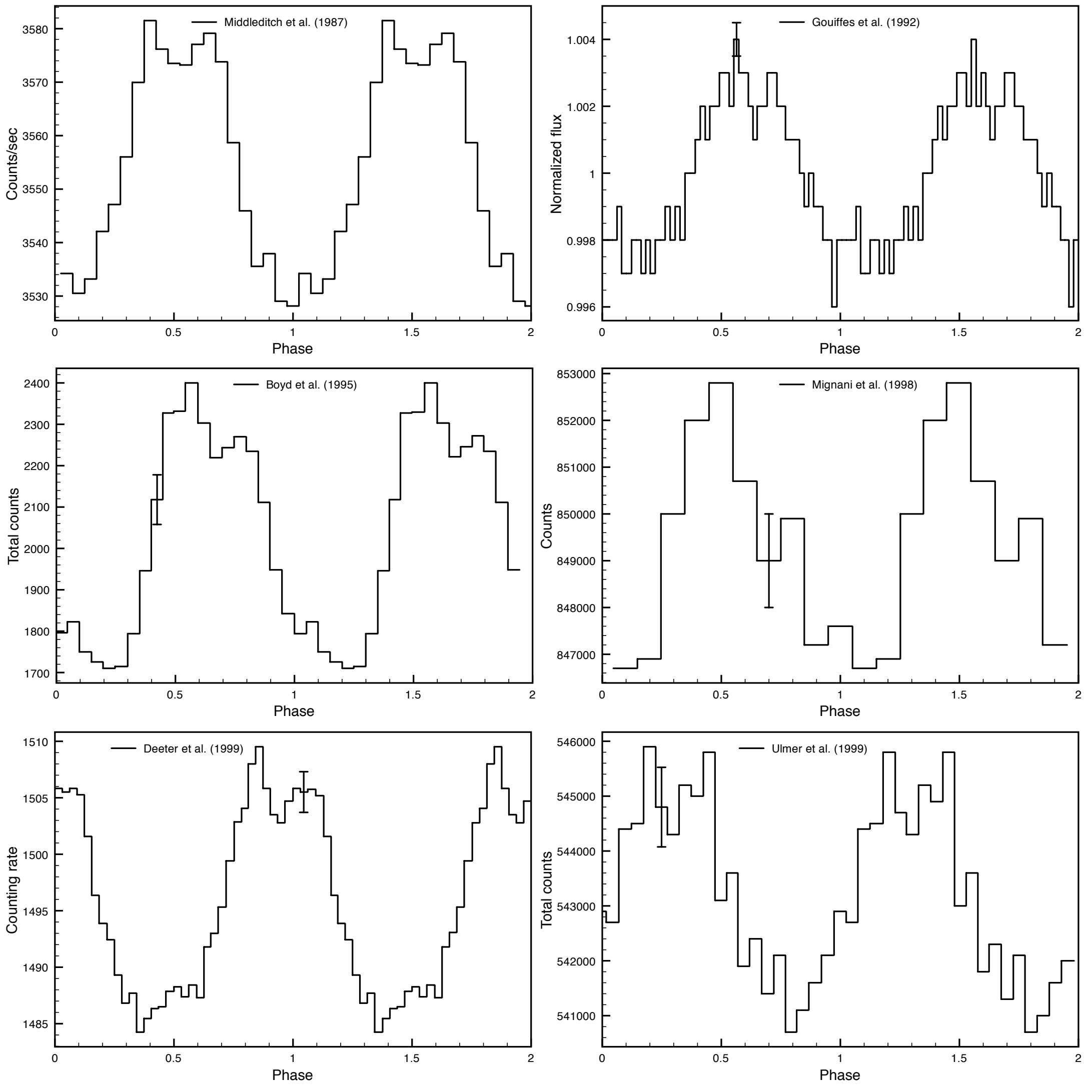

Figure 1: Light curves by Middleditch et al. (1987), Gouiffes et al. (1992), Boyd et al. (1995), Mignani et al. (1998), Deeter et al. (1999), and Ulmer et al. (1999) [27, 13, 3, 28, 9, 40]. The vertical bar indicates the error quoted by the authors. The curves have been arbitrarily shifted in phase.

