A double peaked pulse profile observed in GX 1+4

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September 1996
To appear in
Astronomy and Astrophysics

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 ± 0.2 s^{-1} per detector. X-ray pulsations with a period of 121.9 ± 0.1 s were detected in the source with a broad double peak pulse feature. When observed in December 1993 with the same instrument, the pulse profile of GX 1+4 showed a single peak. This change in the pulse profile to a double pulse structure in about 15 months indicates either activation of the opposite pole of the neutron star if the magnetic field is asymmetric or possibly a change in the beam pattern, from a pencil beam to a fan beam. Assuming a fan beam configuration, the pulse profile is used to find the inclinations of the magnetic axis and the viewing axis with the spin axis. The derived angles support the *GINGA* observations of a dip in the pulse profile which was resolved to have a local maximum in one of the observations and was explained with resonance scattering of cyclotron line energy photons by the accretion column (Makishima et al., , Dotani et al., .). Compared to our previous observation of the same source with the same telescope (Rao et al.,) a period change rate of 0.72 ± 0.40 s yr^{-1} is obtained which is the lowest rate of change of period for this source since its discovery.

Average pulse fraction in the hard X-ray range is low (30%), consistent with its anti correlation with luminosity as reported by us earlier (Rao et al.,) and the observed spectrum is very hard (power law photon index 1.67 ± 0.12).

Subject headings: X-rays: stars - pulsars: individual - GX 1+4

1. Introduction

The galactic center low-mass hard X-ray pulsar GX 1+4 was discovered 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} for a small polar cap region. Follow up observations confirmed the pulsations and showed 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 the early 80's the source made a transition to a low intensity state and attempts to detect the source with EXOSAT failed. The source was observable again in 1987 with the *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 the observations gave the same spin down trend with $\dot{P} = 1.5$ s yr^{-1}. The spin-up and the spin-down episodes of GX 1+4 are explained by the disc accretion model developed by Ghosh and Lamb ;). 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 radius where the Keplerian frequency is the 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 the 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.

To improve the understanding of the neutron star magnetic field with an accretion disc and to verify the models of accretion torque on the neutron stars, periodic observations of GX 1+4 with a balloon-borne large area hard X-ray telescope were started in 1991. In four observations made so far the source was found in a high state during the last two times and the pulse period was determined accurately. Additionally, study of the X-ray spectrum and pulse phased spectroscopy was also carried out. These results will be reported in detail in a later publication. Any observation of change in the energy spectrum with the 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 s spin period. In this paper we report our results on a change in the hard X-ray pulse profile and its implications in terms of the current accretion models.

2. Observations

The X-ray pulsar GX 1+4 was observed with a large area xenon-filled multi-anode proportional counter (XMPC) telescope in the 20–100 keV band in a balloon flight experiment on 22 March 1995. The balloon reached a ceiling altitude of 41.5 km corresponding to a residual atmosphere of 2.5 gm cm^{-2}.

The XMPC telescope consists of two identical xenon-filled proportional counters with a total effective area of 2400 cm^2 and has a 5° × 5° field of view 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. . Observations of the source were carried out by alternately looking at the source and a nearby source-free background region in the tracking mode. Background observations were also made in a tracking mode in a region about 8° away from the source and free of any other known bright X-ray sources.

During the first and the last 10 minutes of the 240 minutes observations of GX 1+4, some noise was present in the lower energy channels in one of the proportional counters. 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 entire balloon flight; the source count rate varied with the zenith distance because of absorption along the varying residual atmosphere along the line of sight. The constancy of the background count rate was checked by fitting a straight line and a reduced χ^2 of 1.1 was obtained.

