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" ROSAT Survey of Emission from Be Stars"

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The objective of the ROSAT study was to obtain PSPC observations of a group of bright, Be stars for which UV spectra could be obtained to ascertain the state of the strong stellar wind at the time of the ROSAT observation. Contrary to expectations prior to the launch of the ROSAT, Be stars as a group have turned out to have fewer x-ray detections than normal B stars of comparable spectral type (Meurs et al. 1993). The observations obtained under this program, which were heavily skewed toward stars with very active stellar winds and correspondingly dense circumstellar envelopes, and a history of at most short episodes of quiescence, proved to be no exception, with a firm detection for λ Eri, and a marginal detection for HD 63462 the only exception to the string of non-detections. The availability of IUE observations made at the time of the ROSAT ASS observation of π Aqr, together with optical spectropolarimetric observations of that star, made in support of Astro-1 WUPPE observations, has enabled us to address the question of the uniqueness of the flare event seen during the ROSAT observation of λ Eri.

$\underline{\lambda\ \text{Eri}}$: An IUE observation coordinated with a 30 ksec ROSAT PSPC observation of the mild B2e star, shows that this putatively single star emists at most times a soft X-Ray flux at a rate and temperature consistent with other B stars. However, during the middle of the observation, this star's X-ray flux increased by a factor of 6 before returning to its basal level. This brightening, due entirely to photon energies >0.7 keV, can be fitted well to a Raymond-Smith temperature parameter of 14 MK and luminosity 4×10^{31} erg s^{-1}; these are characteristic of giant stellar flares. With an estimated duration of 50,000s, this event is arguably the strongest X-ray flare yet observed. Several possible scenarios for the site of the flare, including several with an active cool secondary or degenerate companion were considered. We find that IUE and optical spectra do not support a binary picture, and that it is most probable that the flare site is on or related to λ Eri, itself. This supports other evidence for violent magnetic activity on some B-type stars. An ApJ Letter on this work has appeared.

$\underline{\pi\ \text{Aqr}}$: Analysis of IUE spectra and optical spectropolarimetry obtained around the time of the ROSAT All Sky Survey detection of the bright, putatively single Be star, π Aqr, indicates that the high velocity, stellar wind activity in this B1 III-IVe star is unrelated to the otpical polarization and to the Hα emission. From JD 24447800-24449000, the Hα emission has shown a steady decline, which is reflected in N V emission. The average optical polarization shows a gradual decline in basal polarization level, upon which are superposed short duration (t~150 days) polarization episodes similar to those reported for other bright, polarimetrically active Be stars. The column density of high density, moderately ionized circumstellar gas is apparently correlated with the optical polarization, and may represent a spectral detection of the electron scattering region. The ROSAT detection of π Aqr occured during an epoch of both minimal high density, moderately ionized gas column density, and low average optical polarization, ruling out an episode of enhanced mass transfer onto a compact companion as the source of the comparatively hard x-ray flux. Allowing for the higher T_{eff} of this star, which permits a strong, radiatively driven stellar wind to be detectable at all times, conditions in the circumstellar envelope were similar to those for λ Eri at the time of its ROSAT observation. Detection of log (L_X/L_{Bol}) intermediate between levels typical of normal OB stars and the X-ray flare seen on λ Eri, but 2 orders of magnitude below that characteristic of X-ray bright Be-binary systems, suggests that the ROSAT detection of π Aqr was made during a flare event. Collectively the data for Pi Aqr and Lambda Eri suggest that flaring may be comparatively common on Be stars during periods of ostensible quiescence. The data are interpreted in terms of the model of Bjorkman and Cassinelli (1993). A first draft of a paper summarizing this work has been completed, with the exception of model calculations. Submission to the ApJ is envisioned for the fall of 1993 and will be covered under NASA Grant NAS 5-2677 7 to the University of Wisconsin.

Publications:

Smith, M.A., Grady, C.A., Peters, G.J., and Feigelson, E.D. 1993," A Giant X-Ray Flare on λ Eri", ApJ 409, L49.

Bjorkman, K.S., Grady, C.A., Silvis, J.M.S., and Bjorkman, J.E. 1993 "The Circumstellar Envelope of π Aqr: Long Term Changes in Envelope Conditions and the ROSAT Detection", ApJ (in preparation).

