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Letter to the Editor

Detection of a very low hard X-ray pulse fraction in the bright state of GX 1+4

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Abstract. We have observed the Galactic center hard X-ray pulsar GX 1+4 on 1993 December 11, in the energy range of 20 – 100 keV with a balloon-borne Xenon filled Multi-cell Proportional Counter (XMPC) telescope. The source was detected in a bright state, the average observed source count rate being $10.1 \pm 0.2\ \mathrm{s}^{-1}$ per detector. X-ray pulsations with a period of 121.0 ± 0.4 s were detected in the source at a very high significance level. This, compared with the *BATSE* observations, gives a spin down rate of $\dot{P} = 1.6 \pm 1.4$ s yr^{-1}. The pulse fraction in the hard X-ray range is low (35%), and the observed spectrum is very hard (power law energy index 0.54 ± 0.18). The observed source luminosity in the 20 – 100 keV range is $7.9 \pm 0.3 \times 10^{37}$ erg s^{-1}. These properties are similar to those seen during the high luminosity spin up state of early 1970s and suggest that the source should revert back to a spin-up episode.

Key words: X-rays: stars - pulsars: individual - GX 1+4

1. Introduction

The Galactic center X-ray pulsar GX 1+4 was first observed by Lewin et al. (1971) in a balloon observation and they detected a pulse period of about 135 seconds. Further observations confirmed the pulse period and the pulsar was found to be spinning up at a rate of -2.68 s yr^{-1}, i.e., a spin-up time scale of 40 years (Elsner et al., 1985). This is the fastest rate of change of period amongst all the known pulsars. Assuming the source distance to be 10 kpc, appropriate for the Galactic center, the X-ray luminosity was estimated to be $10^{37} - 10^{38}$ erg s^{-1} (Lewin et al., 1971; Doty et al., 1981; White et al., 1983). The source exhibits a hard spectrum in X-ray region, in fact the hardest of known X-ray pulsars (Mony et al., 1991).

The source entered an extended low luminosity state in 1983 when several *EXOSAT* observations failed to detect it (Hall and Davelaar, 1983). It reappeared in 1987 and was detected by the *Ginga* satellite and found to be spinning down (Makishima et al., 1988). The spin change sign reversal occurred some time in the low luminosity period and since then it is spinning down at an average rate of 1.5 s yr^{-1} (Sakao et al., 1990).

The spin-up and spin-down episodes of GX 1+4 are explained by the disc accretion model developed by Ghosh and Lamb (1979). According to this model, GX 1+4 has a fastness parameter ω_s (ratio of angular velocity of neutron star rotation to the Keplerian angular velocity at the boundary layer) close to the critical fastness parameter ω_c and the surface magnetic field is derived to be $\sim 10^{14}$ G (Ghosh, 1993). Depending on the X-ray luminosity and the pulse period of the source the dimensionless torque parameter $n(\omega_s)$ can change sign and the high luminosity spin-up episode of 1970s and the present low luminosity spin-down episode are consistently explained by this model.

After the extended low state of 1983, GX 1+4 has been found to be brightening in X-rays (Greenhill et al., 1989; Dotani et al., 1989; Mony et al., 1991). According to the accretion disc theory, when the X-ray luminosity increases beyond a certain critical value (such that ω_s becomes less than ω_c) the source should revert back to a spin-up state. Any delay between the onset of the high luminosity state and the onset of spin-up state will provide important constraints to our understanding of the accretion disc around the compact object.

We have been monitoring GX 1+4 in hard X-rays using a balloon-borne Xenon filled Multi-cell Proportional Counter (XMPC) telescope for the last few years (Agrawal et al., 1994a). In this *Letter* we report the results obtained from a balloon flight carried out on 1993 December 11, where we find the source to be in a bright state, with a hard X-ray luminosity similar to the one during the bright spin-up state of 1970s. The observation details are given in §2, data analysis in §3, and discussion on the results in the last section. A preliminary report of this work has been given in Agrawal et al. (1994b).