3. Analysis and results

3.1. Timing analysis

In each of the two detectors the 20-100 keV photons were detected 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 with an FFT algorithm based on the Lomb-Scargle method. For 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 a periodogram peak of smaller height compared to that in the other detector. A period search in two different broad energy bands also gave clear periodograms with smaller peaks at the same value of the period. Finally to improve accuracy in determination of the period, 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 s. The false alarm probability of the 121.88 s peak in the periodogram for an average background rate and the number of data points used, was calculated to be negligible($\sim 10^{-9}$). Pulsations in the same source were also detected in a previous balloon observation with the same telescope. The pulse period as seen on 11 December 1993 was 121.0 ± 0.4 s (Rao et al., . Over this period of 15 months, the overall spin down rate of 0.72 ± 0.40 s yr^{-1} is somewhat smaller than the average spin down rate of 1.4 s yr^{-1} since 1987. *BATSE* observations in the intervening period have reported a reversal of the spin change rate (Chakrabarty et al.,), from spin-down to spin-up thereby supporting the smaller rate of change derived from the present observation. Pulse profiles in different energy bands were obtained by folding the photon counting rates with the measured period of 121.88 s. A plot of the pulse profile in the 20–100 keV energy range is shown in fig 1. for two cycles. The pulse profiles were obtained by adding data from the two detectors. The pulse fraction in the 20–50 keV range is estimated to be 25% and that in the 50–100 keV range it is 34%. The anti correlation between the pulse fraction and the luminosity found in the 1993 observation is still found to exist. The 20–50 keV pulse profile, which is the most clear one, shows a 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. in the 2–20 keV range. In our earlier observation in December 1993 there was no indication of a 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. A phase difference in the pulse profile with the energy was explained by a switch over in the beam pattern for a cylinder of emission at higher luminosity (White et al., . To investigate whether the difference in the pulse fraction in the two energy bands is significant, we have obtained the hardness ratios (ratio of counts in the 20–35 keV range to that in the 20–100 keV range) in the pulsed (phase 0.45 to 1.05 in the pulse profile in the top panel of *fig.* 1.) and unpulsed (phase 0.05 to 0.45 in the pulse profile) parts of the profile. The derived values are 0.69 ± 0.02 and 0.71 ± 0.03, respectively for the pulsed and the unpulsed part of the profile. Hence we conclude that there is no clear indication of any change in the pulse fraction with the energy. A detailed analysis of the spectra with the pulse phase has also been done and will be reported separately.

3.2. Spectral analysis

The observed energy spectrum was fitted well with an incident power law spectrum with a photon index 1.67 ± 0.11 (reduced $\chi^2 = 1.1$). A thermal Bremsstrahlung model gave a temperature of 99 keV. Spectral fits were also attempted with two Compton scattered Bremsstrahlung models. A temperature of 18.5 keV and an optical depth of 7.7 was obtained for the first model while the second model gave a temperature of 17.5 keV and an optical depth of 6.8. Pulse phased spectra for the pulsed and the non-pulsed components of the 122 s spin period were also obtained. These spectra were also fitted well with the power law and the thermal Bremsstrahlung models with similar values of the parameters but somewhat larger error bars. The X-ray luminosity in the 20–100 keV range is deduced to be $2.5 \pm 0.3 \times 10^{37}$ erg s^{-1} for a distance of 10 kpc with a 20% uncertainty on the higher side.

3.3. Pulse profile modeling

Very complex changes in the pulse profile with luminosity are seen in many X-ray pulsars. An intensity-dependent widely varying pulse profile was observed in the transient pulsar EXO 2030+375 which was modeled with both the fan and the pencil beams of unequal intensity from the two offset magnetic poles, the most complex modeling of a X-ray pulsar profile done so far (Parmar et al.,). The pulse profile observed in the high luminosity state changed as the source strength dropped by a factor of 100 and in a later bright state the initial bright state pulse profile was again seen. In EXO 2030+375 the relative luminosity of the two poles was found to change by a factor of 10. A change by a factor of 10^2 in the overall luminosity and dominance fan beam emission over pencil beam emission was found when luminosity was $> 10^{37}$ erg s^{-1}. At lower luminosity ($< 10^{37}$ erg s^{-1}) the emitting material is in the form of a slab over the polar cap and since it emits more along the local field lines, this results in a pencil beam pattern. At the higher accretion rate, the material goes closer to the pole before it is halted and it is held more like a cylinder. In this case the emission is more in the direction of the magnetic equator, resulting in a fan beam pattern.

