# 500 - 3200 Å OBSERVATIONS OF THE INTERACTING BINARY STARS V356 SGR AND $\beta$ LYR

R. S. Polidan
Lunar and Planetary Laboratory-West
University of Arizona
Tucson, AZ 85721
U.S.A.

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ABSTRACT. In this paper we present new results from the Voyager ultraviolet spectrometers and the IUE spacecraft on V356 Sgr and $\beta$ Lyr. The V356 Sgr observations cover, in detail, two eclipses and include one IUE high dispersion SWP image. During both eclipses the total strength of the UV emission lines were found to be invariant. Also, an uneclipsed UV continuum was detected at wavelengths shorter than 1600 Å. The IUE high dispersion SWP spectrum revealed that the emission lines are extremely broad, almost symmetrical lines with weak, slightly blue shifted absorption components. No evidence of carbon is seen in the emission or absorption spectrum of V356 Sgr in eclipse. A model for the origin of the circumstellar matter in this binary system is presented. The Voyager ultraviolet observations of $\beta$ Lyr show a strong far-UV continuum that is detectable down to 912 Å The far-UV continuum flux level was variable on time scales shorter than the orbital period and displayed no obvious orbital modulation *or* eclipses. The spectral shape of the far-UV continuum closely resembles that of a UX UMa type cataclysmic variable. On 16 August 1985 an rapid brightening of the far-UV continuum was observed which was also reminiscent of cataclysmic variables. Analysis of the $\beta$ Lyr data suggest that the central object must be small, with a radius on the order of 1 $R_{\odot}$ or less.

## 1. INTRODUCTION

In this paper we present observations obtained with the Voyager and IUE spacecraft of two massive eclipsing binaries: V356 Sgr and $\beta$ Lyr. The IUE spacecraft and its capabilities are well known to most observers. The Voyager Ultraviolet Spectrometers (UVS) are less well known. These instruments are sensitive in the 500-1700 Å region and have an effective spectral resolution of ~18 Å (~2 channel resolution with 9.26 Å per channel). The instruments have been fully described by Broadfoot et al. (1977).

## 2. V356 Sgr

V356 Sgr is a massive eclipsing binary with a period of 8.896 days and a total eclipse of 11 hours duration. Both components of the binary are spectroscopically visible in the optical. Eclipse depths in V are 0.87 and 0.39 magnitudes, respectively, for primary and secondary minimum. Period changes suggest a steady, very low rate of mass transfer (~$10^{-7}$ $M_{\odot}$ $yr^{-1}$) is occurring within the system. V356 Sgr also has some of the best determined

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physical dimensions of any interacting binary (cf. Popper 1980). Table 1 lists the physical characteristics of this binary. V356 Sgr is moderately reddened, with an E(B-V) as determined from the individual colors of the components and from the 2200 Å feature of 0.23±0.03 magnitudes. The most quoted model for V356 Sgr is that proposed by Wilson and Caldwell (1978). In their model they propose the B3 star is critically rotating and that there is a geometrically thick, opaque, non-luminous ring or disk round the B3 star. The assumption of critical rotation would remove the problem of the unexpectedly high but well determined mass for the B3V star but introduce the complication of a stellar surface that can no longer be characterized by a single effective temperature (cf. Slettebak, Kuzma, and Collins 1980). Ultraviolet ($\lambda$ > 1200 Å) emission lines were subsequently discovered with IUE in this star by Plavec et al. (1984). The UV emission lines are amongst the strongest detected in any Algol system. Despite this they can be seen only during the total eclipse of the system; the ultraviolet flux from the B3 star overwhelms them at all other times. No optical emission lines, including H$\alpha$, have ever been reported in V356 Sgr. However, recent high signal-to-noise spectroscopic observations of V356 Sgr obtained in the H$\alpha$ region during primary eclipse show a probable weak, broad filling "emission" in the H $\alpha$ line.

