ROSAT observations of a soft X-ray emission component in the intermediate polar RE 0751 + 14

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ABSTRACT

ROSAT pointed observations of the intermediate polar (IP) RE 0751 + 14 reveal, for the first time in an IP, a distinct soft X-ray component reminiscent of that seen in the strongly magnetic polars. The soft X-ray light curve, which is modulated on the 13.9-min spin period of the white dwarf, is characterized by a large-amplitude, quasi-sinusoidal variation, the rising phase of which is cut into by a dip feature with a deep, narrow core. In conjunction with the results of a more complete analysis of the previous Ginga hard X-ray observation of the star, the energy dependence of this dip suggests that it is caused by absorption, probably arising from the passage of dense, accreting material in front of the emission region. The presence of the dip feature in both the ROSAT and Ginga light curves is used to derive a rotational ephemeris. Phase-resolved spectral analyses of the separate Ginga and ROSAT data sets are presented. When combined, spectral fits indicate that models involving partial covering are, in general, a better description of the observed spectra than simple absorber models. We find no clear evidence of a gross imbalance between the luminosities of the hard and soft spectral components in RE 0751 + 14. We discuss the implications of these results on our understanding of this particularly important binary which, despite being an intermediate polar, exhibits several properties that are more characteristic of the AM Her stars.

Key words: stars: individual: RE 0751 + 14 – stars: magnetic fields – novae, cataclysmic variables – X-rays: stars.

1 INTRODUCTION

The discovery of the intermediate polar (IP) RE 0751 + 14, using the Wide Field Camera during the ROSAT all-sky survey, and the identification of its optical counterpart are described in Mason et al. (1992, hereafter Ma92). They also discuss the subsequent detection of a coherent 13.9-min pulsation in the infrared, optical and Ginga hard X-ray light curves, together with the probable presence of a longer (5–6 h) radial velocity modulation which led to its classification as an IP. In these systems, an asynchronously rotating magnetic white dwarf accretes material from a low-mass companion via Roche lobe overflow, possibly via an accretion disc.

Several properties set RE 0751 + 14 apart from all other known members of the IP group. Its discovery by the Wide Field Camera makes it the first EUV-selected IP and indeed one of only two to be detected at these energies, the other being EX Hya (Pounds et al. 1993). Its 13.9-min modulated K-band light curve exhibits an intriguing second dip which is approximately centred on the peak of the underlying quasi-sinusoidal modulation. Ma92 also showed that, while the medium energy (2–6 keV) Ginga light curve displays a complex double-peaked profile modulated at 13.9 min (attributed to the white dwarf spin period), the higher energy light curve (above 10 keV) shows a single-peaked, broadly sinusoidal shape. On the basis of this energy-dependent behaviour, Ma92 suggested an interpretation incorporating
elements of both competing IP accretion scenarios, i.e. occultation of the emission region by the white dwarf itself, producing an energy-dependent modulation (King & Shaviv 1984) and phase-variable absorption on the spin period producing an antiphased energy-dependent modulation (Rosen et al. 1988).

More recent observations have confirmed the 13.9-min white dwarf rotation period in RE 0751 + 14 via the presence of systematic radial velocity variations in the wings of the optical emission lines (Rosen et al. 1993, hereafter RMH). They have also shown that there is a colour dependence of the light-curve structure and periodicity in the optical/IR. While the R- and I-band photometric light curves show a double-peaked profile at the spin period (similar to the earlier K-band observations, though more pronounced), the B-band light curve is apparently dominated by a 14.5-min, roughly sinusoidal pulsation. The latter probably represents the beat period between the spin and orbital periods, implying an orbital period of 5.3 h, consistent with the spectroscopic constraints obtained by Ma92. This colour dependence is strongly suggestive of a cyclotron origin for the red/IR light, an interpretation underpinned by the detection of variable circular polarization in the R band (RMH; Piilo, Hakala & Coyne 1993; Mason et al., in preparation). RE 0751 + 14 is only the second IP in which polarization has been detected and the first in which this is seen to vary with the spin period.

In this work we present the results of a pointed ROSAT observation of RE 0751 + 14 which permits the first detailed spectral and temporal studies to be made of its soft X-ray emission. We also re-examine and extend the analysis of the previously reported Ginga observation.

2 OBSERVATIONS

RE 0751 + 14 was observed using the X-ray telescope (XRT) in combination with the Position Sensitive Proportional Counter (PSPC) and the Wide Field Camera (WFC). Descriptions of the satellite, XRT and PSPC are given in Pfeffermann et al. (1986), and of the WFC in Sims et al. (1990). Briefly, the XRT and PSPC combination provides an imaging instrument with moderate spectral resolution in the energy range 0.1-2.5 keV, while the WFC is an EUV-imaging instrument which is used in conjunction with one of four filters, for this observation the S1a filter (88-190 eV).

The observation was carried out on 1992 April 1-2, when 9292 s of exposure were obtained, in blocks of order 1-2 ks, over a period of 81549 s. It was made in 'offset mode' (with the source 40 arcmin off-axis) so as to avoid the effects of the periodic occultation of the source by wires in the PSPC window (since the spatial resolution at this off-axis angle effectively blurs the image to a size much larger than the wires). The data were reduced using the ASIERR software package (Saxton 1992) using a background region offset from the source region, but at the same off-axis angle.

Ginga observed RE 0751 + 14 on two separate occasions. The first consisted of a short observation from 1991 April 15 23.14 UT to April 16 01.04 UT, whilst the second, much longer run, occurred between about 1991 May 4 13.00 UT and May 5 18.00 UT. For the short run, a background measurement taken immediately after the source observation and spanning about 16 h was employed for background subtraction, whilst, for the long exposure, the background contribution was derived from an observation performed on 1991 May 1 and 2, covering an interval of ~31 h. During the processing, background data were accepted when the pointing direction lay within 1°5 of the nominal pointing position, whilst for the source data, the maximum departure allowed from the nominal position was 0°6. Data taken when the source position in the FOV resulted in a collimator transmission efficiency of less than 70 per cent were also excluded.