The observed change in the GX 1+4 pulse profile from December 1993 to March 1995 can be explained in two ways. One possibility is an activation of the second pole, which is possible if the magnetic field is asymmetric in latitude (so that the distribution of mass accretion onto the two poles depends on the Alfven radius r_A or in turn on the luminosity). The second plausible explanation is a gradual change in the beam pattern, from a pencil beam to a fan beam in spite of a decrease in luminosity by a factor of 3 in 20–100 keV energy band. In our modeling we have assumed a simple fan beam pattern of GX 1+4 with a symmetric magnetic dipole and equal intensity on both sides of the equator with a constant overall emission. The luminosity is maximum towards the magnetic equator from the neutron star center and decays exponentially towards the poles. The sum of the two angles, θ_m the angle between the magnetic axis and the spin axis and θ_r the angle between the observer line of sight and the spin axis needs to be more than $\frac{\pi}{2}$ so that the line of sight crosses the magnetic equator twice in one period and shows two peaks. Intensity has two minima, corresponding to the phases when the two poles are closest to the viewing

axis. Such simple considerations were used successfully to reproduce roughly the pulse profiles of many pulsars by Leahy . To get the detailed features of pulse profiles, many other possibilities like offset in the two magnetic poles, unequal brightness of the two sides, gravitational bending near the neutron star surface for photons direction not normal to the surface, unequal size of the two emission regions etc. are to be considered. But for a pulse profile with few bins and relatively large errors on the data points, a simple geometry as described above gave reasonably good fit and we obtained the following values for the parameters
$\theta_m = 56 \pm 8, \quad \theta_r = 56 \pm 8$ with $\theta_m + \theta_r = 112 \pm 2$
and the exponential intensity decay towards the pole has an angular scale of $\theta_d = 32 \pm 4$.

The model considered here is actually unable to distinguish between θ_m and θ_r because of their interchangeability. However the values we have obtained are the same for both the parameters. The constraint is more on the sum of the two angles which defines the closest position of the second pole with the viewing axis ($180^\circ - \theta_m - \theta_r$) and produces the valley in between the two peaks. Similar value of the two angles θ_m and θ_r ensures that we see very close to the first pole at phase 0.25 and the intensity there is an overall background emission. Two *GINGA* observations in 1987 and 1988 in 10-37 keV range discovered two peculiar pulse profiles (Dotani et al.,). In the first observation at the peak of the profile, there was a dip with a local maximum in it and the intensity was 1.2×10^{36} erg s^{-1}. In the second observation about 150° away from the peak, again there was a dip but without any local maximum there unlike the previous observation and the intensity was 5.8×10^{36} erg s^{-1}. A hollow cylinder of accretion column causing resonance scattering at the energy of the cyclotron line explained the first observation. At the center of the column there was no scattering and that resulted in the local maximum. At a higher intensity level in the second observation, the accretion column was full and the local maximum in the dip was absent. For this to happen the observer has to see just through one of the poles and that is supported by nearly the same values of θ_m and θ_r that we have obtained. The offset of the dip with the peak in the pulse profile as observed in the second *GINGA* observation is also explained with the present value of θ_m and θ_r. In the second observation probably a gradual change from fan beam to pencil beam was taking place with an increase in luminosity, and the peak in the second observation is at the place of the two magnetic equator crossings and the dip is at the phase when one is seeing through the first pole. A larger value of θ_d can produce the wide peak in the second observation and the valley also may become less significant. GX 1+4 showed both single and double peaked pulse profiles on different occasions (Mony et al.,). We have observed both types of pulse profiles on two different occasions with the same X-ray telescope.

The source geometry obtained here with the double peaked pulse profile can generate the single peaked profile observed in 1993 December if a pencil beam emission is considered. Very regular observations of GX 1+4 and accurate measurement of luminosity, pulsation period, period derivatives and epochs may help in establishing this scenario of change in the beaming pattern.

