

# Inter-Eclipse Spectroscopic Snapshot of Epsilon Aurigae with *HST*

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## ABSTRACT

A single-epoch low resolution GHRS spectrum of the eclipsing binary Epsilon Aurigae was obtained while the secondary was orbiting towards eclipse by the primary. The spectrum as recorded between 1175–1461 Å is rich with emission and absorption lines which include stellar and interstellar components. The emission line profiles have the appearance of double-peaked emission with a stronger red component at a radial velocity of +108 km s<sup>-1</sup>, an overlying unresolved absorption component at -20 km s<sup>-1</sup> and a weaker blue emission bump at ca. -92 km s<sup>-1</sup>. We compare these observational results with known orbital properties of the ε Aur binary system, and propose that the emission originates at the inner radius of the disk surrounding the enigmatic secondary. We interpret the kinematic data as a possible means to uncover the underlying stellar masses and we speculate about the binary’s relationship to other “high-mass” models.

*Subject headings:* binaries: eclipsing — line: profiles — stars: individual (ε Aur)  
— techniques: radial velocities — ultraviolet emission

## 1. INTRODUCTION

The EA-type variable star Epsilon Aurigae (HD 31964, HIC/P 23416, spectral type F0 Ia) exhibits fadings of about 0.8 mag in  $V$  every 27.1 years, which are attributable to eclipses by an invisible flattened disk of “dark matter” (Huang 1965, Wilson 1971). The nature of the disk and the identity of whatever is lurking at its center are so far undetermined in spite of observations extending back to the 1824 work of Fritsch (as related by Wood 1985). With only 4 eclipses occurring per century, each 2-year long eclipse plays to an observational crowd of a different generation, at times equipped with a dramatically improved instrumentation. The last one of 1982–4 was the first to be monitored by spacecraft in the ultraviolet (UV), predominantly via low-resolution spectroscopy done with the *International Ultraviolet Explorer (IUE)*.

Indeed, during the last eclipse enough observational data were obtained to enable some crude modeling of a giant disk of gas and dust in orbit around the F type supergiant (see, e.g., Kemp et al. 1985, Ferluga and Hack 1985, Backman 1985, Lambert and Sawyer 1986, Saitō et al. 1987). The data included shell absorption lines, excess ultraviolet continuum flux, black-body fitting of infrared fluxes, and polarization measurements. The current consensus about the secondary star promotes a doughnut-shaped disk with a central clearing around the star, see e.g., Carroll et al. (1991) and Lissauer et al. (1996), in order to account for the remarkable mid-eclipse brightening of  $\epsilon$  Aur. It is not clear how the hole is maintained since no observational data so far has ever been directly linked to any object that may reside at its center (but see Lissauer and Backman 1984 and Eggleton and Pringle 1985 for proposing  $\epsilon$  Aur as a triple stellar system).

Since the system is visible throughout its 27-year long cycle, it deserves scrutiny at all times, especially in the UV where the secondary may be detectable (Hack and Selvelli 1979, Parthasarathy and Lambert 1983). For this reason we have observed  $\epsilon$  Aur with the GHRS

on the *Hubble Space Telescope (HST)* at a time intermediate between two primary eclipses (the next one will be centered on the year 2010). Our principal goal was to detect evidence of the enigmatic secondary. The now-retired GHRS provides data of a quality far surpassing that achieved with the *IUE* satellite. In this paper we describe and analyze our GHRS spectrum and interpret our data by comparison with the predicted orbital configuration of the binary.

## 2. OBSERVATIONS AND REDUCTIONS

The *HST* was trained onto  $\epsilon$  Aur under program GTO 6289 (with DLL as PI) as part of Cycle 5. Using the G140L grating to capture wavelengths between 1174.8–1461.2 Å, 13 exposures of equal exposure time and totaling 3536-sec were acquired starting at 09:26:54 UT on 1996 February 16. These were taken through the Small Science Aperture (SSA,  $0.22'' \times 0.22''$  in size) to provide a nominal resolving power of  $R = \lambda/\Delta\lambda = 2000$  (at 1300 Å). Normal reduction routines have been followed by processing the spectrum in the STSDAS environment of IRAF, where we combined the 13 sub-exposures into a single spectrum. Each sub-exposure was acquired four times but with the spectrum shifted by 1/4-diode steps yielding about 3.7 pixels per resolution element.

