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This proposal was for a joint X-ray/ultraviolet/ground-based study of the abnormal Be star lambda Eri, which has previously shown evidence of X-ray flaring from ROSAT observations in 1991. The X-ray component consisted of observations from the both ASCA (subject of this task) and ROSAT satellites.

The 1991 flare event observed by ROSAT caught the astronomical hot star community by surprise because X-ray flares have not been observed from other single B-type stars, before or since. It was important to obtain additional observations to estimate whether flares in this star are common or rare. My collaborators in India and Japan and I were able to schedule observations with the ASCA, IUE, and Voyager satellites, as well as ground stations in the US and India.

The program was conducted from Feb. 26-March 7, 1995. ASCA and optical observations were scheduled on Feb. 26-27. The ASCA data was reduced and fit to models at the ISAS facility in Tokyo by Dr. T. Murakami and H. Ezuka. The results of these data can be summarized as follows: (1) the mean X-ray flux level agrees to within 10% of the 1991 quiescent flux level found by ROSAT, (2) no significant variability can be seen, and (3) the X-ray spectrum can be fit with a Raymond-Smith (optically thin plasma) model having a temperature of 1X10^7 degrees.

Both optical (H-alpha) and UV/Voyager observations provide evidence for transient heating events near the surface of lambda Eri. The absence of strong associated X-ray fluctuations suggests these heatings are mild, and are much less than 10^6 degrees.

A manuscript has been written and submitted to the Astrophysical Journal and is appended to this report.

Dynamic Processes in Be Star Atmospheres. VI. Simultaneous X-ray, Ultraviolet, and Optical Variations in λ Eridani

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ABSTRACT

We document the results of a simultaneous wavelength monitoring on the B2e star λ Eri. This campaign was carried out from ground stations and with the ROSAT, ASCA, IUE, and Voyager 2 space platforms during a week in February-March 1995; a smaller follow-up was conducted in September 1995. During the first of these intervals λ Eri exhibited extraordinary wind and disk-ejection activity. The ROSAT/HRI X-ray light curves showed no large flares such as the one the ROSAT/PSCA observed in 1991. However, possible low level fluctuations in the February-March ROSAT data occurred at the same time as unusual activity in Hα, He I λ6678, He II λ1640, and the C IV doublet. For example, the hydrogen and helium lines exhibited an emission in the blue half of their profiles, probably lasting several hours. The C IV lines showed a strong high-velocity Discrete Absorption Component (DAC) accompanied by unusually strong absorption at lower velocities. The helium line activity suggests that a mass ejection occurred at the base of the wind while the strong C III (Voyager) and C IV (IUE) lines implies that shock interactions occurred in the wind flow. It is not clear that the X-ray elevations are directly related to the strong C IV absorptions because the former changed on a much more rapid timescale than absorptions in the C IV lines.

Within hours of the mild X-ray flux variations found by ROSAT on February 28, the Voyager UVS observed a "ringing" that decayed over three 3-hr. cycles. The amplitude of these fluctuations was strong (50%) at λλ950-1100, decreased rapidly with wavelength, and faded to nondetection longward of λ1300. Various considerations indicate that these continuum variations were not due to an instrumental pathology in the UVS. Rather, they appear to be due to a time-dependent flux deficit in the λλ950-1250 region. We outline a scenario in which a dense plasma structure over the star's surface is heated and cooled quasi-periodically to produce such flux changes. Observations of new examples of this phenomenon are badly needed. Amateur astronomers can make a significant contribution to its understanding by searching for ringing in light curves of Be stars during their outburst phases.

Finally we draw attention to an increase in the emission of the Hα line that occurred at about the time the FUV ringing started. This increased emission hints that ~50,000K plasma near the star's surface can influence the circumstellar disc at ~12R_* by its increased Lyman continuum flux.

Subject headings: stars: individual λ Eri, stars: emission-line, Be – stars:

1. Introduction

The early 1990's has been a golden period in the study of Be stars because it has permitted multi-wavelength monitoring observations of the variability of these objects to be carried out from a variety of space platforms as well as ground stations. In this paper we discuss results from a coordinated campaign comprised of optical and UV spectroscopy and X-ray observations with the ROSAT and ASCA satellites of a perennial favorite mild B2e star, λ Eri. This star has been routinely observed in the optical region since a 0.9 day periodicity, usually attributable to nonradial pulsations, was discovered in its optical line profiles and radial velocities (Penrod 1986, Bolton and Stefl 1989, Smith 1989). This star has been the subject of a large number of IUE and optical campaigns (Peters 1991, Smith and Polidan 1993, Kambe et al. 1993). In 1991 February the ROSAT satellite observed a strong, several-hour X-ray flare on this star during an epoch of weak mass ejection and wind activity (Smith et al. 1993). λ Eri is also well known for the erratic rapid variations in its photospheric He I λ6678 line. These variations take the form of "dimples" and micro-emissions at frequent irregular occasions, during both Hα emission and quiescent phases (Smith 1989, Smith and Polidan 1993, Kambe et al. 1993, Smith et al. 1994, Smith et al. 1996, Smith 1997). This rapid optical line variability develops over 10's of minutes or less, implying that violent high-energy events occur close to the surface of this star. The reported correlations of strong UV resonance lines with dimples and emissions in optical lines (Smith and Polidan 1993, Smith et al. 1996), together with the 1991 X-ray flare, suggested to us that a more concentrated X-ray/UV/optical campaign might shed light on a high energy connection with erratic optical line activity. Toward this end we were able to arrange a new campaign in 1995, just a year before the termination of the operation of the IUE satellite and soon after the launch of ASCA. In a recent paper (Smith et al. 1997) we have also reported the nondetection of $<\lambda 400$ flux from this star by the EUVE satellite.

The purpose of our multi-wavelength campaign is to address two questions: first, does λ Eri show major X-ray flares frequently? If it does, λ Eri may be somehow abnormal, for X-ray surveys of hot stars, Be stars included, are not finding variability to be common (e.g. Cassinelli et al. 1994). The second question was: are there optical or UV proxies of high energy transient activity? It is essential to establish what this might be because of the difficulty of setting up concentrated X-ray campaigns on a type of star that is not known for its X-ray variability. In our new observations we found no examples of a second major X-ray flare. Clearly, then, the first question may be answered "no." The response to the second question hinges on possible small-scale X-ray variations that may be present in the ROSAT data. We observed marked variations in the UV and optical spectra that coincided with these putative X-ray excursions.

Aside from its X-ray flare, λ Eri appears to have normal parameters for a B2 star. Following Smith, Peters, and Grady (1991) Smith, Hubeny, and Lanz (1994), and Smith et al. (1994), we will adopt the following parameters for this star in our discussion: T_{eff} = 23,000K, R = $6R_{\odot}$, and an inclination, i $\sim 6^{o}$, between our line of sight and the equatorial plane.

2. Observations

We were allocated 30 ks of ROSAT time and 24 ks of ASCA time during the 1995 season. The ROSAT data were obtained with the High Resolution Imager (HRI). This instrument does not have the energy discrimination of the Position Sensitive Proportion Counter (PSPC) which was used to observe the 1991 flare, nor is it quite as sensitive. However, it provides five times the spatial resolution on the sky and still produces a light curve limited in accuracy mainly by photon statistics. The ASCA satellite provides a pair of moderate spectral resolution ($E/\Delta E$) Solid-State Imaging Spectrometers (SIS) sensitive to energies from 0.5-10 keV and a pair of lower resolution Gas Imaging Spectrometers (GIS), which responds to 1-10 keV energies (see Tanaka, Inoue, and Holt 1994).