Table 1. V356 Sgr

| | | |
|---|---|---|
| Period (days) | 8.896106 | |
| Spectrum | B3V | A2II |
| Mass ($M_\odot$) | 12.1±1.1 | 4.7±0.6 |
| Radius ($R_\odot$) | 6.0±0.7 | 14.0±1.5 |
| Log g | 3.96±0.10 | 2.82±0.10 |
| $V_{escape}$ (km s$^{-1}$) | 877±65 | 358±30 |
| V sin i (km s$^{-1}$) | 350 | 90 |
| $V_{sync}$ (km s$^{-1}$) | 33 | 77 |
| $T_{eff}$ (K) | 16500±750 | 8600±300 |
| $\dot{P}$ | 4 x $10^{-9}$ | |
| $\dot{M}$ ($M_\odot$ yr$^{-1}$) | 4 x $10^{-7}$ | |

## 2.1 Observations

The new IUE and Voyager UVS observations were obtained in 1986 and 1987, with most of the data taken during two primary eclipses (when the B3 star is occulted). The eclipse of 15 August 86 was covered with 12 SWP and 8 LWP IUE low dispersion images and 9 hours of Voyager UVS data. The eclipse of 25 Mar 87 was covered with 7 SWP and 6 LWP IUE low dispersion images and 1 high dispersion SWP image. No Voyager UVS data was obtained during this March eclipse. Additional IUE SWP and LWP low dispersion images were obtained after the two observed eclipses. Supplemental Voyager UVS data were obtained prior to the eclipse on 15 August 86 and in May 87.

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## 2.2 Optical Light Curve

The IUE FES was used to obtain an optical light curve for the eclipses in V356 Sgr. The FES light curves suggest two conclusions: 1) The quadratic ephemeris of Hall, Henry, and Murray (1981), 2433900.766 + 8.896106E + $3.5 \times 10^{-8}E^2$, best fits the data. The significance of the second order term is confirmed. 2) There is suggestive evidence of changes in the shape of the eclipse shape from the two IUE FES light curves.

## 2.3 Ultraviolet Flux Distribution

UV light curves were generated from the IUE low dispersion images in three narrow continuum bands in the UV, 25, 65, and 250 Å bands centered, respectively, at 1262, 1908, and 2625 Å. These three light curves and the FES light curve were then ratioed to a reference spectrum (the observed IUE spectrum, appropriately scaled and reddened, of the A3 star 38 Lyn). The 1908 and 2625 Å light curves appear relatively normal. The 1262 Å curve, however, showed a substantial excess over that expected. Detailed comparison of the mid-eclipse spectrum of V356 Sgr with standard A stars in the IUE archives showed a strong UV excess beginning near 1600 Å (see Polidan 1988). During the total phase of the eclipse the B3 star can contribute no observable flux. Therefore, this UV excess *cannot* arise in the B3 star. Voyager 500-1200 Å observations produced only a marginal detection of V356 Sgr during eclipse. This suggests that the characteristic temperature of the UV excess is comparable to or slightly cooler than that of the (composite temperature) B3 star. Since the source of the flux is also (predominantly) uneclipsed by the A2II star it must either arise outside the domain of the B-star or be of significantly larger radius than the A2 giant. The eclipse spectrum was compared to an appropriately scaled and reddened spectrum of 38 Lyn, a single A3 star. The fit was excellent for $\lambda > 1600$ Å. Subtraction of this reference spectrum from the observed eclipse spectrum then revealed the spectral shape of the ultraviolet "excess." It was immediately apparent that the shape of this UV excess was strikingly similar to that of V356 Sgr observed outside of eclipse. A synthetic "electron scattered" spectrum was then generated by taking the observed maximum light spectrum of V356 Sgr and smoothing it with a 20 Å boxcar smoothing function. This synthetic "scattered light" spectrum was scaled and added to the 38 Lyn spectrum discussed above. A superb fit was obtained to the observed V356 Sgr eclipse spectrum, over the entire spectral range, assuming that one percent (1%) of the total system light is scattered into our line of sight during the eclipse (see Polidan 1988). Thus, the origin of the ultraviolet flux excess in V356 Sgr appears to be system light scattered into our line of sight by electrons that reside in an extended cloud or clouds some distance from the two stars in the binary. This model makes one prediction: the ultraviolet flux shortward of ~1600 Å seen in V356 Sgr during the total eclipse should be polarized since it arises solely from electron scattering.