Flux and wavelength calibrations were performed by the Space Telescope Science Institute (STScI) pipeline. However, for precise radial velocity work, refinements of the zero offset were secured with the help of an acquired Pt/Ne lamp spectrum on-board the *HST*. Indeed, on closer inspection, the calibration lines were found to be shifted away from their expected rest wavelengths. The task of measuring Pt/Ne line profiles was complicated by the high fraction of close blends among the observed lines, as can be seen in the listing of Pt/Ne lines by Reader et al. (1990). Our selection of 31 isolated or de-blended lines (fitted by Gaussian profiles in the IRAF SPLIT environment) yields the following results.

There is a shift to longer wavelengths,  $\Delta\lambda = +0.117\pm 0.012 \text{ \AA}$ , and the average full-width at half-maximum (FWHM) of the lines is  $0.655\pm 0.039 \text{ \AA}$ , which corresponds to a spectral resolving power of  $R = 1980\pm 120$  at  $1300\text{\AA}$ . No significant dependence on the wavelength is detected for these parameters from the line sample which spans the entire spectrum. In order to derive the correct radial velocity information from the stellar spectrum we had to correct its STScI-given wavelength scale by subtracting the wavelength shift present in the Pt/Ne calibration spectrum. Since the correction due to geocentric motion has already been applied during the calibration at STScI, the velocities are reported in heliocentric frame.

Due to its distance of about 0.6 kpc on a line of sight only  $1^\circ.2$  from the Galactic plane,  $\epsilon$  Aur suffers appreciable interstellar extinction in the UV. We have chosen to de-redden the GHRS spectrum using Seaton’s (1979) recipe and the accepted reddening towards  $\epsilon$  Aur,  $E(B - V) = 0.30$  (Hack and Selvelli 1979). After correction, the flux is higher by 3.2 and 2.5 mag at 1174 and 1461  $\text{\AA}$ , respectively, i.e., a differential enhancement of the spectrum’s blue end by  $\times 1.9$  relative to its red end. All our flux measurements reported below are from the extinction-corrected data. No correction is made for additional reddening from dust in the binary system that might be affecting the observed spectrum.

### 3. EMISSION LINE INVENTORY

The fully reduced, co-added, and dereddened spectrum is shown in Figure 1. It exhibits a sloping continuum level that is higher at redder wavelengths, upon which about a couple of dozen emission lines are superimposed. The emission lines are readily discernible below about  $1350\text{\AA}$ . We have identified 18 transitions that appear in emission in the spectrum of  $\epsilon$  Aur. The identified lines are all transitions to ground and very low-excitation ( $\leq 0.04 \text{ eV}$ ) states of abundant atoms and ions: H I, C II, N I, O I, Si II, and S II. In the main, species not listed but which might be expected do not have strong resonance lines in the observed

region. At the reddest one-third of the spectrum it is difficult to tell if emission lines are present due to the emission-like appearance of continuum gaps between absorption lines of the F0 supergiant.

### 3.1. Profiles and Velocities

Table 1 lists for each line its species identity, multiplet number of said species, the rest wavelength, the shift-corrected observed wavelength, the derived radial velocity, value of  $A_{ij}$ , observed flux and its error bar as determined by summing all pixels within the line profile and above the continuum in both the spectrum itself and in the flux uncertainty distribution (shown as the lower curve in Fig. 1), and finally, the FWHM of the emission lines. Note that the observed wavelengths have been corrected by  $-0.117 \text{ \AA}$ , as described in §2. Determinations of line centroids for the observed wavelengths and of line FWHM values have been accomplished by fitting of Gaussian profiles within SPLOT. All atomic transition parameters were taken from Smith et al. (1996).

On inspection, it is apparent that the emission lines' profile comprises a strong red peak and a weak blue peak separated by a central absorption. The three panels in Figure 2 demonstrate the shape of the emission line profiles for (a) Si II lines around  $1190 \text{ \AA}$ , (b) S II lines around  $1250 \text{ \AA}$ , and (c) the three lines of O I, Si II, and C II at  $1302$ ,  $1309$ , and  $1334 \text{ \AA}$ , respectively. For proper graphic comparison we have subtracted the local continuum for each line and then re-scaled the peak flux to unity. In general, towards the red there is a sharp drop that reaches the continuum at a radial velocity of about  $+275 \pm 25 \text{ km s}^{-1}$ , while the more gradual decline to the blue terminates at about  $-200 \pm 25 \text{ km s}^{-1}$ . Therefore, the full-width at zero-intensity (FWZI) is about  $475 \pm 35 \text{ km s}^{-1}$  with an average radial velocity at about  $+37 \pm 18 \text{ km s}^{-1}$ .

