GX 1+4: pulse period measurement and detection of phase-variable iron line emission

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Summary. Observations of the X-ray source GX 1 + 4 (1728 − 247) made by Ariel 6 in 1979 July and 1980 April show that the pulse period decreased at a faster rate during 1978–80 than over the period 1970–78. Compared with that measured in 1976, the pulse profile had become more sinusoidal, with an apparent phase lag ~ 0.1 between the 4–8 keV pulse and that seen at energies above 25 keV. The 1–4 keV range does not show pulsations and is stronger than hitherto. There is also an iron emission feature whose equivalent width varies with pulse phase.

1 Introduction

In observations made between 1971 and 1978 by Becker et al. (1976), Doty, Hoffman & Lewin (1980 and references therein, hereafter DHL) the period of the X-ray pulsar GX 1 + 4 was seen to decrease from 135 to 117 s. Measurements by DHL have shown that the spin-up is not uniform, probably due to a varying accretion torque. Their analysis of the X-ray spectrum as a function of pulse phase showed that the modulation depth increased with energy without a change in the pulse profile. They also found a significant decrease in the flux below 5 keV over a small phase-range ~ 180° from the pulse peak.

The optical counterpart first suggested by Glass & Feast (1973) has been studied spectroscopically by Davidsson, Malina & Bowyer (1977) who found a composite spectrum indicative of a symbiotic star, with strong Hα flux and other emission lines up to [Fe x], interpreted as photoionization of gas around the X-ray source. The measured colours indicate a distance of 10 kpc and thus an expected column $N \sim 1 \times 10^{22} \text{cm}^{-2}$. The value of $N_\text{H} \sim 4–10 \times 10^{22} \text{cm}^{-2}$ seen in earlier X-ray spectra (DHL) is thus probably mainly due to material local to the X-ray source.

2 The Ariel 6 instrument

The Leicester University instrument on Ariel 6 consists of four multi-layered, xenon-filled proportional counters with a total effective area of ~ 300 cm² and with an approximately
circular field of view of 3° FWHM viewing along the satellite spin axis. Separate energy-spectra are recorded from the front and rear sections of the detectors covering the energy ranges 1–20 and 10–50 keV, each with 16 logarithmically spaced energy channels. The beryllium window allows 20 per cent transmission at 1.5 keV. The spectrum observed from the Crab Nebula agrees well with the published spectra (Toor & Seward 1974; Toor, Palmieri & Seward 1976) over the whole 1–50 keV range. A full description of the instrumentation is given by Whitford et al. (1982 in preparation).

The satellite pointing errors are typically 0.3° and there is a 1° coning angle, giving a modulation of the source flux at the satellite spin period (which is maintained in the range 1 to 4 s) the depth of which depends on the offset from the source. The orbital inclination of 55° results in two useful low-background periods per orbit of ~ 20 min each. During one of these the source may be occulted by the Earth and there have been further losses due to spurious electronics commands.

3 Observations

In 1979 July the observations spanned 2.5 days with good data being obtained on 15 orbits, while in 1980 the figures were 25 orbits in 4 days. The dates and durations of the observations are listed in Table 1(a). Table 1(b) summarizes the different data collection modes. The background subtracted from the raw data was obtained from several periods when the instrument was neither viewing the galactic plane nor any known X-ray source. With the same coincident-event rate limit, the background data sets were not significantly different from one another.

4 The pulse period and profile

The data, consisting of 10–20-min samples of the pulse train at intervals of 90 min or more were folded over a range of trial periods, testing the hypothesis that the data were due to a steady flux at the mean counting-rate. For the 1980 data the $\chi^2$ plot was sharply peaked, with only a single possible period value but the 1979 data showed two significant peaks, at

**Table 1(a).**

<table>
<thead>
<tr>
<th>Observation:</th>
<th>1979 July</th>
<th>1980 April</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJD range</td>
<td>44061.7–44064.2</td>
<td>44345.1–44348.8</td>
</tr>
<tr>
<td>Epoch for period</td>
<td>44063</td>
<td>44347</td>
</tr>
<tr>
<td>Barycentric period</td>
<td>112.076 ± 0.003</td>
<td>109.668 ± 0.003</td>
</tr>
<tr>
<td>$P/P$ (per year)</td>
<td>-0.026 ± 0.007</td>
<td>-0.023 ± 0.003</td>
</tr>
</tbody>
</table>

**Table 1(b).**

<table>
<thead>
<tr>
<th>Data collection modes</th>
<th>Energy range</th>
<th>No of PHA channels</th>
<th>Time resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad band (BB)</td>
<td>1–50</td>
<td>8</td>
<td>4 s</td>
</tr>
<tr>
<td>Full range (FR)</td>
<td>1–50</td>
<td>32</td>
<td>32 s</td>
</tr>
<tr>
<td>Reduced range (RR)</td>
<td>1–10 (1979)</td>
<td>8</td>
<td>4 s</td>
</tr>
<tr>
<td></td>
<td>2.5–13 (1980)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single channel</td>
<td>as RR</td>
<td>1</td>
<td>0.5 s</td>
</tr>
</tbody>
</table>
112.0 and 114.3 s. The longer value, in addition to being of lower significance, was ruled out on the grounds that it would require significant phase jitter of the pulse profile. The barycentric values for the period are given in Table 1(a).