## 2.4 Ultraviolet Emission and Absorption Lines

Using the data obtained from the low dispersion IUE images it was discovered that the total strengths of the UV emission lines in V356 Sgr were invariant during both eclipses (Figure 1). This suggests that the UV emission line formation region is outside the immediate domain of the two stars in the binary. These observations imply a possible association of the UV emission line formation region with the region responsible for the ultraviolet excess seen in V356 Sgr and discussed above. A high dispersion IUE SWP spectrum obtained in March, 1987 revealed that these UV emission lines are extremely broad, FWHM ~1100 km $s^{-1}$, almost symmetrical emissions with weak, slightly blue shifted absorption components (Figure 2). Also, apparent in the high dispersion IUE image is that

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the "C IV" emission line reported in previous investigations is *not* the carbon doublet but rather dissolves into numerous weak emissions of, probably, Fe III. No evidence of carbon, C II, C III, or C IV, is seen in the *emission* spectrum of V356 Sgr during eclipse. Line profile fits to the emission line data suggest that *all* lines can be fit with the same line shape parameters. *No* evidence supporting a stratified line formation region was found. The strengths of the carbon emission lines (C II, C III, and C IV) in V356 Sgr are at least a factor of twenty weaker than the silicon lines (Si II, Si III, and Si IV). Similarly, no evidence is found for carbon in the photosphere of the A2II star in V356 Sgr (Figure 3). Inspection of the high dispersion non-eclipse IUE images of V356 Sgr reveal a relatively normal early-B stellar spectrum, *including* carbon lines. A comparison of the relative strengths of the photospheric C III $\lambda1247$ and Si II $\lambda1264$ lines for B3 in V356 Sgr and a set of normal B2.5 to B5 stars with similar rotational velocities showed that the C III line in V356 Sgr is of at least normal strength, if not somewhat stronger than expected, for its spectral type. Thus, we must conclude that the B3V component of V356 Sgr has an essentially normal carbon abundance while the A2II star and the circumstellar matter in the system have no observable carbon. How are these two carbon line observations compatible? Simple arguments (cf. those presented for other binaries in Peters and Polidan 1984) can show that the secondary (A2II) star has likely lost enough mass to have reached its CNO processed layers. These layers will be virtually devoid of carbon and slightly nitrogen rich (cf. Peters and Polidan 1984). Thus, a compositional difference is *expected* to exist between the two components of the binary system.

Two questions remain to be answered: how are these high ionization lines formed and what is their geometrical distribution? We have begun to address the first problem of the line formation mechanism using detailed, multi-level, atomic calculations. At this, very preliminary, stage of the calculations it appears that resonance scattering is the most likely method for formation of the high ionization lines seen in V356 Sgr. In an attempt to constrain the geometrical properties of the extended line formation region the emission lines of Al III 1855, 1863 were examined in detail. These lines are seen superimposed on the photospheric spectrum of the A star. Any gas in the emission line region existing along the line of sight to the A star, i.e. in the orbital plane of the binary, would absorb (or scatter) light from the A-star. *No* significant absorption of the A star's photospheric light was detected in either line of the doublet, suggesting a small optical depth for the gas in the orbital plane. The apparent lack of absorption thus argues for a line formation region that is predominately outside the orbital plane. These observations suggest that the probable distribution of the high ionization line formation region and, by association, the scattering cloud in V356 Sgr is in "polar caps," regions located above and below the orbital plane, with little gas in the orbital plane.

## 2.5 Stellar Components

The Voyager UVS and IUE data inside and outside of eclipse observations have also supplied information regarding the two stellar components of the V356 Sgr system. With the exception of the carbon abundance, discussed above, the A2II star appears spectroscopically and photometrically similar to standard A2/3 stars of similar luminosity class. The same cannot be said for the "B3" star. The combined 912-3200 Å flux distribution of this star cannot be fit with a single Kurucz stellar model atmosphere. A model with an effective temperature near 16500 K will adequately fit the ~1300-3200 Å region but falls far below the observed flux at 1000 Å. A hotter model will fit the far-UV but not the near-UV. However, the entire 912-3200 Å spectral region can be fit using a Collins and Sonneborn (1984), critically rotating, stellar model atmosphere. A generalized conclusion of their model calculations is that a critically rotating star has, for the most part, the flux distribution and spectral characteristics of a star one or two spectral subclasses cooler yet retains, essentially, the mass, radius and luminosity of the earlier (non-rotating) spectral type. Given these results, a more accurate characterization of the B-star in V356 Sgr is a B1 star that is critically rotating and only *looks*, longward of 1200 Å, like a B3 star. The $T_{eff}$ listed in Table 1 is the best fit to this 1200-3200 Å continuum. At shorter wavelengths the hotter, polar regions are more important (cf. Slettebak, Kuzma, and Collins 1980) and the continuum is characterized by a higher effective temperature. These results strongly support the suggestion of Wilson and Caldwell (1978) that this B-star is critically rotating.