The short observation was badly affected by poor attitude stability of the satellite and only yielded about 700 s of usable data. During the longer run, approximately one-third of the observation was taken under 'night' conditions (i.e. with the satellite in the Earth's shadow), so that data from all eight detectors are available. During the remainder of the observation, which was performed in 'day' conditions, three of the detectors were shielded from the Sun by the solar arrays. Spectral tests reveal no evidence for solar contamination in the data from these three detectors, and we therefore include information from them in our analysis. The results published in Ma92 excluded both data from the short observation and the data at energies below ~4 keV taken under 'day' conditions during the long run.

3 RESULTS

3.1 The PSPC light curve

Fig. 1 shows the PSPC light curve of channels 11-50 (approximately 0.1-0.5 keV) for the entire observation. The general structure of the light curve is apparently rather simple, showing a roughly sinusoidal profile with a dip on the rise to maximum. However, the light curve does show significant cycle-to-cycle amplitude variations, with the peak count rate varying from ~6 count s⁻¹ at φ = 15.2 up to ~18 count s⁻¹ at φ ~ 58.2. The profile of the dip also varies. It exhibits apparent 'standstills' on the sharp rise in some cases (e.g. φ = 1.2) whilst in others the rise is extraordinarily fast (e.g. φ ~ 86.1) with the count rate rising from ~1 count s⁻¹ to ~8 count s⁻¹ in about 10 s. The flux in the dip can be totally or nearly totally extinguished, (φ ~ 15.0, 16.0, 17.0, 18.0, 86.0, 87.0), partially extinguished (φ ~ 1.0, 2.0) and the dip is sometimes even apparently absent (φ ~ 93.0, 98.0).

The core width also varies from ~20 s (φ ~ 17.0) to ~70 s (φ ~ 1.0). There is sometimes an apparent secondary peak (e.g. φ ~ 1.2-2.0) in the curve, though this could be interpreted as the beginning of the main peak which is then 'cut into' by the dip.

Another marked cycle-to-cycle change in behaviour occurs from φ = 92.0 to 94.0 and to a lesser extent φ = 97.0 to 98.5. The decline from maximum just missed by the data block at φ = 92.1 is particularly rapid, but the count rate only declines to about 3-4 count s⁻¹, higher than is typical. This high 'base' level, however, continues until the rise to the next maximum at about φ = 93.0, without any sign of a dip. The next peak does not appear as asymmetric, but still declines relatively rapidly to an uncharacteristically sharp minimum at φ = 93.5. Even outside this sharp minimum (~20 s wide), the base level is much lower (~2 count s⁻¹) than just the other side of the peak. Although there is again no compelling evidence of a narrow dip apparent in the cycle centred at
\( \phi = 98.0 \), the structure of this section of data is otherwise similar to that of the average pulse. The lack of detectable dips in the last two cycles is intriguing. It is possible that the depth of the dip is a function of orbital phase – if the orbital period is 5.2 h, none of the other 13.9-min cycles covered by ROSAT falls within the orbital phase interval delineated by these two cycles. However, the orbital phase of the dip at cycle 2.0 is only 0.05 earlier than that of the dip expected at cycle 93.0 so that, if the presence/absence of dips is related to the orbital cycle, the transition must be rapid. The limited orbital phase coverage of the ROSAT data precludes a detailed study of this phenomenon. RE 0751 + 14 also exhibits random flaring activity on a time-scale of a few tens of seconds in several cycles (e.g. \( \phi \sim 1.2-1.6 \)) during the long decline from maximum.

The PSPC data set was searched for periodicities using both standard and \texttt{clean} Fourier algorithms. Fig. 2 shows both the raw and cleaned power spectra of RE 0751 + 14,
3.2 The Ginga light curve

An inspection of the complete Ginga data set, including the data taken under ‘day’ conditions (which comprises two-thirds of the entire observation) during the run on 1992 May 4–5, concurred with the findings of Ma92, that there is a long-term variation present but that this is apparently not associated with the likely 5–6 h orbital time-scale in RE 0751 + 14. The presence of the 13.9-min periodicity reported by Ma92 was confirmed, via Fourier analysis, in the complete data set. No other prominent periods were evident. In particular, a folding analysis enables us to place a 3σ upper limit of 5 per cent on the semi-amplitude (about the mean) of any modulation at the likely beat period of 14.53 min that was detected in the B-band photometry of RMH.

3.3 The rotational X-ray light curves

As will be seen in Section 4.1, the PSPC spectrum is composed of two distinct components which can be almost cleanly separated. To probe the energy dependence of the 13.9-min pulsation, the ROSAT data were therefore divided into two spectral bands corresponding to PSPC channels 11–50 (0.1–0.5 keV – the ‘soft’ band) and 61–250 (0.6–2.5 keV – the ‘hard’ band). The contamination of each band by flux from the component that dominates the other was estimated to be less than 5 per cent in each case, based on model fits to the average PSPC spectrum (Section 4.1). The time-series of the two bands, folded on the ephemeris in equation 2 (Section 3.4), are shown in the top two panels of Fig. 3 (the choice of folding period from those quoted in equations 1–3 of Section 3.4 has no perceptible effect on the structure of the modulation). The bottom five panels of Fig. 3 show the Ginga data, resolved into five energy bands (2–4, 4–6, 6–10, 10–18 keV and the mean 2–18 keV), also folded on this ephemeris. We note here that, whilst the folded light curves in the lowest three Ginga energy bands are similar to those presented in Ma92, the highest band shows a significantly lower mean level. This is probably due to the use of different background observations – the weak net source signal in this band is sensitive to differences in the background model used. Interpretation of the variation in the 10–20 keV band should take this into account.

The energy dependence of the 13.9-min variation is striking in both the PSPC and Ginga data sets. In the Ginga data, the light curve in each band is double peaked, except perhaps in the hardest (10–18 keV) range, where the variation can be satisfactorily described by a simple sinusoidal variation (fractional semi-amplitude about the mean of 18±7 per cent). To test whether the lower energy band Ginga light curves can be simply decomposed into a sinusoidal modulation with a superimposed Gaussian dip, we compared the data in each band with such a model. Satisfactory fits (χ^2_ν ≤ 1.3 for ν = 24) are obtained at energies above 4 keV. The phase of the underlying sinusoid does not show a significant energy dependence, reaching a maximum at phase 0.11 ± 0.03. However, the lowest (2–4 keV) band is not well described by this function (χ^2_ν = 1.7 for ν = 24) since the minimum at phase 0.55 is narrower (or conversely, the breadth of the apparent secondary maximum at phase 0.8 is broader) than can be accommodated by the synthesized profile. As one moves to even lower energies (the hard
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Figure 3. Phase-folded light curves for the 'soft' (0.1–0.5 keV) and 'hard' (0.6–2.0 keV) ROSAT PSPC spectral bands (top two panels), excluding the last two data blocks in which a somewhat different structure is apparent, and five energy-resolved Ginga bands.

