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A 40,000 second on-target observation was made of lambda Eridani for this study on December 25-26 1993 by the EUVE satellite. Near-simultaneous observations were conducted (two SWP exposures) with the IUE satellite. Ground-based optical observations at Kitt Peak were conducted on the first cloud-free night following the EUVE observations.

An analysis of the EUV observations with the SW, MW, and LW cameras was carried out at the University of Wisconsin using CEUVA software, Version 1.5. Backgrounds were subtracted and the resulting data were summed in spectral format over time and also summed over wavelength to search for temporal variations. We compared the spectra with predicted spectra for plasmas at various temperatures. We found no statistically robust signal at expected wavelengths in the spectra. This negative result owes to the large column density ( $1 \times 10^{20} \text{ cm}^{-2}$ ) of interstellar matter in the direction of lambda Eri. However, we did discover that an Fe XII line at 80 Angstroms could be detectable if plasma were present with an Emission Measure as large as that from a 1991 X-ray flare that we observed in this star. This suggests that hypothetical future EUV observations at an auspicious time could detect transient plasma at coronal temperatures. The integrated fluxes were plotted in time and found to show a weak signal consistent with the known 0.71 day pulsation period in this star. However, documentation on the Lexan filter indicates that this signal probably arises from a mid-UV light leak from this filter and not from the star's EUV continuum.

We have also investigated the rapid variability of optical and UV HeI/HeII lines in this star and found that they are correlated in time. Both the ratio of the HeI singlet/triplet line emissions and the ratio of the optical and 1640 Angstrom emissions are consistent with recombination producing helium line emission variations. We are currently working with non-LTE atmospheric radiative transfer models which attempt to test whether the recombination mechanism can quantitatively produce the observed amounts of optical and UV helium line emissions while at the same time not producing sufficient EUV radiation to be observed against the level of interstellar extinction quoted above.

A paper is currently being written on these results and will soon be submitted to the Astrophysical Journal.

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## Dynamic Processes in Be Star Atmospheres. V. Correlated Helium Line Emissions in $\lambda$ Eridani

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## ABSTRACT

Multi-line observations of the optical spectrum of  $\lambda$  Eri demonstrate that rapidly varying, low-velocity emissions occur in several several He I lines even when  $H\alpha$  shows no emission. A peculiar aspect of the He I emissions is that the ratio  $\lambda 5876/\lambda 6678$  is  $\approx 1$ . The theory of helium line formation generally admits two common emission mechanisms. The first is recombination/cascades, which is well known to give a ratio of  $\geq 3$ . The second is a non-LTE effect that occurs in hot (O-type) photospheres when resonance He I  $\lambda 584$  radiation becomes transparent and drives singlet lines alone into emission. To accommodate a ratio of  $5876/6678 \approx 1$  may require that both processes sometimes operate at the same time, presumably in separate localities near the surface of this star.

A strong argument can be made that recombination at least sometimes plays a major role in the He I based of a strong but rapidly decaying emission feature observed in the red wing of the  $\lambda 6678$  line profile on one occasion. Assuming the emission is due to recombination leads to a gas density of  $10^{11}$ - $10^{12}$   $\text{cm}^{-3}$ ). This is consistent with estimates for densities within slabs which appear to be responsible for transient “dimples” in this star’s He I lines.

Using “NEWSIPS”-processed IUE data, we have found an instance during  $\lambda$  Eri’s active phase in 1987 November when weak variable emission in the He II  $\lambda 1640$  line coincided with an emission in  $\lambda 6678$ . This event as well as a correlation of  $\lambda 1640$  emissions when dimples occur in  $\lambda 6678$  demonstrate that  $\sim 10^5\text{K}$  plasma is often released from this star’s surface into the immediate “exospheric” environment.

Putting these observations together, we examine the requirements on transient high energy sources that could be responsible for the production of features in both in the highly ionized and optical spectra.

*Subject headings:* stars: individual  $\lambda$  Eri, stars: emission-line, Be – stars: flare

## 1. Introduction

Although hydrogen Balmer line emission has long been known to originate from the disks surrounding classical Be stars, much less is known about the origin of their He I line emissions. Taking a characteristic temperature of  $T_{eff} \sim 25000$  K, one finds that the Stromgren sphere for helium is much smaller than for hydrogen. For this reason, the excitation of He I lines is effective only near the star’s surface, and model atmospheres should give some indication of the physical conditions where He I emissions arise. Since the pioneering work of Auer and Mihalas (1972, 1973; “AM72,” “AM73”), rather few studies have dealt with the formation of He I lines in atmospheres of B stars. Consequently, it is still unclear how even absorption lines vary with  $T_{eff}$ , let alone how these lines are driven into emission in Be star atmospheres. Various authors (e.g. Heasley, Wolff, and Timothy 1982, Smith, Hubeny, and Lanz 1994) have shown that non-LTE models give good agreement for blue He I lines ( $\lambda 4026$ ,  $\lambda 4388$ ,  $\lambda 4471$ ,  $\lambda 4713$ ,  $\lambda 4922$ ) of normal B stars. However, these authors have found that the red lines ( $\lambda 5876$ ,  $\lambda 6678$ ) are stronger than theory predicts. Non-LTE models also predict that weaker  $\lambda 10830$  lines than observed and they even predict that this line could go in emission in earliest B stars (Dufton and McKeith 1980, Leone et al. 1995). A point often overlooked in the literature is that the trend of predicted vs. observed strengths of  $\lambda 10830$  is similar to the trends of the red lines at  $\lambda 5876$  and  $\lambda 6678$ . All three lines are stronger in absorption than predicted, and this discrepancy increases with stellar temperature.

The He I lines in B star spectra show additional curious aspects. First, although both AM73 and recent non-LTE models for the atmospheres of main sequence B stars suggest that collisions between singlet and triplet atomic levels are too weak to affect their relative populations, the observations give the appearance of a segregation of behaviors by *wavelength* (principal quantum number) – not by multiplicity as published non-LTE models

indicate. For singlet lines the strengthening of emission with wavelength can be partly attributed to simulated emission. It is not as easy to understand this trend for triplets, because these transitions do not show the necessary condition of having underpopulated lower states. A second curious aspect of the helium lines is that different subclasses of B stars show different equivalent widths (Smith, Hubeny, and Lanz 1994). It is difficult to see how this might occur even if one allows for uncertainties in metallic line blanketing and atomic rates. An alternate variable or physical mechanism is needed. Recently Mitsekev and Tsymbal (1992) have described models of hypothetical B star coronas that emit X-rays. This high energy flux produces an overionization of He, followed by recombination and cascade primarily to the triplet states. This mechanism causes the  $\lambda 10830$  line to go into weak emission. Blake et al. (1995) have suggested that variable  $\lambda 5876$  emission from the X-ray Be binary HD 153919 is caused by photoionization from X-ray transients. However, an adequate optical monitoring campaign has not been set up yet for this or any other Be X-ray system.

The sometimes rapid variability of He I emissions in Be stars permits a search for correlations with each other and with other diagnostics. If these are found one can attempt to simulate the results with various dynamical instability models, e.g. from magnetic flares, wind shocks, or gravitational infall. As part of a general investigation on the atmospheric instabilities in Be stars, we focus in this paper on the B2e star  $\lambda$  Eridani. This star has been monitored extensively in the optical and ultraviolet (see Peters 1991, Gies 1993, Smith 1993) and in addition has exhibited an X-ray flare lasting several hours (Smith et al. 1993).