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A GIANT X-RAY FLARE ON λ ERIDANI (B2e)

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ABSTRACT

A 30 ks observation with the *ROSAT* PSPC distributed over 39 hr shows that the putatively single, mild B2e star λ Eri emits at most times a soft X-ray flux at a rate and temperature consistent with other B stars. However, during the middle of our observations this star's X-ray flux increased by a factor of 6 before returning to the basal level. This brightening, due entirely to photon energies ≥ 0.7 keV, can be fitted well to a Raymond-Smith temperature parameter of 14 MK and luminosity 4×10^{31} ergs s^{-1}; these are characteristics of giant stellar flares. With an estimated duration of $\sim 50,000$ s, this event is arguably the strongest X-ray flare yet observed. We consider several possible scenarios for the site of the flare, including several with an active cool secondary or degenerate companion. We find that *IUE* and optical spectra do not support a binary picture and that it is most probable that the flare site is on or related to λ Eri itself. This supports other evidence for violent magnetic activity on some B-type stars.

Subject headings: stars: emission line, Be — stars: flare — stars: individual: λ Eridani

1. INTRODUCTION

The launching of X-ray satellites kindled the hope that classical early-type Be stars might show variable, strong X-ray emission that could clarify the mechanism behind their sporadic mass-loss episodes. However, with the exception of a class of hard and often pulsed X-ray emitters known as X-ray Be-neutron star binaries, this hope abated when it became apparent that on average Be stars exhibit an X-ray flux no higher than nonemission OB stars do. For example, the *ROSAT* All-Sky Survey now suggests that the detection rate of X-ray emitters among Be stars is no higher and may even be lower than for normal B V stars (Meurs et al. 1992), probably because of X-ray attenuation by Be disks. To date, the X-ray flux of only one classical Be star, γ Cas, has been monitored extensively. Indeed, this star is similar to Be-neutron star binaries in some respects (e.g., copious X-rays, "hot" temperature of ~ 100 MK, possible X-ray pulses [Frontera et al. 1986]) but not in others (e.g., optical thin plasmas, rapid flares; Murakami, Inoue, & Agrawal 1987; Peters 1982). Thus, it is still not clear whether the X-rays from γ Cas arise from true magnetic flares or from wind material falling into a shocked magnetosphere around a degenerate companion.

To detect unambiguously a varying X-ray flux intrinsic to a single Be star, we selected the mild B2e λ Eri for a pointed monitoring program with the *ROSAT* soft X-ray satellite. This star undergoes only occasional mild Be outbursts, permitting the star's surface to be visible most of the time, and it has a history of extensive optical line monitoring (e.g., Smith 1989). On some occasions following short-lived Hα emission episodes, orbiting rings of material are observed to fall back to the star. Their impact produces strong shocks and high temperatures (Smith, Peters, & Grady 1991). On most other occasions, λ Eri's spectrum shows no emission. Even during these periods its He I λ6678 line exhibits nearly continuous "transients" indicative of plasma disturbances over the star's surface. These disturbances must propagate at velocities $\sim 10^3$ km s^{-1} (Smith & Polidan 1993), velocities sufficient to produce X-rays if the motions are thermalized. To search for possible high-energy emissions from activity on this star, we requested *ROSAT* time with the Position Sensitive Proportion Counter (PSPC) detector.

2. DATA ANALYSIS

A detailed description of the *ROSAT* satellite, launched on 1990 June 1, are given by Truemper (1983) and Pfefferman et al. (1986). Among the first scheduled *ROSAT* guest observations, λ Eri was scheduled for 8 hr of on-target time. Although the *ROSAT* schedule was announced before we could arrange simultaneous ground-based observations at a cloud-free site, we were able to obtain one near-simultaneous *IUE* spectrum. In addition, ground-based observations were made intermittently during the 1990–1991 season. These indicate that λ Eri remained in an apparently dormant state during the *ROSAT* observations. Our program observations were made over 20–40 minute stretches during 13 orbits. These orbits were distributed in two blocks of time beginning at 1:58 UT on February 21 and ending at 17:16 UT on February 22. The total total integration time was 29,695 s.

