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LETTER TO THE EDITOR

Multi-Phase *Suzaku* Study of X-rays from β Lyrae

R. Ignace[1], L. M. Oskinova[2], W. L. Waldron[3], J. L. Hoffman[⋆3,4], and W.-R. Hamann[2]

[1] Department of Physics, Astronomy, & Geology, East Tennessee State University, Johnson City, TN 37614
[2] Lehrstuhl Astrophysik der Universität Potsdam, Am Neuen Palais 10, D-14469 Potsdam, Germany
[3] Eureka Scientific, Inc., 2452 Delmer Street Suite 100, Oakland, CA 94602-3017
[4] Department of Astronomy, UC Berkeley, 601 Campbell Hall, Berkeley, CA 94530

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ABSTRACT

Aims. We report on *Suzaku observations of the eclipsing and interacting binary β Lyrae. This system involves an early B star (possibly B0 V, the "Gainer" star) embedded in an optically and geometrically thick disk that is siphoning atmospheric gases from a less massive late B8 II star companion (the "Loser" star).*
Methods. Motivated by an unpublished X-ray spectrum from Einstein suggesting unusually hard emission, we obtained time with Suzaku for pointings at three different phases within a single orbit.
Results. From the XIS detectors, the softer X-ray emission appears typical of an early type star. What is surprising is the remarkably unchanging character of this emission, both in amount and in spectral shape, despite the highly asymmetric geometry of the system. We see no eclipse effect below 10 keV. On the other hand, the hard emission from 10–60 keV shows a declining power law spectrum in which we do appear to have captured an eclipse with one of the pointings. The hard emission drops down to the background level, suggesting a complete eclipse. Our preliminary interpretation is that the constancy of the soft emission is related to the gainer, and the eclipse seen in the hard emission is related to a "hot spot" in the disk owing to the accretion stream from the loser.

Key words. binaries: close – binaries: eclipsing – stars: β Lyrae – X-rays: binaries

1. Introduction

The binary β Lyr is a nearly edge-on, semi-detached interacting system that has undergone mass reversal and remains in a phase of large-scale mass transfer. The primary, mass-losing star (the "Loser") is a B6-B8 IIp star. The mass-gaining star (the "Gainer") is embedded in an optically thick accretion disk and is not directly visible. Although the embedded source had been considered as a possible compact object (Stothers & Lucy 1972), it is probably a main sequence B0 star (Hubeny & Plavec 1991). The system is very complex, having bipolar jet-like structures (Harmanec et al. 1996; Hoffman et al. 1998), a circumbinary envelope (Batten & Sahade 1973; Hack et al. 1975), and a substantial kilo-Gauss magnetic field (Leone et al. 2003).

The optical light curve of the system features a primary minimum that is $\approx$ 1 magnitude deep and a secondary minimum $\approx$ 0.4 magnitudes deep (see Fig. 1); however, the secondary minimum is deeper than the primary minimum at shorter wavelengths, and below Lyα the eclipses no longer appear (Kondo et al. 1994). A summary of the system properties is given in Table 1. The orbital period is 12.9 days, and light curves appear stable with epoch. The UV spectrum of β Lyr is dominated by an anomalous continuum and emission lines with unusually strong P Cygni profiles typical of hot star winds (Hack et al. 1975; Aydin et al. 1988; Mazzali 1987).

Despite numerous and ongoing modeling attempts (e.g., Wilson 1974; Linnell & Hubeny 1996; Linnell 2002; Nazarenko & Glazunova 2003, 2006ab), no model is yet capable of matching the observed light curves of β Lyr from the IR through the UV. Strangely, β Lyr has been largely unstudied in the X-ray regime, despite the strong X-ray flux detected by the *ROSAT* HRI (Berghöfer & Schmitt 1994). An unpublished spectrum taken with the *EINSTEIN*/SSS in 1979 reveals X-ray emission at high energies, suggesting that phase-dependent observations may provide new clues to resolving the puzzle of the β Lyr geometry and interactions. Exploiting its excellent sensitivity to hard X-rays, we were awarded time with *Suzaku* to study this system with three pointed observations within the same orbit. In the following section the observations and reduction of data are detailed. Analyses of the spectra with phase are described in §3, and a discussion of the results is presented in §4.