Smith et al. (1995) were able to ascribe some of the strength of the red wing of  $\lambda$  Eri's  $\lambda 6678$  emission profile to localized hot, downward-moving plasma. These authors pointed out that their TLUSTY (Hubeny 1988) non-LTE models confirmed AM73 predictions that suprathermal conditions ( $T \sim 50,000\text{K}$ ,  $N_e \sim 10^{14} \text{ cm}^{-3}$ ) can cause the resonance single  $\lambda 584$  line to become transparent and to depopulate the  $2P^1$  level. This sequence of events,

which we will call the Auer-Mihalas (Auer and Mihalas 1972) mechanism after the original discoverers, forces the singlet lines and especially  $\lambda 6678$  into emission. An important question posed by this result is whether the superionization of helium in “hot sites” could be caused by collisions within a hot plasma (shocks) or by a transient, high-energy irradiation source above the star (flares). To begin to answer this question, we proceed herein by combining optical He I multi-line observations and comparing features from contemporaneous optical and International Ultraviolet Explorer (IUE) databases. Next, we will also discuss new evidence of explosive phenomena observed in the helium lines. We will also apply the nondetection of the EUV flux by the Extreme Ultraviolet Explorer satellite to the problem of the He I line emission via radiative recapture-cascade processes. We conclude by showing that models of high energy irradiation sources are capable of producing the at least He II line emissions occasionally observed in  $\lambda$  Eri.

## 2. Observations

### 2.1. Multi-Line Monitoring of Optical Lines

On 1993 October 28 and 29 we monitored  $\lambda$  Eri using the Lick 120-inch telescope echelle spectrograph (Vogt 1987). This instrument provides a wide spectral coverage that include several He I lines arising from the 2-singlet and 2-triplet levels ( $\lambda 4388$ ,  $\lambda 4922$ ,  $\lambda 5015$ ,  $\lambda 6678$ , and  $\lambda 4471$   $\lambda 5876$ , respectively). As a check on the Lick data, observations of  $\lambda 6678$  were made also with the solar-stellar spectrograph on the McMath-Pierce telescope. The Lick data for the first night consisted of 18 echellograms having a signal to noise (SNR) of 250-300 ranging from 9:32 UT to 13:48 UT at a cadence of  $\sim 15$  minutes/spectrum. The humidity at Lick on this night was low so that telluric water vapor lines did not contaminate the red line spectra. A sequence of 20 McMath observations was also taken

on this night with similar SNRs, resolutions, and time samplings. The interval covered was 6:08-13:05 UT except for an interruption from clouds during 9:45-11:15 UT. On the second night, October 29, nine spectra were obtained between 8:27 UT and 11:07 UT. The observing parameters were similar to those of the first night except that the humidity was so high that telluric water features rendered the  $\lambda 5876$  line unmeasurable. A series of 10 McMath spectra, again interrupted by clouds between 9:15-10:50 UT, was obtained between 8:04 UT and 12:11 UT. The spectral resolutions and sampling at  $\lambda 6678$  were  $\sim 48,000$  and  $0.057$  (Lick) or  $0.094 \text{ \AA pix}^{-1}$  (McMath). Fringing was not apparent in any of the datasets so that bias and flatfield corrections could be applied with standard IRAF *twodspec* and *onedspec* packages.

Although  $\lambda$  Eri was in an  $H\alpha$ -nonemission state at the epoch of our campaign, the helium profiles were quite variable on both nights. The  $\lambda 6678$  line displayed both a pair of “dimples” (Smith and Polidan 1993) in the first few spectra and a marked emission feature in the central photospheric profile in the middle of October 28. In general, it is possible to confuse an emission feature with occasional simultaneous pairs of dimples when only the  $\lambda 6678$  or  $\lambda 5576$  profile is observed. If the higher series members are observed simultaneously, this ambiguity can be resolved. This is because we find empirically that the blue lines such as  $\lambda 4922$  shows nearly no response, or even an absorption, when a transient emission component appears in  $\lambda 6678$  (Smith et al. 1994) whereas they generally show dimples when the  $\lambda 6678$  profile does (Smith et al. 1996). We exploit this fact in our interpretation of transient emissions below.

At  $\sim 12$ -13 UT on October 28 a central-profile emission feature appeared which was prominent in  $\lambda 5576$ , moderate in  $\lambda 6678$ , quite detectable in  $\lambda 5015$ ,  $\lambda 4922$ , and  $\lambda 4388$  and nihil in  $\lambda 4471$ . Figures 1 shows the central core of the four lines in which emission is most noticeable. In each case we show a spectrum before, during and after this transient feature appeared. Here we display the McMath  $\lambda 6678$  profiles because there was some evidence



of saturation on one edge of this order in the Lick echellograms for this night. Note the weak emissions near line center which appeared in all four lines to some extent. A second emission is apparent in the second and third of the observations depicted.

Our spectra of October 29 showed flickering emission the cores of the He I lines. This emission was shortlived and unpredictable. For example, it was absent in an early McMath observation at 8:04 UT and appeared in a Lick observation 23 minutes later. The He I emissions coincided with rather weak emission ( $\sim 0.7\%$ ) in the central core of  $H\alpha$ . In Figure 2 we show two observations of the helium singlet lines taken an hour apart during momentary flickering maxima.

The range in emission strengths in the 1993 October observations is far smaller than the range of atomic line strengths. The emission strengths also differ considerably from those predicted from models of hot (50000 K) atmospheres. For these temperatures the models predict insignificant strengths of all these lines except  $\lambda 6678$ . We note that our non-LTE models fail to predict  $\lambda 5876$  emission at all, a point we will take up again in Section 3.

## 2.2. A Serendipitous “ $\lambda 6678$ Flare”

On 1995 September 12 we obtained three consecutive observations of the  $\lambda 6678$  line alone as part of the McMath nighttime service observing program. Each exposure was 10 minutes long. The first observation (Figure 3) betrayed a spectacular emission spike in the red wing of the line. This feature has a square top and drops off precipitously without hint of wings. The second observation shows the identical shape with an attenuated amplitude while the final observation one betrays no hint of the feature. There are several reasons why this emission cannot be an artifact of a cosmic ray (CR) hit: (1) the feature is much too broad and flat-topped (most “direct-on” cosmic rays are far narrower; oblique-hit CRs

show extensive, asymmetric comas), (2) the feature is present in a second spectrum (the McMath CCD erases 10 times before commencing a new exposure), and (3) inspection of the two-dimensional image before spectral processing showed no evidence of a bright feature present above or below the spectrum. We conclude confidently that this feature is a true astrophysical transient. Flare-type emissions such as this are rather rare but have also been reported recently in this line, again on the red side of the profile, for  $\gamma$  Cas (Smith 1995).

### 2.3. He I $\lambda 6678$ vs. He II $\lambda 1640$ Emissions

We have searched the IUE archives for observations of  $\lambda$  Eri taken when ground-based He I line monitoring programs were being conducted to determine what response the  $\lambda 1640$  line shows to transient features displayed by the optical He I lines. We found one instance of overlapping programs in late 1987 when  $\lambda$  Eri was in the midst of a strong emission episode (Smith 1989, Smith, Peters, and Grady 1990). One remarkable sequence of observations is a group of four spectra taken on November 5 (U.T.) followed by one on the next night<sup>1 1</sup>. The lower panel shows the subsidence of a particularly strong emission on the red wing of the  $\lambda 6678$  profile. As already noted, the phenomenon of “flickering red wing emission” in this line has been well documented and can be attributed to downward-moving hot material in or above the photosphere. The IUE observations were obtained in a 36-hour continuous campaign set up by Dr. Geraldine Peters. The IUE sequence numbers for this campaign are the even numbers between SWP32228-62, except for SWP32242. To see whether the important He II  $\lambda 1640$  line might show a response to the emission variations in  $\lambda 6678$ , we reprocessed the raw IUE images through the IUE prototype-NEW Spectral Image Processing System (“NEWSIPS”). This new software contains algorithms that register

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<sup>11</sup>See Figure 11 of Smith 1989. The caption on that figure erroneously gives the civil date.

the pixels of the science images with the original flatfield images (Linde et al. 1987), that make only a single geometric remapping to a spatial format convenient for echelle order extraction, that improve the background flux fitting with a polynomial surface, and, finally, that make use of extensive new flux and wavelength calibrations (Linde and Dravins 1988, De La Peña et al. 1990, Shaw 1990, Smith, 1990, De La Peña et al. 1994). The result is a two-fold improvement of the photometric SNR, a reliable equivalent width scale, and an improved continuum placement in SWP high dispersion images (Smith, 1994). We also determined that the noise in NEWSIPS-processed spectra is virtually white. Therefore, line strength errors determined from a series of spectra are more representative of the true photometric errors than IUESIPS-processed data. We derived an equivalent width error of  $\pm 4\%$  from the measurements of the  $\lambda 1640$  profile in the Peters spectra.