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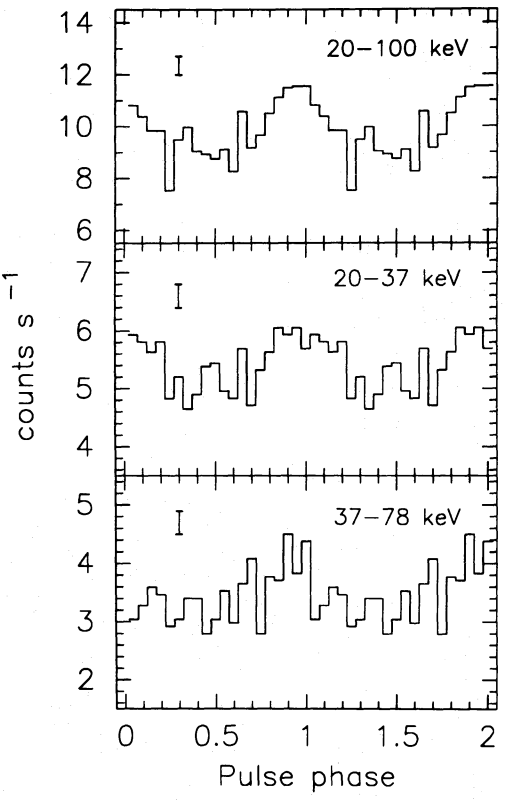

Fig. 1. Pulse profile of GX 1+4 obtained from the XMPC observations, in different energy ranges. Typical errors in the data are shown as vertical bars.

2. Observations

Observations were carried out on 1993 December 11, from a balloon flight made from Hyderabad, India with two Xenon filled Multi-cell Proportional Counters (XMPC) of area 1200 cm^2 each. The active volume of the detectors is divided into three layers with cell sizes of 48 mm × 48 mm. The detection efficiency is about 50% over the energy range of 20 – 100 keV. Field of view of the detectors is defined by a passive tin copper graded collimator to $5^\circ \times 5^\circ$. The set of detectors have overall energy resolution of 13% at 22 keV (for detector details see Rao et al., 1991). The balloon was launched at 23:45 UT on 1993 December 10 and reached the ceiling at 01:30 UT (on December 11) and was at the float altitude till 06:00. The vertical air mass during the observations was 3.9 gm cm^{-2} and the zenith angle of the source was in the range of 44° to 50°. During source observation pointing towards the source was well within 0.5°. With the two detectors, 50 minutes of source observation and 22 minutes of background observation were obtained. Background count rate was measured in a region 8° away from the source and it is free of any other known bright X-ray sources.

During the observations one detector showed intermittent corona in the high voltage supply. The effect of such voltage fluctuations due to corona was carefully checked and data in those regions were rejected for the affected detector. Gondola motion during source to background transitions and any other perturbations were also checked and data were rejected whenever system was in motion. After such screening, the effective observation time in the two detectors were 2110 and 2775 seconds respectively. The observed average source count was 10.1 ± 0.2 s^{-1} per detector.

3. Analysis and results

3.1. Period analysis

Source count rate was found to vary with zenith angle (by about 16% from the mean) as the atmospheric depth in the line of sight changes with it. The source observation time was divided into four different regions such that the change in zenith angle was less than 2° in each region. In these sections of the data a constant fit to the count rate gave acceptable values of χ^2. Hence a constant value was subtracted from the count rates in each region separately. This type of detrending of the count rate removed the effect of different line of sight air mass. The background count rate during the flight was found to be a constant.

To search for the pulse period in the source a FFT algorithm based on the Lomb-Scargle method was used (Horne and Baliunas, 1986; Press and Rybicki, 1989). We detected pulsations in the source at 121.0 ± 0.4 s with a false alarm probability of 5.8×10^{-5} in the total counts from the two detectors. Search for pulsations in individual detectors also gave similar pulse periods. Pulsations were also detected when data were divided into two broad energy channels. For further confirmation, χ^2 maximization was also done which gave the same pulse period as the FFT method. Combining this pulse period with the period measured by *BATSE* on 1993 September 5 (Finger et al., 1993) we calculate a spin-down rate ($\dot{P}$) of 1.6 ± 1.4 s yr^{-1}.