The ROSAT observations could not be scheduled during a single short epoch. About 65% of our time was scheduled during the period 1995 February 26 through March 5. The balance of our allotment was scheduled during 1995 September 9-18. The ASCA observations were more concentrated and occurred within a 22-hour period on February 26-27. We were also allocated 8 hours of IUE time to cover these X-ray observations. Seven optimally exposed high dispersion SWP IUE observations (exposure time: 1 min.) were made on February 27, 21:34-24:37 U.T. In addition, Hα observations were made with the Fabry-Perot spectrometer at the 1.2-m Guruskihkar Infrared Telescope (GIT) operated by the Physical Research Laboratory on Mount Abu, India on the nights of February 26-28. McMath telescope service observations of the Hα and He I lines at Kitt Peak were carried out on the nights of February 27 and 28 (UT). Additional IUE observations were carried out on March 7 (one), on September 7-9 (11) and September 16 (one).

Our target was observed on-axis by the HRI during both portions of our ROSAT program. The data were reduced with the IRAF/PROS package and the HEASARC XSELECT software. Source counts were extracted from a circular region of radius 30 arcsec. Background counts were taken from a nearby region. We time-binned the data using 2000 sec (orbital window) segments in order to maximize the signal to noise ratio and to minimize the loss of sensitivity to possible short-timescale variability. We initially extracted flux by excluding the first three channels of the 30 HRI channels because of the UV light leak known to affect these these channels for hot sources. The centroid of the HRI image of the source was only 1 arcsec off the optical position of the star. This small error is typical of the pointing errors for the HRI instrument. The centroid position did not shift appreciably when channel 4 counts were subtracted.

Because the HRI has a known UV leak and because λ Eri is a strong UV source, we were obliged to correct for UV contamination in the HRI counts. We compared the pulse-height distribution in our observations with the the pulse-height distribution obtained for Vega (David et al. 1996), a UV-bright star which has little known X-ray emission. We found that Vega distribution is peaked below channel 4, with very little emission in higher channels. The pulse distribution for λ Eri is also high for channels 1-4, but with significantly more counts above channel 4. This suggests that channels 5 and above are dominated by X-rays. Therefore, we ignored all pulse-height channels below channel 5 in our HRI reductions. As a check we compared the apparent flux derived from spectral fitting of the basal PSPC spectrum and also with the contemporary ASCA SIS data (see below). Using a Raymond-Smith model and a standard count to energy conversion factor for the HRI, we found that the HRI flux agreed to within 10-20% of the old PSPC and contemporary ASCA values, indicating that most of the UV contamination of the HRI data was successfully removed. The light curve discussed below was obtained by binning the data in segments of about 2000 sec.

The reductions of the ASCA data proceeded in an analogous manner using ISAS analysis software. Because of the soft distribution of λ Eri's X-ray flux and the absence of any flaring by a harder component, we confined our attention to the SIS detectors, which are more sensitive at lower energies than the GIS. The ASCA observation of λ Eri started at February 26 12:36 (U.T.) and covered roughly 22 hours except for occasional Earth occultations. The two detectors (SIS0 and SIS1) are virtually identical, so we have combined the two data sets to enhance the signal to noise ratio. Source counts were extracted from a circular region of 4.5 arcmin radius. The background-subtracted spectrum was fitted, as discussed below, with various Raymond-Smith models, though alternative types of models would have fit the data fluctuations equally well.

All IUE spectra were reduced by the prototype NEWSIPS spectral processing system

(Nichols and Linsky 1996). Extensive comparisons of the signal to noise ratios of NEWSIPS to the old standard IUESIPS processings by the IUE Project has determined a consistent improvement of a factor of two in the measurement of the equivalent width of a rotationally broadened line. Much of this improvement comes from a reduction in the pixel-to-pixel noise. An additional enhancement that is important for broad-lined spectra is the more reliable estimate of the continuum placement with NEWSIPS, which permits more consistent equivalent width measurements. For example, we estimate an error of ±4% in the equivalent width measures of He II λ1640.

Several hours of high data rate spectra were obtained by the Voyager 2 Ultra-Violet Spectrometer (UVS) beginning at February 27 18:37 U.T. (heliocentric) and ending 23.5 hours later. These data were obtained in the rapid-readout (3.84 sec.) cadence with these data pre-binned to 3:1 such that each spectrum examined has an effective integration time of 11.5 secs. The UV Spectrometer data were reduced by J. Holberg and J. Collins of the LPL Voyager-GO laboratory using an updated version of the data reduction package described by Holberg and Watkins (1992). The raw data showed no indication of abnormal spacecraft or UVS functioning. Seventeen clean "drift scan cycles were obtained with the star passing close to the center of the field aperture in each cycle. The aperture functions constructed from these cycles in all cases included data from both halves of the field aperture. As a result extrapolations of the count rate from the star being at various positions within the field aperture were minimal. The effective integration time for each of the final 17 time-binned spectra was 12-29 mins, and the effective spectral resolution is 15Å. Light curves were synthesized from several bandpasses of size 75-150Å between λ500 and λ1500.

Because the errors in the monochromatic light curves from the Voyager data are important to our results, we took care to insure that the fluctuations we found were not instrumental artifacts. Smith and Polidan (1993) have published a light curve for λ Eri.

That curve showed apparent constancy to within ±3%. This is also consistent with errors found by other observers of bright B stars (e.g. Porri et al. 1994, Smith 1995, and references cited therein). The fluctuations in the $\lambda\lambda$1300-1500 bandpass of our data suggest an error of ±5%, which is consistent with the lower instrumental response in this wavelength region. Since we believe the short wavelength data contain real stellar variations, we cannot use the data to obtain a reliable error estimate. However, we may still take the median value of the point-to-point fluctuations in each light curve as an estimate of this error. Of course this figure will be high if the star is actually variable. Using this as a criterion for the error, we find an r.m.s. of $\leq \pm5\%$, from the $\lambda\lambda$912-1050, $\lambda\lambda$1050-1100, and $\lambda\lambda$1100-1200 light curves. Thus, we have no reason to believe that the errors for the short wavelength data are much larger with the ±3% value expected for a B star of this brightness.

The McMath optical spectra were reduced in IRAF. These spectra exhibit a level of Hα emission unmatched for λ Eri since its discovery as a Be star, nearly 1.4I_c. The epoch of our primary campaign is near the time of the maximum Hα-emission outburst, which was first reported by Stefl in 1994 October (Stefl 1994). The Violet (V) and Red (R) emission maxima were separated by 177±5 km s^{-1}. This separation corresponds to an orbital radius of about 12R_* assuming a nearly edge-on, detached disk with Keplerian orbital velocities (Smith, Grady, and Peters 1991).

3. Results

Figure 1 shows a plot of the background-corrected ROSAT fluxes during the February-March campaign. The times of the ASCA, IUE, Voyager, and optical observations are indicated. There are no highly significant X-ray variations in these data. There are two mildly elevated flux observations during the second day as well as a weak upward trend for the third through fifth day. Both trends are significant to at least the 95% level from standard χ^2 and Kolmogorov-Smirnov tests against constancy.

In order to look at the possible variations in the ROSAT data and their correlations with other signals, it is convenient to break up the February-March campaign into three intervals. These are described as follows:

i) Day 0.0-0.5 (February 26-27) [11]

The two orbits represented in this period show a just credible detection, with a mean HRI count rate of about 0.0016±.0007 $^{-1}$. This rate is consistent with the mean rate of 0.0014±.003 $^{-1}$ in our September data, which showed no trends or variations at all. Theoretical models may be constructed in principle to link the 1991 PSPC observations of this star with the current flux level measured by the HRI. Fortunately this connection can be made by referring the HRI count rate to apparent flux rate from the far better statistics in the ASCA/SIS data for the same day. The background-corrected count rate from the SIS for February 26 is $5.1\pm0.7\times10^{-3}$ s^{-1}.