In Table 2 we list all emission transitions that provided a clean and clear view of the blue peak and/or the central absorption, together with radial velocities and component widths that were extracted by means of multi-component Gaussian profile fits within SPLOT. The central absorption features exhibit different strengths (more about this absorption in §4.1). The blue peaks are weaker than the red peaks: on average, they are  $0.27 \pm 0.14$  of the red-side flux. Such a state of affairs makes these blue peaks more susceptible to noise and they are hard to distinguish when transitions are starting to blend. Hence, the number of emission profiles (in Table 2) which are suitable for blue peak and central absorption analysis is only about half of the number that is available for red peak analysis from Table 1.

The average radial velocity from 16 red emission peaks (from Table 1 but without H I) is  $+108 \pm 18$  km s<sup>-1</sup>. We also did not include the 1260Å Si II line due to blending with absorption from C I on its blue side. The emission lines appear to have a FWHM which is narrower than that of the Pt/Ne lamp lines: the mean FWHM of 15 stellar lines is  $0.63 \pm 0.10$  Å, not including the known blends of  $\lambda\lambda$  1264 and 1304. This is in good agreement with *HST* performance where the stellar profile is ca. 95% the width of the SSA FWHM (Stevens 1998). From Table 2 data, the following averages emerge. The radial velocity for nine blue peaks is  $-92 \pm 21$  km s<sup>-1</sup> and their average FWHM is  $0.56 \pm 0.09$  Å. Values for the central absorption features are  $-20 \pm 14$  km s<sup>-1</sup> and  $0.50 \pm 0.15$ , respectively.

The only emission line not attributable to  $\epsilon$  Aur is Ly $\alpha$  of H I. It is an expected contamination from the Geo-coronal background observed through the GHRS aperture. Luckily, the SSA is significantly smaller than the *IUE* apertures so that the Ly $\alpha$  emission seen here is not strong enough to mask wide parts of the spectrum, as happened with *IUE* spectra. This emission line is the only spectral feature to vary appreciably in strength among the GHRS sub-exposures; its derived “error” computed by STSDAS is an indicator

of the true variability and is a solid proof of Geo-coronal origin. As such, this line also serves as an indispensable check on our radial velocity scale. The line is within 0.1 pixels (or  $+4 \text{ km s}^{-1}$ ) of the predicted position. The Geo-coronal H I emission line plays another supporting role by exhibiting a single Gaussian component, thus showing that the other emission lines with more complex profiles are definitely signatures of velocity fields within the  $\epsilon$  Aur system and of absorbing matter far from Earth. Here,  $\text{Ly}\alpha$  emission is found inside a wide, saturated absorption feature, of interstellar origin.

### 3.2. The O I Lines from Multiplet 2

The complex of “four” emission lines between  $1302\text{\AA}$  and  $1309\text{\AA}$  (see Figure 1 and Table 1) is composed of three O I lines of multiplet 2 and two Si II lines of multiplet 3. Only four lines out of five are readily visible due to blending of O I  $1304.86\text{\AA}$  with Si II  $1304.37\text{\AA}$ . In the low-resolution *IUE* spectra, the entire group of transitions were seen as a single unresolved feature. Furthermore, we should keep in mind that during the 1983 eclipse there was no weakening of the  $\lambda 1305$  complex (Parthasarathy and Lambert 1983). Together with the UV continuum below  $\sim 1400\text{\AA}$ , the two cannot be associated with the eclipsed portion of the primary’s face, but rather they originate in the vicinity of the non-eclipsed secondary or in a chromosphere-like region larger than and around the eclipsed hemisphere the F0 supergiant, as described by Parthasarathy and Lambert.

An interesting story is told by the relative fluxes of the O I lines. The three lines share the same upper state so that, if the emitting atoms were in an optically thin environment, the relative fluxes would be in the ratio of the Einstein  $A_{ij}$ -values:  $F_{1302} : F_{1304} : F_{1306} = 1.0 : 0.6 : 0.2$ . This expectation is not confirmed. Inspection of the spectrum (Figure 1) shows clearly that the  $1306\text{\AA}$  line is much stronger than the  $1302\text{\AA}$  line, not markedly weaker as expected: the flux ratio is  $1.7 \pm 0.2$  not 0.2 (see also Table 1). The  $1304\text{\AA}$  blend appears

$1.9 \pm 0.2$  times stronger than the  $1302\text{\AA}$  line. If the Si II contribution to the blend is simply estimated from the flux of the Si II line at  $1309\text{\AA}$  and the assumption that both lines are optically thin, we can adjust the flux of the O I  $1304\text{\AA}$  line. The flux ratio relative to the  $1302\text{\AA}$  line is then  $1.4 \pm 0.2$ , not the expected 0.6.