(0.6–2 keV) ROSAT band, the minimum at phase 0.55 essentially disappears. Whilst this might be attributable to a change in the emission from the source between the two observations, an alternative interpretation is that it simply represents a continuation of the energy-dependent trend in the width of the minimum at phase 0.55 that is seen in the Ginga data. If so, then at low energies (~0.6–4 keV), either the underlying modulation departs substantially from a sine wave, or an additional component is contributing to the maximum at phase 0.8.

In contrast, the profile of the soft ROSAT band (0.1–0.5 keV) is dominated by a high-amplitude modulation and the dip, with no convincing evidence for a broadened secondary maximum near phase 0.8. We note, however, that the presence of such a feature in the soft band would be hard to detect if its count rate there were similar to that in the 0.6–2 keV band, since, at this phase, the soft-band count rate (2 count s⁻¹) of the soft component (see Section 4.1) would be about four times larger. Applying the previous model to the 0.1–0.5 keV band light curve, we find that a sinusoidal variation provides a poor description of the underlying variation, the light curve being more highly peaked than the model function. Nevertheless, assuming a symmetric profile, we estimate that the pulse maximum occurs at phase 0.19 ± 0.05.

Regarding the dip, we find that, in the Ginga band, neither the phase of the dip minimum nor its width shows any significant energy dependence. The mean FWHM is 0.22 ± 0.07 in phase. In comparison, the dip width in the hard PSPC band is 0.12 ± 0.05, whilst in the soft band it is 0.09 ± 0.03. The phases of dip minimum in the two PSPC bands are coincident within the uncertainties (<0.02). The apparent narrowing of the dip in the PSPC data might represent a true energy-dependent phenomenon but, equally, could simply reflect changes in the parameters of the occulting or occulted regions between the Ginga and ROSAT observations. The depth of the dip does, however, appear to be strongly energy dependent. Expressed as a percentage of the underlying sinusoidal modulation, evaluated at the phase of the dip, the depth varies from 59 ± 22 through 42 ± 12, 26 ± 14 and 40 ± 42 per cent for the 2–4, 4–6, 6–10 and 10–18 keV bands, respectively. The large uncertainty ranges arise primarily because the presence and phasing of the dip reduces the stringency of the constraints that can be imposed on the amplitude and mean level of the sinusoid.

3.4 An X-ray ephemeris

Since both the ROSAT and Ginga X-ray light curves are dominated by the 13.9-min rotational modulation, and in particular contain a prominent, apparently stable dip event which acts as a useful fiducial marker (see Fig. 3), we have used them to derive an ephemeris. The dip profile in the Ginga data was found to be best defined in the 2–6 keV range. Templates of the rotational light curve were generated separately for both the eight and three detector data by folding the respective 2–6 keV band time-series into 50 phase bins on the 13.9-min period. A function of the form \( a + b(f(\phi)) \) was then fitted to consecutive segments of the 2–6 keV band Ginga light curve, where \( f(\phi) \) is a spline representation of the appropriate template profile. In performing this analysis, we point out that the full spin profile template was matched to complete cycles in the light curve, rather than focusing on a limited phase region around the dip (though see below). This approach was adopted because the dip in the Ginga data is not as narrow as that in the ROSAT time-
series. Reduced chi-squared values of ~1.0 were achieved for the fit to each cycle. Uncertainties on the dip epochs were determined by stepping the template away from the best-fitting value until the fit statistics showed an increase corresponding to the 68 per cent confidence level for two parameters of interest. The short Ginga observation, although spanning only about 85 per cent of the 13.9-min cycle, also shows a clear dip feature whose spectral characteristics are indistinguishable from those of the dips visible in the more extensive data set. We therefore obtained a dip timing from this observation too.

Table 1 shows, for each dip in the Ginga light curve, the cycle count relative to the first dip of the long data set, the HJD at dip minimum and the estimated 1σ uncertainty. The fiducial point was taken to be the minimum of a Gaussian profile fitted to the core of the dip profile template.

Extrapolation of an ephemeres based on the long data set alone (for which we obtain a period of 0.0096455(12) d) gives an unambiguous cycle count of 1926.06 ± 0.24 at the epoch of the dip in the short observation. Combination of all the Ginga dip epochs yields the following ephemeres:

$$T_{\text{min}}(\text{HJD}) = 2448362.48631(25) + 0.009645770(124)E.$$  

(1)

We point out here that we also tested the appropriateness of applying full template fits to the Ginga cycles by fitting templates covering only a restricted phase interval (~±0.2 of the dip centre) to the time-series. Such an approach would be particularly relevant if, for example, the dip exhibited phase jitter. We find that, although the uncertainties on the individual dip epochs are larger, as might be expected, extrapolation of the resulting ephemeres to the dip in the short observation yields a phase of ~1926.0 ± 0.5, i.e. a cycle count of ~1926 is still strongly favoured at that epoch. Moreover, when combined, the Ginga dip epochs derived by this method give an essentially identical ephemeres to that quoted in equation (1), though the uncertainties on the reference epoch and period are larger than those quoted there by factors of 2.3 and 3.5, respectively.

The ROSAT data were analysed in a similar manner, using a template derived from the energy-averaged PSPC light curve. However, here we were able better to exploit the definition of the dip profile and we therefore used only data within a phase interval of about ±0.1 of the dip. Table 2 gives the cycle count relative to the first dip in the ROSAT data and the HJD of each discernable minimum in the ROSAT observation. The last two cycles in Fig. 1 do not show significant evidence for the dip and we have not attempted to obtain timings for these cycles. The period determined from the ROSAT data alone is 0.0096446(11) d.