Table 1. Properties of β Lyrae

Component	Gainer	Loser
$T_{\rm eff}$[K]	32,000	13,300
Spectral Type	≈B0 V	B6-8 IIp
$M/M_\odot$	≈13	≈3
$\dot{M}^a[M_\odot\ {\rm yr}^{-1}]$	4.7×10^{-8}	7.2×10^{-7}
v_∞^a[km s$^-$1]	1470	390

System Property	Value
Orbital Period	12.9 days
Binary Separation	$55 - 60 R_\odot$
Distance	270 pc
$\log N_H$ (cm^{-2})	20.76
ROSAT PSPC:	0.07 cps
Einstein SSS:	0.11 cps

[a] Mass-loss and terminal speed for the stellar winds of the respective binary components.

Send offprint requests to: R. Ignace, e-mail: ignace@etsu.edu
⋆ NSF Astronomy and Astrophysics Postdoctoral Fellow

2. Observations and Data Reduction

The joint Japan/US X-ray astronomy satellite, *Suzaku* (Mitsuda et al. 2007), observed β Lyr in May 2006 on three occasions at orbital phases as shown in Fig. 1, with corresponding viewing perspectives of the β Lyr system illustrated in Fig. 2. (Note that the primary minimum occurs when the giant star is eclipsed, and the secondary minimum when the disk component is eclipsed.) The pointings were spaced approximately 4.3 days apart to sample the orbit of the binary. Exposure times and count rates are tabulated in Table 2.

Suzaku carries four X-ray Imaging Spectrometers (XIS; Koyama et al. 2007) and a collimated Hard X-ray Detector (HXD; Takahashi et al. 2007). The field-of-view (FOV) for the XIS detectors is $17' \times 17'$. One of the XIS detectors (XIS1) is back-side illuminated (BI) and the other three (XIS0, XIS2, and XIS3) are front-side illuminated (FI). The bandpasses are $\sim 0.4 - 12$ keV for the FI detectors and $\sim 0.2 - 12$ keV for the BI detector. The BI CCD has higher effective area at low energies, however its background level across the entire bandpass is higher compared to the FI CCDs.

The angular resolution of the X-ray telescope onboard *Suzaku* is $\approx 2'$. Therefore in the XIS image, β Lyr is not resolved from two nearby B-type stars: HD 174664 (β Lyr B) and HD 174639. While the latter star was not detected by *ROSAT*, the former one has a *ROSAT* HRI count rate of 4×10^{-3} cps, as compared to the β Lyr *ROSAT* HRI count rate 4×10^{-2} cps. We are confident that the X-ray flux detected by *Suzaku* is at least $\approx 90\%$ dominated by β Lyr.

The HXD consists of two non-imaging instruments (the PIN and GSO, see Takahashi et al. 2007) with bandpasses of $\sim 10 - 70$ keV (PIN) and $\sim 40 - 600$ keV (GSO), and a FOV of $34' \times 34'$ (PIN). Both of the HXD instruments are background-limited. The background subtraction for the HXD is performed by modeling the background spectrum. Presently, the non-X-ray background model (e.g., particle events) is known for the PIN detector with $\sim$ 3-5% accuracy (Kokubun et al. 2007). In this paper we do not report on GSO measurements of β Lyr because the background modeling is currently far less certain. Note that passages of the spacecraft through the South Atlantic Anomaly (SAA) influence the HXD background (see Kokubun et al. 2007); however, our observations of β Lyr were performed when the background count-rate associated with the SAA was lowest.

HXD-PIN data reduction and extraction of spectra were performed using the latest calibration sources and background models. We account for cosmic X-ray background (CXB) in fitting the spectral models using the procedure suggested by the *Suzaku* team based on a "typical" CXB spectrum (see *Suzaku*'s website).