The source count rates were folded at the period of 121.0 s to obtain pulse profiles in the 20 – 100 keV, 20 – 37 keV and 37 – 78 keV energy ranges. These pulse profiles are shown in figure 1, with phase bins of width 0.05. The data points are plotted twice, in two cycles, so that any trends in the profiles will be clearly seen. Typical errors are shown as vertical bars. A single broad peak can be seen in all the profiles. The pulse fractions, defined as the ratio of maximum minus minimum to maximum, were derived. The pulse fraction in the total source count is 35%, and in the low and high energies it is 23% and 38%, respectively. To investigate whether the difference in pulse fraction in two energies is significant, we have obtained the hardness ratios (ratio of counts in 37 – 78 keV range to the counts in 20 – 37 keV range) in the pulsed and unpulsed parts of the profile. The derived values are 0.63 ± 0.01 and 0.65 ± 0.01, respectively for the pulsed (in the phase range of 0.70 to 1.10) and the unpulsed (in the phase range of 0.10 to 0.70) part of the profile. Hence we can conclude that there is no clear indication of any change in the pulse fraction with energy. A detailed analysis of the spectral change with the pulse phase is in progress.

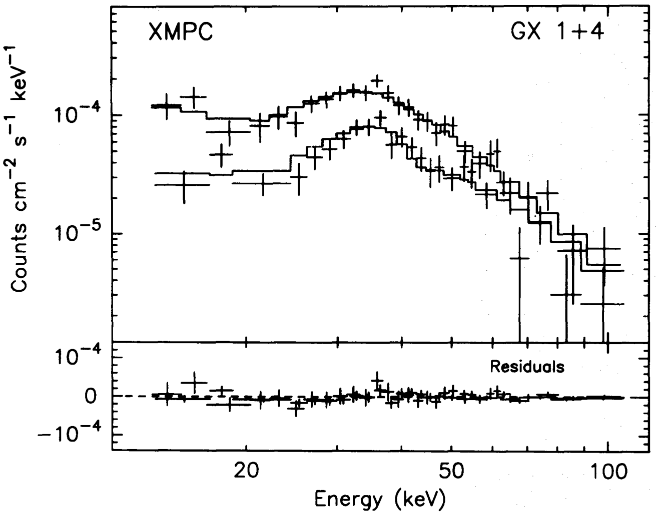

Fig. 2. Observed count rate spectrum of GX 1+4 shown separately for the top and bottom layers of the XMPC detectors. The best fit power law model with an energy index of 0.54 is shown as histograms, after convolving through the detector response functions. Residuals to the fit are plotted in the lower panel of the figure.

3.2. *Spectral analysis*

The response function of the detectors were generated using a Monte Carlo routine. Various input parameters to this routine like the layer-wise gain and energy resolution, event selection logic thresholds etc., are computed by calibrating the detectors with various radioactive X-ray sources of known energies. It was found that the observed response of the detector to X-ray sources of known energies compares well with the simulated response (see Chitnis et al., 1994a for details).

Spectral files were generated separately for the different layers of the detectors for the four source regions and the background regions. Correctness of the background subtraction was verified for different energy channels. It was found that the channel to energy conversion for the third layer in one of the detectors was nonlinear and data from this layer were not taken for spectral fitting. This effect, however, did not affect the count rates and the period analysis described in §3.1. Finally, total source spectrum was obtained for the top two layers of one detector and 3 layers of the other detector, in 40 channels each.

The XSPEC package (Shafer et al., 1991) was used for the spectral fitting. A power law was found to be adequately fitting the data for the two detectors. The fitted values of the energy index are 0.59±0.30 and 0.48±0.30, respectively for the two detectors with the respective values of reduced χ^2 being 1.11 and 0.94 (for 79 and 119 degrees of freedom). To improve the accuracy of the derived spectral parameters, a combined fit was attempted for the data from the two detectors, with appropriate relative normalization constants. A power law energy index of 0.54±0.18 was derived with reduced χ^2 value of 1.15 for 199 degrees of freedom. The observed flux in the 20 – 100 keV range is 6.7 × 10^{-9} erg cm^{-2} s^{-1}. The observed count rate spectra are shown in figure 2 along with the fitted spectrum convolved through the detector response function. For clarity, the data from the top layer of the two detectors are summed together and data from all other layers are also summed together, for plotting purposes only. The residuals to the fit are shown in the bottom panel of the figure. The X-ray luminosity in the 20 – 100 keV range is 7.9±0.3 × 10^{37} erg s^{-1} for a distance of 10 kpc.