Figure 4 shows a comparison of NEWSIPS equivalent widths for the He II Balmer-alpha  $\lambda 1640$  feature versus three observations of  $\lambda 6678$ . The first pair are taken about 45 minutes apart, the third 22 hours later. The dashed line indicates a mean line strength of  $\lambda 1640$  inferred from three IUE shifts of observations of  $\lambda$  Eri during 1990 when the star’s spectrum showed no Balmer or He I emissions and negligible wind activity. The IUE spectra in Figure 4 were taken every two hours. In the lower panel the first optical spectrum shows strong emission in red wing of  $\lambda 6678$ . This emission underwent a rapid decrease during 12-13 UT and remained weak on the following night. The upper panel shows a decrease in the equivalent width of  $\lambda 1640$  at this same time. Figure 5 shows the  $\lambda 1640$  NEWSIPS-processed profile just before, during (SWP32236), and after the  $\lambda 6678$  emission event. Although not as prominent as the changes in  $\lambda 6678$ , the weakening of  $\lambda 1640$  is significant and, like  $\lambda 6678$ , may be more pronounced on the red side of the profile. We believe that the weakening of the  $\lambda 1640$  can occur in no other credible way than by incipient emission in the profile. This signature leads us to turn to high temperature radiative mechanisms that can produce emission in lines of both ion stages.

## 2.4. EUVE Observations

Emission in the  $\lambda 1640$  line indicates a temperature of  $\sim 80,000\text{K}$  in solar chromospheric plasma (Athay 1988). The visibility of this emission in the dominant ion stage of helium suggested that resonance  $\lambda 304$  He II line might be present in  $\lambda$  Eri. To test this idea, we applied for time on the Extreme Ultraviolet Telescope (EUVE). We were fortunate to receive 40 ksec of on-target observations as part of NASA's EUVE Guest Observer Program, Cycle 1. These EUV spectra acquired during 25 consecutive orbits during 1993 December 26.00-27.59. We also acquired two high resolution exposures (SWP 49687, 49690) with the IUE during this same which show a weak wind feature in the C IV doublet at  $\sim 200\text{ km s}^{-1}$ . Optical spectra of  $\lambda$  Eri at the McMath and Okayama observatories within a day of the EUVE observations show no emission in either  $\text{H}\alpha$  or  $\lambda 6678$ , though dimpling activity in  $\lambda 6678$  was prominent.

The EUVE telescope has three spectrographs which cover the wavelength range of  $70\text{-}740\text{\AA}$  with an average spectral resolution of  $\sim 250$ . We used the Center for EUV Astrophysics software, Version 1.5, to reduce our data. The data were time filtered to include only the nighttime portions of each orbit and to exclude times of high detector background and bad pointing direction. We calculated the effective exposure time for each spectrometer by making deadtime and telemetry saturation corrections. These effective exposure times are 32, 30, and 35 ksec for the Long-, Medium-, and Short-Wavelength spectrometers, respectively.

Next we extracted both the source spectrum from a strip 24 pixels wide on each detector and also the background spectrum from two 50-pixel wide strips above and below the source spectrum. The background spectrum was subtracted from the source and photon counting uncertainties were calculated and propagated into the net spectra files.

The total count rate we derived for each spectrograph is consistent with no detection at better than the  $2\sigma$  level. We searched for line emission in the spectra by measuring the flux in each set of adjacent pixels and then searching for positive detections above a  $3\sigma$  level. We detected no lines in the Short- and Medium-Wavelength spectrometers and only one fluctuation larger than this in the Long-Wavelength spectrometer. However, this feature is narrower than the instrumental resolution and does not correspond to the position of any strong lines, so we consider it to be a statistical fluctuation.

Based on the EUVE spectrum of the bright B giant  $\epsilon$  CMa, we might expect the He II 304Å line to be the strongest spectral feature. If this is the case, it would provide a strong source of helium ionization and could play a role in mediating the interaction between the X-ray flares observed in  $\lambda$  Eri and the variability of optical helium lines. From the Long-Wavelength EUVE data we determine a  $1\sigma$  upper limit for 304Å flux of  $6.8 \times 10^{14}$  ergs s $^{-1}$  cm $^{-2}$ . Unfortunately the estimated interstellar column density of at least  $10^{20}$  cm $^{-2}$  (Smith et al. 1993) implies an interstellar optical depth of  $\sim 50$  at 304Å, so the upper limit on the luminosity of this line is physically uninteresting. However, the ISM attenuation at the high energy end of the Short-Wavelength spectrometer is much less severe. At 80Å the ISM optical depth is only two. Combined with the  $1\sigma$  upper limit on the flux at this wavelength of  $1 \times 10^{-14}$  ergs s $^{-1}$  cm $^{-2}$  we can derive an upper limit on the luminosity of the star at this wavelength of  $9 \times 10^{28}$  ergs s $^{-1}$ . The strongest line near this wavelength in model spectra is an Fe XII line at 80Å in plasmas with temperatures with  $T \approx 2 \times 10^6$  K. Taking the emissivity from Mewe, Gronenschild, and van Oord (1985) models, our detection threshold leads to an upper limit of  $3 \times 10^{53}$  cm $^{-3}$  for the emission measure. This limit is almost an order of magnitude larger than that derived from the quiescent ROSAT spectrum, but is similar to the emission measure of the X-ray flare event noted by Smith et al. (1993). Therefore, it is conceivable that new EUVE observations could detect other large flares in the EUV.

A periodogram (PDM) analysis of the light curve obtained by merging our Medium- and Long-Wavelength spectrometer count rates revealed a weak signal centered at  $0.70 \pm 0.02$  days. This detection agrees with its known period of 0.70 days (Bolton and Stefl 1990) generally attributable to nonradial pulsation or possibly to rotational modulation. We were able to simulate the EUV light curve with an SNR of 1. The count rate from this signal is quantitatively consistent with the well known 2300-2800Å light leak from the Lexan/B filter in the Medium-Wavelength detecting system (see McDonald et al. 1994). Therefore, while the variations probably do originate from the star, they are probably not germane to the star's true EUV properties.

### 3. Discussion

#### 3.1. Evidence for Recombination in Helium Line Emissions

Let us return to the remarkable 13% transient emission feature discovered in the  $\lambda 6678$  profile on 1995 September 12. This emission cannot be reconciled with the Auer-Mihalas non-LTE mechanism discussed for this star by Smith et al. (1994). If one assumes the emission arises from a doppler-imaged strip in the polar direction of the stellar disk, the emission in the line core would have to be  $\approx 2I_c$ . Of course, a strip is an unrealistic shape for a real disturbance, and if it were to have a circular area the line flux would be several  $I_c$ . The strongest  $\lambda 6678$  line flux that Smith et al. were able to produce in their models was  $1.55I_c$ . This peak emission cannot be pushed much higher because the Auer-Mihalas mechanism relies on the line being optically thick, and therefore the line flux should approximate the local temperature of formation. Then for this emission to have even  $4I_c$  would imply local plasma temperatures of  $\approx 1 \times 10^5$  K. At these temperatures helium is far too ionized to irradiate in He I lines. Therefore the transient emission cannot be understood through this non-LTE process.