The MPE *ROSAT* facility in Garching runs a package of Standard Analysis System Software (SASS) routines for all PSPC fields observed. The SASS data for our observations indicate that the PSPC detected 1325 raw events from an object located only 6" from the expected position of λ Eri. This offset is probably due to known boresight errors in the satellite aspect solution (*ROSAT* Project 1992). SASS identified this object with our target λ Eri. The "wobble" option was mistakenly turned off during the observations. However, a correction for the occasional obscuration of the source behind a member of the fine wire mesh of the detector window was made later using a response matrix. This correction brought the estimated number of actual counts to 1553. SASS also indicated that λ Eri is the only source in the field of view to show signifi-

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cant flux variations. These take the form of a significant brightening during our (nonconsecutive) orbits 3–8. The source showed no evidence of rapid variability.

We investigated the λ Eri detection in detail at Goddard HEASARC using several programs in the *ROSAT* IDL Library written by M. Corcoran and G. Reichert and using the MPE response matrix of 1992 March 11.

3. RESULTS

3.1. *Image Stability*

After examining the event arrival times and finding no rapid variability, we binned the events into orbital segments. Background counts were determined from a surrounding annulus out to 7′.5 and subtracted from the actual count rates; this correction amounts to a total of ~ 2 counts. The image contours for λ Eri appear featureless, circular, and do not change from orbit to orbit. The PSF of the images has a FWHM of 27″, consistent with the pre- and in-flight center of field PSFs found for the PSPC at 1 keV (Hasinger et al. 1992) at 1 keV. We found the centroid between pre- and postbrightening images to shift by $\sim 8''$. This minor positional discrepancy can be explained by larger positional errors associated with the pre/post brightening image folded in with the inherent uncertainties of repointing the telescope. Hence, one can be confident that the same source is responsible for both the "high" and "low state" fluxes.

3.2. *Soft X-Ray Luminosity and Time Variability*

Figure 1 shows the *ROSAT* light curve for λ Eri, corrected for background counts. The mean count rate of pre/postbrightening orbital segments (Nos. 1, 2, 8–13) is 45 ± 0.4 counts orbit^{-1}, or 0.0190 ± 0.0013 counts s^{-1}. The orbit-to-orbit errors are consistent with Poisson statistics, as are the means of the count rates before and after the flux brightening. The "low state" count rate corresponds to 9×10^{-14} ergs cm^{-2} s^{-1} over the interval 0.2–1 keV, assuming a $T \sim 2$ MK thermal plasma as described below. From our own T_{eff}, log g calibration of λ Eri and other B stars, and adopting a stellar

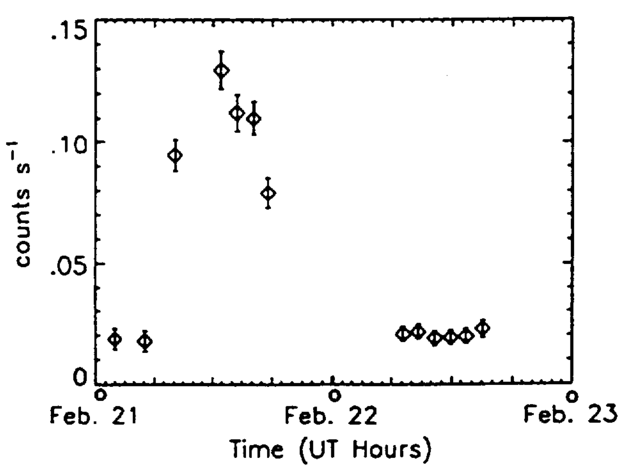

FIG. 1.—The *ROSAT* soft X-ray light curve for λ Eridani during 1991 February 21–22. The flux brightening during the middle of the run is the extended flare referred to in this paper.

mass of 10 $M_\odot$, we find $L_* = 6 \times 10^{37}$ ergs s^{-1} and a distance of 270 pc. These values lead to $L_x \sim 9 \times 10^{30}$ ergs s^{-1}, when corrected slightly for ISM extinction, and to $L_x/L_{Bol} = 1.8 \times 10^{-7}$. As this ratio is typical of emission from B/Be star (1×10^{-7}, Pallavicini et al. 1981; Meurs et al. 1992), we conclude that λ Eri's low X-ray flux state is its basal state, and that it is unremarkable for a B/Be star.

