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A double peaked pulse profile observed in GX 1 + 4

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Abstract. The hard X-ray pulsar GX 1+4 was observed several times in the last few years with a pair of balloon-borne Xenon filled Multi-cell Proportional Counters (XMPC). In a balloon flight made on 22 March 1995, the source was detected in a bright state, the average observed source count rate being $8.0 \pm 0.2\ s^{-1}$ per detector. X-ray pulsations with a period of 121.9 ± 0.1s were detected in the source and a broad double pulse features the pulse profile. This double pulse structure is observed for the first time in this source in high energy band and indicates activation of the opposite pole of the neutron star. Compared to our previous observation of the same source with the same telescope a period change rate of 0.72 ± 0.40 is obtained which is the lowest rate of change of period for this source since its discovery. A reversal in the spin change, from spin down to spin up in the mean time is consistent with our period determinations. *BATSE* observations in this period have also indicated the same trend. Pulse fraction in the hard X-ray range is low (30%), consistent with its anti correlation with luminosity and the observed spectrum is very hard (power law energy index 0.67 ± 0.12). Power law spectrum, thermal Bremsstrahlung and two Compton scattered Bremsstrahlung models are fitted well with the spectrum. No indication of change in the spectrum with the pulse phase is observed. The observed source luminosity in the 20 — 100 keV range is 2.5×10^{37} erg s^{-1}. Pulse phased spectra did not show any indication of change in the hardness with phase.

1. Introduction

GX 1+4, the galactic center low mass hard X-ray pulsar was discovered in 1971 by Lewin *et al.* in a balloon observation with a pulse period of 135 seconds. The source X-ray luminosity with an assumed distance of 10 kpc was estimated to be 10^{37} - 10^{38} erg s^{-1}, very close to L_{edd}. Follow up observations confirmed the pulsation and observed a very fast spin-up rate with a time scale of 40 years. In the conventional accretion disc theory such a fast spin up was difficult to explain. In early 80's the source made transition to a low intensity state and EXOSAT attempts to detect the sourced failed. The source was observable again in 1986 with Ginga satellite and by then the spin change had reversed from spin-up to spin-down. Since then, until a very recent increase in luminosity, all observations gave the same spin down trend with $\dot{P} = 1.5 s yr^{-1}$

The spin-up and spin-down episodes of GX 1+4 are explained by the disc accretion model developed by Ghosh and Lamb (1979). The total torque acting on the central object is resultant of three torques, 1) the torque carried by the in-falling matter, 2) positive torque acting through the magnetic lines by the disc inside the corotation radius, i.e. the radius where the Keplerian frequency is same as the rotation frequency of the core object and 3) negative torque acted through the magnetic lines by the disc outside the corotation radius. In low luminosity state the third component can be dominant over the first two and a resultant negative torque will cause spin down of the pulsar. If that was the case with GX 1+4 after its rediscovery by Ginga in 1986, then in its recent bright state when the luminosity is comparable to its brightness in the spin-up state, the source should start spinning up. An observation of the spinning up phenomenon will verify the model describing disc-magnetosphere interactions.

To improve the understanding of the neutron star magnetic field with an accretion disc and to verify the models of accretion torque on neutron stars a regular monitoring of GX 1+4 with a balloon borne large area hard X-ray telescope was started in 1991. In four observations so far the source was found in high state during the last two times and pulse period was determined accurately. In addition to observing the pulse period change in the pulsar, the hard X-ray spectrum and pulse phased spectroscopy is also carried out. Any observation of change in the spectrum with pulse phase will give interesting information about either the emission regions or the environment through which photons come out in different phases of its 122 sec spin period.

2. Observation

The X-ray pulsar GX 1+4 was observed with a large area (2400 cm^2) xenon-filled multi-anode proportional counter (XMPC) telescope in 20-100 keV band in four balloon flight experiments during the period 1991-95.