As depicted by Figure 2, the SIS spectrum can be matched very well with a Raymond-Smith thermal emission model. To obtain a fit we fixed the ISM column density at 1×10^{20} cm^{-2}, based on the fit with the 1991 PSPC data and a pair of UV interstellar Zn II lines (see Smith et al. 1993). We also assumed a solar-like chemical composition. With these assumptions the best derived model has a temperature kT = 0.86 +0.09,-.05 keV (χ^2 = 1.19). The errors for the ASCA data refer to a 1σ level. The Raymond-Smith is shown as a histogram in the figure. We note that this temperature estimate is preferable to the value *assumed* by Smith et al. (1993), which is twice this determined value. Our best-fit model corresponds to a flux of 8.1×10^{-14} ergs $cm^{-2}s^{-1}$ for the 0.5-5 keV bandpass. The correction

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[11] All times are reckoned from the start of the ROSAT observations at February 26 at 15:13 U.T. ASCA Observations commenced at 12:36 U.T. on this date.

of the integrated model fit to the PSPC bandpass was found to be only 10% higher than this value (Smith et al. 1993). The 10% difference is also comparable to the flux differences we estimate for different kinds of fits to the X-ray continuum. This same uncertainty is also comparable to the ratio of count rates in the HRI data for February-March and September. The near agreement for these two instruments suggests that the low flux in 1995 February and September are essentially the same as the basal flux measured in 1991. For an assumed a distance of 270 pc, the soft X-ray Emission Measure from λ Eri is about 3×10^{52} cm^{-3}.

ii) Day 0.5-1.5 (February 27-28)

During this interval ROSAT showed two orbits for which the soft X-ray fluxes were slightly elevated over the mean, followed by two which are 2σ over the average. Hα and He I λ6678 were also observed at the beginning and end of this time, and seven IUE spectra were obtained in the middle. The V and R emission components in the initial Hα profile on February 27 6 UT rose to $1.29I_c$ and $1.32I_c$. The profile on Febuary 28 5 UT was much stronger, at $1.39I_c$ and $1.34I_c$. This comparison is exhibited in the top panel of Figure 3. The GIT (Mt. Abu) Hα profiles on February 27 14-18 UT support this difference, showing a V component that is marginally strong than on the previous night. (On February 28 this emission is at least as strong and the emission in the R wing grew by about 10%.)

The λ6678 photospheric profile was appeared filled in slightly on February 27; the incipient emission was more noticeable on the following night. The equivalent width decreased from 0.60Å to 0.48Å during this period. Figure 3, middle panel, shows these two profiles. An equivalent width of 0.48Å is a rather low value for λ6678 in this star, even for disc ejection epochs (Smith, Hubeny, and Lanz 1994, Smith et al. 1996). Emission in this line means that the site responsible for the emission is necessarily much less than one R_* from the star's surface (Smith et al. 1997). The fact that no concomitant emission was observed in either the V or R wings of λ6678 implies that much or all of the emitting volume lies probably along the line of sight to the stellar disk, i.e. it is foreground material. In contrast, the strengthening of the entire Hα emission profile in this period suggests that most of the circumstellar (CS) disc reacted to a change near or on the star. The filling in of this line on February 27 is consistent with some level of emission-triggering occurring before the more extreme activity found on the next day.

In addition to the emissions in the optical He I and Hα lines, and He II Bα λ1640 line also showed remarkable incipient emission, during the three hours of IUE observations on February 27. Similarly, the C IV lines showed weakened absorption in these data. The lower panel of Figure 3 shows the difference between these observations and a reference spectrum, which is actually a composite of SWP49687 and SWP49690 observations obtained during a quiescent phase on 1993 December 23. Figure 4 shows that the C IV doublet showed a pronounced DAC at -925 km s^{-1} (depicted at -1430 km s^{-1} in the figure) and a strong low velocity absorption enhancement. When present at all, a DAC in λ Eri's C IV line is generally weaker than is shown here. Moreover it is not shifted to such large negative velocities. We have been unable to find as strong an integrated wind absorption for this doublet in the IUE archival spectra for λ Eri which extend over 1982-1995. Figure 4 shows an additional spectrum obtained four days after the end of the ROSAT campaign. The C IV profiles may be compared with the optimally Fourier-filtered spectrum of the average of two observations when the DAC feature was relatively weak. We will refer to as this as a template spectrum. By way of reference the mean equivalent widths of the DAC and the lower velocity wind features for the seven IUE spectra of February 27 are 0.44Å and 0.17Å, respectively. If one scales the DAC equivalent width to the same feature in the Be star γ Cas found by Henrichs et al. (1982) and Telting and Kaper (1994), one finds rather high wind C^{+++} column densities of 1.6×10^{14} cm^{-2} for the DAC and 4×10^{13} cm^{-2} for the lower-velocity wind. Note also that the presence of an abnormally strong wind is confirmed by the observation of a strong C III line at 977Å in Voyager data discussed below.

Table 1 summarizes the absorption strengths of He II λ1640. This table includes the mean strength of this feature for February 27, for the single observation on March 7, and for 12 on September 7-9 when the signatures of the disc had weakened according to its Hα emission strength. We tabulate also the nominal strength of this feature compiled from measurements during non-emission epochs by Smith et al. (1996, 1997) as well as from the template spectra. The table shows clearly that the equivalent width of the He II line was abnormally weak on February 27, even compared to March 7. Closer inspection shows no significant fluctuations in the strength of λ1640 during the three hours of IUE coverage. However when the profiles are compared with observations of 1995 March 7, 1995 September, or the template spectrum, the mean λ1640 shows a filling in over the blue half of the profile (Figure 3). This asymmetry suggests this emission is excited from within a volume of $\leq R_*^3$. Note that these IUE observations were made within a few hours after the optical observations in India. Both the Hα and He I λ6678 observations also show an increased emission in the blue half of their profiles. The coincidence of the differential emission is readily apparent in Figure 3.

The behavior of the photospheric UV resonance lines from three ionization stages of silicon supports our finding of particularly strong spectroscopic activity at this time. The equivalent width of the λ1265 line arising from the subordinate Si II ion decreased 20% from its template spectrum value of 0.30Å. The Si III λ1206 line strength likewise decreased 10% from its nominal value of 2.3Å. The weakening of the λ1403 line from the C IV line was only 7% (from 1.04Å). It was caused entirely by a distinct filling in of the blue side of the line core. The weakening of the lines from lower species is perhaps easiest understood as being caused by a local temperature increase which increases the degree of ionization of silicon species. We believe the filling in of the Si IV line core is caused by a transient emission, perhaps by recombination in the photosphere or within a structure not far above it such as determined by Smith et al. (1997) for He I lines.

Table 1: He II λ1640 Strengths

Date	Equiv. Width	Date	Equiv. Width
Nominal	0.55±.005	1995 March 7	0. 52±.020
SWP49687,90	0.56±.014	1995 Sept. 7-9	0.54±.010
1995 Feb. 27	0.44±.010		

Voyager UVS light curves during February 27-28 are shown for five spectral bandpasses indicated in Figure 5. The most notable characteristic of these curves is the "decayed ringing" or flickering appearance in the first three, which begins at 8 U.T. on February 28 (JD2449776.8). Note that this is just *after* the positive excursions in ROSAT flux, the IUE observations, and the Mt. Abu observations for this day. In the first and largest cycle the range in flux is ≈50% at short wavelengths. Therefore this feature is highly statistically significant. Points #13-16 in the plot, which comprise the second and third cycle, actually represent integrations obtained over portions of two drift scans each, and point give largely redundant results. We have chosen to group these observations in order to maintain constant errors even though this grouping makes the two flux cycles appear undersampled in our figure. Inspection shows that the level of short wavelength flux is uncorrelated with the position of the star in the field. Moreover, no instrumental pathologies are known which could mimic this effect (Holberg 1996). Figure 5 shows that the highs and lows of these cycles decreases with increasing wavelength. A comparison of the spectral plots from these times also shows that the amplitude decreases quickly across the low sensitivity $\lambda\lambda$1200-1300 region until it disappears at $\lambda\lambda$1300-1400. The fluctuations appear to arise from a continuum flux deficit at minimum phases and not from variations in the Lyman line strengths.