The brightening event reaches a peak soft *ROSAT* flux of 0.130 ± 0.02 counts s^{-1} (4×10^{31} ergs s^{-1}), or about an increase of 5.9 times above the low state value. The peak count rate, occurring during our fourth orbit, is marginally higher than rate during the following orbit. Figure 1 does not allow a comparison of rise (≤ 1 hr) and fall times. However, one can use the finding that λ Eri is observed nearly equator-on (Smith, Peters, & Grady 1991) and the sharpness of the light curve at maximum to conclude that this profile is unlikely to arise from rotational modulation of a constant X-ray source. In addition, current estimates of the rotational period of this star lie in the range 0.7–0.9 days. Thus, there is no remnant of the brightening during our last orbital segments one stellar rotational cycle later. For these reasons, it is appropriate to use the term "flare" to describe this event. Using an effective lifetime of $\sim 50{,}000$ s, the total energy output from this flare is a record 2×10^{36} ergs (see Montmerle et al. 1983).

3.3. *Spectra Distribution*

Because of their weak response, the four lowest-energy PSPC channels were excluded from our spectral analysis. Inspection of the remaining 30 channel histogram discloses that the excess flux from λ Eri's flare falls mainly above 0.7 keV. By contrast, the low-state counts are concentrated ≤ 0.5 keV. Thermal XANADU/XSPEC software models folded with the instrumental response show that the observed dichotomy in photon distribution is real and is not an artifact of the 0.6 keV dip in the PSPC's sensitivity.

Our data have a high enough SNR to significantly constrain two spectral parameters, but not the four parameters (T_{low}, T_{high}, N_H, and normalization) required for a two-temperature model (there were too few events in the nonflare state to permit a solution). As a result, we have had to rely upon separate information for the low temperature, its emission measure, and the attenuation unknowns. For this component, we adopt the estimate of a Raymond-Smith temperature of ~ 2 MK for λ Sco (Cassinelli et al. 1992), which is a B2 IV star with similar physical parameters to λ Eri. We have estimated an interstellar column density from the measurement of the interstellar Zn II $\lambda\lambda 2025$, 2062 line strengths in several UV spectra of λ Eri obtained from the *IUE* data archive. These lines suggest a value log $N_{Zn\,II} = 12.59 \pm 0.2$ cm^{-2}, or log $N_H = 20.1 \pm 0.3$ cm^{-2}, assuming a cosmic abundance of Zn. Our best multicomponent fit to the *ROSAT* spectrum for these parameters in log $N_H = 20.11 \pm 0.1$ cm^{-2} and $T_{low} = 0.29 \pm 0.1$.

Figure 2 shows the best fit to our spectral data during λ Eri's flare. The best-fit value for the hot component is 14 ± 1.2 MK. The associated reduced chi-squared value of this fit is 0.60, with 26 DOF. A power-law fit to $\alpha = 2.2$ gives nearly as good a fit. The corresponding emission measure (EM) derived for the hot plasma component is $2.8 \pm 0.3 \times 10^{53}$ cm^{-3}. The EM of the cooler component is $4.2 \pm 1.0 \times 10^{52}$ cm^{-3}. Thus, assuming similar densities both the volume and temperature of flare-emitting plasma are several times that seen in the quiescent component.

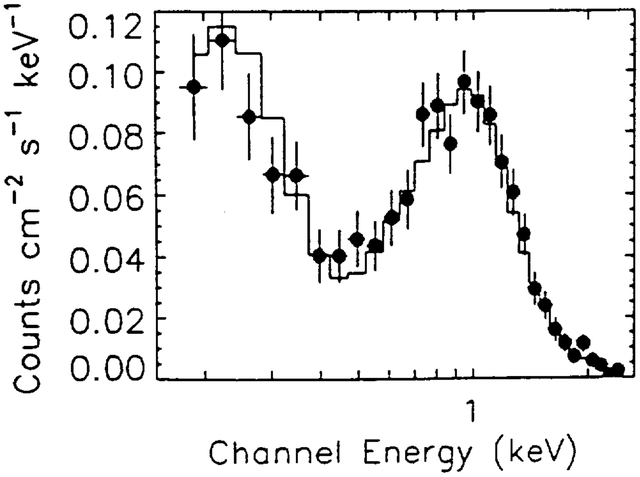

FIG. 2.—The X-ray flare spectrum fit to a Raymond-Smith temperature parameter of 14 MK, with an assumed cool component temperature of 2 MK and an interstellar gas column density of 1.3×10^{20} cm^{-2}.