### 2.6 Model

Shu et al. (1988) have proposed a model for a magnetically assisted accretion driven wind for critically rotating pre-main sequence stars. This "X-celerator" mechanism model can, with little modification, be directly applied to V356 Sgr. Carbon poor material will be transferred to a small accretion disk surrounding the B3 star. Using Shu's arguments, a portion (~75%) of this disk material will be accreted by the B3 star with the remainder being driven away in a wind with a characteristic velocity near the escape velocity of the B3 star and ejected preferentially in directions away from the orbital plane. Thus, this model predicts a gas outside the orbital plane with the chemical composition of the secondary but the velocity characteristics of the primary.

## 3. $\beta$ Lyr

$\beta$ Lyr has puzzled investigators for decades. This binary has a 13 day orbital period and consists of a B8II star that is prominent in the near-UV and optical regions and a luminous disk-like secondary. The physical parameters and exact nature of the secondary object are currently disputed. The best model for $\beta$ Lyr remains that of Wilson (1974). Recently, Dobias and Plavec (1985) have rediscussed the system in terms of the its distance, reddening, luminosity, and age. The UV spectrum of $\beta$ Lyr has been known to be dominated by an anomalous UV continuum and very strong emission lines since the first spacecraft observations (cf. Hack et al. 1975).

### 3.1 Observations

The majority of the Voyager UVS data on $\beta$ Lyr discussed in this paper were obtained during one nearly continuous observing period between 3 and 18 August 1985. During this period one UVS spectrum was obtained every 3.84 seconds. Gaps exist in the data because of ground station difficulties and attitude drift in the spacecraft. In addition to the 1985 data, two UVS observations obtained in 1983 and 1984 have been included in the analysis.

Figure 4 shows the Voyager UVS spectra of $\beta$ Lyr at four phases. The strong emission lines seen by previous observers are apparent in these spectra. Longward of ~1200 Å the flux is dominated by the B8II star and exhibits the expected orbital variation. Shortward of 1200 Å it is expected that the B8II star should show a dramatic drop in flux, producing little detectable flux. What is observed is a surprisingly strong, constant flux. Figure 5 shows the light curve for $\beta$ Lyr at two *continuum* wavelengths: 955 Å, where the anomalous far-UV flux dominates and 1475 Å, where the B8II star dominates. There is no statistically significant evidence for eclipse effects in the 955 Å light curve of $\beta$ Lyr. The 1475 Å light curve, however, displays the expected light variations. Thus, *$\beta$ Lyr is not an eclipsing binary at wavelengths shortward of 1200 Å.*

From the 955 Å light curve in Figure 5 it can be seen that there is no obvious orbital modulation. Significant variations are seen in the data but they do not repeat; it appears that the disk in $\beta$ Lyr is unstable. This is graphically illustrated in Figure 6 where the observation of a cataclysmic variable (CV) like "outburst" in $\beta$ Lyr is shown. In this figure the 955 Å data for $\beta$ Lyr is plotted versus unfolded orbital phase. Note the rise in flux beginning near orbital phase 1.6 (16 August 1985). This rise is not an orbital modulation (note the flux level one cycle earlier at phase 0.6) but a significant increase in the brightness of the disk. At 955 Å the flux increased by ~50% in approximately 40 hours. The amplitude of this flux increase decreases rapidly toward longer wavelengths, reaching almost undetectable levels at 1475 Å (Figure 5). The spectrum of this added flux is identical to the far-UV continuum seen in $\beta$ Lyr, *minus the lines.*