iii) February 28 - March 3

The ROSAT data during this time are best fit with a sloped line rising to a rate of

0.007 cts s^{-1}. This is a few times the basal X-ray flux level for this object. There are no other data taken at the same time with which to compare this rise. The IUE observation a week later still showed a strong amount of wind activity. However, the C IV DAC feature and λ1640 emission were notably weaker than on February 27 (see Table 1).

iv) September 9-18

As already mentioned, the ROSAT data showed the same count rate as for the beginning of the February observations. The IUE spectra showed little or no variability. The C IV DAC feature was only 70% as strong as in the earlier campaign and was centered at -850 km s^{-1}, which is slightly lower than during February-March. The C IV profile showed only weak absorption to the red of the DAC feature, again unlike the earlier observations. The optical McMath observations on September 10-12 show no Hα emission and, with one exception, exhibit little hint of activity or filling in of the λ6678 line. The exception was a spectacular "flare-like" emission rising 13% above the continuum in the red wing of this line. This event, discussed by Smith et al. (1997), lasted ~20 minutes and must have been emitted from a structure seen over the projected limb of the star. Using the decay time as a recombination timescale, the density of the structure must be at least 4×10^{11} cm^{-3}. This event is the strongest and most rapidly decaying emission yet documented in λ6678 for this star or possibly any other Be star.

4. Discussion

We believe that ours is the second report of simultaneous X-ray, UV, and optical variations in a classical Be star, the first being a panchromatic flare observed in γ Cas (Slettebak and Snow 1978, Peters 1982). The weakest element in an argument for a multiwavelength correlation for λ Eri is the low significance of the X-ray fluctuations. Yet, the suspicion that these X-ray elevations are stellar in origin is strengthened by the nonvariable ROSAT count rates a half day earlier when concentrated ASCA observations showed constancy as well as its constancy again in September (right panel of Figure 1). In the remaining discussion we will tacitly assume that the marginal X-ray fluctuations are real, but this assumption does not impact any of the conclusions drawn in this paper.

4.1. X-ray and UV Fluctuations in the Wind

The abnormally strong C IV absorption shown in Figure 4 and the strong 977Å feature in our Voyager spectra are consistent with a picture that recently ejected matter was injected into the wind and become involved in X-ray generating shock interactions. Berghöfer et al. (1996) have found that X-ray variations can occur also in the O-stars ζ Pup (possibly periodic) and ζ Ori (single event). The X-ray variations in ζ Pup appear to correlate with Hα emission with a period of 16.7 hrs. These authors explain their events by invoking a rotationally modulated density enhancement near the base of the wind which propagates out to where X-rays become self-transparent. Berghöfer and Schmitt (1994, 1995) have also found a single excursion in an otherwise constant soft X-ray light curve of ζ Ori. These authors interpret this as the result of varying numbers of wind shocks of equal strengths. Our IUE and optical data for February 27 (but not the subsequent ringing in the FUV) suggest that the spectral and temporal variations arise from a single atypical strong event rather than a larger than average fluctuation of many smaller ones. As evidence of this, we point to the asymmetric He I and He II profiles on this date as well as the strong absorption in the Si IV lines at low and high velocities. We comment below on the limitations of interpreting X-ray fluctuations as the cause of optical and UV spectral variations.

An interesting result of our observations is that to within the several percent accuracy of measurement, the basal soft X-ray flux of λ Eri was the same in 1991 during a quiescent phase as it was during the particularly strong mass ejection outburst in 1995. Even during the 1995 March observations the bulk of the CS disc was at $\geq 12R_*$ in the equator. The inclination of the star's disk to the line of sight is very small, perhaps only $\approx 6^o$ (Smith, Peters, and Grady 1991). It is now believed that the wind-shocked X-ray sites are located at most a few stellar radii from the star (e.g. Cranmer and Owocki 1996). If this is true, the majority of X-ray emission probably originates from centers located in intermediate latitudinal or polar regions. In the equatorial plane, X-ray emissions from these centers will be strongly attenuated by the circumstellar disc, if not by the wind (Cohen et al. 1996). Conversely, one may make use of disc attenuation to place weak limits on the disc height in the polar direction. Assuming a typical distance of $2R_*$ for the X-ray sites and that the wind is transparent to soft X-rays, this limit has to be somewhat less than a stellar radius.

Could the putative X-ray elevation on February 28 be related to the abnormally strong wind features at the same time? While it is tempting to believe that they might be, the timescales of the respective changes do not fit into a simple cause-and-effect picture. As Figure 1 indicates, the X-ray elevation occurred within one 96-min orbit. The decline was almost as rapid. The C IV wind features show considerable absorption at moderate velocities already at the start of the putative X-ray fluctuation. Three hours of observations showed no substantial evolution of this absorption. If the X-ray flux and C IV absorption at low velocities were simply related, the latter would have to have just appeared at the time of our first observation and then remained constant over three hours. More likely, the moderate velocity wind absorptions had been essentially as we first observed it before the X-ray increase. Then the increased X-ray flux might have nothing to do with the C IV absorptions (indeed the former may not be real). In addition, we note that the FUV ringing event observed by Voyager occurred just as the X-ray flux appeared to decrease (seventh ROSAT orbit).

4.2. Hα Variations

We consider now the relationship of the X-ray and Hα fluctuations on February 27. We begin by noticing that Hα emission increases cannot be the redward-extrapolated flux from a Raymond-Smith distribution because this flux is far too low to photoionize enough hydrogen atoms in the circumstellar disc (even if they were near the star). Perhaps instead the disc brightens for the same reason that it glows already in Hα under steady state conditions, namely that an increased supply of *Lyman continuum photons* from the star ionizes additional atoms in the CS disc. The disc atoms would then recombine and emit increased Hα radiation. In this connection, we note that Smith et al (1997) have shown that λ1640 emission can be caused by dense plasma at ~50,000K above the surface. Gas at this temperature emits continuum radiation efficiently at ~900Å. Standard model atmospheres (e.g. Kurucz 1979) show that a (50,000K, 4.0) model emits $\sim 4\times10^3$ times as much flux near 900Å as a 22,500K model does appropriate to λ Eri. Then let us consider a suspended slab, such as that discussed by Smith et al. (1996) to explain He I line emissions, only heated to 50,000K. To be conservative, we will posit that this slab is optically thin and has an emissivity of, say, 1/3 the irradiance of the Kurucz 50,000K atmosphere. We also specify a filling factor of 10% of the stellar disk. If we further assume a geometrical dilution factor of 1/200 as seen from the CS disc, we can compute that a hot slab suspended somewhere in the vicinity the star would increase the number of Lyman photons available to ionize hydrogen atoms in the disk by a factor of $4{,}000/(3\times10\times2\times10^2) = \sim 67\%$. Then even if one allows for attenuation of Lyman flux from intervening wind atoms, the increase in Lyman flux is enough to match the comparatively small emission increase shown in Figure 3. Notice that our estimate of surplus Lyman flux, while necessarily rough, does not require that the X-ray flux on February 28 was enhanced. It requires only that the mass injection is accompanied by a modest heating above T_{eff}, which we already suspected from the near simultaneous weakening (emission) of He II $\lambda1640$ and weakening of lines of three stages of silicon. If one estimates the wind density as $\sim10^8$ cm^{-3} at $12R_*$, the recombination timescale will be at least a few hours. Thus a single impulsive event near the star could sustain an enhanced Hα emission from the CS disc long enough to be observed in Hα from the a random longitude zone on the Earth.