The procedure used to centre faint pulsating objects is to bin the arrival times in convenient time bins, e.g. 1/20 of the expected period, so that standard time-series analysis algorithms can be applied to single out the frequencies in the signal. Different positions are then tested until the best signal is found. In the case of B0540-69, the Power Spectral Density of the data was dominated by a frequency at the expected (according to the ephemerides available in the literature) value of 19.7433 Hz (period around 0.05065 s) for January's data and 19.7380 Hz (period around 0.05066 s) for December's data with a statistical significance higher than 20 standard deviations (σ's) of noise. In December, this standard procedure was greatly helped by the availability of a very deep finding chart, kindly provided by Mignani et al. (2010) [29] (their fig. 1) before publication.

The photons collected by each SPAD arrive from four different sub-pupils of the NTT aperture:

Date	UTC (hh mm ss)	MJD (d) (mid-exposure time)	Observation duration (s)	Diaphragm diameter (arcsec)
2009 01 18	05 11 10.0	54849.21665	5994	3.5
2009 01 20	04 03 19.0	54851.16190	5874	5.2
2009 12 14	07 27 59.9	55179.31111	3600	3.5
2009 12 15	02 42 00.0	55180.11250	3600	3.5
2009 12 16	01 39 59.6	55181.06944	3000	5.2
2009 12 18	02 30 00.3	55183.10417	3600	3.5

Table 1: Log of the observations of Iqueye at the NTT.

this allows us to consider the system as four parallel smaller telescopes, each focused on one SPAD. The addition of a fifth SPAD in the December run enabled also the acquisition of the signal from adjacent sky. The stored data contain long strings of time tags. With these data, all possible types of post-processing analysis can be done without affecting the integrity of the original data. A lot of time and work have been dedicated to devise dedicated Matlab algorithms for the analysis of Iqueye data.

The arrival times of the photons have been referred to the barycentre of the solar system, by using an adapted version of Tempo2 software [16] with the DE405 JPL Ephemerides [38]. The assumed celestial coordinates of the source are RA2000 = 05h40m11s.202 ± 0s.009; DEC2000 = $-69^{\circ}19'54''.17 \pm 0''.05$ [29], with zero proper motion [29, 7].

The spin period, P, of the pulsar was determined by an epoch-folding technique similar to that expounded by Leahy et al. (1983) [20]. The spin period P was computed separately for each night. For each period, the χ^2 values against the zero hypothesis of a flat curve was calculated, obtaining a well defined distribution peaked around the expected value. The best period was then obtained through a least-squares fit of the χ^2 distribution with a Gaussian curve. The mean value of the Gaussian is the best fitting period, while its variance provides an estimate of the period dispersion. In Table 2 we report the results of the procedure, in terms of both the measured period P and the corresponding pulsar spin frequency ν. The quoted errors on P are the standard deviation on the mean value of the Gaussian curve fitted to the χ^2 distribution while those on ν are obtained by error propagation.

The combined Iqueye light curve for all nights of January and December 2009 is shown in Figure 2 using 50 phase bins and displayed for better visualization over two cycles. All light curves were shifted to match the phase of December 18 because of the better S/N ratio of those data. Each curve has been weighted for the respective χ^2 value of the period determination and the alignment by minimizing the distance between the curves using again the χ^2 method.

The light curve obtained with Iqueye is very similar to that shown by the light curves resulting from the published observations performed at other ground based telescopes. All available light curves published over the last 27 years have approximately the same modulation, and broadly show the same features.

Given the high number of acquired (indicatively a mean rate of 2500 counts/sec) photons, and

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Date (MJD)	Period (s) and error (s)	Frequency (Hz) and error (Hz)
54849.21665	0.050 649 974 5 (0.30×10^{-9})	19.743 346 6 (0.12×10^{-6})
54851.16190	0.050 650 017 3 (0.25×10^{-9})	19.743 329 9 (0.09×10^{-6})
55179.31111	0.050 663 549 8 (0.32×10^{-9})	19.738 056 3 (0.13×10^{-6})
55180.11250	0.050 663 632 9 (0.26×10^{-9})	19.738 023 9 (0.10×10^{-6})
55181.06944	0.050 663 671 5 (0.38×10^{-9})	19.738 008 9 (0.15×10^{-6})
55183.10417	0.050 663 753 2 (0.27×10^{-9})	19.737 977 1 (0.11×10^{-6})

Table 2: Periods and frequencies of PSR B0540-69 determined with Iqueye data obtained during 2009.