As noted in Section 3.3, the similarity of the light curves in the hard PSPC band and the softest (2–4 keV) Ginga band suggests that these two bands essentially sample the same spectral component, a view supported by the spectral decomposition discussed in Section 4.1. Coupled with the fact that we find no evidence for any significant shift (<0.02) in the phase of dip minimum between the hard band PSPC light curve (0.6–2.5 keV) and the soft (0.1–0.5 keV) or overall (0.1–2.5 keV) band PSPC light curves (see Section 3.3), we make the assumption that the dip features in the PSPC (soft and hard bands) and the Ginga time-series are coincident in phase, reflecting the same, phase-stable phenomenon. With this premise, and using the more tightly constrained dip epochs derived from the 0.1–2.5 keV band PSPC light curve, we attempted to refine the ephemeres by combining both sets of epochs. Extrapolation of the above ephemeres (equation 1) gives a cycle count of 34518.49 ± 0.47 at the epoch of the first dip in the ROSAT data. Thus we cannot provide unique cycle counts for both data sets. We can, however, provide an ephemeres for each of the two most probable integer cycle count solutions.

### Table 1

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<th>Cycle count</th>
<th>HJD (min) – 2448300</th>
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<tr>
<td>−1926</td>
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<td>0</td>
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<td>6</td>
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<tr>
<td>13</td>
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<tr>
<td>14</td>
<td>81.19915 ± 0.00012</td>
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<tr>
<td>20</td>
<td>81.25700 ± 0.00030</td>
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<td>21</td>
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<td>115</td>
<td>82.17328 ± 0.00013</td>
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### Table 2

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<td>15</td>
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<td>4.84124 ± 0.00005</td>
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<tr>
<td>86</td>
<td>4.85094 ± 0.00008</td>
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</table>
Adopting a cycle count of 34 518 we obtain
\[ T_{\text{min}}(\text{HJD}) = 244 8362.486 05(4) + 0.009 645 905 3(14)E, \] (2)
whereas if the cycle count is 34 519 we obtain
\[ T_{\text{min}}(\text{HJD}) = 244 8362.486 58(4) + 0.009 646 26(14)E. \] (3)

Each of these results is consistent with the (less tightly constrained) ephemeris derived from the optical \( I \)-band data of RMH. We advise caution in the use of these two ephemerides, however, because the extrapolation of an ephemeris based on template fits to only the cores of the \textit{Ginga} dips results in a more poorly constrained cycle count of 34 518.49 \( \pm \) 1.6 at the epoch of the first \textit{ROSAT} dip which admits at least two additional solutions. Further, the most likely cause of the dip, namely obscuration by the accretion flow (see Section 5.3), suggests that long- (and even short-) term changes in the phase of the dip might occur, which could invalidate the linking of the \textit{ROSAT} and \textit{Ginga} dip epochs.

4 SPECTRAL RESULTS

In this section we present a detailed spectral analysis of the X-ray data from RE 0751+14. Since the \textit{ROSAT} and \textit{Ginga} observations were spaced apart by some 300 d, we first discuss the results derived from each instrument separately, beginning with the phase-averaged spectrum and then focusing on phase-resolved investigations. Exploiting both the apparent similarity between the 0.6–2.5 keV (\textit{ROSAT}) and 2–4 keV (\textit{Ginga}) band data sets (Section 3.3) and the fact that the flux levels of the spectra from the two instruments are in reasonable agreement around 2 keV, where the detector responses overlap, we also present a phase-resolved analysis of the combined \textit{ROSAT} and \textit{Ginga} spectra.

4.1 The overall spectrum – a soft X-ray component in an IP

RE 0751+14 was detected strongly in the PSPC as a very soft source. The spectrum, however, evidently comprises two components. A power-law fit to the phase-averaged spectrum highlighted the presence of a soft excess in the range 0.1–0.6 keV. We therefore applied two component models, achieving the best fit (\( \chi^2 \approx 1.0 \)) for a blackbody plus power-law emission model (see Fig. 4). However, the placing of stringent constraints on the parameters of the soft component is hampered by the modest spectral resolution of the PSPC detector, which effectively provides only two independent spectral channels in the energy range where the soft component dominates. Formally, we derive a blackbody temperature of 46.\( \pm \)13 eV and a neutral hydrogen column density of 1.7\( \pm \)2\( \times \)10\(^{22}\) cm\(^{-2}\) (confidence limits are 99 per cent), the two parameters being highly correlated.

The best fit to the phase-averaged 2–18 keV \textit{Ginga} data alone, using a bremsstrahlung continuum model, together with a narrow iron line and neutral absorption, gives a temperature of \( \sim \) 70 keV, a line energy of \( \sim \) 6.65 keV and a column density, \( N_{\text{HI}} \), of \( \approx \) 1.8\( \times \)10\(^{22}\) cm\(^{-2}\) but the fit is poor, with a reduced \( \chi^2 \) of 1.62. We emphasize at this point, that, although the simple fit presented here suggests a rather high emission temperature, as will be shown later, the spectrum below 10 keV is apparently subject to complex absorption effects. We therefore note, as did Ishida (1991), that, if one fits the data only in the range above 10 keV, where absorption effects should be minimal, the fitted continuum temperature of the mean spectrum is \( \sim \) 20 keV. If we then fix the continuum temperature at this value, we find that the single absorber model fails, with a reduced \( \chi^2 \) of 3.9. We then tested a model invoking partial covering (i.e. a leaky absorber), a scenario frequently employed to provide adequate fits to the X-ray spectra of IPs (e.g. Norton & Watson 1989; Ishida 1991). Here, flux from the emission source passes through an inhomogeneous absorbing medium, the absorber being parametrized by two columns, each covering a different fraction of the source, with the two fractions summing to unity. Such a model could, for example, mimic the effects of an intrinsically clumpy local absorber or the combination of a more uniform local absorber and the interstellar medium. A better, though still unacceptable, fit was achieved (reduced \( \chi^2 \) of 1.47) using this model although the poor match is probably due, at least in part, to the fact that it is a fit to the average spectrum of a variable source. The iron line energy (6.65 keV) is very similar to that (6.7\( \pm \)0.05 keV) observed in the IP EX Hya (Rosen et al. 1991) whereas, in other IPs, fluorescent Fe emission from 6.4 to 6.5 keV dominates (Norton, Watson & King 1991). It should be noted, however, that both a 6.4-keV and a 6.8-keV feature have recently been detected in the ASCA X-ray spectrum of FO Aqr (Mukai, Ishida & Osborne 1994). EX Hya was also the only other IP to be detected in the EUS (WFC) band during the \textit{ROSAT} all-sky survey.