The spin-up rate within the span of each observation was checked by comparing the epoch of phase-zero in each data-set with that expected for the measured mean period. A least-squares fit to the differences gave values for \( \dot{P}/P \) of \(-0.026 \pm 0.007 \) yr\(^{-1} \) and \(-0.023 \pm 0.003 \) yr\(^{-1} \) for the 1979 and 1980 observations respectively. This compares with a mean value of \(-0.028 \) yr\(^{-1} \) for the interval between the observations. Depending on the magnitude of the short-term fluctuations, the 1978–80 decline rate may have been faster than for earlier years of the decade; Fig. 1 shows all the known period measurements.

From observations at higher energies, it has been reported that the fundamental period consists of two of the \( \sim 100 \) s cycles. Koo & Haymes (1980) found evidence for a period of \( \sim 4.3 \) min in 1974 data for the energy range 20–64 keV, while Strickman, Johnson & Kurfess (1980) observed differences between alternate 2 min pulses in the range 20–75 keV. We folded the data used for the period determination (energy ranges as RR mode) into 32 bins at periods twice those given in Table 1(a). Comparison of the pulse profiles in the two halves of the 1980 data yields a reduced chi-squared, \( \chi^2_r = 2.73 \). The only differences greater than 1 \( \sigma \) were among the six highest bins and these did not systematically differentiate the alternate pulses. For the 1979 data \( \chi^2_r = 2.53 \) and again large deviations were only found in the bins of highest flux. We also folded the data at three times the basic period and found similar
differences between pairs of the three profiles. Folding the 1980 data for the range 26–50 keV gives a flux ratio between alternate pulses of 0.96 ± 0.13. Thus we find that flux variations occur from one cycle to another on the peak of the pulse, but alternate pulses are indistinguishable. However, if the magnetic axis were to be in the spin plane, pulses from the two poles might normally appear identical, so one cannot exclude the possibility of two pulses per spin-period.

The data from the eight broad-band channels, collected over ~1 day, are shown in Fig. 2 folded at ~110s into 32 phase bins. The modulation depth, defined as (max−min)/mean, is seen to be zero for the 1–4 keV channel, ~0.5 for 8–13 keV and ~1.5 above 26 keV. There is also an apparent lag in phase of ~0.1 between the high- and low-energy pulse profiles. Above 26 keV the pulse shape is similar to that of 1976, with peaks at phases ~0.8 and 1.0 while the 4–8 keV peaks occur at phases ~0.9 and 0.15. An alternative to invoking a lag in phase is to introduce a low-energy pulse at phase ~0.15; the profiles at different energies are not sufficiently similar to exclude this. For 1979 and 1980 the pulse profiles for comparable energy ranges are shown in Fig. 4(b) and (c) and compared with the

![Figure 2](https://academic.oup.com/mnras/article-abstract/201/3/759/992719)

Figure 2. The phase-binned broad-band data, background subtracted and plotted over two cycles. The overlapping channels of the high and low energy system have been combined and quoted as 11–18 keV. Representative error bars (1σ) are shown.
1976 profile (DHL) in Fig. 4(a), though the phase alignment here is arbitrary. The pulse profile below 25 keV was much more sinusoidal in 1980; in neither observation was there a low energy dip as seen by DHL.

5 Spectra

5.1 The Continuum

The phase analysis of the spectrum is concentrated on the 1980 observations as the data are significantly better. The counting rate in each channel is compared with that obtained by

Figure 3. Spectra from the 1980 observations. Broad-band data has been taken for the high energy system and the top broad channel of the low energy system, equivalent to full range channels 13–16. The lowest 4 channels of LE data are from the FR observation (32 s resolution) while channels 5–12 are from the reduced range observations, interleaved with the broad band. The FR and RR normalizations have been adjusted by 15 per cent to the BB data; the differences may be due to variations in either the collimator transmission or in the source flux.
folding trial spectra through a model of the detector system, using calibrations made close to the observations. The standard spectra were considered and, in the case of the power law, a high-energy cut-off factor was included, giving an attenuation of \( \exp \left( \frac{(E - E_1)}{E_2} \right) \) above \( E_1 \). Spectra were plotted by applying the spectrum-dependant efficiencies found in each fit and the errors were determined as by Lampton, Margon & Bowyer (1976). Fig. 3 shows the overall spectra for two quarters of the period, centred on the peak and trough of the pulse profile. Only the power-law model gave acceptable fits for the range 4–30 keV; the spectral parameters determined for each eighth of the phase range are given in Fig. 4(d) to 4(g).