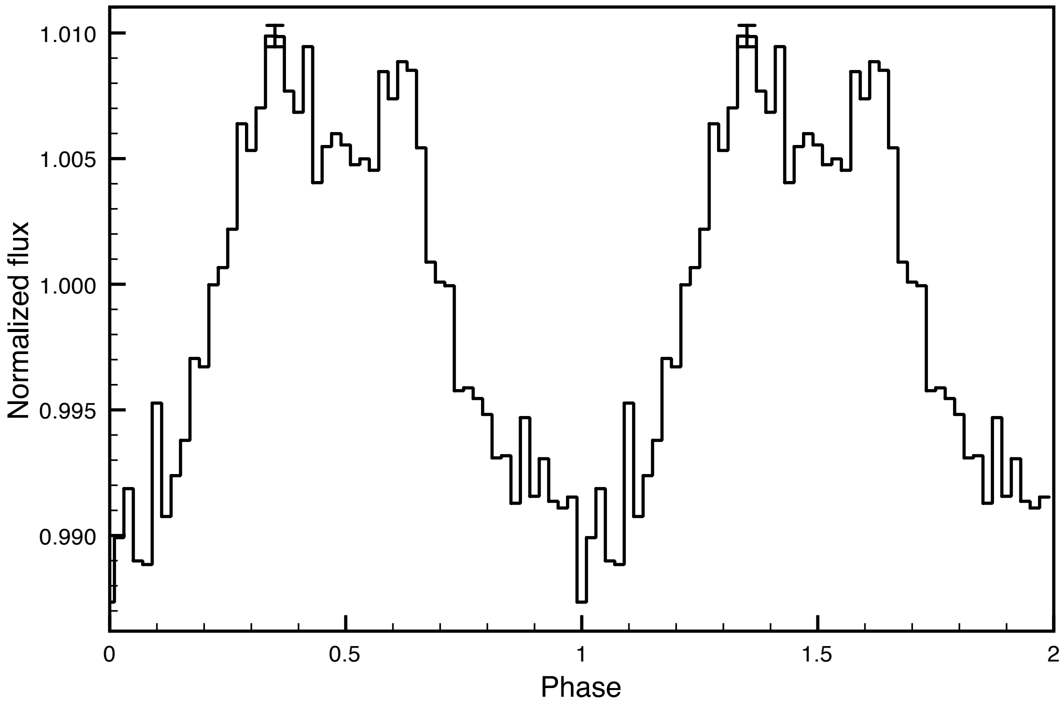

Figure 2: The overall Iqueye light curve in Jan and Dec 2009, from the individual curves weighted according to the respective χ^2 value and binned in 50 phase intervals. The counts have been normalized to the average count value during a period. For clarity the curve is shown over two cycles. The vertical bar shows the 1 sigma error. All light curves were shifted to match the phase of December 18.

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the extremely accurate time tagging guaranteed by Iqueye, we feel confident to say that our light curve is the best available so far in the optical. The total duration of the main peak is approximately 22 ms (FWHM), with a central shallower feature suggesting the superposition of at least two peaks. Therefore we have fitted the broad central peak with two Gaussian components (see [8]) separated by 0.29 ($\pm$ 0.02) in phase, the leading one approximately 1.02 times higher than the second one, and with a FWHM of 13.3 $\pm$ 0.2 ms and 15.5 $\pm$ 0.2 ms respectively.

3. Discussion of the braking index and age

In commonly assumed models for pulsar spin-down, a braking index n and a characteristic age τ_c are defined [22] by:

$$\dot{\nu} = -K\nu^n \tag{3.1}$$

$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2} \tag{3.2}$$

$$\tau_c = \frac{\nu}{2\dot{\nu}} \tag{3.3}$$

where ν is the pulse frequency, $\dot{\nu}$ and $\ddot{\nu}$ are the first and second frequency derivatives respectively, and K is a constant. The actual value of the braking index is strictly related with the pulsar spin-down mechanism. It is well known [23] that, for magnetic dipole emission, $n = 3$. Different values of n would correspond to different processes of rotational energy loss and, in particular, values lower than 3 indicate that an additional torque is contributing to the spin-down.