5. The FUV Continuum Variability

There are two aspects to the FUV fluctuations observed by Voyager 2 which are novel. The first is the temporal characteristics summarized in Figure 5, and the second are changes in the spectral characteristics as the FUV flux changes from its high to low state. We consider each of these characteristics as follows.

Although ringing in the FUV such as found in our Voyager observations not been noticed in other B stars, Balona (1990) has reported the precedent of a similar flickering being observed in the *optical* flux of the Be star κ CMa. Balona's observations showed the ringing had a timescale of about 0.2 days, or about twice the cycle length shown in Figure 5, and damped out in a day or so. The occurrence of this event coincident with a 0.1 mag. brightening associated with an Hα emission outburst of this star. We believe that this behavior in κ CMa is rather similar to what our Voyager observations show.

We have surveyed the recent literature for other examples of ringing in stellar flux, and we have become aware only of similar behavior in the X-ray and microwave regions from oscillating loops above the Sun's surface Zaitsev and Stepanov (1989; "ZS") have suggested that transient ringing is initiated by an unspecified mechanism. The instability sets up magnetic Alfven waves which travel along the loop field lines and are reflected at their footpoints until they eventually damp from electronic-ionic collisions. ZS argued that if the period, amplitude, and number of effective cycles is known one may solve for a characteristic temperature, density and magnetic field strength in the oscillating loop. Mullan, Herr, and Bhattacharyya (1992) have applied ZS theory to damped X-ray oscillations observed in active red dwarfs and have been able to derive reasonable physical parameters for the gas and field in such loops. We have found that an application of ZS theory to our Voyager data leads to badly inconsistent values for the loop gas temperature (too high) and density (too low). The physical cause of this inconsistency can be traced to the long quasi-period of 10^4 sec. A second problem is that the oscillating FUV continuum flux must form in an optically thick medium rather than an optically thin one as this theory assumes. One can avoid this problem in principle by arguing that the ~50% FUV flux variations occur from backwarming of the photosphere by transient X-ray flux. However, the simultaneous ROSAT observations show that such strong heating could not have occurred, at least for very long. We conclude the ZS mechanism cannot be responsible for the FUV flux variations. Because this is the first observation of its type, we do not wish to attempt to speculate further on what might cause this periodic behavior.

The flux distribution of our Voyager spectra provide additional clues to the FUV ringing, but they do not resolve its mystery. With the help of R. Polidan we have compared these spectra with spectra of the Voyager standard stars ϵCMa (B2 II) and β Hyi (B9 III) plus Voyager 1 spectra of λ Eri taken in 1990 and discussed by Smith and Polidan (1993). Aside from their utility in detecting strong Lyman and C III lines in the spectra of hot stars, Voyager spectra can be used to assess the effective temperatures of stars both from the steep rise in flux at $\lambda\lambda$912-975 and from the slope over $\lambda\lambda$1300-1650. We have found that both these gradients are the same for λ Eri and ϵ CMa within the errors. This confirms results from various optical studies that the two stars have very similar temperatures, perhaps to within ±1500K. The gradients at the blue and red ends are similar for spectra obtained at both maxima and minima of the FUV oscillation cycle. A comparison of the high- and low-state spectra with 1990 spectra showed two properties. First, the 1995 spectra obtained by Voyager 2 appear some 13% fainter than the 1990 spectra obtained by Voyager 1. This apparent dimming is actually most likely caused by a loss of sensitivity of Voyager 2 relative to Voyager 1 after the last calibrations of these instruments were made (Holberg 1996). Thus we will disregard it from further consideration. A second peculiar property of our new UVS spectra is that the high-state spectra mimic the flux distribution of the 1990 archival spectra: it is the *low-state* spectra that appear anomalous. The latter show a flux deficit in the region $\lambda\lambda$950-1250. We now consider two ways this spectral difference might arise, first with a dual-temperature composite model and second with the imposition of a wavelength-limited opacity source. We are indebted to R. Polidan for putting forth both of these concepts.

In the first case we consider a large, cool, optically thick blob situated such that part of its area obscures the Be star while the rest of it is seen against the projected limb of the star. The latter primarily adds low emissivity flux in the red. One can then play with the parameters to match the observed spectrum with a two-temperature model of the partially eclipsed star. As a typical case, we find that if one dilutes the high-state flux of the Be star by 27% and arbitarily adds enough red flux from the blob, one can duplicate the low-state Voyager spectra well. In this case the red gradient emulates that of a late-B star spectrum while the $\lambda\lambda$912-975 gradient is still unaffected. The gradient of the red flux needed to do this is consistent with a $\approx$12,000K star similar to β Hyi. However, a fatal flaw with this model is that the emissivity of the B9-type structure is so low that one must postulate a blob radius several times that of the Be star to match all the hypothesized excess red flux. We have rejected this model for this reason.

As a second model, we accept at face value the flux deficit in the λ950-1350 region and consider mechanisms that could produce transient excess opacity in this band. A prospective candidate is the C I ion which has strong bound-free edges at 1100Å and 1240Å. These edges are located in the middle of a forest of strong Fe II lines. If a means could be found to force carbon to recombine to C I periodically in a slab-like structure above the star, one could explain the transient spectral-dependent variations. A high carbon opacity could occur only if the slab were much cooler than equilibrium conditions would warrant. For example, if the temperature were 10,000K the ionization fraction of carbon drops enough for its opacity to dominate over Balmer continuum opacity and even to become the dominant feature in this wavelength region (Hubeny 1996). The challenge then becomes how to explain the slab temperature can drop to a value much lower than temperatures found in a static model atmosphere of a B2 star. We conjecture that a sudden injection of superheated material into a magnetic loop could produce an instability in which radiative losses from the slab could briefly overcome the ability of stellar radiation to maintain its equilibrium temperature. The most reasonable way this could happen is if an ionization/recombination wave moved through the slab periodically and caused alternate high and low thermal excursions. At the low temperature phase the carbon-induced flux deficit would become prominent while at the high temperature phases the FUV spectrum would remain basically unchanged. Note incidentally that during the hot phase an excess of <912Å flux would be produced, and this could be the source of the increases in disc Hα emission discussed above. Yet all of this is conjecture. At this early stage we must keep in mind that there is no precedent and little context for the FUV ringing. The Voyagers have not observed any facsimile of damped ringing has been seen the B stars they have monitored (Holberg 1996).

6. Conclusions

The absence of sharp brightenings in either the February-March or September observations has established that extended soft X-ray flares are not the rule for λ Eri. In one sense the nondetection of a second strong flare should remove concerns that λ Eri may be somehow atypical of other classical Be stars. Also, the nondetection of additional strong flares in λ Eri ironically strengthens the argument that X-ray survey observations of Be stars should not be used as a basis for contending that these stars do not show any flares at all. A wide variety of flare stars show a power-law distribution in flare amplitude, and our combined X-ray observations of λ Eri are so far consistent with this behavior. If flaring plays a role in the mass loss episodes of these stars, multi-wavelength campaigns can attempt observations of optical He II lines to monitor the recombination rates in this ion.

We have found that several signatures of wind/disk activity, namely elevated X-ray fluxes, abnormally strong wind absorption in C IV, and enhanced V-wing emission in Hα, occurred on February 28 just when the same velocity range of the He I and He II lines showed a filling in. Helium lines are thought to show emission only when excited well within $\sim$1R$_*$ of the surface. The behavior of these diagnostics indicates that a strong shock, perhaps a flare, originated close to the star, and yet it may have also excited emission by recombination in the disc at $\sim$12R$_*$ from the star.

With the IUE mission now closed, observers may have to look with high signal to noise ratios to other proxies of high energy events to build on recent multiwavelength results. Smith et al. (1997) have suggested that He II λ4686 might serve as an alternative, at least for hotter members of the Be class such as types O9e-B0e. We also would stress that optical photometrists, including amateur astronomers, can make a significant contribution to the study of Be star instabilities by monitoring newly active Be stars for optical-wavelength flickerings such as that found by Balona (1993).