Table 1. Details of GX1+4 observations

Date of balloon flight	Observation time (UT)	Ceiling altitude (g/cm2)	Useful source exposure (sec)	GX1+4 count rate in (20-100)keV (count s-1)
Dec. 11, 1991	0612-0757	3.2	3100	1.3 ± 0.2
April 5/6, 1992	2118-0118	4.0	6307	1.1 ± 0.2
Dec. 11, 1993	0445-0559	3.4	3120	12.4 ± 0.2
Mar. 22, 1995	0130-0530	2.5	7980	8.0 ± 0.2

The XMPC telescope consists of two identical xenon-filled proportional counters with a total effective area of 2400 cm^2 and has a field of view 5° x 5° defined by a passive tin copper graded collimator. The telescope mounted on an orientation platform can be pre-programmed to track a given source by an onboard automated tracking system. For details of the X-ray telescope refer to Rao *et al.* (1991). Observations of a source are carried out by alternately looking at the source and a nearby source-free background region in tracking mode. The details of GX1+4 observations in four balloon borne experiments during the 1991-93 period are listed in table 1. In the last fight a larger balloon was used and a reduced residual atmosphere of 2.5 gms cm^{-2} was achieved.

Active volume of the two proportional counters are divided into three layers with cell sizes of 48 mm x 48 mm. Three sides of the active volume are covered with veto cells of smaller size, the signals from which act in anti-coincidence with the main anodes to reject the charge particle background and Compton interaction of γ rays which is dominating at the balloon altitude. Escape gating technique is used to accept the genuine double events which are generated when a fluorescent X-ray escapes from one cell and gets registered in another cell. The detection efficiency is about 50% over the energy range of 20-100 keV. Overall energy resolution of the two detectors is 13% at 22 keV. Azimuthal pointing of the payload is done taking The Earth's magnetic field as reference and a flux gate magnetometer is used for sensing the zero magnetic field direction. For elevation pointing the local direction of gravity is taken as reference. Both azimuth and elevation angles during the balloon flights are measured with shaft encoders with accuracy of 0.1°. On board source triangulation is attempted by scanning the sky around Cyg X-1 both in azimuth and elevation to have on board measurement of the payload orientation accuracy. Because of shorter duration of the last two flights caused by highlevel winds at the ceiling, source triangulation was not possible. During source observation pointing towards the source was well within 0.5° in the first three flights. In the last flight balloon position was not available within 50 km which may add upto another 0.5° in orientation error. Background count rate is usually found not to vary fast with the zenith angle. Background observations are made in a region about 8° away from the source and free of any other known bright X-ray sources.

The average source count rate after carefully screening the data for gondola motion or any change in high voltage supply because of intermittent corona in one detector in one of the balloon flights etc. for each observation is given in the table below.

It will be noticed from the table above that during 1991 and 1992 observations, GX1+4 was in a low state and hence detected at significance level of only 5 to 6 σ. On 1993, Dec 11, and 1995, Mar 22, it was in a bright state as indicated by much higher count rate.

No pulsations were detected in the observations of 1991, Dec 11 and 1992, April 6 as the source was found in a low intensity state. It was, however, in a bright state on 1993, Dec 11 and detected at high significance level. Pulsations with period of 121.1 ± 0.4 sec were detected in the 20-100 kev observation band. The timing and spectral analysis of the Mar 22, 1995 balloon observation are reported here.

3. Analysis and results

3.1 Timing analysis

The number of photons detected in the 20-100 keV range in the two detectors are obtained with 128 channel energy information with a time resolution of 1.28 ms. The count rate was binned with 5 sec and 10 sec bin widths and a period search was done in the 50-200 sec range. During the first 10 minutes and last 10 minutes of the 240 minutes observations of GX1+4 in one of the proportional counters, some noise was present in the lower energy channels. All data from that detector during that time were discarded. Data in those lower channels for the entire duration of the observation were also discarded to remove any ambiguity. The background count rate was found to be constant during the duration of the entire balloon flight and the source count was seen to vary with the zenith distance as the residual atmosphere causing absorption along the line of sight changes with it. The constancy of the background count rate was checked by fitting a straight line and a reduced χ^2 of 1.1 was obtained.

For period analysis an FFT algorithm based on the Lomb-Scargle method was used. In both the detectors very clear periodograms with single sharp peaks around 121.9 seconds were obtained. The reduced data length and energy range in one of the detectors gave periodogram peak of smaller height compared to the other detector. Period search in two different broad energy bands also gave clear periodograms with smaller peaks at the same period value. Finally to improve accuracy of the period value, data from both the detectors were added and a periodogram was obtained. The pulse period of GX 1+4 as seen on 22nd March 1995 is determined to be 121.88 + –0.09. The false alarm probability of the 121.88 sec peak in the periodogram for an average background rate and the number of data points used to obtained it was calculated to be practically zero 10-9.

