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ASCA Observations of the Crab-Like Pulsar PSR B0540−69

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Abstract. We report on the spectral and temporal properties of the 50 ms pulsar PSR B0540−69 using ASCA archival data obtained during 1993 to 1995. From the spectral analysis it was found that the spectra of the whole (nebular and pulsed) emission and pulsed emission in the range 1-10 keV can be represented by a single power law of photon index, $\Gamma = 2.00 \pm 0.02$ and $\Gamma_{\rm pulsed} = 1.7 \pm 0.3$ respectively. The parameters for pulse frequency change during 1993-1995 were obtained using the 9 pulse frequency measurements with ASCA. The parameters derived from the ASCA observations are consistent with the previous measurements, suggesting high stability of this pulsar, $\Delta\Omega/\Omega \lesssim 0.5 \times 10^{-7}$ over the past 10 years. These results confirm similarity of this pulsar with the Crab pulsar.

1. Introduction

The 50 ms pulsar PSR B0540−69 in the Large Magellanic Cloud was first discovered in soft X-ray band near the center of a synchrotron nebula (Seward et al. 1984). Follow-up ground-based observations revealed optical pulsations of magnitude $m_V \sim 22.5$ (Middleditch & Pennypacker 1985). This pulsar is faint (~ 0.4 mJy) in radio band, although the radio pulsation was detected from long time integration (Manchester et al. 1993). HST observations (Hill et al. 1997) confirmed the astrometric position of the pulsar given by Caraveo et al. (1992) and provided a high quality optical spectrum of the pulsar.

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Table 1. Journal of ASCA observations of PSR B0540−69 and measurements of pulse frequencies.

ID	Observation Date	Exposure time (ks)	Epoch (MJD)	Pulse Frequency ν (Hz)	Error (μHz)
A	93/06/13	15.7	49151.589853	19.8356915	3.6
B	93/09/22	23.8	49252.080619	19.8340554	4.5
B&C*	—	—	49253.321078	19.8340355	0.7
C	93/09/24	36.8	49254.461630	19.8340170	2.0
D	94/10/01	7.2	49626.100997	19.8279677	8.9
D&E*	—	—	49627.132475	19.8279515	0.6
E	94/10/03	8.4	49628.130331	19.8279374	7.2
F	94/10/11	2.4	49636.378558	19.8277991	19.8
F&G*	—	—	49637.048671	19.8277903	1.4
G	94/10/12	8.5	49637.716262	19.8277812	11.2
H	94/11/07	3.8	49663.206701	19.8273635	15.1
I	95/11/07	36.6	50028.453569	19.8214242	0.9

* Pulse frequencies are determined by combining two adacent data sets with a few days separations for B&C, D&E, F&G.

A measurement of the braking index of $n = 2.02 \pm 0.01$ was reported by Nagase et al. (1990) from the X-ray pulse timing using the Ginga data. Deeter, Nagase & Boynton (1999; DNB ephemeris) recently derived more precise braking index of $n = 2.080 \pm 0.003$ for about 4 years from 1987 to 1991. In this paper, we report the results of spectral and timing analyses using ASCA archival data obtained in the period of 1993 to 1995.

2. Observations

During the perfomance verification phase of ASCA in 1993, a systematic survey of bright LMC regions including the pulsar PSR B0540−69 was performed. Several snap-shot observations of the source were performed in 1994 October to November to monitor the pulse frequency. During the observation of SN1987A in 1995 November, the pulsar was observed at the corner of the GIS field. Data for PSR B0540−69 were extracted from these archival observations are summarized in Table 1. The dataset C in the table was used for the spectral analysis, whereas all data listed in Table 1 were used for pulse timing analysis. Details of data reduction and analysis procedure are given elsewhere by Hirayama et al. (1999).

3. Energy Spectrum

A point-like X-ray source is detected clearly at the position of PSR B0540−69 in all the data sets. To derive the spectral parameters accurately we used data obtained on September 23-24, 1993 for spectral analysis, when the pulsar was observed at the nominal position in the GIS field and the exposure time is largest. The X-ray spectrum of the whole source is well represented by a single

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Table 2. Pulse frequency parameters of PSR B0540-69 obtained from the present analysis are compared with those by Deeter et. al. (1999).*

Parameter	DNB ephemeris	This work
t_0 (MJD)	47700.0	49590.021711
ν_0 (Hz)	19.8593584982(52)	19.82855532(92)
$\dot{\nu}_0$ (10^{-10} Hz s^{-1})	−1.8894081(10)	−1.88323(25)
$\ddot{\nu}_0$ (10^{-21} Hz s^{-2})	3.7388(49)	3.77 ± 2.25
braking index n ..	2.0799(27)	2.11 ± 1.26

* Derived by fitting to the quadratic ephemeris, $\nu(t) = \nu_0 + \dot{\nu}_0\,(t - t_0) + \frac{1}{2}\ddot{\nu}_0\,(t - t_0)^2$. Values in the parenthesis are the errors in the last decades of each parameter.

power-law model of photon index, $\Gamma = 2.00 \pm 0.02$, with a small photoelectric absorption, corresponding to $N_{\rm H} = (4.3 \pm 0.2) \times 10^{21}$ cm^{-2}. This results in an X-ray luminosity of $L_{\rm X} = (1.16 \pm 0.03) \times 10^{37}$ erg s^{-1} in the energy range 1-10 keV, assuming the source distance to be 55 kpc.