Based on the Rosat All-Sky Survey (RASS), there are a few X-ray sources in the $34' \times 34'$ PIN's FOV centered on β Lyr; however, our target β Lyr A is by far the brightest. The stellar coronal X-ray sources present in the FOV are expected to be faint in the HXD's energy range. There is an AGN – QSO B1847+3330 – that is located about 15′ away from β Lyr. This AGN is cataloged in the RASS with a count-rate of 0.05 cps. To estimate its potential contribution to the $10 - 70$ keV energy range, we adopted a standard AGN power-law spectrum with $\Gamma = 2$ and a low interstellar absorption column of $N_{\rm H} = 5 \times 10^{20}$ cm^{-2}. The predicted count-rate for the *Suzaku* PIN is ≈ 0.006 cps. The observed non-X-ray background subtracted HXD-PIN count-rates are listed in Table 2. The contribution of QSO B1847+3330 is between 10–30% of the detected flux.

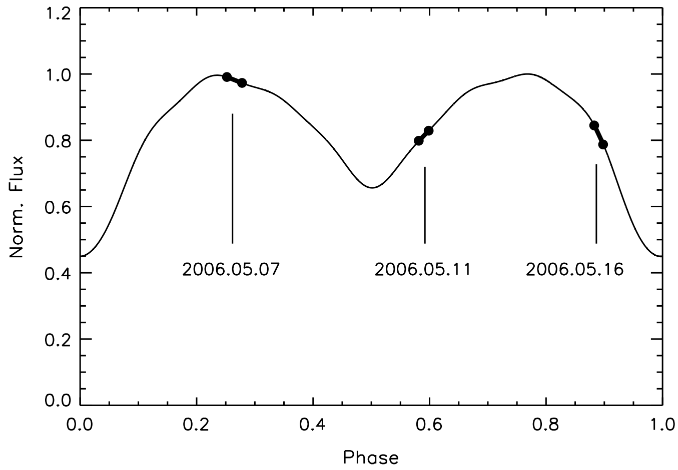

Fig. 1. Illustration of the Suzaku pointings with respect to the binary phase. The solid line represents the normalized V-band light curve (Fourier fit by Harmanec et al. 1996), where phase 0.0 corresponds to the eclipse of the loser by the gainer + disk component. The three intervals marked on the curve represent our Suzaku pointings, which occurred during a single orbit in May 2006. Phases were calculated from the quadratic ephemeris of Harmanec & Scholz (1993).

3. Analysis

3.1. Soft X-rays

A visual comparison of spectra below 10 keV with the XIS detectors indicates very little variability with phase (see Fig. 3). Based on chi-square model fits to the data, there is no evidence for statistically significant differences between the three spectra. For illustration a model fit for the $\varphi = 0.89$ pointing appears as the solid histogram in all three panels of Fig. 3. Independent fits to the pointings are all very similar. Note that in the modeling of these spectra, solar abundances were adopted except that N was enhanced by a factor of 5 to achieve an adequate fit.

These XIS X-ray spectra are fairly soft and most probably thermal in nature, since emission lines are detected at 1.35 keV (Mg XI) and 1.86 keV (Si XIII). The model fits indicate a two-component model with the majority of the XIS X-ray emission arising from a temperature of ≈ 7.2 MK and a hotter but much weaker component of $\gtrsim 20$ MK.

3.2. Hard X-rays

Curiously, the X-ray emission above 10 keV *does* show variability. Although the counts are lower than those of the XIS detector, the signal-to-noise is relatively high, and Fig. 4 reveals a power-law spectrum at each of the three pointings. However, the pointing for $\varphi = 0.59$ shows a substantial drop in brightness. There are three key points to be made about these data.

1. The count rates for phases $\varphi = 0.26$ and 0.89 are essentially equal, but at $\varphi = 0.59$ the count rate drops by nearly an order of magnitude down to that of the CXB. Given the perspective of Fig. 2, it seems consistent to claim that this drop in brightness might be associated with the eclipse of a "hot spot". Such a spot would presumably be formed by the accreting stream from the loser entering the disk of the gainer.
2. Continuing with this suggestion, we would not expect to see an eclipse at phase 0.26 because the spot would be in the forefront of the system, as shown in Fig. 2.