To reconcile expected and observed fluxes, it is necessary to relax the assumption that the gas is optically thin. Several possible combinations of geometrical and physical conditions may be considered. Three will be mentioned here. First, suppose the emitting volume is itself optically thin to the O I lines but an optically thick absorbing layer lies between us and the emitting volume. If the absorbing gas is not cold ( $T \geq 1000$  K), the relative populations of the three levels of the oxygen atom's  $^3P_{(2,1,0)}$  ground term will be given by the statistical weights ( $g$ ) and the line absorption coefficients will be in the ratio of the  $gf$ -values and also the  $A_{ij}$ -values, as the three lines share the same upper state. In this scheme, if the optical depth in the  $1302\text{\AA}$  line is sufficiently large, the line ratio will be reversed with the  $1306\text{\AA}$  line stronger than the  $1302\text{\AA}$  line. Second, if the emitting region is optically thick but in LTE, the emitted line fluxes, which are approximately equal, can be modified by an absorbing layer but of lower optical depth than in the previous example. In each case the required column density of the absorbing layer could be reduced considerably if the layer were cold. Then the line absorption coefficient for  $1302\text{\AA}$  line from the  $^3P_2$  ground level could greatly exceed that for the  $1306\text{\AA}$  line from the uppermost ( $^3P_0$ ) level. Since we have already mentioned the presence of an absorption feature on top of the emission profile, it is obvious that some flux ratio reversal is caused by radiative transfer under conditions of varying optical depth and local temperature. Finally, the third possibility is that the observed emission line fluxes might be generated by non-LTE effects. One recalls the standard problem of a 2-level atom in an infinite slab (Mihalas 1978). Since the source function declines toward the boundary ( $S_\nu = \sqrt{\epsilon} B_\nu$  in standard notation) and rises into the slab saturating at  $S_\nu = B_\nu$ , an emission line shows a central reversal (perhaps,

unresolved at the low resolution of our spectra) and lines of lower central depth will have higher intensities.

### 3.3. Four Other Emitters: Si II, C II, S II, and N I

Eight emission lines out of 19 are contributed by the Si II ion. Here, as is the case with O I, we have line pairs that share an upper state for their transitions: 1190 with 1194Å from 10.40 eV; 1193 with 1197Å from 10.38 eV; 1260 with 1264Å from 9.83 eV; and 1304 (blended with O I) with 1309Å from 9.49 eV. The typical spacing of the pairs (ca. 4.5 Å) reflects the two lower levels of Si II at 0.000 and 0.036 eV. For the three pairs free of non-Si II blending, the  $A_{ij}$  ratios of the redder line to the bluer line are 5.0, 0.5, and 1.4. The corresponding observed flux ratios are  $1.2\pm 0.3$ ,  $1.3\pm 0.3$ , and  $6.8\pm 1.7$ , which confirm the O I result that these transitions are not emitted by an optically thin medium. With a  $A_{ij}$  ratio of 2.0, it seems plausible to predict that 1309Å should be stronger than 1304Å by at least a factor of 2, so that the latter’s share of the flux in its blend with O I is  $\lesssim 25\%$ .

Other line pairs involve: (1) two C II lines of multiplet 1, 1334Å and a doublet at 1335Å with a combined  $A_{ij}$  ratio of  $0.2 + 1.2 = 1.4$ , observed flux ratio is  $3.1\pm 0.8$ ; (2) three S II multiplet 1 lines of a common lower level with  $A_{ij}$ -ratios of 0.9 and 0.75, observed flux ratios are  $1.8\pm 0.3$  and  $0.5\pm 0.1$ . The latter ratio cannot be considered as optically thin because the 1259Å is blended with at least one absorption feature, and hence its actual strength and ratio are expected to be higher; (3) two N I lines of multiplet 1 with a  $A_{ij}$ -ratio of 1.0, observed flux ratio is  $0.9\pm 0.2$ . This last coincidence of predicted and observed flux ratios from N I indicate that perhaps this is the only species with optically thin transitions. However, it seems odd that we see only two N I lines, whereas three are expected. The missing middle line at 1200.2Å shares an identical  $A_{ij}$  value with its detected neighbors. We suspect that the absorption component of the 1200.7Å line is responsible for

this discrepancy by overlapping the neighboring emission line.