Pulsation in the same source was also detected in a previous balloon observation made with the same telescope. The pulse period as seen on 11 December 1993 was 121.0 + –0.4. Over this period of 15 months, an overall spin down rate of 0.72 sec yr-1 is somewhat smaller than the average spin down rate of 1.4 sec yr-1 since 1986. BATSE observations in the intervening period reported a reversal of the spin change rate, from spin down to spin up.

Pulse profile of the source was obtained in different energy bands by folding the photon counting rates with the measured period of 121.88 sec. The pulse profiles in the 20-50 keV, 50-100 keV, and 20-100 keV energy ranges are plotted in fig.1. in two cycles. To obtain pulse profiles data were added from the two detectors. The pulse fraction in the 20-50 keV range is 25% and 50-100 keV range is 34% with an average value of 30%. The anti correlation between the pulse fraction and luminosity is still found to exist. The 20-50 keV pulse profile which is the most clear one shows a very wide pulse with a valley at the center or two pulses with unequal separation. A double peaked pulse profile similar in structure but narrower in width was seen earlier by Makishima *et al.* (1986) in 2-20 keV range. In the earlier observation in 93 December there was no indication of double pulse and the detected pulse was also narrower. It is possible that during the recent source brightening there might have been a gradual change in the emission, from a pencil beam to a fan beam, which is more common to a pulsar in its bright state.

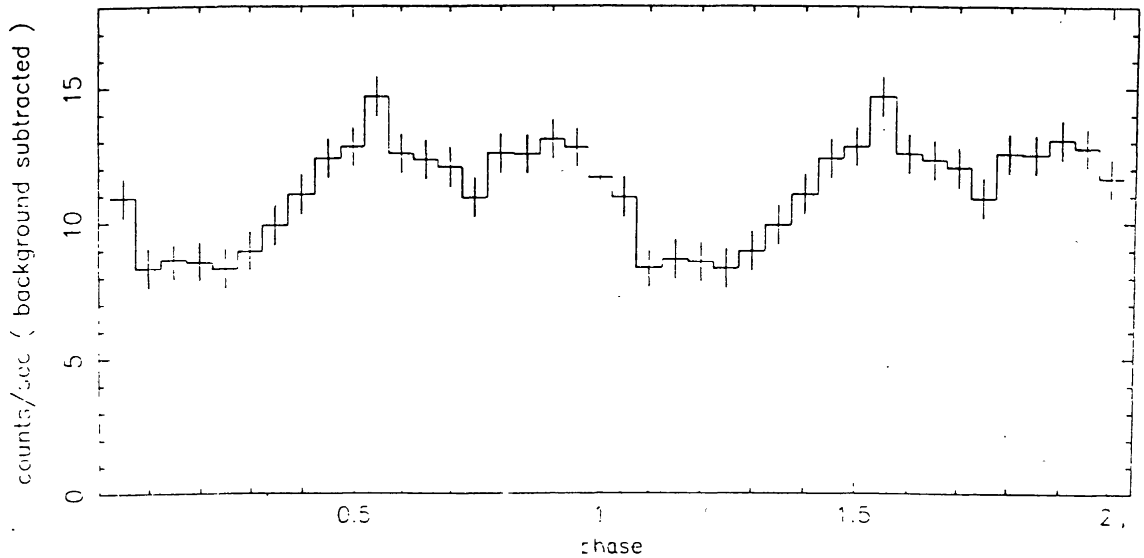

Figure 1. Pulse profile of GX 1+4 obtained from the XMPC observations, in different energy ranges plotted in two cycles for clarity. Typical errors in the data are shown as vertical bars. Data from two detectors have been added to reduce the errors in each bin.