![Figure 4](https://example.com/figure4.png)

**Figure 4.** The phase-binned data for 1979(b) and 1980(c) for broadly similar energy ranges; the phase alignment is arbitrary. (a) is the pulse profile recorded in 1976 (from Doty *et al.*); their phase has been shifted by 0.125. For fitting to the broad-band data above 4 keV the energy spectrum, \( S(E) = S_p E^{-\alpha} f \), where \( f = 1 \) for \( E < E_1 \), \( f = \exp \left( \frac{(E - E_1)}{20} \right) \) for \( E > E_1 \) (d) shows the power-law index, \( \alpha \); (e) the normalization, \( S_p \) and (f) the cut-off energy \( E_1 \). (g) gives the equivalent width of the iron line.
power-law index (Fig. 4d) is almost symmetrical about phases 0.45 and 0.95, except that the phase range 0.13 to 0.25 shows a softer index and greater normalization than the corresponding phase before the peak, a result of the excess flux at low energies for phases 0.1–0.3. Above ~30 keV most fits were improved by including the high-energy cut-off factor; the e-folding rate was fixed at 20 keV and the starting energy, E1 fitted as shown in Fig. 4(f). Single-temperature bremsstrahlung or blackbody spectra did not give satisfactory fits but a multi-temperature blackbody with a maximum kT ~ 7 keV could be fitted.

The mean and range for the 4–50 keV flux density was \((5.9^{+1.8}_{-2.7}) \times 10^{-9} \text{erg cm}^{-2} \text{s}^{-1}\), or \(S(\nu) = 54^{+11}_{-10} \mu\text{Jy}\). Below 4 keV, as Fig. 3 shows, the data lie above the extrapolation from higher energies, but since the hydrogen column cannot be distinguished the actual source spectrum may be different from that fitted. The power-law fit to this energy range gives \(\alpha = 0.8 \pm 0.15\) for the energy index with \(N_H = (0.4 \pm 0.2) \times 10^{22} \text{cm}^{-2}\). The data also fitted a blackbody spectrum of \(kT = 0.75 \pm 0.1 \text{ keV}\). The flux density was \(0.6 \times 10^{-9} \text{erg cm}^{-2} \text{s}^{-1}\), or \(S(\nu) = 66 \mu\text{Jy}\). In 1979 when the spectrum was only measured down to 2.5 keV, the data indicated a smaller excess over the spectrum fitted above 4 keV. The ratio of the 1–50 keV flux in 1980 to that in 1976 (DHL) is 0.7 ± 0.2, the error being mainly the estimated instrumental uncertainties. So the overall output from the GX 1+4 in this range appears to be less, with a lower flux density above 4 keV being partially offset by a greater output below 4 keV.

### 5.2 Iron fluorescence

Interleaved with the broad-band data sets were those in the reduced range mode, where eight channels of the PHA were recorded. They show a prominent iron emission feature, the significance of which can be seen from the fact that \(x^2_{\text{min}}\) decreases from 90 to 4 for the phase range 0–0.25 and from 38 to 2 for phases 0.63–0.88 for the 8-channel fit when a line is allowed. Before the line was fitted, the data excluding the line were fitted by the power-law index allowing also attenuation by iron alone as would be possible by a hot gas; a poor fit to the continuum would affect the subsequent line-fitting. The values found for the iron column, \(N_{\text{Fe}}\) for phase bins 1–7 were in the range \((0–3.2, \pm 2.4) \times 10^{18} \text{cm}^{-2}\). For bin 8 the value was \((8 \pm 2.4) \times 10^{18} \text{cm}^{-2}\).

As Fig. 4(g) indicates, the phase range 0.63–0.88 shows an equivalent width significantly below the mean. The data for this range are compared in Fig. 5 with that for phases 0.0–0.25, for which the mean power-law index is approximately the same. The minimum 90 per cent confidence regions in equivalent-width/line energy space just overlap. Considering the equivalent width alone, the value for the phase range 0.63–0.88 is \(0.31 \pm 0.07 \text{ keV}\), compared with \(0.50 \pm 0.045 \text{ keV}\) for the rest of the cycle. Subdivision of the data does not reveal any significant variation of the equivalent width, either phase averaged or between bins of the same phase-range. With only two PHA channels covering the 20 per cent FWHM detector resolution, no significant broadening was observed.