4.2 Phase-resolved spectral behaviour

4.2.1 \textit{ROSAT} PSPC data

Spectra from both the PSPC and \textit{Ginga} detectors were accumulated into five phase bins, chosen to match the important features in the folded 2–4 keV band \textit{Ginga} light curve. These correspond to phases 0.49–0.71 (minimum), 0.71–0.915 (secondary maximum), 0.915–0.09 (dip), 0.09–0.49 (primary maximum) and 0.965–0.015 (dip core).

Initially, we used the \textit{ROSAT} data to investigate the spectral properties of the soft component. This is justified by the fact that parametrization of the blackbody component is...
largely unaffected by the presence of the hard source. A time-series of the softness ratio was formed, defined as the ratio of counts in the energy range 0.11–0.23 keV to those in the range 0.23–0.50 keV (essentially covering only the soft component), which yields an average ratio of approximately 1.0 (Fig. 5). This indicates that the source hardens at the time of the minimum in the underlying modulation ($\phi \sim 0.7$) and, as may be naively expected, around the main dip ($\phi \sim 0.0$). The softness ratio probably peaks near the phase of flux maximum.

Spectral variations are also evident from cycle-to-cycle in the light curve. This is amply demonstrated by the softness ratio (as defined above), calculated for the phase range 0.15–0.30 in each rotational cycle, which varies between 0.87 and 1.26, being inconsistent with a constant value at greater than 90 per cent confidence. This suggests that the variation in the peak count rate of the maxima observed in the time-series is not due simply to a change in the luminosity of the soft component, but that it is accompanied by a variation in temperature and/or the column. Fig. 6, however, shows that there is no clear correlation between the count rate of the soft component and the associated softness ratio for data from the peak of the pulsation. Thus the variation in count rate is also not due to a simple variation in the column or temperature.

### 4.2.2 Ginga data

The phase-resolved Ginga data were also tested for spectral variability using a thermal bremsstrahlung continuum model and a narrow iron line. In performing these fits, we fixed the continuum temperature at the 20-keV value determined from the 10–20 keV range of the mean spectrum (see above).

It was found that a simple spectral model involving a single absorbing column provided unacceptable fits ($\chi^2 > 1.3$) in most cases, the model systematically over-representing the data around 3–4 keV. Fits involving a partially covered bremsstrahlung source yielded improved fits (reduced $\chi^2 \sim 1.0$). The parameters for the latter fit to each phase bin are given in Table 3. The results indicate that, amongst the fitted parameters, only the covered fraction and the smaller of the two column density values vary significantly, and then only during the dip. However, the apparent stability of the other parameters may, in part, be due to the modest statistical quality of the data, which is reflected in the substantial uncertainty ranges of the parameters.

#### 4.2.3 Combined ROSAT and Ginga spectra

To investigate the model constraints that can be imposed if the spectra from the two instruments are combined, for each phase bin we also simultaneously fitted the Ginga and ROSAT spectra using a variety of two-component models. The simplest uniformly absorbed models, employing a soft blackbody component, together with a harder thermal bremsstrahlung (again with the temperature fixed at 20 keV) or power-law component and a narrow iron line, gave unsatisfactory fits (reduced $\chi^2$ values $> 1.5$). The largest discrepancy with these models occurred for phase bins containing the dip, and arose because the Ginga data require a large absorbing column to explain the sharp turn down at the low-energy end of its response, whereas this turn down is not apparent in the high-energy end of the ROSAT band.

We next considered models in which the requirement of a single absorbing column was relaxed, i.e. in which the fluxes from each of the two continuum components were subjected

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**Figure 5.** Phase-folded softness ratio (0.11–0.23/0.23–0.50 keV) time-series. There is evidence for a hardening of the spectrum around phases 0.0 and 0.7.

**Figure 6.** Plot showing the total 0.11–0.50 keV count rate against the (0.11–0.23)/(0.23–0.50) keV softness ratio for the phase range 0.15–0.30, for each cycle of data.

---

**Table 3.** Fit parameters and 1σ limits for the best-fitting partially covered thermal bremsstrahlung model plus iron line, applied to rotationally phase-resolved Ginga spectra. The continuum temperature is fixed at the best-fitting value of 20 keV derived from the 10–18 keV range of the mean spectrum.

<table>
<thead>
<tr>
<th>Phase bin</th>
<th>$n_{H1}$ ((10^{22} \text{ cm}^{-2}))</th>
<th>$n_{H2}$ ((10^{22} \text{ cm}^{-2}))</th>
<th>Covered fraction</th>
<th>2–10 keV flux ((10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}))</th>
<th>Line energy ((\text{keV}))</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary maximum</td>
<td>$35^{+4}_{-3}$</td>
<td>$1.6^{+1}_{-1}$</td>
<td>$0.39^{+0.04}_{-0.03}$</td>
<td>2.52</td>
<td>$6.65^{+0.75}_{-0.75}$</td>
<td>0.95</td>
</tr>
<tr>
<td>Minimum</td>
<td>$47^{+2}_{-3}$</td>
<td>$1.3^{+0.6}_{-0.6}$</td>
<td>$0.34^{+0.02}_{-0.02}$</td>
<td>1.92</td>
<td>$6.56^{+0.64}_{-0.64}$</td>
<td>1.11</td>
</tr>
<tr>
<td>Secondary max</td>
<td>$57^{+3}_{-5}$</td>
<td>$1.3^{+0.6}_{-0.6}$</td>
<td>$0.39^{+0.04}_{-0.04}$</td>
<td>2.25</td>
<td>$6.71^{+0.82}_{-0.82}$</td>
<td>0.94</td>
</tr>
<tr>
<td>Dip</td>
<td>$57^{+3}_{-5}$</td>
<td>$4.0^{+0.8}_{-0.8}$</td>
<td>$0.49^{+0.09}_{-0.09}$</td>
<td>1.87</td>
<td>$6.78^{+0.92}_{-0.92}$</td>
<td>0.75</td>
</tr>
</tbody>
</table>
to transmission through separate absorbing columns. Again, however, these models proved unsatisfactory ($\chi^2 > 2$), substantially underestimating the flux around 2 keV for the phase bin containing the dip, due largely to the high column density demanded by the turn-over in the Ginga spectrum. Motivated by the evident incompatibility between the large column density required to match the Ginga data and the much lower column density needed to explain the FSPC spectrum, we returned to a partial covering model – here the line-of-sight flux from both emission components traverses an inhomogeneous absorbing medium. Formally, these give significantly better reduced $\chi^2$ values of 1.0–1.1 (if the bremsstrahlung temperature was fitted) and 1.0–1.35 (if it was fixed at 20.4 keV), though in the latter case there is some evidence that the data depart systematically from the model around 3–4 keV in the spectra from the secondary maximum and primary maximum phase bins. Fig. 7 shows a representative fit to the spectrum of the dip for the case where the temperature is fixed at 20 keV. We further tested this model by fixing the lower column density ($n_H = 1.5 \times 10^{20}\text{ cm}^{-2}$) and the blackbody (51 eV) temperature at the values derived from the phase-averaged spectrum. The resulting fits differ little from those where the same parameters were adjustable. The results of these fits are presented in Table 4.