After this paper was essentially completed, we received a preprint from R. d'Oudmaijer and J. Drew on the observations of a rapid increase in the Hα emission profile of the Be star HD76534. In their paper these authors conjectured that an increase in Lyman continuum flux from this Be star could explain the Hα brightening over a few hours. Their suggestion is similar to the inference we made above that heated slabs cause the increased Hα emission of February 28 in λ Eri. The rapid timescale for the HD76534 event these authors found is reinforced by the case we have made from He II λ1640 reemission for illumination of the CS disk by a transient suprathermal event near the Be star. We note also that rapid though smaller-amplitude Hα brightenings have been found for λ Eri itself (e.g. Smith 1989, Fig. 35). We are grateful to these authors for sending us a preprint of their work on HD76534.

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Fig. 1.— The light curve for ROSAT HRI observations during the 1995 February-March campaign (left panel). Starting time is referenced to February 26 at 15:13 UT. Times of ASCA, IUE, Voyager, and optical (McMath/Kitt Peak and Mt. Abu) observations are indicated. Error bars refer to the 1σ level. Note the slightly elevated HRI fluxes in the fifth and sixth orbit (point) and the general trend towards increasing soft X-ray fluxes The right panel shows 1995 September HRI observations; this shows the scatter expected for a source having λ Eri's mean X-ray flux.

Fig. 2.— The ASCA/SIS spectrum of λ Eri on 1995 February 26-27. The histogram is a fit to a Raymond-Smith (optically thin, thermal) model with kT = 0.86 keV. Error bars refer to the 1σ level. The χ^2 differences are shown in the lower panel.

Fig. 3.— Upper panel: comparison of the Hα profiles obtained on February 27, 6 UT (solid line), and February 28, 5 UT (dotted line). Middle panel: spectra of the He I $\lambda6678$ line obtained at nearly the same times. Lower panel: difference plot of the He II $\lambda1640$ line from IUE observations on February 27, 21-24 UT, relative to a template spectrum from this profile - for this spectrum a difference of 0.0 is arbitrarily shifted represented as "0.7" in continuum units. Note the emission present on the blue side of each of these spectral lines.

Fig. 4.— A comparison of the C IV $\lambda\lambda1548$-52 doublet for the mean of seven spectra on February 27 and a spectrum on March 7. The thick line shown is the template spectrum taken for a pair of spectra when the mass loss activity of λ Eri was mild. Note the strong narrow DAC feature at -930 and -1430 km $^{-1}$ as well as continuous lower velocity absorption from the wind.

Fig. 5.— FUV continuum light curves of λ Eri for 1995 February 28 in offset magnitudes. Bright star is up, and Feb. 27 corresponds to HJD 2,499,775.5. Estimated 1σ error bars are shown. Note the flickering which rapidly decreases in amplitude with increasing wavelength.

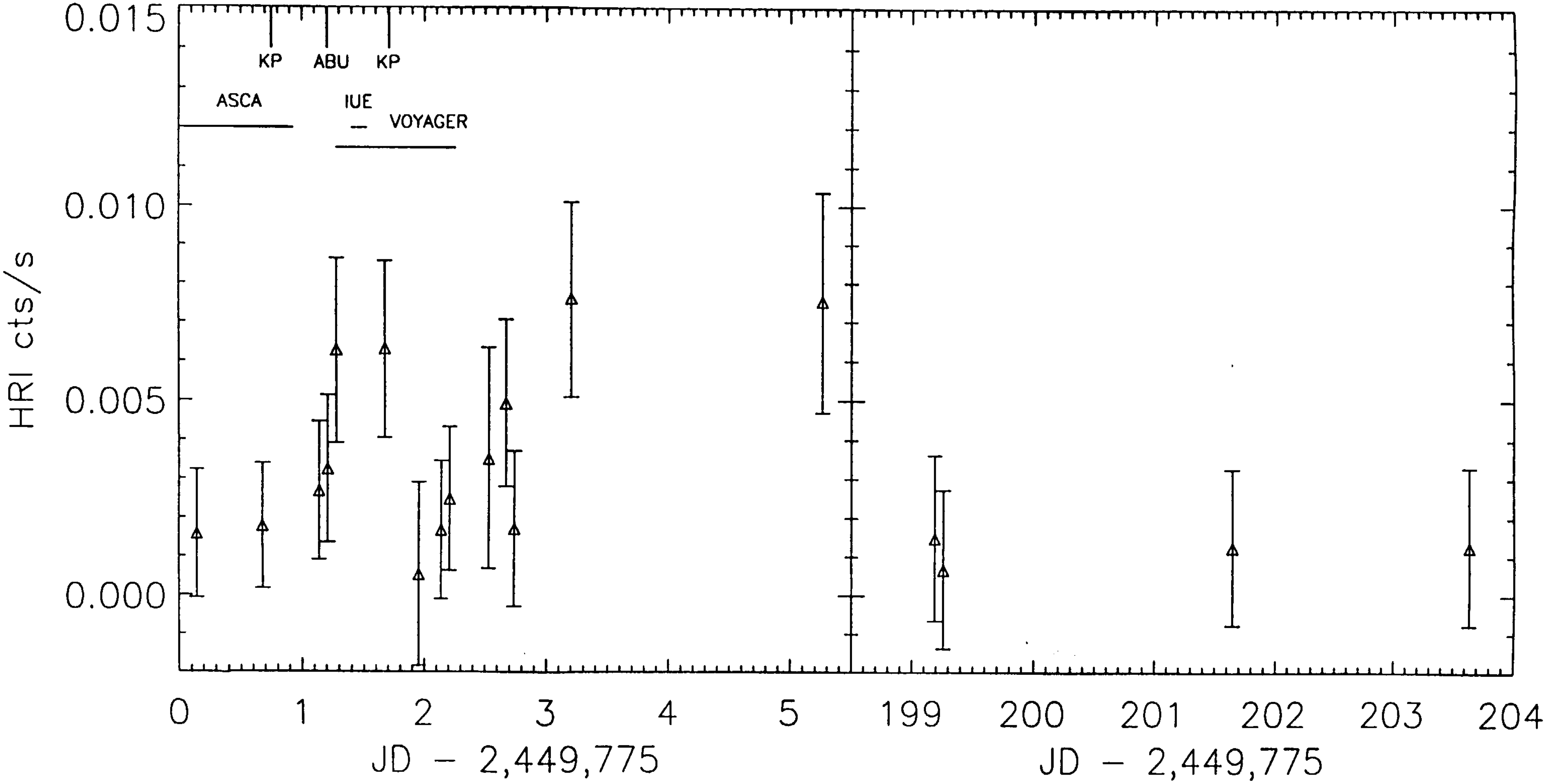
0.015
0.010
0.005
0.000
HRI cts/s
KP
ABU
KP
ASCA
IUE
VOYAGER
0
1
2
3
4
5
JD − 2,449,775
199
200
201
202
203
204
JD − 2,449,775