The failure of the Auer-Mihalas mechanism is an indirect argument for recombination causing the transient emission. We may formulate a more direct argument for this process by using it to estimate the mean electron density of an optically thin plasma. We proceed in two ways. First, we may fix a low density limit by equating the 10-minute transient decay to the plasma recombination timescale itself,  $t_{recomb}$ . Taking the recombination coefficient to the He I  $2^1P$  state,  $\alpha_T = 8 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$  (Osterbrock 1974), one finds a limit of  $1/(\alpha_T t_{recomb}) \sim 1.3 \times 10^{14} \times 1.7 \times 10^{-3} \sim 2 \times 10^{11} \text{ electrons cm}^{-3}$ . The density can be estimated a second way by evaluating the transient’s peak flux. We found the emission in the first observation to correspond to a strength of  $0.22 \text{ \AA}$  and to cover a range of  $1.9 \text{ \AA}$ . TLUSTY model atmospheres appropriate to  $\lambda$  Eri give a continuum flux near  $\lambda 6678$  of  $3.3 \times 10^7 \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ . If one assumes a characteristic intrinsic line emission width from our hot atmosphere models of  $0.4 \text{ \AA}$ , an effective emitting volume of  $3 \times 10^{32} \text{ cm}^{-3}$ , then the line emission flux from the disturbance comes out to  $6 \times 10^{28} \text{ ergs s}^{-1}$ . For densities above  $10^{10} \text{ cm}^{-3}$  3-body recombination enhances He I line emissivities. We will estimate a value for  $\lambda 6678$  of  $10 \times 10^{-26} \text{ ergs-cm}^3 \text{ s}^{-1}$  (Almog and Netzer 1989). Assuming a standard abundance of  $N_{He}/N_H = 0.1$ , the electron density becomes  $N_e \approx 1 \times 10^{12} \text{ cm}^{-3}$ , which is comparable to the estimate from our timescale argument.

This density value is typical of the upper chromosphere region on the Sun, a site where recombination-cascade processes begin to be important. Smith and Polidan (1993) used TLUSTY to compute artificial slab models to arrive at low density density of  $\approx 2 \times 10^{11} \text{ cm}^{-3}$  for the slab-like structures they hypothesized to be responsible for dimples which as already mentioned commonly disrupt  $\lambda$  Eri’s  $\lambda 6678$  profile. Additionally, the mass of a spherical blob with this density,  $6 \times 10^{-13} M_\odot$ , is comparable to the minimum mass determined for dimple-slabs by based on the visibility of dimples in weaker blue He I lines (Smith et al. 1996). We may reasonably conjecture that recombination-emissions and optically thick dimples are weak and strong manifestations, respectively, of the same injection process into

the star’s exosphere. This idea is given further credence by the rarity of the appearance of strong emission transients such as the one of September 12. If the amount of mass injected has been much greater, the event might have developed into a dimple.

### 3.2. Recombination in the Multi-Line Helium Observations

Recombination theory makes specific predictions about the emission line ratios of He I. These ratios depend only slightly on photoionization temperature and are insensitive to density until the collisional excitations and ionizations become important. If the parcel volume is large the lines absorb their own radiation and eventually settle to ratios of a common radiation temperature. Table 1 gives predicted ratios for 20,000K and  $N_e = 10^6 \text{ cm}^{-3}$ . The table shows that  $\lambda$  Eri’s He I lines show much less triplet line emission than expected from recombination theory. This tells us already it is unable to explain our observations, at least under the assumptions of low optical depth and low densities.

A second way of getting He I singlet lines to go into emission is via the Auer-Mihalas mechanism which may operate in dense layers of hot ( $T \sim 50000\text{K}$ ) stellar atmospheres. Such atmospheres differ from planetary nebula in having a “dilution factor” of  $2\pi$  steradians, a density high enough to thermalize the upper but not the lower level populations of He I atoms, and (He II being dominant) an optically thin  $\lambda 584$  line. These conditions drive  $\lambda 6678$  into emission, a state enhanced by stimulated emission. If the collision rate among 2-singlet states is high, the  $\lambda 5015$  line follows  $\lambda 6678$ ’s behavior. Of all the singlet lines  $\lambda 4922$  shows the most interesting behavior with density: a competition develops between the radiative deexcitation of this transition’s lower state ( $2^1\text{P}$ ) from  $\lambda 584$  radiation being optically thin on one hand, and various collisional processes that deexcite the upper state on the other. For very high densities and temperatures  $\lambda 4922$  can go into absorption while  $\lambda 6678$  remains in emission (Smith et al. 1994). The same is true perforce for  $\lambda 4388$



(Table 1,  $\lambda$  Eri entries).

**Table 1: Relative Strengths of He I Emission in  $\lambda$  Eri and Selected CVs**

| Site                                                                   | $\lambda 5876$ | $\lambda 4471$ | $\lambda 5015$ | $\lambda 6678$ | $\lambda 4922$ | $\lambda 4388$ |
|------------------------------------------------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Lower Atomic Term                                                      | $2^3P$         | $2^3P$         | $2^1S$         | $2^1P$         | $2^1P$         | $2^1P$         |
| Recombination Theory: <sup>a</sup><br>( $T = 20,000K$ , $N_e = 10^6$ ) | 3.5            | 1.37           | 0.94           | 1.0            | 0.37           | $0.13^b$       |
| $\lambda$ Eri; 10/28:                                                  | $1.2 \pm .03$  | $0.0 \pm .04$  | $0.31 \pm .04$ | 1.0            | $0.39 \pm .04$ | $0.25 \pm .05$ |
| $\lambda$ Eri; 10/29:                                                  | —              | $0.1 \pm .04$  | $0.63 \pm .04$ | 1.0            | $0.52 \pm .04$ | $0.40 \pm .05$ |
| Cataclysmics:                                                          |                |                |                |                |                |                |
| T Leo <sup>b</sup>                                                     | 2.0            | —              | 0.69           | 1.0            | 1.07           | 1.1            |
| SU UMa <sup>b</sup>                                                    | 1.5            | 0.5:           | 0.86           | 1.0            | 1.07           | 2.0            |
| V603 Aqr <sup>b</sup>                                                  | 0.6            | —              | —              | 1.0            | 0.85           | 1.5            |
| J1802.1 +1804 <sup>c</sup>                                             | 1.8            | 1.3            | 0.7            | 1.0            | 0.8            | 0.3            |
| Symbiotics (S-Type) <sup>d</sup>                                       |                |                |                |                |                |                |
| He2-467 <sup>e</sup>                                                   | 0.43           | 0.13           | 0.15           | 1.0            | 0.40           | —              |
| HB475 <sup>f</sup>                                                     | 1.4            | 0.44           | —              | 1.0            | —              | —              |
| Z Cas <sup>g</sup>                                                     | 1.2            | 0.23           | —              | 1.0            | 0.47           | 0.3            |
| AS 289 <sup>g</sup>                                                    | 1.6            | 0.62           | 0.69           | 1.0            | 0.69           | 0.5:           |
| CL Sco <sup>g</sup>                                                    | 1.7            | 0.72           | —              | 1.0            | 0.77           | 0.2            |

<sup>a</sup> After Smits (1991)

<sup>b</sup> After Williams and Ferguson (1982)

<sup>c</sup> After Szkody et al. (1995)

<sup>d</sup> After Roga, Mikolajewska and Kenyon (1994)

<sup>e</sup> Munari and Buson (1992)

<sup>f</sup> Schmidt and Schild (1990)

<sup>g</sup> Blair et al. (1983)

The  $\lambda$  Eri  $\lambda 5015$  entries suggest that this line’s emissions show larger variations from event to event than  $\lambda 4922$  does. This could arise because variations in  $\lambda 4922$  strengths are attenuated by the existence of strong Stark broadening and a nearby forbidden component. These circumstances tend to deemphasize the effect of the underpopulation of the lower state ( $2^1P$ ) which would otherwise drive  $\lambda 4922$  into emission along with  $\lambda 6678$ . The alternative deexcitation routes for  $\lambda 5015$  are far less effective, and so changes in density can drive its source function more freely in one direction or the other. A similar explanation may hold for the small range of emission strengths in  $\lambda 4471$ .

One cannot take current model atmosphere theory much further. As with the confrontation with low-density recombination theory, the observed  $5876/6678$  ratio of  $\sim 1$  is a serious disagreement with Auer-Mihalas, which predicts  $\sim 0$ . This failing requires a search for an intermediate parameter range in both density and optical depth that can satisfy even the rather few constraints set in the table.