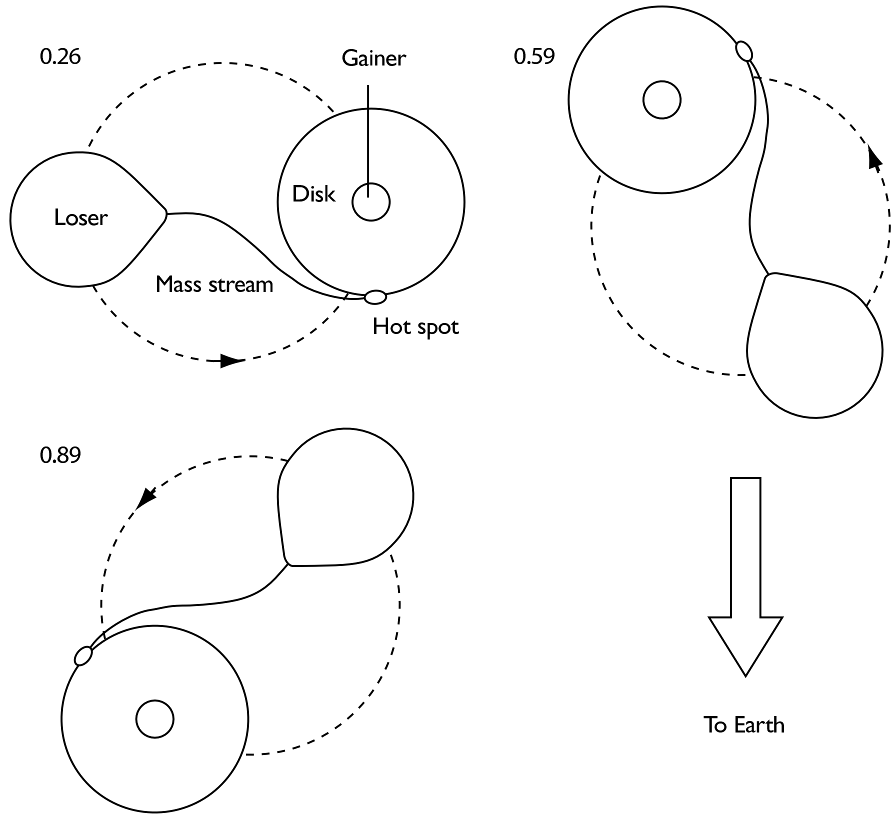

Fig. 2. Graphic topview representation of the β Lyr star-disk system, following the model of Hoffman et al. (1998). Components are illustrative and not to scale. The three *Suzaku* pointings occurred at phases $\varphi = 0.26$, 0.59, and 0.89 all within the same orbit. The large arrow indicate the direction to the Earth.

3. At $\varphi = 0.89$, one might expect some eclipse effect of a hot spot owing to the disk, but this would depend on the absorbing column of the disk. Taking an inner disk number density of $n_0 \sim 10^{14}$ cm^{-3}, a disk radius of $30R_\odot$, and a conservative density distribution of r^{-1}, the radial column density becomes $N \approx 2\times10^{25}$ cm^{-2}. However at $\varphi = 0.89$, the sightline traces only a chord through the outer disk, in which case the column density drops to around 10^{24} cm^{-2}. This is a rough upper limit since the disk is not viewed exactly edge-on. It is also approximately the column density needed for absorption to be important at energies above 10 keV, and indeed there is the suggestion from the data at this phase of a turnover in the power-law counts between about 10–13 keV. Thus the observation at phase 0.89 also appears consistent with a hot-spot eclipse model.