Clearly these results are neither unique – other models may be allowed – nor perhaps even valid, since the object was observed at very different epochs by the two instruments. If taken at face value, however, they imply that a

![Graph showing the relationship between energy and photon flux.](image)

**Figure 7.** The best fit to the combined Ginga and ROSAT spectra that samples the dip (phase 0.0). The model employed consists of a soft blackbody component, a bremsstrahlung source and an iron line, subject to partial covering effects.

<table>
<thead>
<tr>
<th>Phase bin</th>
<th>$A_{BB}$ ($1 \times 10^{-3}$)</th>
<th>$A_{TB}$ ($10^{52} \text{ cm}^{-2}$)</th>
<th>$n_H$ ($10^{20} \text{ cm}^{-2}$)</th>
<th>Covering fraction</th>
<th>2–10 keV flux ($10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>687_{-613}^{+727}</td>
<td>1.71_{-1.61}^{+1.82}</td>
<td>8.4_{-0.6}^{+1.6}</td>
<td>0.55_{-0.51}^{+0.60}</td>
<td>1.9</td>
</tr>
<tr>
<td>Secondary max.</td>
<td>679_{-611}^{+733}</td>
<td>2.03_{-0.93}^{+1.15}</td>
<td>7.2_{-0.9}^{+1.6}</td>
<td>0.58_{-0.21}^{+0.22}</td>
<td>2.2</td>
</tr>
<tr>
<td>Dip</td>
<td>2168_{-196}^{+247}</td>
<td>2.19_{-0.73}^{+2.64}</td>
<td>13.6_{-1.3}^{+3.3}</td>
<td>0.81_{-0.78}^{+0.84}</td>
<td>1.9</td>
</tr>
<tr>
<td>Primary max.</td>
<td>2739_{-255}^{+277}</td>
<td>2.42_{-0.61}^{+2.52}</td>
<td>10.3_{-0.6}^{+3.2}</td>
<td>0.64_{-0.61}^{+0.66}</td>
<td>2.5</td>
</tr>
</tbody>
</table>

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5 DISCUSSION

The ROSAT observation presented here, together with our re-examination of the previous Ginga data, has exposed diagnostically important X-ray properties in this currently unique binary. In this section we consider the implications of these results. Before discussing these further, however, we briefly summarize the principal results.

(i) For the first time in an Intermediate Polar, the 0.1–2.5 keV (PSPC) band flux is shown to be dominated by a powerful, soft X-ray spectral component which, if characterized by a blackbody spectrum, has a temperature in the range 23–58 eV.

(ii) The rotational light curve of this component is most readily decomposed into a high-amplitude (∼80 per cent) modulation, similar to but more peaked than a sine wave, and a dip possessing a deep, narrow core, which punctuates the ascending phase of the underlying modulation, occurring about 0.15 in phase prior to flux maximum.

(iii) The complete Ginga data set confirms the basic properties of the subset presented in Ma92. The 13.9-min light curve of the hard (10–20 keV) band can be described by a broadly sinusoidal variation, but, as one moves to softer (2–10 keV) energies, an additional dip feature, super-imposed on the ascending phase of the curve, becomes increasingly prominent. The breadth of the maximum in the underlying modulation also appears to increase with decreasing energy, leaving only a rather narrow minimum (ϕ = 0.55) in the softest Ginga band and no obvious dip at all in the 0.6–2 keV (PSPC) band. This phenomenon might, however, also reflect the presence of a soft, secondary maximum that occurs just prior to the dip.

(iv) Spectral analyses of the separate ROSAT and Ginga data sets indicate that disparate columns apparently affect the data in each band. With the assumption that the data from the two instruments can be combined, the rotationally phase-resolved spectra can be reconciled by invoking a partial covering model. On this basis, the dip can be characterized primarily by an increase in the fraction of the source that is covered by the denser absorbing component. The general rotational modulation, on the other hand, is governed principally by the normalization of each spectral component, changes of which are most readily interpreted in terms of variations in the emitting volume of the hard component and of the projected emitting surface area for the soft component.

Throughout this section, we assume that the 13.9-min period represents the rotation period of the white dwarf in RE 0751 + 14. Evidence that this is the case appears overwhelming. The dominant periodic behaviour at X-ray, optical and infrared wavelengths and in the circular polarization all occur on a 13.9-min time-scale (Ma92; RMH; Pirola et al. 1993). Radial velocity motion is also present on this time-scale (RMH). The expected negative sideband beat period has also been convincingly detected in blue optical light, with a period of 14.53 min (RMH), a claim consistent with the fact that the orbital period appears to be near 5.2 h (Mittaz, private communication; Hellier, private communication).

We also point out that RE 0751 + 14 is likely to be a disc accretor. This hypothesis is supported both by the rather tight limit on the presence of any beat period X-ray modulation in the Ginga band (see, for example, Wynn & King 1992) and by theoretical arguments (e.g. Hameury, King & Lasota 1986) which indicate that a partial disc is permitted within a binary whose period exceeds 5 h, even when the primary possesses a strong magnetic field, B < 10^7 G, as may be implied by polarization measurements (Pirola, Hakala & Coyne 1993).