Anomalous singlet/triplet emission ratios are known to originate in the circumstellar regions surrounding cataclysmic and symbiotic variables. Table 1 gives He I emission ratios for three dwarf novae and a classical nova (V603 Aql) taken from Williams and Ferguson (1982, “WF”), as well as for the AM Her object, CV J1802.1 +1802 (Szkody et al. 1995). WF noted  $6678/5876$  ratios  $\sim 1$  along with rather flat decrements (not shared by  $\lambda$  Eri). They were able to model these ratios only by assuming high densities, large optical depths, and a He/H ratio of  $\sim 100$ . The abundance ratios of CVs are not currently thought to be quite so peculiar, so it can be concluded that the He line ratios of these objects should be reexamined.

The second group of stars to show similar behavior are the so-called S-type symbiotic stars which are interacting binaries consisting of a normal late giant and hot compact star. Mass exchange is responsible for circumstellar nebulae with densities of  $10^8$ - $10^{12}$

$\text{cm}^{-3}$  and thicknesses of several AU. A compilation by Raga, Mikolajewska, and Kenyon (1994, “PMK”) shows that their spectra have 6678/5876 ratios in just our range of interest, 0.44-2.3. Although the emission ratios show a range of values, the decrement values are uniformly steeper than the flat ones observed in CVs. The S-type symbiotics give a generally good match (cf. Z Cas) to the values found for  $\lambda$  Eri. This suggests that the solution to the  $\lambda$  Eri emissions can be found in the difficult-to-model intermediate densities where collisions ( $\lambda 5876$ ) and photoexcitational ( $\lambda 6678$ ) processes are respectively dominant among the various lines. For the optical He I lines this comes about at critical densities of  $N_e \sim 10^{11} \text{ cm}^{-3}$ .

Recent modeling of helium emission spectra in high density nebular environments has shown that the neglect of both collisional excitations and ionizations can be important (Clegg 1989). Almog and Netzer (1989, “AN”) have particularly emphasized the role of 3-body recombination in enhancing the line’s emissivity coefficient for  $\tau_{line} \geq 1$  and at  $N_e \sim 10^{11} \text{ cm}^{-3}$ . At still larger depths self-absorption causes the line emissivities to drop. The emissivity maxima of the lines occur at different depths because of their different critical densities, so that it becomes possible for different nebula to produce a range of line ratios depending on their precise conditions. For example, the 6678/5876 ratio goes through a maximum at moderate optical depth ( $\tau_{3889} \sim 10$ ). RGK have utilized AN’s methodology to recompute the line ratios for specific symbiotic systems. They showed that the 7065/5876 and 6678/5876 ratios can be used to determine both the  $N_e$  and optical depth for these environments. Their models indicate that the nebular densities can reach  $10^{12} \text{ cm}^{-3}$  and  $\tau_{3889} \sim 100$ -1000 in some cases. Thus they become relevant to the transient emissions of  $\lambda$  Eri. We used these results earlier to estimate spatial scales and emissivities in Section 3.1.

### 3.3. Emissions by Recombination or Auer-Mihalas (or Both)?

Triplet He I lines of stellar spectra are formed in tenuous, extensive chromospheres such as in cool giants and Cepheids (O’Brien and Lambert 1985, Sasselov and Lester 1994). These atmospheres bear little similarity to atmospheres of hot main sequence stars, so one does not normally think of recombination playing even a secondary role in early-type spectra. This makes the importance of recombination all the more intriguing as a possible dominant line formation mechanism in  $\lambda$  Eri’s exosphere. On the other hand, despite the agreement of the  $\lambda$  Eri and symbiotic star results, we do not believe that we can rule out the Auer-Mihalas mechanism yet. It is possible that the  $\lambda 6678$  and  $\lambda 5876$  emissions shown in Figure 1 occur primarily in separate high and low density regions, respectively. Although we do not prefer this explanation, there are a few arguments in favor of it. The first is that the emission profile of  $\lambda 5876$  is broader and blueshifted by  $30 \text{ km s}^{-1}$  compared to the singlet emissions. [We are aware of one other object, the interacting Be binary  $\phi$  Per, for which these two lines follow different velocity curves (Hendry 1977, Gies et al. 1993), suggesting separate sites for their formations.] Second, the weakening of the C IV and He II UV lines with the appearance of dimples (Smith et al. 1996) and emissions shows that the line of sight over at least 10% of the projected area of  $\lambda$  Eri is affected by these events. This argues that a large volume of the exosphere is involved. The difference between the high density recombination and two-site models is in one sense the inevitable difference between any single- versus two-parameter representation; hence they are difficult to distinguish. Both pictures rely on a flare-like transient illuminating a region of the star’s surface. The latter supposes a source of corpuscular radiation that impacts and ablates photospheric material. The single-parameter, modified-recombination picture causes emissions by a combination of collisional, photoexcitational, and recombinational processes. We prefer the single-site model for the September 12 event because it clearly shows a decay timescale indicative of an intermediate density plasma. We suspect that the primary discriminant between the two pictures will ride on the similarities or differences in the He I emission

profiles and velocities.

### 3.4. $\lambda 1640$ Emission

Emission in the  $\lambda 1640$  line (Figure 5) presents a similar interpretational problem as the triplet/singlet ratio because emission in this line may occur either from recombinations by irradiation or via radiative excitations from the stellar continuum. As an example of the second process, consider that AM72 predicted emission in the  $\lambda 1640$  line of O star atmospheres as a consequence of the inequality  $J_\nu > B_\nu$  in the far-UV radiation field. For  $\lambda$  Eri the strongest clue is probably the similarly redshifted emissions of the He I and He II lines, indicating they are formed in proximity to one another close to the photosphere. We also note that Wahlstrom and Carlsson (1994) have resolved an old controversy on the origin of solar  $\lambda 1640$  emission in favor of recombination from EUV coronal back-radiation. These authors also found the line’s emission strength to be very sensitive to modest changes in the EUV flux. Finally, we point out that  $\lambda 1640$  emission is common in the spectra of Of stars (Walborn, Nichols-Bohlin, and Panek 1985) probably because of their extended atmospheres. Observations of Balmer He II lines will be needed to resolve whether the  $\lambda 1640$  emissions in Be star spectra occur within or above the photosphere.

### 3.5. Irradiation from an XEUV Source?

To test the idea that recombination might be important for the emission in the  $\lambda 5876$  line of  $\lambda$  Eri, we have adapted J. MacFarlane’s heated-wind program to treat back-irradiation from an external XEUV source. The EUVE observations of  $\epsilon$  CMa show that the strongest EUV spectral feature is a He II  $\lambda 304$  emission line (Cassinelli et al. 1994). We now consider the effect of such an illumination on the optical He I line emissions

in  $\lambda$  Eri.

#### 4. Conclusions

*These are random thoughts; not meant to be part of the text yet:*

High temperature plasma is/is not necessary to excite He II  $\lambda 304$  and He I triplet line emissions.    ????

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Fig. 1.— A comparison of the behaviors of  $\lambda 5876$ ,  $\lambda 6678$ ,  $\lambda 5015$ , and  $\lambda 4922$  lines during transient emissions in the photospheric profiles of  $\lambda$  Eri on 1993 October 28. We show the final observation (dashed smoothed line) in its Fourier-smoothed form for contrast. Note that the emission strength (arrow) diminishes only slightly from  $\lambda 5876$  to  $\lambda 6678$  and is just detectable in the blue lines. The emissions to the red of line center (dashed arrows) show similar ratios as the central emission recorded in Table 1.

Fig. 2.— A comparison of the behaviors of  $\lambda 6678$ ,  $\lambda 5015$ ,  $\lambda 4922$ , and  $\lambda 4388$  lines flickering transient emissions in the cores of He I profiles of  $\lambda$  Eri. The solid and dashed lines represent observations at 8:42 UT and 9:44 UT, respectively, on 1993 October 29.