4. INTERPRETATION

The different temperatures and emission measures computed by XANADU indicate that separate and probably unrelated mechanisms are probably responsible for the flare and basal X-ray emissions. Because the low flux agrees with levels found for other B/Be stars, we assume that it is emitted by the mechanism operative for virtually all OB stars, namely from shocks created from rapidly moving wind clumps overtaking slower moving inhomogeneities (e.g., Cooper & Owocki 1992). These shocks are thought to be localized and distributed throughout the wind. Rapid X-ray variability from these OB winds may be practically undetectable as individual shocks centers are constantly created and destroyed. In contrast, it may be possible to identify flare activity with optical/UV activity. For example, we notice that the EM for the flare is within an order of magnitude of that predicted for the plasma structures responsible for producing "dimples" in the optical He I lines (Smith & Polidan 1993). This coincidence is further reinforced by the nearly equal "duty cycle' of the X-ray flare as compared to dimples from optical observations, $\sim$40%.

Although it was our expectation, the detection of coronal plasma in a Be star is novel. Therefore, one must consider whether the observed flare might originate from a companion to λ Eri. Possible candidates include: a foreground star along the line of sight or from an active late-type or degenerate companion. The first possibility is already discounted by the stability of the source image during the observation.

Binary scenarios require λ Eri to have a nearby low-mass companion, whether it be noninteracting (dK-Me, T Tauri) or interacting (RS CVn, Algols, degenerate). Optical/UV spectroscopy provides considerable evidence against an interacting companion. λ Eri's rotational axis is believed to be nearly at right angles to our line of sight (Smith, Peters, & Grady 1991) and so favorably aligned for us to detect orbital variations. Nonetheless, intensive monitoring (Smith 1989; Bolton & Stenfl 1990) has failed to detect velocity variations above ± 8 km s^{-1}. This fact implies that a putative $\sim 1\ M_{\odot}$ secondary must have a period of ≥ 1 yr, which precludes Roche-lobe mass transfer. Moreover, λ Eri shows none of the UV spectral signatures associated with gas streaming in interacting Be stars. We consider in turn the likelihood of the X-ray flare associated with any of several possible active companions:

1. *dK-Me main sequence.*—In addition to their usual low-amplitude flickering, the dK-Me stars also exhibit true flares at levels $\leq 1 \times 10^{30}$ ergs s^{-1} on time scales of minutes to hours. The most extreme case is an X-ray flare from a Hyades GO/KO binary star, HD 27130 with a peak X-ray flux of $\sim 10^{31}$ ergs s^{-1}, a decay constant of $\sim$ 7 hr, and a total energy of $\geq 3 \times 10^{34}$ ergs (Stern, Underwood, & Antiochos 1983).

2. *Noninteracting T Tauri companion.*—The X-ray luminosity function of low-mass T Tauri stars measured with *ROSAT* indicates that a T Tauri companion of λ Eri would most likely have a quiescent X-ray level of $\sim 10^{28-29}$ ergs s^{-1} (Feigelson et al. 1993). A minority of T Tauri stars are seen at 10^{30} ergs s^{-1}, and a very few have been seen to flare up to 10^{31} ergs s^{-1}. Perhaps most sensationally, a flare in ROX-20, a late-type visual binary in the ρ Oph dark cloud complex, showed a maximum X-ray flux of $\geq 2 \times 10^{31}$ ergs s^{-1}, a decay time of <2 hr, a total energy of $\geq 8 \times 10^{35}$ ergs s^{-1}, and a temperature of 10 MK (Montmerle et al. 1983). Four giant X-ray events have been found among observations of nearly 200 pre-main-sequence stars; only $\sim$2% of T Tauri stars exhibit such flares during a given observation (Feigelson et al. 1991).

We can directly test for the presence of a late-type T Tauri companion by searching for lines from a hypothetical G-K star in three nightly-composites constructed from 46 individual KPNO echelle spectra we recently obtained of λ Eri. We used these composites, each with a SNR of 600–1000, to search for lines of a cool companion in the following manner. The best lines in our data set for the search of G-K star spectrum, Fe I λ4383.5, Mg I λ5183.4, and an Fe I blend at λ5328.4, have an equivalent width of ≥ 1.0 mÅ. In our spectra their threshold equivalent widths are 20–30 mÅ. The relative continuum fluxes at these wavelengths for a "primary" B dwarf and a putative "secondary" G star (with $L \sim \geq 3\ L_{\odot}$) should be ~ 10. From these values, the cool stellar features should be detectable if they were diluted by factors of 45, 80, and 40, respectively; i.e. by a star 4–8 times fainter than an analog of ROX-20. Since we find *no* weak features at these wavelengths, we can state that there is no evidence for a T Tauri companion to λ Eri. In summary, both the line nondetection and the flare statistics arguments show that it is unlikely that a cool companion is responsible for the λ Eri's X-ray flare.