## 4. INTERVENING ABSORPTION FEATURES

### 4.1. Absorption Companions of Emission Lines

Our spectrum shows central absorption components between the blue and red emission peaks (Figure 2). In Table 2 we list all absorption features according to identified species (compare to Table 1), excitation energy, rest wavelength, derived radial velocity, observed equivalent width, and FWHM of the Gaussian profiles that fit the features. All our emission lines are transitions to ground and very low-excitation states ( $E_j \leq 0.04$  eV) and thus their absorption reversal is readily produced in a (cold) intervening gas along the line of sight. We already discussed in §3.2 and §3.3 the implication that the observed emission has been processed through a path of high optical depth, possibly modified by intervening colder medium. As mentioned above, averaging results from eight absorption features yields a radial velocity of  $-20 \pm 14$  km s<sup>-1</sup>. The lines are narrow, with an average FWHM of  $0.50 \pm 0.15$  Å, obviously they are not resolved in this observation.

From Figure 2 and Table 2 it is apparent that a relationship exists between the strength of the absorption (as determined by both species abundance and transition strength) and the apparent radial velocity of the red emission peak. More specifically, two C II and five Si II absorptions are associated with red emission peaks at  $+115 \pm 12$  and  $+116 \pm 11$  km s<sup>-1</sup>, respectively, whereas three S II lines with much weaker absorption display a bluer emission peak at  $+104 \pm 4$  km s<sup>-1</sup>. Furthermore, the three O I lines which decrease in their relative transition strength from 1302 to 1306 Å, also decrease in radial velocity from  $+112$  to  $+78$  km s<sup>-1</sup>. Because of this shifting of emission peaks and the added complication that different species may originate at different physical locations in the optical medium and thus acquire

different radial velocities, the “real” velocity cannot be found without a detailed analysis of the radiative transfer problem. For now, we resort to using average radial velocities of line samples while keeping track of the errors involved.

#### 4.2. “Emission-Free” Absorption

We have identified seven transitions that appear in absorption only in the spectrum of  $\epsilon$  Aur, i.e. do not accompany emission lines. These include six wider features composed of clusters of C I absorption lines and a single strong absorption line ( $W_\lambda = 900$  mÅ) that is the unresolved blend of the Mg II transitions at 1239.93 and 1240.40 Å. From our measurements we derive a radial velocity of +12 km s<sup>-1</sup> for Mg II under the assumption that the feature’s rest wavelength is represented by the average  $\lambda_0$  of the two transitions. This result puts Mg II in a class by itself, not sharing any of the emission component velocities, nor that of the central absorption “on top” on the emission. Again, more accurate velocity results should be pursued via higher-resolution work.

Ground state and very low-excitation ( $\leq 0.005$  eV) levels of interstellar C I appear to form six clusters of blended absorption lines between 1189 and 1329 Å. Thus we report total cluster equivalent widths as follows:  $\lambda$ 1189, 650 mÅ; 1193, 140; 1261, 250; 1277, 650; 1280, 460; and 1329, 670. Two of the C I clusters are irretrievably blended with stellar emission lines, i.e., one cluster is under Si II at 1193 Å, while another is under Si II 1260 Å. In both cases the absorption is still visible to the red and blue of the emission line, the latter being of anomalously weak flux due to attenuation by the C I feature (see Table 1). It is therefore understandable why these two clusters have the two lowest equivalent width values among all clusters. Although the 1189 Å feature lies adjacent to the emission line of Si II 1190 Å, the emission appears to be unaffected.