Fig. 3.— A pair of consecutive observations of  $\lambda 6678$  showing a decaying transient in the red wing. Both the flux and decay timescale of this feature provide strong evidence that the emission is due to recombination in a exospheric structure with a density of  $\sim 10^{11} \text{ cm}^{-3}$ .

Fig. 4.— A comparison of He II  $\lambda 1640$  line strengths (upper panel) against several He I  $\lambda 6678$  profiles (lower panel). Note the dip in the  $\lambda 1640$  line strength at about 13 U.T., coincident with a decrease in the emission on the red wing of the He I line.

Fig. 5.— A comparison of He II  $\lambda 1640$  profiles from IUE SWP images SWP 32234, 32236, and 32238. The middle spectrum coincides with the equivalent width dip noted in *Figure 3* at 12:42 UT. Dashed lines represent the Fourier-smoothed profile of the preceding observation.

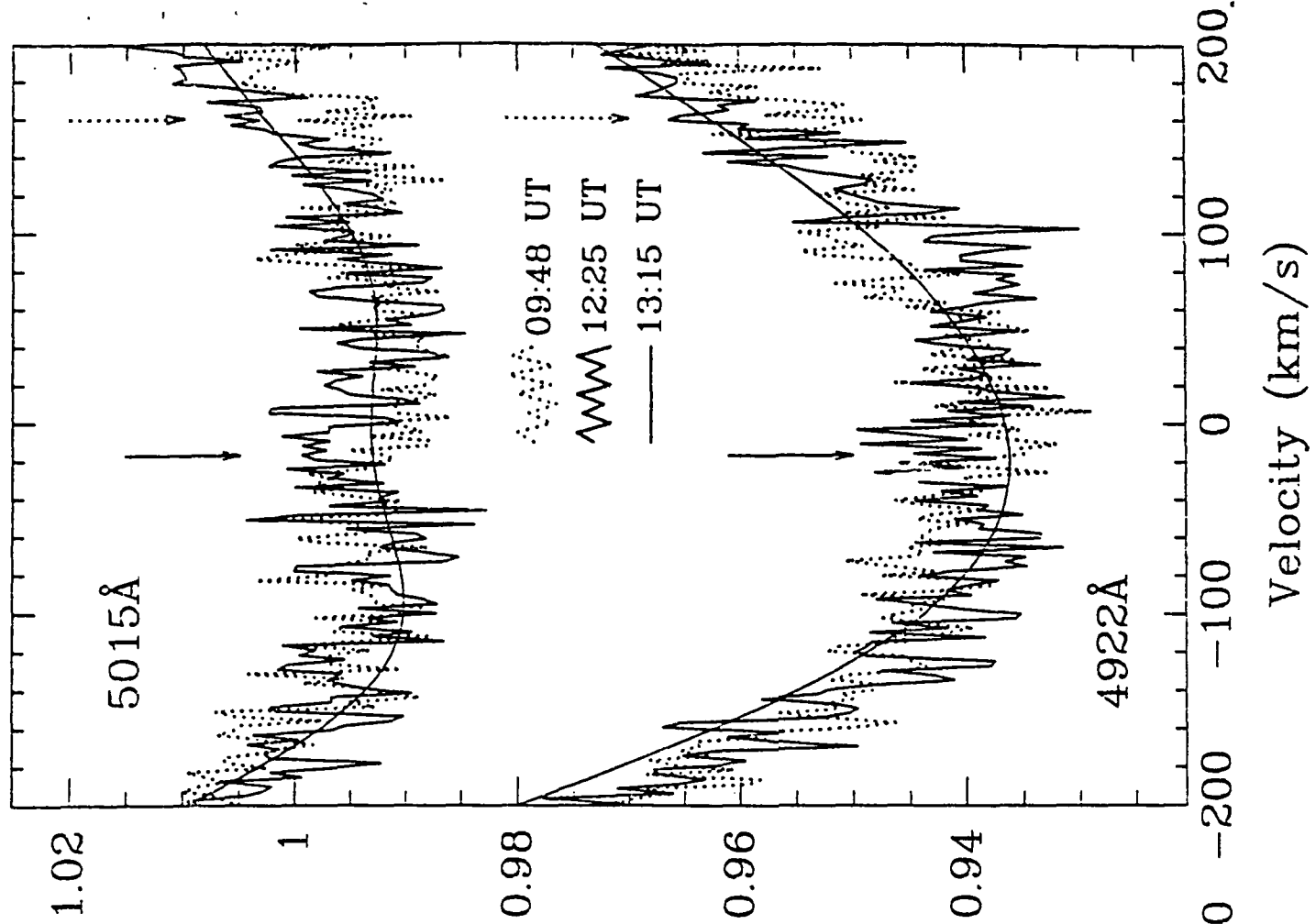
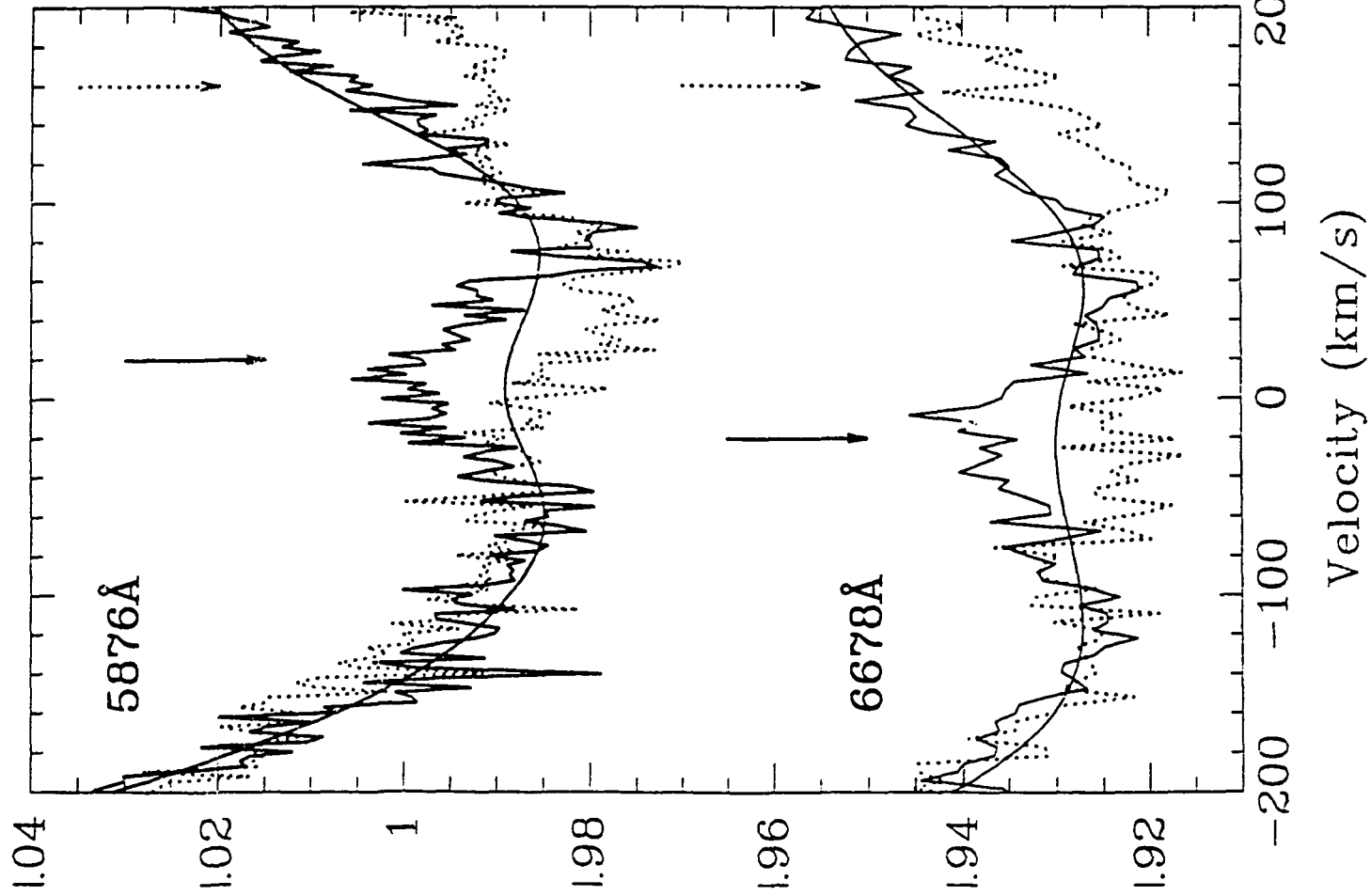
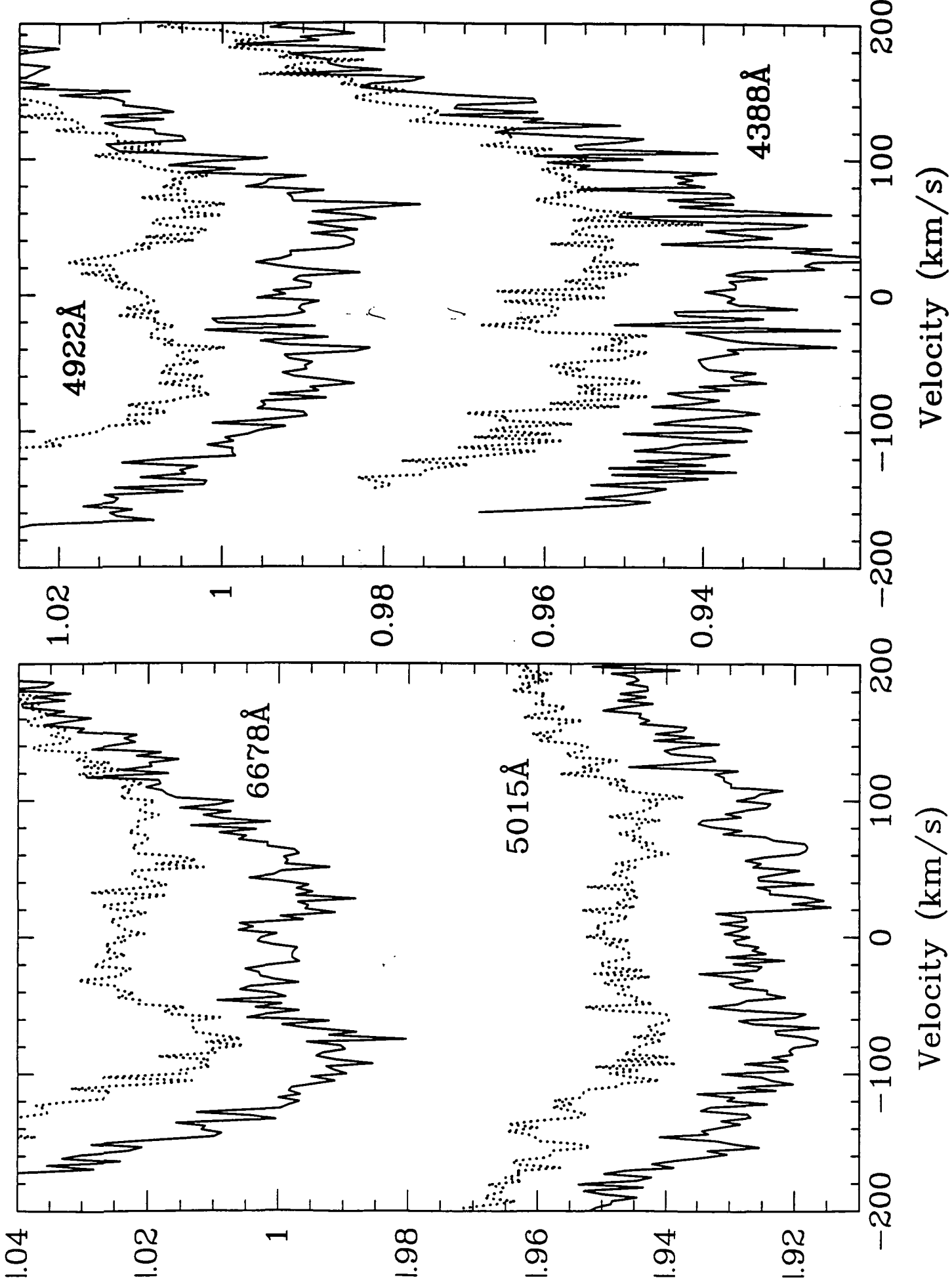