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 the 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 two observations, the period values indicate a very small 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 between our two observations is consistent with our period determinations. *BATSE* observations (Chakrabarty et al.,) in this period has also indicated the same.

In the recent 1995 observation the pulse profile is double peaked, which may be an indication of increased mass accretion on the other magnetic pole. A gradual change in the beam pattern from a pencil beam to a fan beam, also may explain this pulse pattern. We note that the fan beam appeared in the relatively lower luminosity state contrary to the present understanding. Fan beam is more likely to occur in a luminosity state of $L > 10^{37}$ erg s^{-1} but in the 1993 December observation it showed a simple pencil beam pattern in spite of a very high luminosity of 7×10^{37} erg s^{-1}. The pencil beam in the December 1993 observation can be explained if the time scale of change in the beam pattern is long (100 days). The anti correlation between the luminosity and the pulse fraction, that was noticed in an earlier observation is still persistent and it will be interesting to observe whether this feature is present in other pulsars.

Compared to the earlier observations (Laurent et al.) the spectrum is much harder which is evident from a power law photon index of 1.67. The thermal Bremsstrahlung model also fits well with a temperature of 99 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.

A simple modeling of the double peaked pulse profile gave similar values for the inclination angles for the magnetic axis and the line of sight with the spin axis of the neutron star. The geometrical description that fits the present observation also supports the explanation given by Dotani et al. for the dip structure seen in two *GINGA* observations. Our earlier observation of the source profile with single peak also can be explained if a pencil beam emission is considered. One may also note that sometimes in fan beam configuration a larger value of the angular decay scale may hide the valley in between the two peaks corresponding to the two magnetic equator crossings. More frequent long duration observation of the source to determine accurate value of the luminosity, period, period derivative and epoch will help in establishing this possibility of change in the beam pattern.

It is a pleasure to acknowledge the contribution of Shri M.R. Shah, Electronics Engineer-in-charge of this experiment. We are also thankful to Shri D.K. Dedhia, Shri K. Mukherjee, Shri V.M. Gujar, Shri S.S. Mohite, Shri P.B. Shah and Shri D. M. Pawar for their support in the fabrication of the payload. We thank the Balloon Support Instrumentation Group and the Balloon Flight Group led by Shri M.N. Joshi, under the overall supervision of Prof. S.V. Damle.

REFERENCES

Chakrabarty D., Prince T. A. and Finger M. H., 1994, IAU Circular no 6105

Dotani T., Kii T., Nagase F., et al., 1989, PASJ 41, 427

Ghosh P. and Lamb F. K., 1979, Apj 223, L83

Ghosh P. and Lamb F. K., 1979, Apj 234, 296

Laurent P., Salotti L., Paul J., et al., 1993, A&A 278, 444

Leahy D. A., 1990, MNRAS 242, 188

Leahy D. A., 1991, MNRAS 251, 203

Lewin W. G. H., Ricker G. R., and McClintock J. E., 1971, ApJ 169, L17

Makishima K., Ohashi T., Sakao T., et al., 1988, Nat 333, 746

Mony B., Kendziorra E., Maisack M., et al., 1991, A&A 247, 405

Parmar A. N., White N. E. and Stella L., 1989, ApJ 338, 373

Rao A. R., Agrawal P. C. and Manchanda R. K., 1991, A&A 241, 127

Rao A. R., Paul B., Chitnis V. R., Agrawal P. C. and Manchanda R. K., 1994, A&A 289, L43