## 3.2 Model

The wavelength dependent light variations and the spectral appearance of $\beta$ Lyr can be understood if it is assumed that the secondary object in this binary is simply a large, massive, CV-like accretion disk. A comparison of the far-UV flux distribution of $\beta$ Lyr and the flux added to the continuum during the "outburst" with existing Voyager UVS observations of a variety of objects has shown that the closest match is with the spectrum of a "high" state CV-like accretion disk, e.g. V3885 Sgr or SS Cyg in outburst. The Voyager $\beta$ Lyr spectrum is strikingly similar to the observed spectrum of the UX UMa class cataclysmic variable star V3885 Sgr (P~0.2 days) scaled by 4.75 magnitudes. Both stars display the uniquely characteristic spectral flux distribution of a hot, luminous accretion disk. The P-Cygni emission lines seen in V3885 Sgr map exactly into the strong emission lines seen in the Voyager spectrum of $\beta$ Lyr. These results suggest that the disk-like secondary in $\beta$ Lyr can be best characterized as a large, massive CV-like accretion disk. Assuming that the similarities in the flux distributions of $\beta$ Lyr and V3885 Sgr extend to the optical, the visual magnitude of the accretion disk in $\beta$ Lyr would be ~5.5 to 6.0, supplying 10% or less of the total system optical luminosity. The transition of $\beta$ Lyr from eclipsing binary at optical wavelengths to non-eclipsing binary at far-UV wavelengths can be understood if one accepts the radial temperature gradient of the theoretical models for luminous accretion disks and assumes a slightly lower value for the orbital inclination than is given in Wilson (1974). At longer wavelengths, specifically in the visual region, the emitted flux from the accretion disk is dominated by the cooler outer portion of the disk. This outer region is regularly eclipsed by the B8II star. The FUV (955 A) flux, however, arises in the very innermost parts of the disk and because of the inclination of the system these regions are not eclipsed by the B8II star. The absence of secondary eclipses in the far-UV can be understood by realizing that the B8II star intrinsically produces very little (<2%) of the total system flux shortward of 1200 Å. With the intrinsically unstable secondary and the signal-to-noise of the UVS data these small eclipses would not be observable. This model requires one additional change to the current $\beta$ Lyr models. In order to achieve the higher temperatures necessary to produce the observed FUV flux the central accreting object in the disk must be small. Accretion onto a main sequence star cannot reproduce these observations. Using standard accretion disk models (cf. Wade 1984) the central accreting object must have a radius on the order of 1 $R_{\odot}$ or smaller in order to produce the observed far-UV continuum in $\beta$ Lyr.

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## DISCUSSION

Wilson agreed that it is very difficult to account for the absence of eclipses in β Lyr at short wavelengths, since whether there is a star of some kind or a disk, something should be eclipsed. Optical light-curves show that a thin disk cannot produce the observed eclipses of the late B-type star, so there must be a thick disk in the system. He asked if Polidan could rule out completely the possibility that inside the disk there is a main-sequence star, whose radiation, as seen by us, is either thermalized or entirely blocked. In that case, the radiation we see must come from outside the binary system. Polidan replied that this could not be ruled out, but he thought it unlikely. Any star cooler than B0 could be ruled out, and the observed flux distribution does not fit that of B0 star well. Behaviour during outbursts strongly suggests that we are looking at a luminous disk (T ~ 50,000 K) and to match the observed flux distribution requires a small object (not a main-sequence star) at the centre. If the UV flux comes from outside the system, there would have to be a lot of mass out there and the observed outbursts would be difficult to explain. Since, as Guinan had reported (p.39), the optical light-curve is more variable than has been realized until now, perhaps new light-curve solutions are needed taking into account all the available data. He thought that a model incorporating a disk inclined only a few more degrees to the line of sight than currently accepted could reconcile many of the apparently puzzling features. Eaton asked if uneclipsed extreme ultraviolet light could be radiation from the disk scattered by gas from above the disk. Smak asked to what percentage of the total flux the uneclipsed extreme UV flux amounted. To Smak's question, Polidan answered: probably around three per cent to five per cent, and certainly less than ten per cent. He emphasized again that the observed outburst made it difficult to explain the phenomena in terms of anything on the outer edge of the system. Hilditch recalled that Kilkenny (and others) had shown that rapidly rotating B stars appeared to have spectral types about two sub-types later than their true types. Parthasarathy pointed out that there was evidence that the so-called B8 II star in β Lyr was really B6 and helium-rich. We should be cautious in assigning spectral types in this system.