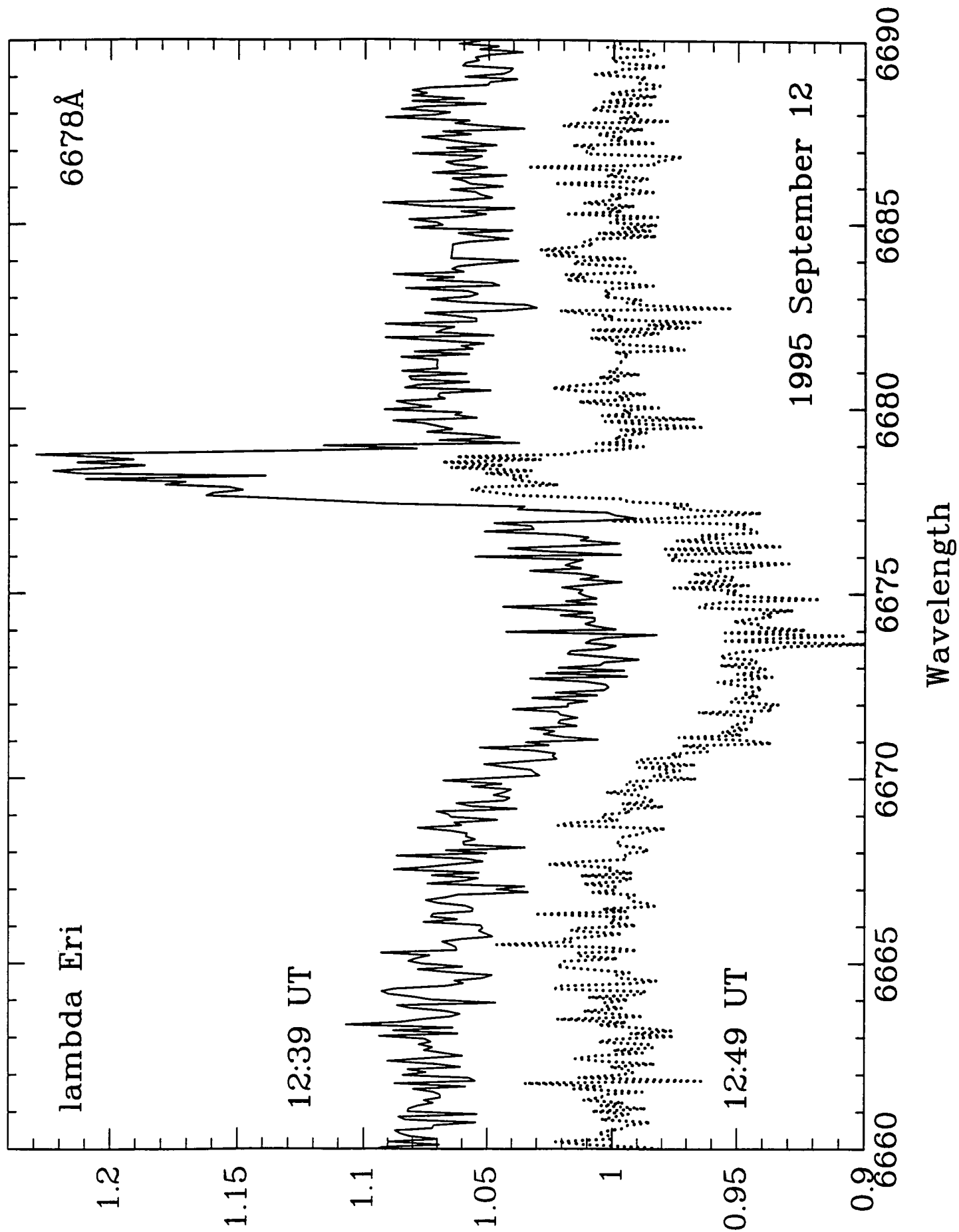
Figure 1

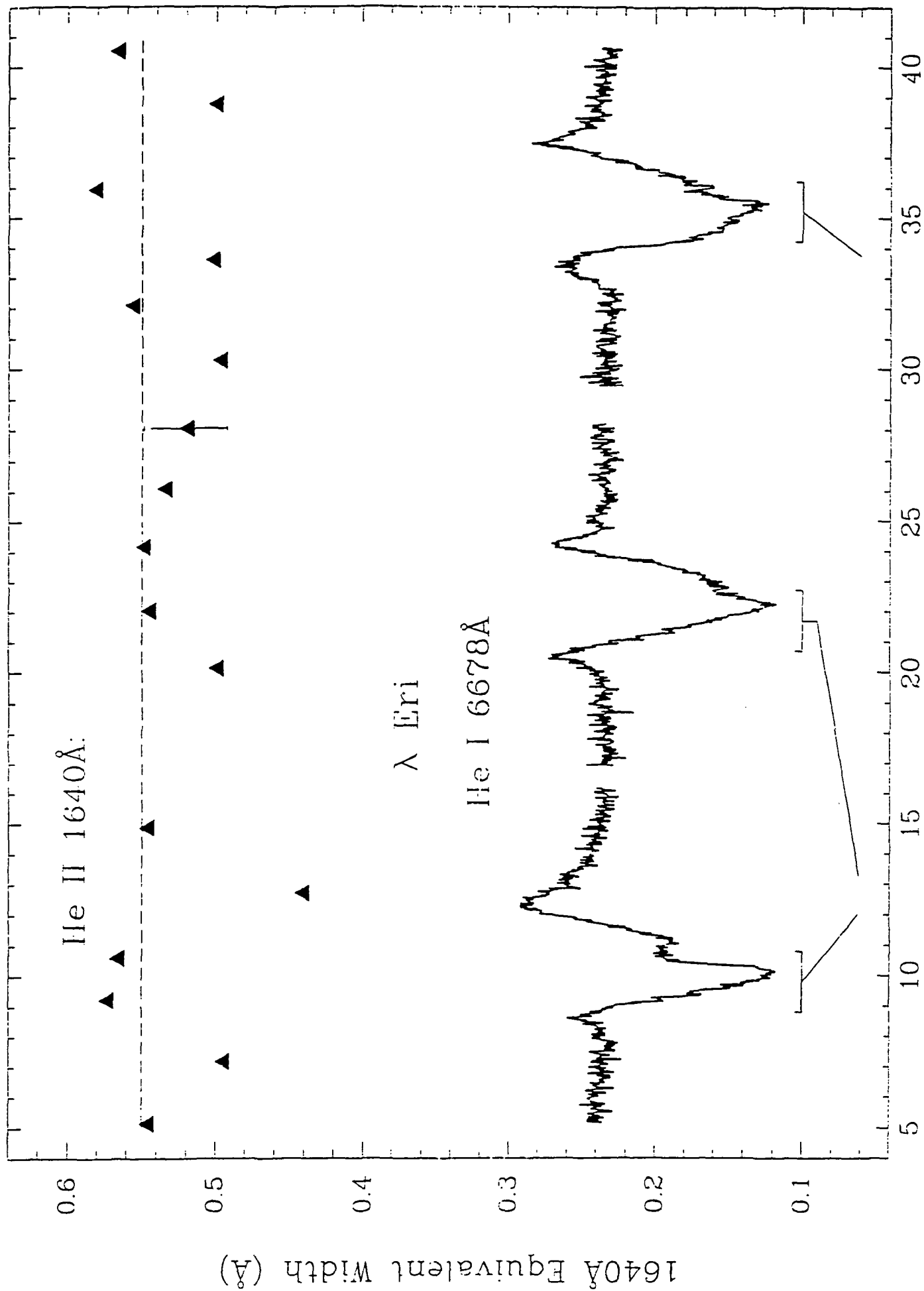
Fig 2



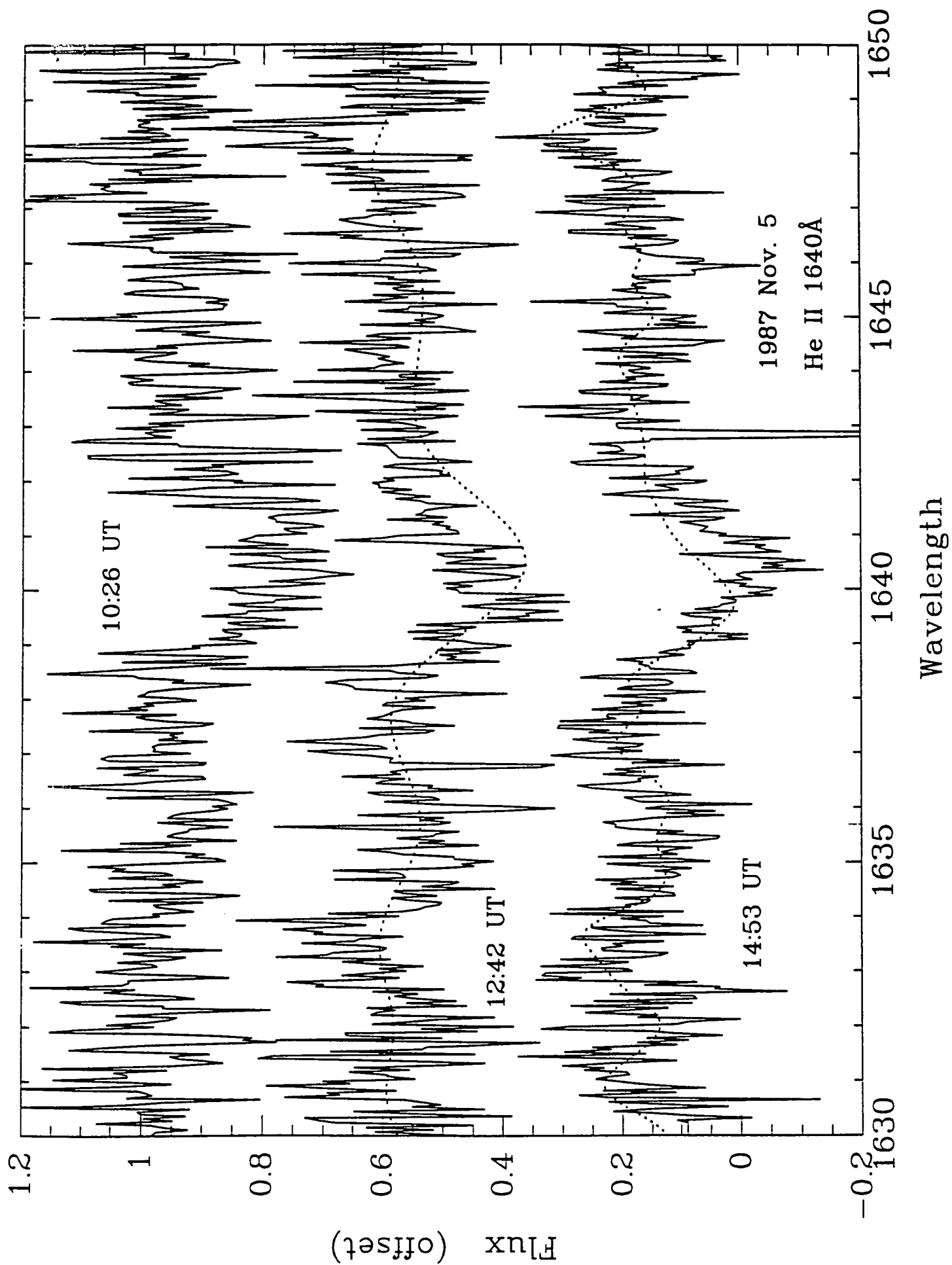
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Fig 3





U.T. on 1987 November 5-6



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