3. *RS CVn and Algol companion.*—X-ray flares in these interacting binary systems have been observed to attain fluxes as high as $\sim 1.6 \times 10^{31}$ ergs s^{-1} (RS CVn-type: Stern et al. 1983; Algol: van den Oord & Mewe 1989). Although these peak emissions come within 2–3 times the λ Eri flare, their durations at maximum are shorter and therefore the total energies emitted are considerably less. As for the dK-Me stars, strong flares on these binaries have higher temperatures, 35–80 MK, than the λ Eri flare.

4. *Accreting degenerate companion.*— λ Eri has none of the conditions found in systems thought to be Be with an interacting neutron star companion: very high X-ray levels, radio/X-ray pulsations, or optical radial velocity variations. Fortunately, we were able to check on the wind status of this star by obtaining an *IUE* spectrum, SWP 40912, 10 hr after the completion of the *ROSAT* observations. Like most Be stars, λ Eri's C IV lines can show substantial evolution over time scales of weeks, including the evolution of Discrete Absorption Features (DACs). In general, the presence of strong DACs correlates well with Hα emission. We found a single very weak blueshifted DAC at -870 km s^{-1} in the stronger C IV doublet

line at λ1548. From this feature we estimate the mass loss from the wind to be at most twice the average rate for a star of λ Eri's luminosity and temperature, viz. $\dot{M} \sim 4 \times 10^{-9}\ M_{\odot}\ \mathrm{yr}^{-1}$ (Garmany & Conti 1984); this is probably an overestimate as DACs probably signify no enhanced loss. The expected X-ray luminosity emission from (all) wind material accreting onto a neutron star is, using the modified Bondi-Hoyle accretion radius formalism of White et al. (1982):

$$L_x = 5 \times 10^{10} \dot{M} M_{1.4}^3 / R_{10} v^3 M_T^{2/3} P_d^{4/3} . \qquad (1)$$

Assuming a neutron star radius R_{10} in units of 10 km, a mass $M_{1.4}$ in 1.4 $M_{\odot}$, a binary system mass $M_T = 11.4\ M_{\odot}$, an orbital period P_d exceeding 365 days, a wind velocity v_3 in 10^3 km s^{-1}, the resulting L_x is 1.2×10^{31} ergs s^{-1}. This value is twice the observed quiescent flux level and twice the level attributed to a shocked wind. Of course, this result can be reconciled to the observed quiescent rate by trivial changes in the estimates of these parameters. However, one cannot reconcile this relation to the flare emission since the observed X-ray flare over its lifetime would require the ejection of $\geq 1.6 \times 10^{-11}\ M_{\odot}$. This amount of mass corresponds to the ejection of a thick disk that would be heralded by rather strong Hα emission. High-dispersion CCD Hα observations obtained 2 weeks later by GJP showed no emission whatsoever. Thus, aside from the absence of X-ray hardness ($\sim$100 MK) and the absence of velocity variations, the C IV/Hα observations all but rule out the mass transfer hypothesis. A white dwarf companion can be ruled out even more strongly as the accreted mass-shocking would be far less efficient.

In summary, while binary models cannot be rigorously excluded, none appear likely explanations for the combination of soft quiescent and a long-lived hard flare X-ray component. Flares from late-type companions are either too weak, have short durations, and/or are very rare. The absence of metal optical absorption lines precludes a late-type giant or T Tauri companion. An accretion event onto a hidden neutron star is plausible only under unusual circumstances, such as the total accretion of a low-velocity high-density blob from the B stellar wind. We believe it is more likely that λ Eri is a single Be star which exhibited a violent flare during the *ROSAT* observation reported here.

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15. Supplementary Notes

16. Abstract

ROSAT pointed observations of bright, classical Be stars have demonstrated that detection of soft x-rays at a level expected for normal B stars of comparable Teff and luminosity is anti-correlated with the presence of episodes of enhanced mass ejection and formation of a dense, moderately ionized equatorial circumstellar disk. At epochs of lower than average disk column density, x-ray flaring has been detected in 2 Be stars, λ Eri and π Aqr.

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