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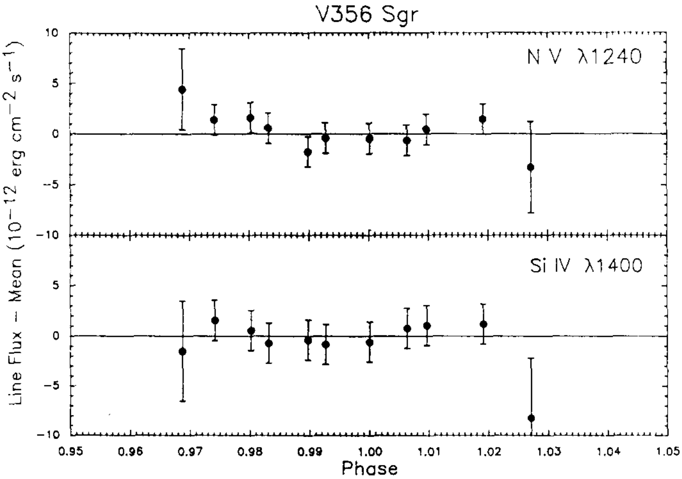


Figure 1. N V 1240 and Si IV 1400 line strength differences (observation - eclipse mean) as a function of phase during the eclipse of 15 August, 1986.

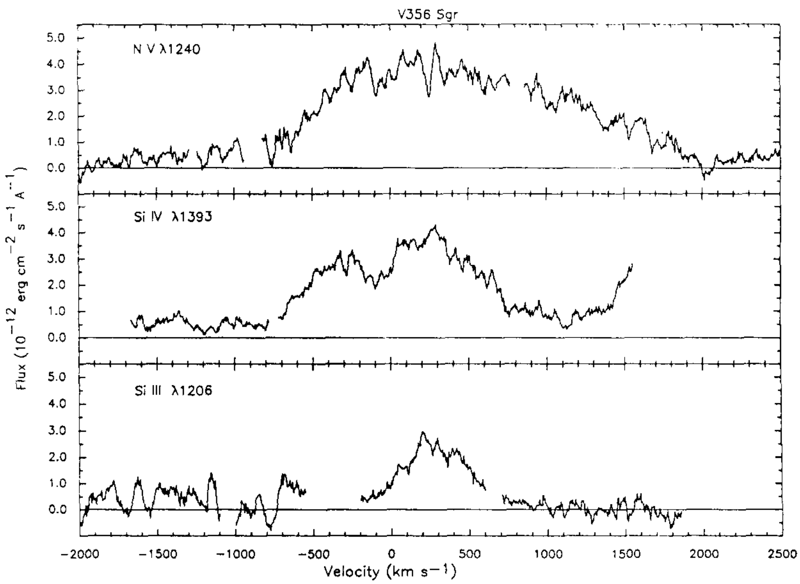


Figure 2. Emission lines of N V λ1238 and 1242 (at +964 km $s^{-1}$ in this velocity plot), Si IV λ1393, and Si III λ1206 from the high dispersion SWP image obtained during the eclipse of 25 March, 1987. Dotted lines are drawn at $\pm V_{escape}$ for the B3 star.

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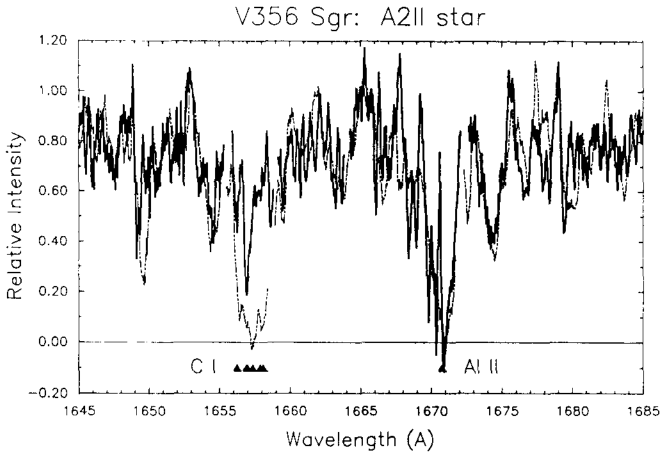


Figure 3. Region of the expected strong photospheric C I line in the A2II component in V356 Sgr. The dashed curve is the spectrum of the A2III reference star ς Sgr. Note the complete absence of a carbon line in the A2II star's atmosphere. The sharp C I line is the interstellar component.