5.1 The soft component

The suggestion that RE 0751 + 14 might possess a strong soft X-ray component was first advanced by Ma92, based on the large S1/S2 WFC filter ratio measured from the ROSAT WFC survey scans of the star. Our more detailed PSPC spectral study has demonstrated conclusively, for the first time in an IP, that such a component is indeed present in RE 0751 + 14. It seems unlikely, however, that a soft component with a temperature similar to that in RE 0751 + 14 is present in other IPs. The S1/S2 ratio of EX Hya, the only other IP detected in the WFC survey, does not point to a luminous soft emission region in that star. For the remaining IP systems, whilst the work of Norton & Watson (1989) and Ishida (1991) indicate that partial covering models provide the best description of the EXOSAT and Ginga data respectively, suggesting that some flux from any putative soft component could leak out, the inclusion of EXOSAT CMA filter constraints by Norton & Watson (1989) reveals no evidence for a substantial soft flux in any of them.

The allowed range for the temperature (∼23–58 eV) of the soft emission in RE 0751 + 14 neatly encompasses the range of more tightly constrained measurements amongst the known AM Her stars (e.g. ∼20 eV in QQ Vul, Osborne et al. 1986; ∼60 eV in Ek UMa, Clayton & Osborne 1994; see also Ramsay et al. 1994). In the synchronous AM Her systems, phase locking and the domination of the accretion flow by the strong (∼10^7 G) field ensures that accretion occurs on to a relatively small region that is essentially fixed (on short time-scales) on the stellar surface. Here, a strong shock may form just above the surface. The soft component in AM Her systems is thought to arise in two ways. First, if the flow is largely homogeneous, the reprocessing of the hard X-ray flux from the post-shock column by the atmosphere of
the white dwarf is the likely origin. This predicts a rough balance between the fluxes of the soft and hard X-ray components (see, for example, Cropper 1990 and references therein). Several AM Her stars, however, are known to possess large soft/hard component flux ratios (e.g. Ramsay et al. 1994). The second explanation, currently favoured for these latter systems in particular, involves predominantly blob-like accretion (e.g. Kuipers & Pringle 1982; Litchfield & King 1990) in which the infalling blobs penetrate and deposit their accretion energy directly into the white dwarf's atmosphere, where it is thermalized and, as in the hard X-ray illumination scenario, re-emerges as a soft X-ray component. This model can, at least qualitatively, explain the enhanced soft X-ray flux seen in some systems.

By analogy with the AM Her stars, we associate the soft components in RE 0751 + 14 with a heated, optically thick surface emission region and the hard component with post-shock column emission. If, as in Section 4.2.3, we assume that the Ginga and ROSAT data from RE 0751 + 14 can indeed be combined (i.e. the system was in the same state at the epoch of each observation), we are then able to compare the flux ratios of the soft and hard components in this star. Estimates of the intrinsic (i.e. unabsorbed) bolometric fluxes for the two components in RE 0751 + 14 were derived from the best-fitting blackbody plus bremsstrahlung model applied to the ROSAT + Ginga spectrum around the 13.9-min flux maximum. This yields soft and hard component bolometric fluxes (with the respective temperatures fixed at 51 and 20 keV) of $\sim 1.9 \times 10^{-10}$ and $0.87 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$, i.e. a soft/hard flux ratio $\lesssim 2.2$ – this ratio comes down to 1.5 if the temperatures are fitted. Based on fluxes computed at the 99 per cent limits of the model parameters, the largest flux ratio we obtain is 5.2. We point out, however, that there is an additional factor of $1/\cos \theta$ to be applied to the soft component flux (where $\theta$ is the angle between the normal through the emission region and the line of sight) since this is optically thick emission and projection effects are important. Nevertheless, by taking the measurement from the bright phase when the pole probably tilts towards the observer (see Section 5.2), this correction is minimized. Thus there seems to be no clear evidence in RE 0751 + 14 for the implied large imbalance between the soft and hard components that is apparent in some AM Her stars. Such a conclusion may indicate that accretion in RE 0751 + 14 occurs predominantly via a homogeneous flow, a view consistent with our belief that accretion occurs via a truncated disc in RE 0751 + 14 – shearing forces at the disc/magnetosphere interface would probably act to produce a relatively smooth flow. This scenario is not incompatible with the implications of the partial covering model fits to the phase-resolved spectra since, as mentioned in Section 4.2.3, the same result can be effected by the combination of local and external (e.g. interstellar) columns.

5.2 The rotational light curve – the underlying variation

In Sections 3.3 and 3.4 we argued that the narrow dip feature seen in the Ginga and ROSAT rotational light curves probably arises from the same (phase-coincident) physical event. On this basis, we find no evidence for any significant variation of the phase of rotational flux maximum with energy at energies above 4 keV. This conclusion may apply to energies as low as 0.6 keV if the broadening of the secondary maximum around phase 0.6−0.8 is attributed to a third component, rather than to the hard spectral component alone. There is marginal evidence that the rotational maximum of the soft component occurs later than that of the hard source. In IPs, the X-ray rotational modulation has generally been attributed to either absorption in the accretion flow (Rosen et al. 1988) or occultation of a large emission region (King & Shaviv 1984). In RE 0751 + 14, as pointed out by Ma92, we appear to be witnessing both processes. In this system, however, the effects of the two mechanisms appear distinct. For several reasons, we attribute the underlying, quasi-sinusoidal variation in RE 0751 + 14 to occultation effects, while the dip at phase 0.0 represents the effects of absorption in a curtain (see Section 5.3). First, we are unable to discern a significant change of the absorbing column between the bright ($\phi = 0.09\pm0.49$) and faint ($0.49\pm0.71$) intervals, which might lend credence to a standard curtain absorber interpretation for this component. In the conventional curtain picture, the minimum of the underlying modulation corresponds to a maximum in the intervening absorbing column. Indeed, if anything, the best-fitting values from the spectra of RE 0751 + 14 suggest a trend of increasing column in the bright phase, the opposite of what is expected in the curtain model. What does vary significantly, however, is the normalization, which peaks for both components during the bright phase and reaches a minimum around the trough of the cycle, indicating that the visibility of the emission site(s) is an important factor. Finally, the presence of the variation at energies above 6 keV demands either occultation or electron scattering as a cause. Each of these aspects suggests that, in RE 0751 + 14 at least, the quasi-sinusoidal component of the rotational modulation is due primarily to occultation effects.