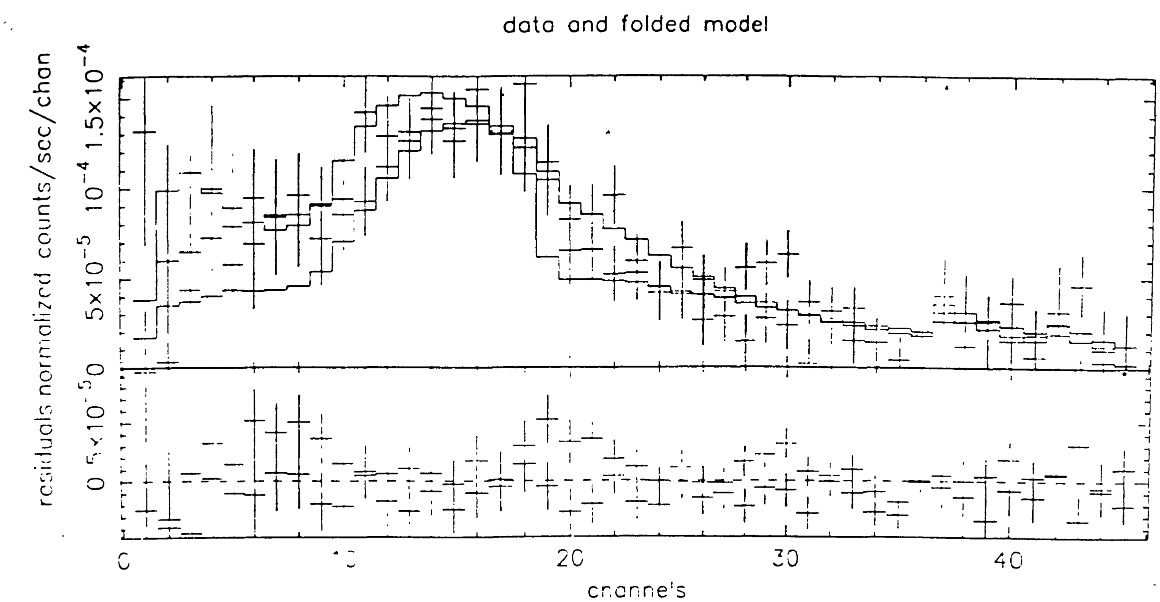

Figure 2. GX 1+4 spectrum as observed with XMPC on Mar 95, in the 20-100 keV range plotted in 45 energy bins. Data from bottom two layers are added and plotted with the top layer. The histogram represents the best fit power law model with an energy index of 0.67 after convolving through the detector response functions. Residuals to the fit are plotted in the lower panel of the figure and all are within 2σ.

To investigate whether the difference in pulse fraction in two energies is significant, we have obtained the hardness ratios (ratio of counts in 20 – 35 keV range to the counts in 20 – 100 keV range) in the pulsed and unpulsed parts of the profile. The derived values are 0.69 ± 0.02 and 0.71 ± 0.03, respectively for the pulsed (in the phase range of 0.40 to 1.00) and the unpulsed (in the phase range of 0.00 to 0.40) 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 has also been studied.

3.2 Spectral analysis

The background spectrum was seen to be constant during the whole flight and so a subtraction of the off-source spectrum from the on-source one gave the GX1+4 spectrum. However a maximum of 1° inaccuracy in the orientation of the payload causes a possibility of 20% reduction in the source flux through the 5° x 5° field of view collimators. From the raw data spectra are extracted for the three detector layers of the two detectors. Spectra of the bottom two layers were added and the 128 channel on board spectra was rebinned to 45 channels to improve the statistics of each bin.

The response function of the detectors were generated using a Monte Carlo routine with layer-wise gain, energy resolution, event selection logic thresholds etc. as inputs. The response matrix thus created was used to fit the ground calibration data with various X-ray sources of known energy and the response matrix was fine tuned until an acceptable value of the χ^2 was obtained for the calibration data. An overall systematic error of 1.5% was applied to each energy bin to take care of variation in the energy channel width in the on-board processor. The modification of the incident spectrum by absorption in the residual atmosphere above the balloon altitude is taken care of by multiplying the response matrix by the corresponding absorption in each energy bin.

The XSPEC package (Shafer *et al.* 1991) was used for the spectral fitting. Spectra from the two detectors were fitted separately for different incident spectra and the parameters for the best fitted spectra were obtained. Identical values for the incident spectrum parameters obtained from the two detectors increased confidence in the spectral analysis procedure. To improve on the error bars the spectra from the two detectors were added and a combined fit was done. The parameters for the different type of best fitted spectra are given in the table 2. The added spectrum from the two detectors for the top layers and the two bottom layers of anode wires are plotted in fig 2. Lower panel in the figure shows the residual to the fit and all residual points are within 2σ values. The normalization parameter has a + 20% uncertainty because of the orientation error in the balloon payload.