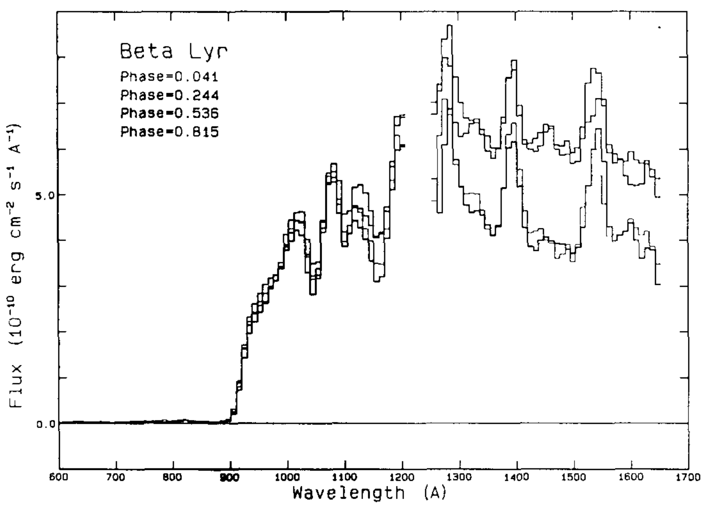


Figure 4. The Voyager specta of $\beta$ Lyr at four phases.

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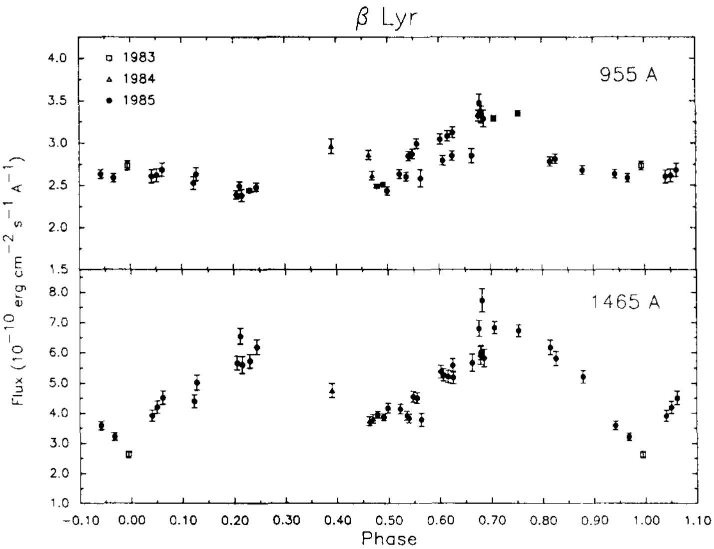


Figure 5. 955 and 1475 Å light curves for $\beta$ Lyr.

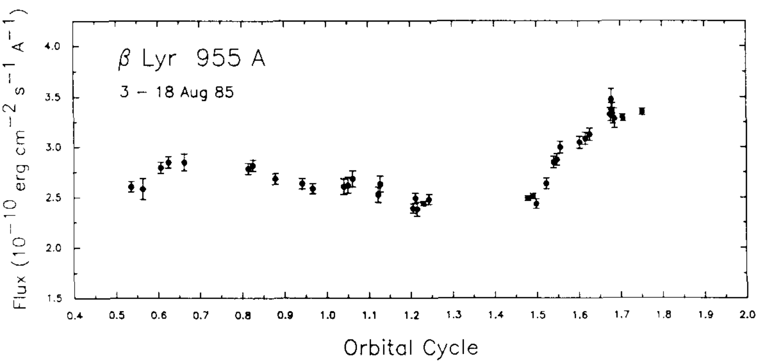


Figure 6. The 955 Å light curve for $\beta$ Lyr between 3 and 18 August 1985 versus unfolded orbital phase showing the "outburst" discussed in the text.