Fig 1

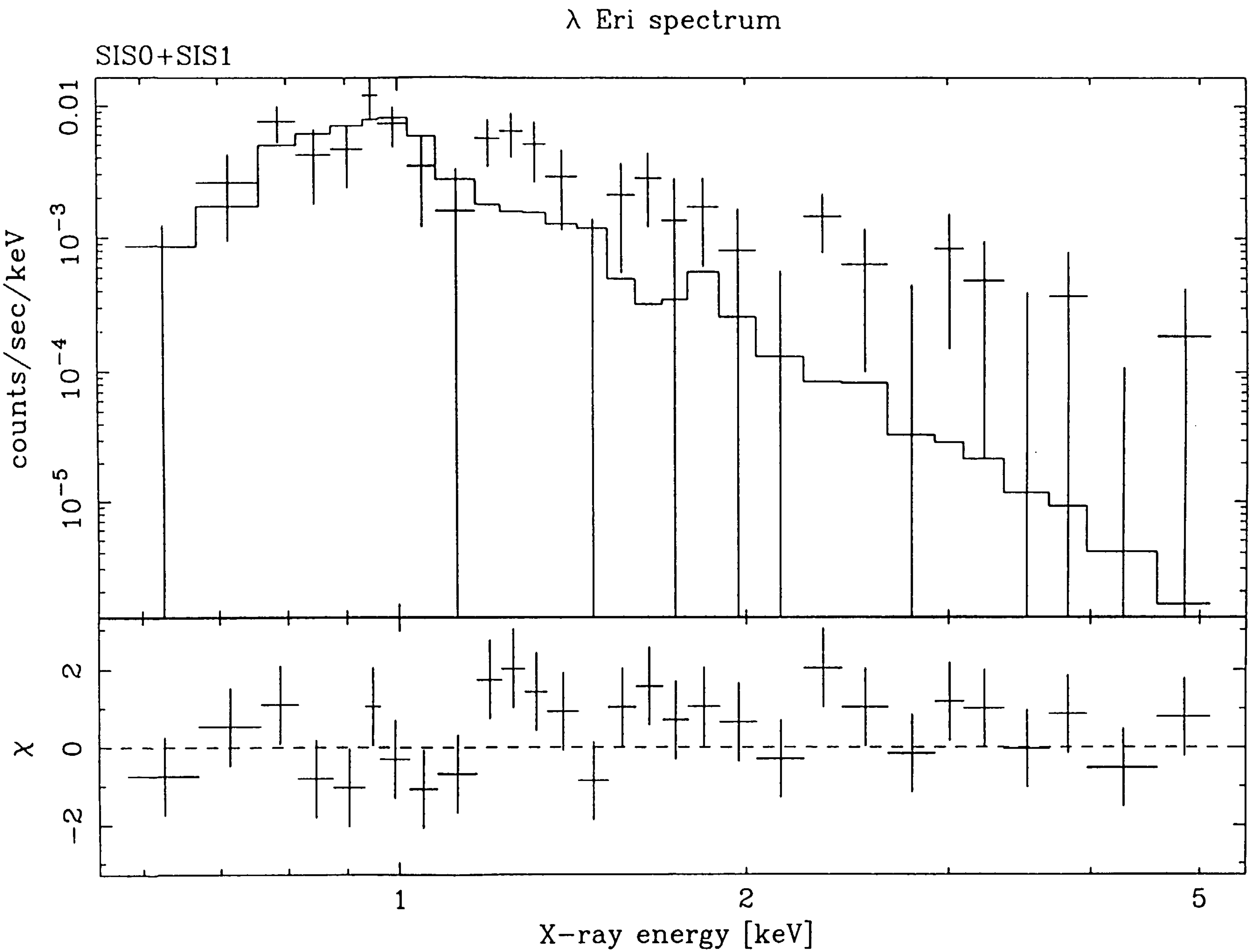
λ Eri spectrum
SIS0+SIS1
counts/sec/keV
0.01
10^{-3}
10^{-4}
10^{-5}
χ
2
0
−2
1
2
5
X−ray energy [keV]

Fig 2

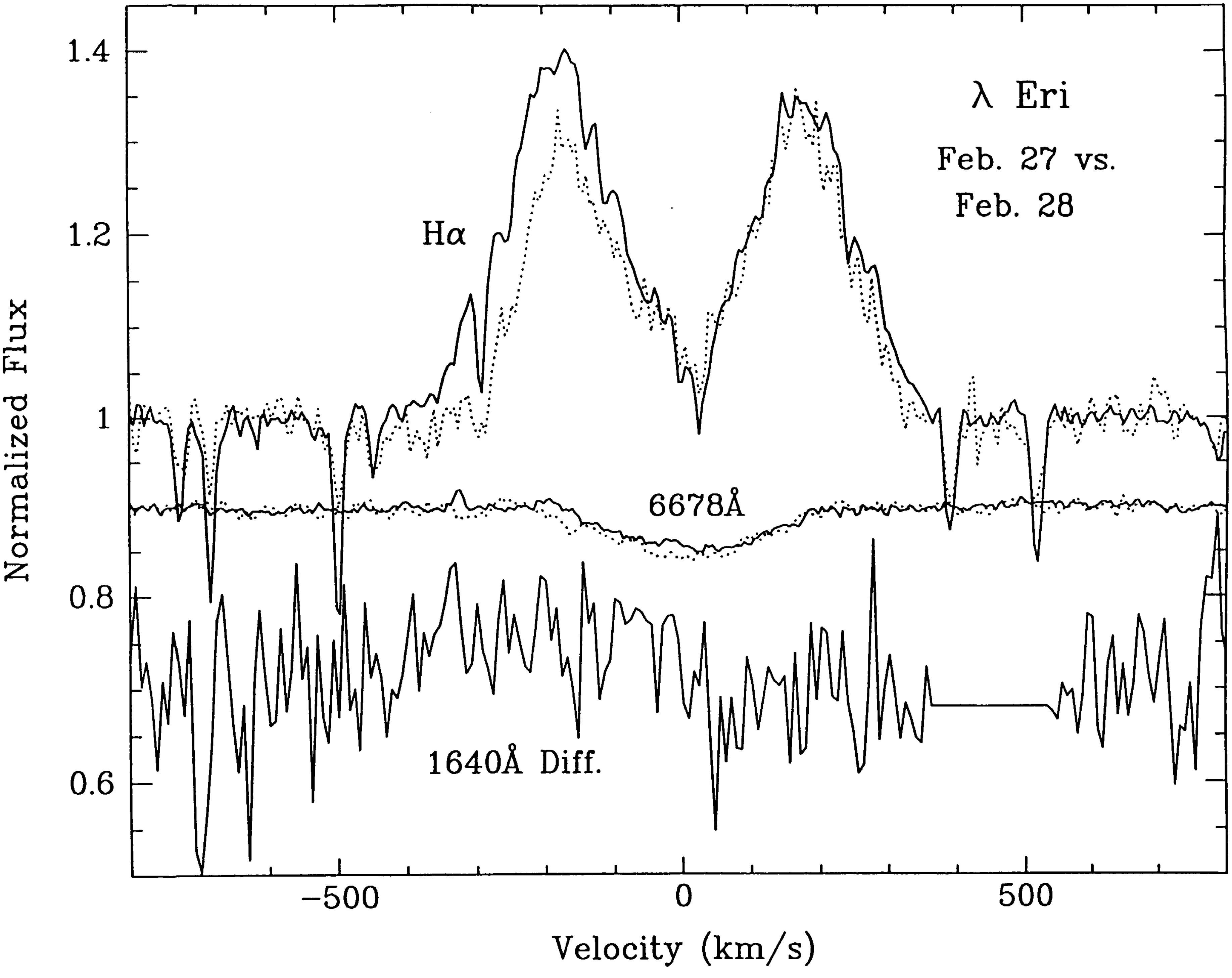
λ Eri
Feb. 27 vs.
Feb. 28
Hα
6678Å
1640Å Diff.
Normalized Flux
1.4
1.2
1
0.8
0.6
Velocity (km/s)
−500
0
500