Pulse phased spectra for the pulsed and non-pulsed duration of the 122 sec spin period were also obtained. These spectra were also fitted well with the power law and thermal Bremsstrahlung models with similar parameter values and somewhat larger error bars.

Table 2. Spectral parameters for different models

Observation and Model	Parameter 1	Parameter 2	Parameter 3 (norm)	reduced χ^2
Mar. 22 1995				
Power law	Photon Index		#	
Total	1.67 ± 0.12		0.23 ± 0.10	1.11
Pulsed	1.60 ± 0.08		0.19 ± 0.06	2.12
Unpulsed	1.83 ± 0.14		0.33 ± 0.17	1.42
Thermal Bremsstrahlung	kT			
Total	100 ± 16		$1.89 \pm 0.37 \times 10^{-2}$	1.10
Pulsed	100 ± 19		$2.05 \pm 0.29 \times 10^{-2}$	2.04
Unpulsed	90 ± 25		$1.65 \pm 0.36 \times 10^{-2}$	1.41
Compton scattered	kT	Optical depth	##	
Brem. (1)	18.7 ± 13.9	7.7 ± 3.0	0.016 ± 0.008	1.08
Compton scattered	kT	Optical depth	##	
Brem. (2)	17.5 ± 3.8	6.8 ± 2.2	0.86 ± 0.07	1.08
Dec 11, 1993				
Power law	Photon Index		#	
	1.54 ± 0.18		0.44	1.15

For power law spectrum the normalization unit is photons $keV^{-1}\ cm^{-2}\ s^{-1}$ at 1 keV. ## For Compton scattered Bremsstrahlung models the normalization is unknown but represents strength of the initial spectrum. Two models used here are due to Lamb and Sanford (1979), & Sunyaev and Titarchuk (1980) respectively.

From the χ^2 values only it is difficult to choose between the different models. The Bremsstrahlung model gives a rather high temperature representing a very hard spectrum of the source in this high state of luminosity. Earlier observations when fitted to similar model gave a temperature of 35-50 keV only compared to the present value of 100 keV. However for a Compton scattered Bremsstrahlung model a much lower temperature ~ 20 keV matches the observed spectrum quite well. In the two Compton scattered Bremsstrahlung models the optical depth is slightly different which needs a factor of 5 lower flux of the original spectrum in the second model to produce the observed spectrum.

The X-ray luminosity in the 20 – 100 keV range is $2.50 \pm 0.3 \times 10^{37}$ erg s^{-1} for a distance of 10 kpc with a 20% uncertainty on the higher side.

4. Discussion

A continuous observation of this pulsar in its present bright state may improve our understanding of the disk-magnetosphere interactions in neutron stars and will also lead to verification of the same. As the luminosity in the present state is comparable to its luminosity in the earlier spin-up phase, a reversal of spin change will help to determine the critical value of fastness parameter at which the resultant torque on the neutron star changes its sign. GX 1+4 being a hard X-ray object, most of its luminosity lies in the 20-100 keV region. To study the L_X vs $\dot{P}$ relation regular hard X-ray observations are needed. In our last two observations the period values, when compared with *BATSE* observations indicate a much smaller spin down rate. Compared to our previous observation of the same source with the same telescope, a period change rate of 0.72 ± 0.40 is obtained which is the lowest rate of change of period for this source since its discovery. A reversal in the spin change, from spin down to spin up in the mean time is consistent with our period determinations. *BATSE* observations in the period has also indicated the same.

In the recent 1995 observation the pulse profile is double peaked, which may be an indication of activation of the opposite magnetic pole. A gradual change in the beam pattern from pencil beam to fan beam, which is more common in high luminosity state of pulsars, may explain this pulse pattern. The anti correlation between luminosity and pulse fraction, that was noticed in an observation earlier is still persistent and it will be interesting to observe whether this feature is present in other pulsars.

In balloon observations of a few hours duration, the flux in the high energy region is not enough to distinguish between the various models described above. However compared to all earlier observations (Laurent *et al.* 1993; Greenhill *et al.* 1993) the spectrum is much harder which is evident from a power law photon index of 1.6. The thermal Bremsstrahlung model also fits well with a temperature of 100 keV which is higher than that measured from the earlier high energy observations.

Significant difference between the pulsed and unpulsed spectra was not observed. To detect any small difference in the hardness or temperature longer duration observations or much reduced background level and bigger effective area telescope will be required.