While the H I emission is of terrestrial origin, the entire contribution to the strong Ly $\alpha$  absorption line is probably from interstellar absorption, since the line is saturated down to zero residual intensity in the continuum, with a typically flat bottom expected under such circumstances (see, e.g., Diplas and Savage 1994). According to Figure 1 of Diplas and Savage (1994), interstellar H I profiles have FWHM of  $\sim 10$  and  $\sim 15$  Å, for H I column densities of  $10^{20.5}$  and  $10^{21.1}$  cm $^{-2}$ , respectively, as observed for stars  $\sim 400$  and  $\sim 800$  pc away and at a galactic latitude of  $\geq 13^\circ 1$ . Since  $\epsilon$  Aur’s galactic latitude is only  $1^\circ 2$  and it is believed to be at least 600 pc away (its parallax is given by *HIPPARCOS* as  $1.60 \pm 1.16$  mas, see Perryman 1997), it is not surprising to find a FWHM of  $21 \pm 1$  Å in our spectrum. The inferred column density of H I is definitely  $\geq 10^{21.1}$  cm $^{-2}$ , according to this comparison with the stars of Diplas and Savage.

## 5. CONTINUUM FLUX LEVELS

### 5.1. *IUE* Archive Spectra

In this section we shall inspect the overall spectral distribution of  $\epsilon$  Aur in order to try and separate the contributions from the primary supergiant and from any UV source that is not occulted during primary eclipse. As mentioned before, such contribution should exist below  $\sim 1400$  Å, because in that region *IUE* observations revealed a diminished eclipse signature (Parthasarathy and Lambert 1983 and references therein). Since the primary star of the  $\epsilon$  Aur system is usually thought to be an F0 Ia supergiant, we have searched the *IUE* archive (King 1997) for similar specimens. The best *IUE* data (taken through the large aperture) sport a resolution appreciably lower than that of the GHRS spectrum, namely, for the SWP, FWHM is between 4.6—5.4 vs. 0.66 Å. Spectra taken in the higher resolution mode of the *IUE* suffer from lack of an appreciable signal in our region of interest.

For proper comparison of archival *IUE* spectra with the GHRs exposure one has to degrade the *HST* data, i.e. transform it into a lower resolution spectrum. *IUE* spectra of  $\epsilon$  Aur come with varying continuum slopes and flux levels, since even the primary supergiant happens to be a variable star. For the purpose of this comparison we chose the *IUE* exposure SWP 29696 (epoch: 1986 November 17) which has one of the highest S/N ratios among  $\epsilon$  Aur spectra obtained in the years following the conclusion of the last eclipse. In Figure 3 we show the *IUE* spectrum of  $\epsilon$  Aur and its resolution-degraded GHRs exposure. The individual emission lines are no longer detected except for the very strong O I/Si II complex at  $1305\text{\AA}$ . We have changed the flux values for the *IUE* exposure by  $\times 0.63$  for proper alignment with our GHRs spectrum in Figure 3. Note that the sharp rise in *IUE* flux below  $1200\text{\AA}$  is spurious. Since the two spectra match pretty well, we conclude that the emission lines could also be present in *IUE* spectra of earlier epochs, not only in the recent GHRs spectrum. Such a good agreement between the spectra also serves as an indicator that no major spectral contribution is attributable to the hemisphere of the primary which is facing the secondary and which was visible around primary eclipse, but is now definitely hidden from view.

## 5.2. $\alpha$ Carinae and $\phi$ Cassiopeiae

From the *IUE* archive we extracted short- and long-wavelength spectra of  $\alpha$  Car (HD 45348) and  $\phi$  Cas (HD 7927), both well-known F0 supergiant comparison stars of  $\epsilon$  Aur. However, caution should be exercised with  $\alpha$  Car since its color index is bluer by about 0.05 mag than that of other F0 giants and supergiants observed with *IUE*, while it is intrinsically a fainter supergiant with a luminosity class II, rather than I.

In Figure 4a we show the short-wavelength comparison between the low-resolution version of our GHRs spectrum and both  $\alpha$  Car and  $\phi$  Cas, which are extracted from the

*IUE* exposures SWP 03382 and SWP 20288, respectively. We have corrected the flux of  $\phi$  Cas for interstellar reddening:  $E(B - V) = 0.50$ , a value averaged from Bersier (1996) and Wolff, Nordsieck, and Nook (1996). Thanks to its nearness, no significant interstellar reddening affects the flux of  $\alpha$  Car. Flux levels have been re-normalized by  $\times 0.21$  and  $\times 4.6$ , respectively, in order to equalize their mean flux levels (over the interval 1600–2000 Å) with that of  $\epsilon$  Aur.