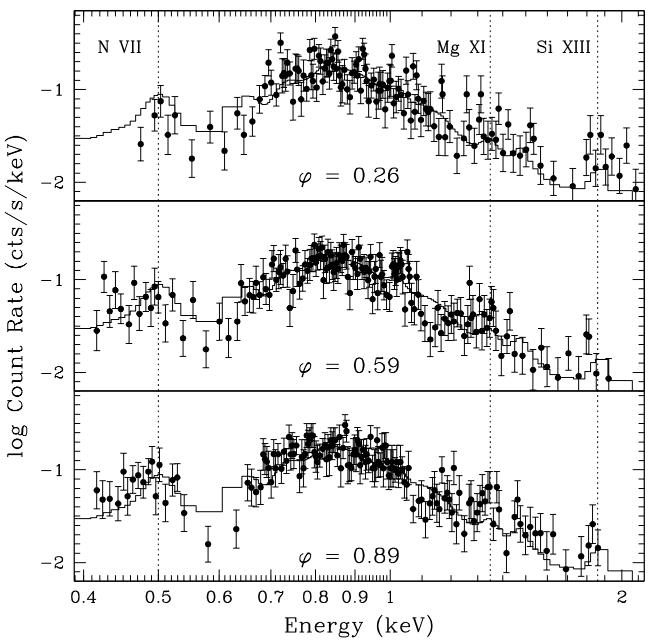

Fig. 3. Spectra of β Lyr from the XIS1 detector for each pointing. Phase within the orbit is indicated in each panel. The data are of reasonably high signal-to-noise, and it is clear that the spectral distribution shows little change with phase, being of nearly constant brightness and spectral shape. The solid histogram is a model fit to the data of $\varphi = 0.89$ that is replotted in the other phases for comparison.

4. Discussion

The results of our *Suzaku* study are both revealing and perplexing. We had expected to see an eclipse of soft X-rays and essentially no hard emission. Instead, we found that the soft X-rays were nearly constant, and that the power-law hard X-ray spectrum showed an eclipse at one phase that seems consistent with a disk/hot-spot phenomenology.

The lack of variability at soft energies is truly surprising. The system is seen near to edge-on. The disk is around $12R_\odot$ in total vertical extension at its outer rim, whereas the giant star companion is about twice this in its diameter. Consequently, the failure to observe any eclipse of the soft X-rays indicates that this emission must come from a relatively large volume, as compared to the size of the star and disk components, and either the soft source is always in eclipse or never in eclipse for our viewing perspective. The spectral characteristics appear compatible with the expectations of a typical early main sequence B star, plus the X-ray luminosity in the XIS band $L_X(\mathrm{XIS}) \approx 6.6 \times 10^{30}$ erg s^{-1} is rather typical of the soft

Table 2. *Suzaku* Observations of β Lyrae

ObsID	φ^a	Exposure (ksec)		Count rate (10^2 cps)					XIS1 Flux	PIN Flux
		(XIS)	(HRD)	XIS0	XIS1	XIS2	XIS3	HXD	(erg/cm^2/s)	(erg/cm^2/s)
401036010	0.26	15.4	14.6	6.35 ± 0.24	8.53 ± 0.36	6.33 ± 0.24	5.15 ± 0.22	17.2 ± 0.67	7.5×10^{-13}	9.2×10^{-11}
401036020	0.59	17.7	16.9	5.76 ± 0.21	8.14 ± 0.33	5.56 ± 0.21	4.86 ± 0.20	1.94 ± 0.57	6.0×10^{-13}	1.1×10^{-11}
401036030	0.89	15.7	14.1	6.15 ± 0.23	9.58 ± 0.36	6.23 ± 0.22	4.93 ± 0.22	12.14 ± 0.66	7.6×10^{-13}	9.0×10^{-11}

^{a} Orbital phase of β Lyr a the midpoint of each observation, were calculated with the quadratic ephemeris of Harmanec & Scholz (1993).