Wang Y. M. and Welter G. L., 1981, A&A 102, 97

White N. E., Swank J. H. and Holt S. S., 1983, ApJ 270, 711

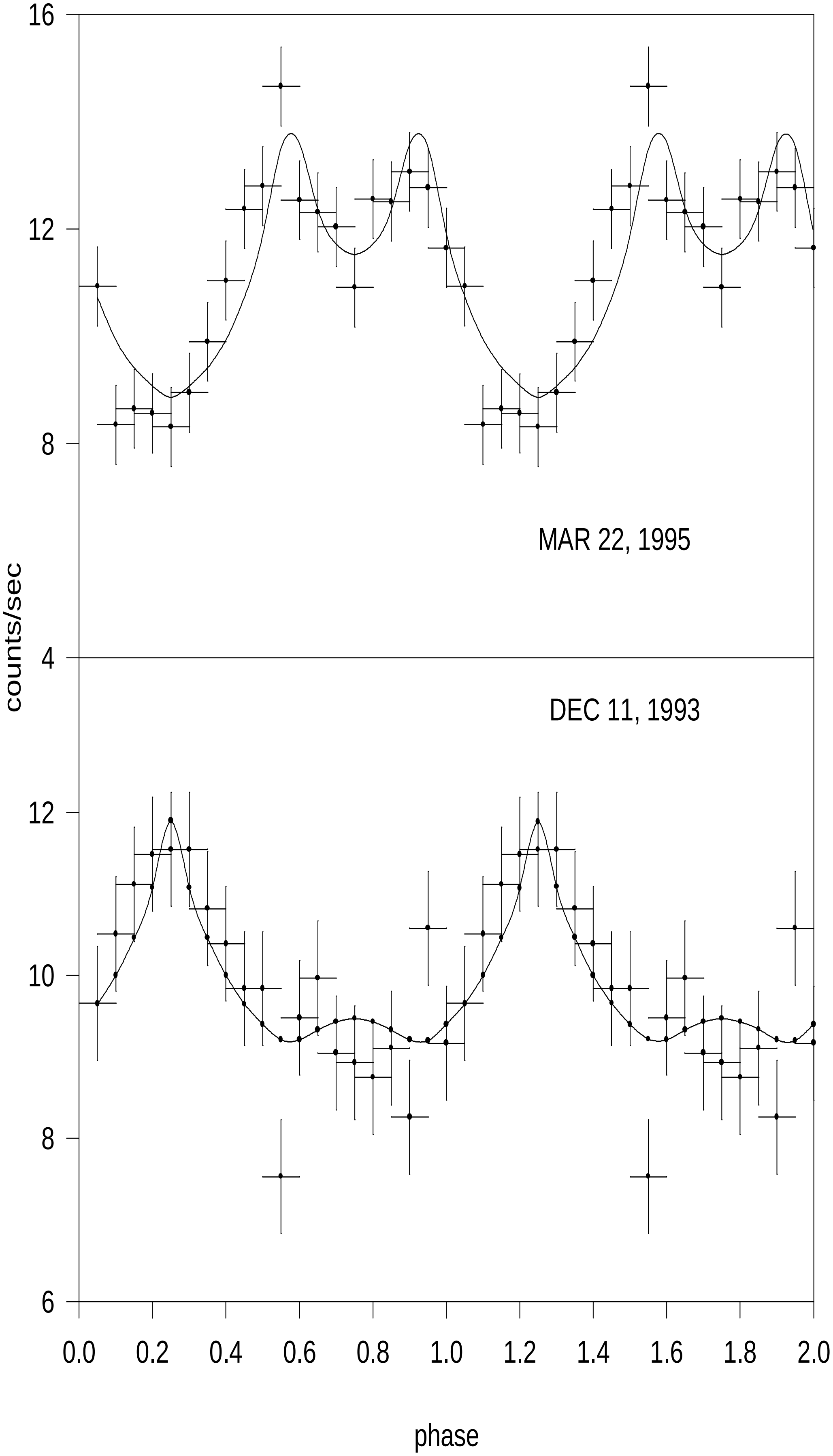

Fig. 1.— Pulse profile of GX 1+4 obtained from the XMPC observations, on two different occasions, plotted in two cycles for clarity. Data from the two detectors have been added to reduce the error in each bin. The lines represent the fan beam and the pencil beam emission patterns in the two cases as shown in the figure. The phase alignment in the two observations is done arbitrarily with the assumption that the pulse profile simulation discussed in the text is valid.