4. Discussion

We have observed the pulsar GX 1+4 near the Galactic center in a bright state and obtained a low hard X-ray pulse fraction of 35%. The observed period of 121.0±0.4 s indicates a continuous spin-down of the pulsar. Since discovery of its spin-down behavior (Makishima et al., 1988), the spin-down rate was around 1.5 s yr^{-1}, as seen in different hard X-ray observations. But recent *BATSE* observations gave a somewhat larger value of $\dot{P}$ around 3.7 s yr^{-1} (Finger et al., 1993). Our observation of the source, in the present high luminosity state, confirms the period with high confidence and from that a spin-down rate of 1.6±1.4 s yr^{-1} can be inferred. Either the source is spinning down at almost constant rate of about 1.5 s yr^{-1} or presently the spin-down rate is decreasing probably indicating a forthcoming period change sign reversal, as the source did in its low luminosity period of early 1980s. Further observations of the source at high energy are essential to keep a good track of pulse history of this interesting pulsar.

The hard X-ray parameters presented here, however, are very similar to those observed during the bright spin-up state of early 1970s. In figure 3 we have plotted the 20 – 100 keV X-ray luminosity and the hard X-ray pulse fraction of the source as it was observed in various balloon flights and satellite missions since 1970, from a compilation from Chitnis et al. (1994b). The pulse fraction was higher in the quiet state of the source, and now with increasing brightness the pulse fraction is decreasing. These hard X-ray characteristics of the source are very similar to the bright spin-up state of early 1970s.

The power law energy index obtained by us (0.54±0.18) is very hard, in fact the hardest reported for this source so far. We have carefully checked our data for any observational artifacts like incorrect air mass etc. and found that these will have negligible effect on the energy index. The fact that similar indices were obtained from the two detectors gives further confidence in the derived parameters. The derived 20 – 100 keV luminosity (7.9 × 10^{37} erg s^{-1}) is a factor of 3 higher than the value measured in 1991 (Laurent et al., 1993). The *BATSE* observations in 1993 September (Finger et al., 1993) gives a pulsed X-ray luminosity of 1.6 × 10^{37} erg s^{-1} (in 20 – 100 keV range). If the pulse fraction during the *BATSE* observations is between 0.3 and 0.5, the corresponding total X-ray luminosity is (4.8 – 9.1) × 10^{37} erg s^{-1}. Hence there is a clear

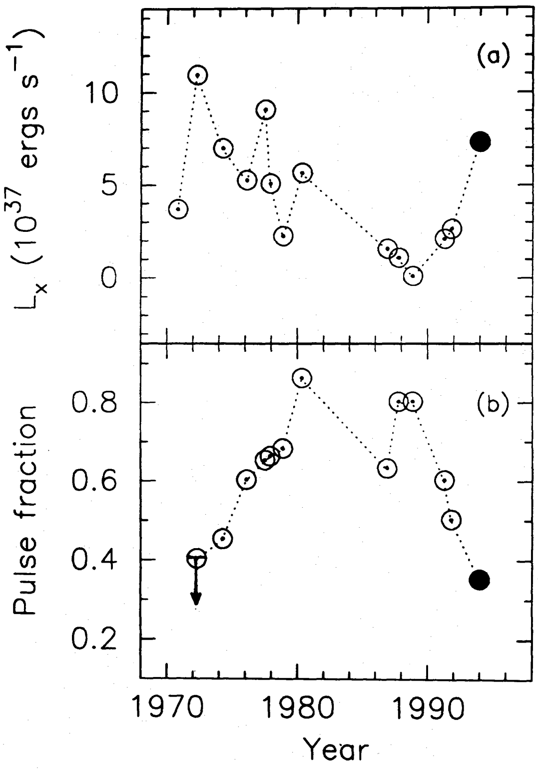

Fig. 3. (a) X-ray luminosity and (b) pulse fraction history of GX 1+4. The luminosity is in 20 – 100 keV range. The pulse fraction is defined as the ratio of maximum minus minimum to maximum counts in the pulse profile. The data points from the present work are indicated as filled circles. The data point shown with an arrow is an upper limit.

indication of the source reaching a bright state. If the surface magnetic field strength of the neutron star in GX 1+4 is ~ 10^{14} G, the source should show a spin reversal for luminosities higher than about 3 × 10^{37} erg s^{-1}, according to the accretion disc theory (Ghosh and Lamb, 1979; Ghosh, 1993). Hence we suggest that the observed hard X-ray parameters are indicative of an imminent period change sign reversal.

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