We have attempted a simple analysis adding the Iqueye frequencies to the available values at the different dates spanned by radio, optical and X data (summarized in Table 3). Then these values have been fitted with a second order polynomial, using least-squares regression, in the assumption of none or very small and infrequent glitches:

$$\nu(t) = \nu(t_0) + \dot{\nu}(t-t_0) + \frac{1}{2}\ddot{\nu}(t-t_0)^2. \tag{3.4}$$

We calculated the first and second frequency derivatives adding the frequency values measured with Iqueye in January and December 2009 to the previously published data sets. The coefficients of the best fitting parabola, where t_0 is the value of the last date of observations, are reported in Table 4.

The resulting value for the braking index is n = 2.087 $\pm$ 0.013, and the characteristic age is τ = 1677.5 years. Our result is consistent within 3 combined sigmas with the value given by Livingstone, n = 2.140 $\pm$ 0.009, by a careful analysis of all X-ray data obtained using 7.6 years of data from the Rossi X-Ray Timing Explorer. The optical data available until our observations provided the following values: Manchester et al. (1989), $n = 2.01 \pm 0.02$ [24], Gouiffes et al. (1992), $n = 2.04 \pm 0.02$ [13], and Boyd et al. (1995), $n = 2.28 \pm 0.02$ [3]. In this scenario, our result confirms that the value of the braking index for PSR B0540-69 is definitely lower than 3.

4. Conclusions

We have observed the LMC B0540-69 pulsar with Iqueye, a novel extremely high time resolution photometer, obtaining data of unprecedented timing accuracy. Over the 27 years spanned

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MJD	Frequency (Hz)	Band	Ref.
44186.91740	19.91687532	X	Seward et al. (1984) [34]
45940.86590	19.88811520	VIS	Middleditch et al. (1985) [26]
46111.07682	19.88533133	VIS	Middleditch et al. (1985) [26]
47860.0000	19.85674751	Radio	Manchester et al. (1993) [25]
47915.0000	19.85584939	Radio	Manchester et al. (1993) [25]
48825.8000	19.84099663	Radio	Manchester et al. (1993) [25]
49225.25570	19.83449650	HST (UV+VIS)	Boyd et al. (1995) [3]
51421.62400	19.79880010	X	Kaaret et al. (2001) [17]
52857.86600	19.77553000	X	Johnston et al. (2004) [19]
53761.76200	19.76092260	X	Campana et al. (2008) [5]
53843.56100	19.75959520	X	Campana et al. (2008) [5]
54849.21665	19.74334657	VIS (Iqueye)	This work
54851.16190	19.74332988	VIS (Iqueye)	This work
55179.31111	19.73805633	VIS (Iqueye)	This work
55180.11250	19.73802395	VIS (Iqueye)	This work
55181.06944	19.73800890	VIS (Iqueye)	This work
55183.10417	19.73797709	VIS (Iqueye)	This work

Table 3: Frequencies used for the calculation of the braking index. Values are taken from the corresponding papers indicated in the last column and ordered by MJD. We have taken into account only measured, i.e. not interpolated, values.

	Value	Error
t_0 (MJD)	55183.1042	
ν_0 (Hz)	19.7379787	1.7×10^{-6}
$\dot{\nu}_0$ (Hz/s)	-1.86548×10^{-10}	9×10^{-15}
$\ddot{\nu}_0$ (Hz/s^2)	3.68×10^{-21}	2×10^{-23}

Table 4: The coefficients of the second order polynomial used for the fit.

by all the data available for this pulsar, our optical data reinforce the previous findings that the pulsar light curve has remarkably similar features in all observed wavelengths. Within the errors, our value of the braking index is in good agreement with almost all other values in the literature. Therefore, there is increasingly consistent evidence that the braking index of PSR B0540-69 is close to n = 2, in agreement with the findings for all young pulsars for which it has been possible to perform such measurement The observations provide also a confirmation of the excellent quality of Iqueye in very high time resolution photometry.

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