The X-ray pulsations were clearly detected and the folded light curves show one broad pulse with a small dip on the top which is consistent with previous observations (e.g., Seward et al. 1984, Deeter et al. 1999). We made pulse-phase resolved spectroscopy and found that the photon index varies with pulse phase ranging from 2.0 to 2.2, while the photoelectric absorption remain constant. It is found from the phase resolved analysis that the pulsed emission can be represented by an absorbed single power-law model with photon index, $\Gamma_{\rm pulsed} = 1.7 \pm 0.3$ with an X-ray luminosity of $L_{\rm X,pulsed} = (2.9 \pm 0.3) \times 10^{36}$ erg s^{-1} in the 1-10 keV range. These are smoothly connected with the soft X-ray spectra derived from ROSAT in 0.1-2.4 keV range (Finley et al. 1993) and confirm the similarity of the nebular/pulsed spectra of this system with those of Crab nebular/pulsar system.

4. Pulse Timing Analysis

Local pulse frequencies derived from the 9 data sets are given in Table 1 together with the epoch of determination, where we adopted the mid-time of each observation as an epoch. We also derived pulse frequencies by combining two consecutive data sets of 1-2 days separation (B plus C, D plus E and F plus G) to get more accurate values of the pulse frequencies, as shown in the table. The resulting pulse frequencies are fitted by a quadratic function and the derived parameters are listed in Table 2. Residuals from the best-fit quadratic fit are plotted in the left panel of Figure 1.

The pulse frequency ephemeris derived with ASCA is consistent with that given by Deeter et al. (1999; DNB ephemeris), although the accuracy of determination is worse by about two orders of magnitude. This is because the data sampling of ASCA is sparse and the length of data interval is short. In addition the current analysis is limitted to the fit to locally determined pulse frequencies, while the DNB ephemeris was derived finally by pulse phase coherent analysis. Differences of the ASCA measurements of pulse frequencies to the DNB ephemeris are plotted in the right panel of Figure 1 together with those of the

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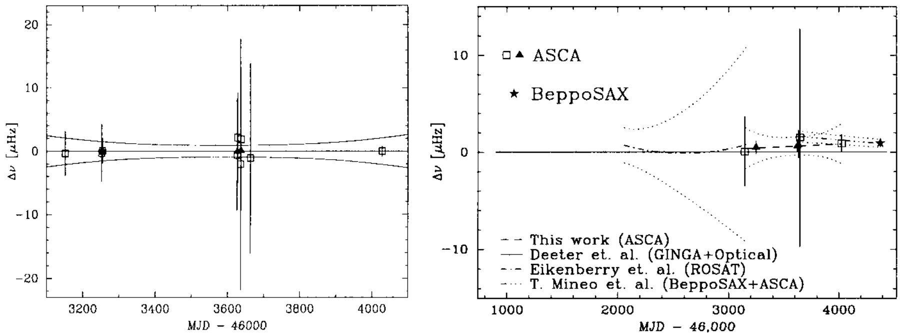

Figure 1. Left: Residuals from a quadratic ephemeris for pulse frequencies determined from ASCA observations of PSR B0540−69. Right: Differences of pulse frequencies and ephemeris of ASCA to the DNB ephemeris are plotted together with those of the ROSAT ephemeris (Eikenberry et al. 1998) and BeppoSAX pulse frequency (Mineo et al. 1999). The solid (left panel) and dashed/dotted (right panel) curves are the ±90 % significance regions of ephemeris solutions.

ROSAT ephemeris (Eikenberry et al. 1998) and the BeppoSAX pulse frequency (Mineo et al. 1999). This demonstrates that the stability of the neutron star spin in PSR B0540−69 is $\Delta\nu \lesssim 1$ μHz (or $\Delta\Omega/\Omega \lesssim 0.5 \times 10^{-7}$) over the past 10 years. This suggests that the braking index measured by DNB holds for about 10 years to the ASCA period and during this period PSR B0540−69 did not experience a large glitch as is seen in Vela pulsar. These confirm the Crab-pulsar like nature of this pulsar.

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