Fig 3

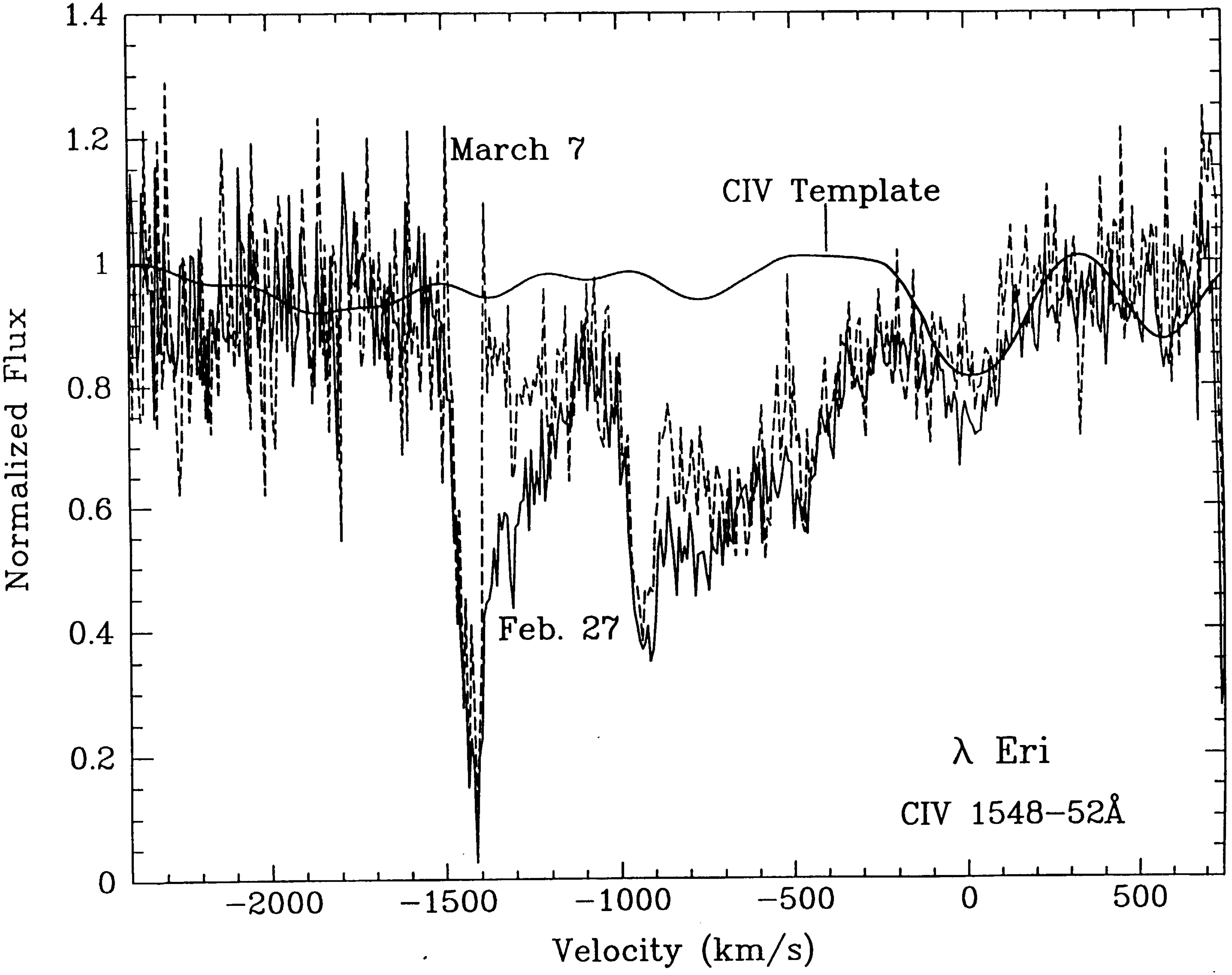
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Normalized Flux
−2000
−1500
−1000
−500
0
500
Velocity (km/s)
March 7
CIV Template
Feb. 27
λ Eri
CIV 1548−52Å

Fig. 4

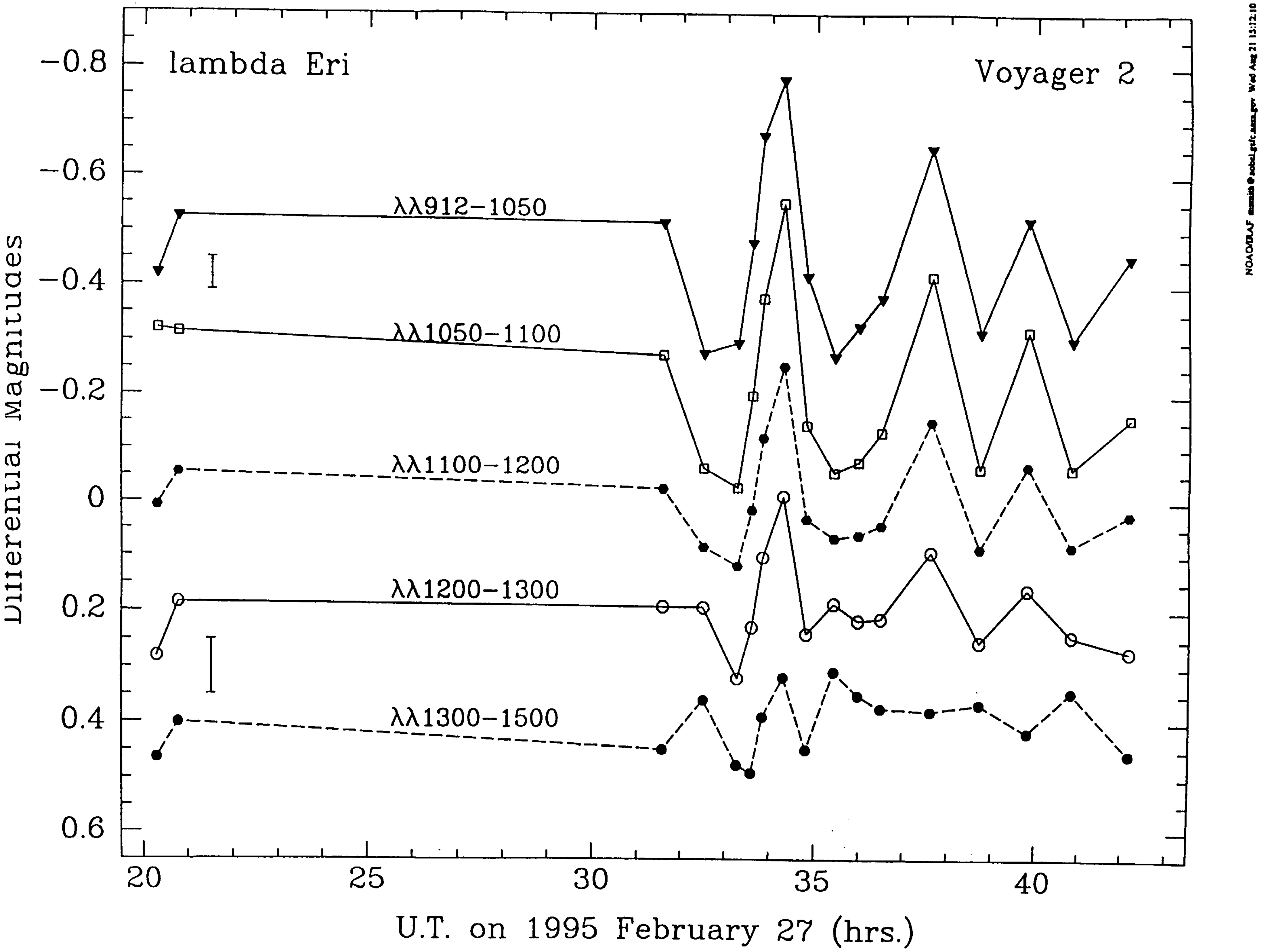
lambda Eri
Voyager 2
λλ912–1050
λλ1050–1100
λλ1100–1200
λλ1200–1300
λλ1300–1500
Differential Magnitudes
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
20
25
30
35
40
U.T. on 1995 February 27 (hrs.)
NOAO/IRAF nobel.gsfc.nasa.gov Wed Aug 21 15:12:10

Fig. 5