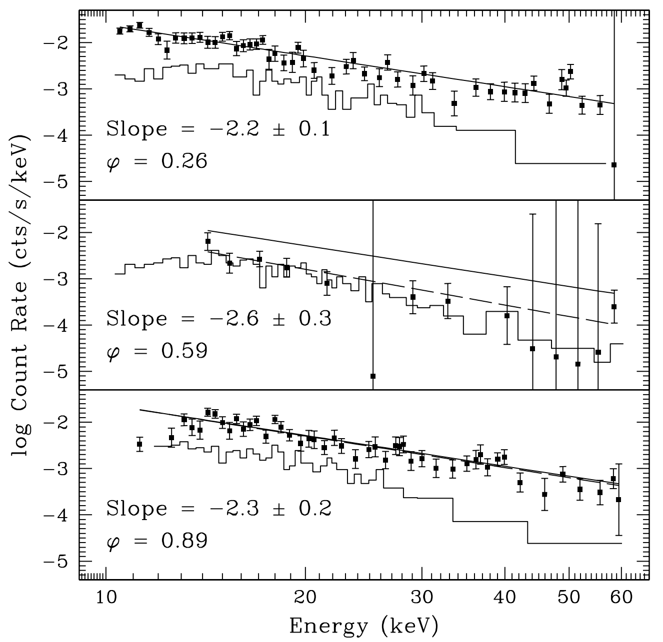

Fig. 4. As in Fig. 3, but for the PIN detector between 10 and 60 keV. The solid line in each panel is a power-law fit to the $\varphi = 0.26$ data, shown here for reference. Dashed lines and slope values represent fits to the data at the respective phases. We associate the drop in brightness by a factor of 10 at $\varphi = 0.59$ with an eclipse of a disk hot spot. The histograms represent the spectra of the cosmic X-ray background (CXB) at each phase. At phase 0.59, the observed counts are consistent with the CXB.

emission expected from an early B star (e.g., Cohen, Cassinelli, & MacFarlane 1997). We know from the polarimetric study of Hoffman et al. (1998) that there is substantial scattering opacity in the system, above and below the disk. We suggest that the near constancy of the X-rays seen with the XIS is the result of a kind of extended “halo”. The soft X-rays originate in the shocked wind of the early gainer star. Part of the emission is observed directly from hot plasma at large radii in the wind. Some of the X-rays generated at inner radii of the wind can be scattered into our line-of-sight from above and below the disk.

The hard emission is also not easy to understand, but for different reasons. The luminosity of the hard PIN emission is $L_X(\mathrm{PIN}) \approx 8.1 \times 10^{32}$ erg s^{-1} out of eclipse. This is two orders of magnitude higher than the soft component. Although we have not attempted a detailed discussion for the production of this X-ray emission, a topic beyond the scope of this report, we can consider the overall energy budget. We are supposing that the hard X-rays arise from a hot spot created by the accretion stream feeding the disk. The mass accretion rate is about $2 \times 10^{-5} M_\odot$ yr^{-1} (Harmanec 2002). If this stream is moving at around 300 km s^{-1}, then the mechanical luminosity of the accretion flow is $L_{\mathrm{Mech}} \approx 6 \times 10^{35}$ erg s^{-1}. This is more than enough to account for the energy budget of the hard emission. It does imply a conversion efficiency of around 0.1% to transform the mechanical luminosity into X-ray emissions above 10 keV. (Note that if the soft component arises from shocks in the gainer wind, a similar level of efficiency is required to convert the wind mechanical luminosity to X-ray emissions.) The origin of the power-law spectrum may relate to the strong kilo-Gauss level magnetic field of the system (Leone et al. 2003).

With the nature of the disk-embedded source still ambiguous, perhaps the X-ray properties of β Lyr could be understood in relation to a central compact object (as previously noted, a scenario suggested by Stothers & Lucy 1972). This seems rather unlikely; however, the X-ray observations certainly do not conform to our original expectations, and so at least a reconsideration of the possibility seems in order. Although the X-ray pointings by *Suzaku* offer the tantalizing promise of providing new and valuable information about the β Lyr system, it is clear that a far more rigorous sampling of the X-ray lightcurve and source spectrum and new models for the system will be needed to test the suppositions that we have put forth.

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