The 1979 data were processed in a similar manner, except that the initial fit was to the energy range 4–10 keV. The mean equivalent width found was \(490 \pm 50 \text{ eV}\) compared to the 1980 average of \(450 \pm 30 \text{ eV}\). No variation with phase was discernible; a fluctuation at the 1980 level would have been obscured by the poorer statistics.

### 6 Discussion

#### 6.1 The continuum and pulse profile

The general features of accretion on to a magnetized neutron star have been widely discussed (see e.g. Lamb 1975; Lamb, Pethick & Pines 1973). The phase-averaged continuum observed
in GX 1 + 4 can be fitted by the Comptonized spectrum from a hot ($kT \sim 5\text{--}7\text{ keV}$) plasma with optical depth, $\tau \sim \sqrt{m_e c^2 / kT} \sim 9$ (Illarionov & Sunyaev 1972). Accounting for the pulse profiles, however, has proved a more intractable problem (Rappaport & Joss 1977; Pravdo et al. 1979).

GX 1 + 4 showed in 1976 a double-peaked profile with the second peak dominating the first by a factor 2, but no detectable lag between high and low energies (DHL). In 1980 the profile was just resolvable into two peaks and there was an apparent lag and broader pulse in the 1--18 keV compared with the 18--50 keV range. These characteristics are difficult to fit by either axial or fan-beam models.

The 1976 profile is similar to that of Her X-1 (Holt et al. 1974) which Pravdo et al.
interpreted as a single axial pulse from the hotspot with two Thompson-scattering regions in the line-of-sight and positioned asymmetrically with respect to the beam and with a maximum optical depth $\sim 1$. The reversed profile in GX 1+4 requires the accretion funnel to be curved in the direction of rotation at increasing radii. The 1979 data can be fitted by an asymmetric axial beam from a spread polar cap without any scattering, in the method of Wang & Welter (1981), although they did not consider this source because of the doubt about the number of pulses per rotation period.

The 1980 data suggest a fan-beam interpretation, since the spectrum emitted by the accretion column is expected to harden with increasing angle to the magnetic field (e.g. Pravdo & Bussard 1981), but the apparent lag (or change in spectrum through the pulse) still requires some asymmetry of the emission region with respect to the magnetic field. The pulse is broad as expected, but retains the two peaks, albeit much less distinct, with the same phase separation as seen in 1976. Thus there has been no fundamental change in the pulse-formation process over this time and the differences in the profiles must be allowed by any viable model.

Although a long-term trend to spin-up faster is noted, the value of $\dot{P}/P$ measured in 1980 is significantly lower than that recorded by Doty et al. in 1976 ($-0.032 \pm 0.0015$) when the pulse profile was much narrower. Thus the broadening of the profile may be correlated with a lower accretion rate.

6.2 IRON EMISSION LINE

The large mean equivalent width is most easily interpreted as fluorescence from a shell of material at the Alfvén surface. Following Hatchett & Weaver (1977) and Pravdo (1979), the ratio of the line strength to the number of photoionized iron atoms is a measure of the photoionization yield, $\epsilon(\sim 0.34)$ and the solid angle, $\Omega$ subtended by the fluorescing target. For the phase-averaged line strength and spectrum, $\epsilon \Omega/4\pi = 0.24$, a value similar to those Pravdo gives for Her X-1 and Vela X-1. Thus if the $7-20$ keV spectrum we observe is typical of that seen by the fluorescing target, a large fraction of the solid angle around the source is subtended, implying the disc/Alfvén surface rather than the companion.

The phase range for which the equivalent width is lower overlaps that where a significant improvement to the continuum fit is made by including absorption by Fe. For the phase range $90 \pm 45^\circ$ ahead of the pulse peak, either the fluorescing material is obscured from view or the beam illuminates much less of the visible target area. The lack of strong Fe absorption above $7$ keV indicates a reflecting target rather than a transmitting one (Langer, Ross & McCray 1978) unless it is optically thin. If illumination of the disc is concentrated in two regions near the magnetic poles which themselves are not in the plane of the disc, the material accreting on to the nearer pole could hide part of the fluorescing disc from view for a part of each period.

This may be analogous to the variation seen in the He II 4686 Å line of DQ Her by Chanan, Nelson & Margon (1978) where both the phase and amplitude of the line are variable and interpreted as fluorescence from regions on the disc surface illuminated by the white dwarf. The cause of the amplitude modulation was only speculated upon and could be due to obscuration by accreting material.

Although other X-ray pulsars exhibit more complicated pulse profiles than GX 1+4, these observations indicate that there is probably a lot more to be learned from high-resolution pulse-phase spectroscopy of the source at different brightnesses.
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References