Using the ephemerides of Section 3.4, we can relate the Ginga (and, by inference, the PSPC) light curves to the K-band light curve presented in Ma92. Using equation (3), we find that the X-ray maximum occurs at phase $0.98\pm0.02$ with respect to the maximum of the sinusoidal envelope representing the K-band profile. The ephemerides of equations (1) and (2) yield corresponding phases of $0.84\pm0.06$ and $0.72\pm0.02$, respectively. If the X-ray variation is due to occultation effects, the first case would at least be consistent with the hypothesis that the double-peaked red/IR band rotational light curves are due to cyclotron beaming (a possibility suggested by RMH), since both phenomena indicate that the accreting pole is inclined towards the observer at this time (though see Pirola et al. 1993).

Finally, we return to the issue of the non-sinusoidal nature of the hard PSPC and soft Ginga band light curves. This is manifested by the appearance of the secondary maximum at phase 0.8 in the 2–4 keV band, which appears partially to fill in the minimum at phase 0.55 in this band, and may explain the absence of a significant minimum at this point in the 0.6–2 keV band. The energy dependence of the narrow dip (phase 0.0) ought to have the opposite effect on an underlying sine-like variation to that observed, i.e. flux in the pre-dip maximum at phase 0.8 should be increasingly suppressed at lower energies. The increasing prominence of this maximum at low energies invites two plausible explanations. First, there may be a third emission component which
contributes at phases ~0.6–0.8, whose spectral distribution is rather softer than the hard component. The lack of a strong peak at phase 0.8 in the soft PSPC band from this component is not inconsistent with this picture. If its 0.1–0.5 keV band flux is comparable to that in the 0.6–2 keV band, it would account for only about 20 per cent of the total flux in the soft band at that phase. Moreover, such a third component may suffer intrinsic absorption which could diminish its contribution to the 0.1–0.5 keV band. This third emission component, however, must be tied to the rotation of the white dwarf – it could not, for example, be associated with a stream/magnetospheric impact region. A physical origin for this source is unclear, although a second pole, not diametrically opposite the main pole, is a possibility. The existence of a second pole in RE 0751+14 was raised by Piirola et al. (1993), based on their discovery that the circular polarization changes sign during the rotation cycle. Current uncertainties in the rotational ephemerides, however, mean that we are unable to relate securely the phasing of the X-ray and polarization variations. The alternative scenario is that the underlying modulation at low (<6 keV) energies arises from the low-energy tail of the hard bremsstrahlung component and is intrinsically non-sinusoidal. This might arise, for example, from a spatially extended emission region that is not isothermal, for example in which the leading part is rather softer than the trailing area. In this case, however, one might naively expect the leading region to be surrounded by a local surface emission zone whose flux would contribute to the soft PSPC band at similar phases, producing a crudely similar soft band light curve to that in the hard PSPC band.

5.3 Constraints on the origin of the dip

The identification of the origin of the dip at phase 0.0 is particularly important. This feature appears phase stable, but apparently variable in amplitude given its disappearance in the last two cycles covered by ROSAT. We have shown that the spectral changes manifested through this event can be represented primarily via changes in the fraction of the emitting source that is occulted by the dense component of the absorbing medium. During the dip, the mean column density inferred for the dense material is \( \sim 11–16 \times 10^{22} \) cm\(^{-2}\), and the covering fraction for this component is \( \sim 80 \) per cent, compared to other phases when the emission can be modelled as having a slightly lower column density and a covering fraction of around 60 per cent (see Section 4.2.3).

We emphasize again, however, that an apparent variation in the covered fraction could also arise if the line-of-sight column density is changing rapidly within the spectral phase bin containing the dip.

A puzzling aspect of the dip is its phasing relative to the underlying modulation. It arises roughly 0.15 ahead of flux maximum, implying that the obscuring medium leads the emission region by about 50°. In RE 0751+14, we suspect a disc is present. This means that, unlike in AM Her stars, material is available to the magnetosphere at all azimuthal locations. Thus, to explain a stream-like entity rotating with the field would require that material is accepted into the magnetosphere over only a rather restricted azimuthal range. We must be careful here, however, because, although the core width of the absorption feature is only \( \sim 0.1–0.2 \) in phase, the dip possesses broader wings which, in total, may span a phase interval of up to 0.4, indicating that the absorber subtends a large solid angle to the source. This could arise because the accretion flow is azimuthally extended, i.e. an accretion curtain, in which case the narrow core probably reflects an enhancement in the azimuthal density profile. Alternatively, if the pointing direction of the emission region remains close to the line of sight during the rotation cycle, the absorption could be taking place much closer to the emission site. It seems unlikely, however, that a small variation of the viewing angle with rotation phase could account for the large modulation amplitude of the soft component.

6 CONCLUSIONS

We have presented ROSAT pointed observations and re-examined the Ginga observations of the exceptional intermediate polar system RE 0751+14. We find unambiguous evidence for a soft spectral component in this star with a temperature in the range 23–58 keV, similar to that witnessed in the AM Her stars. By analogy with AM Her stars, this soft component most probably arises from a heated surface region at the footprints of the accretion flow. The light curve is strongly modulated and displays a dip possessing a deep, narrow core on the ascending side, which is probably caused by absorption as magnetically funnelled accreting material rotates through the line of sight to the X-ray emission region. A separate hard component is associated with the post-shock flow near the surface. The overall modulations of both components are broadly in phase. Spectral analysis indicates that the underlying modulation arises from occultation effects rather than absorption. We find no strong evidence for a large ratio of the soft to hard component fluxes.

These results confirm that RE 0751+14 is a highly unusual IP, exhibiting properties of both IPs and polars. Increasing evidence suggests that it inhabits a previously uncharted region of physical parameter space between these two subclasses. RE 0751+14 may well be an example of the long-sought-after, long-period progenitors of the AM Her systems that are required in most evolutionary scenarios (e.g. King 1993).

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