The long-wavelength exposures LWP 09537 ( $\epsilon$  Aur) and LWR 16215 ( $\phi$  Cas) match very well below ca. 2900 Å, especially considering the differing amounts of dereddening applied to the two supergiants. (There is no *IUE* spectrum for  $\alpha$  Car at this low resolution.) Based on mean flux values over 1850–3350 Å, the comparison  $\phi$  Cas has been normalized by  $\times 3.2$  for proper alignment with  $\epsilon$  Aur. As seen in Fig. 4b, we achieve a good match with  $\epsilon$  Aur over the 1600–2900 Å interval, with both stellar continua following very similar undulations. Between 2900–3350 Å the two spectra are more separated from each other, but by switching roles in being “on top” their average fluxes are in better agreement. This situation happens in a region of lowest detector sensitivity for the LWP.

Below  $\sim 1600$  Å the spectrum of  $\phi$  Cas is very noisy due to very low signal which must be dominated by scattered light. At longer wavelengths any flux from the secondary object of  $\epsilon$  Aur is insignificant relative to the brightness of the primary supergiant. Other workers have documented and analyzed detections of an excess flux, see e.g., Hack and Selvelli (1979) and Parthasarathy and Lambert (1983), the latter using *IUE* spectra taken outside and inside of eclipse in order to decouple the contributions from the primary, secondary, and scattered light in the spectrograph. Although we cannot at this time deconvolve the GHRs spectrum into two contributions (from the primary and secondary bodies), we confirm that the procedure used by Parthasarathy and Lambert (1983) was correct. They were able to derive that about 75% of the observed flux level at 1250 Å i.e., about  $7.5 \times 10^{-13}$  erg cm<sup>-2</sup>

$\text{s}^{-1} \text{ \AA}^{-1}$ , was due to the secondary (or un-eclipsed) source, with 25% of the flux attributable to *IUE* scattered light. Indeed, our GHRS spectrum is outstanding thanks to absence of any scattered light, as revealed by the zero flux bottom of the interstellar Ly $\alpha$  absorption line, and it shows that the flux level at 1250 $\text{\AA}$  is, indeed, at  $7.2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ , after being degraded to *IUE* resolution. We submit that this should be the observable continuum from the secondary, or any other source that is not occulted by the secondary and its disk during primary eclipse.

## 6. BINARY RAMIFICATIONS

Thirteen years have elapsed since the last mid-eclipse time of  $\epsilon$  Aur until our GHRS spectrum was secured. That puts the secondary body of the system squarely on the other side of its orbit, i.e., behind the plane of the sky passing through the primary. However, although 13 years also happen to be very close to one-half of the period of the binary, 1996 was not expected to be the year of the secondary eclipse due to the appreciable eccentricity of the system (Morris 1962; Wright 1970).

### 6.1. Orbital Kinematics

The key quantity is the mass ratio of the two stars,  $q = M_1/M_2$ , which fixes the ratio of the radial velocity amplitudes, i.e.,  $q = K_2/K_1$ , where  $K_1 = 15.0 \pm 0.6 \text{ km s}^{-1}$  (Wright 1970). On 1996 February 16, the orbital phase was 0.6971 from the time of periastron (T = 1977 April 02 = JD 2443236). The primary supergiant's radial velocity at the time was  $v_1 = -10.3 \text{ km s}^{-1}$ . For sample mass ratios of  $q = M_1/M_2 = 1.0$  and 2.0, one predicts secondary radial velocities of  $v_2 = +7.5$  and  $+16.4 \text{ km s}^{-1}$ , after correcting by the  $\gamma$ -velocity.

If the emission features are associated with the disk around the secondary, there is the

possibility that the secondary’s radial velocity can be derived from the emission lines. We have described how some of the emission lines are split by an absorption line that originates either in the ISM or even in the secondary’s disk or other local cool gas. This mix of absorption and emission complicates the use of the emission as a speedometer. In particular, the red peak is demonstrably not providing the secondary’s radial velocity. The observed radial velocity of the red peaks ( $+108 \text{ km s}^{-1}$ ) yields a mass ratio  $q = v_2/v_1 = 12 \pm 2$  but this with the well-determined mass function of  $3.25 \pm 0.38 M_{\odot}$  (Webbink 1985, who used Wright 1970) gives stellar masses of 6600 and 550  $M_{\odot}$ , respectively. These extraordinary masses show that the red peak is not a tracer of the secondary’s velocity. Even more firmly, we reject the blue peak as a tracer because the expected radial velocity of the secondary cannot be negative! A chromospheric origin around the supergiant for the emission lines, which was one solution suggested by Parthasarathy and Lambert (1983), calls for emission centered on the smaller negative radial velocity of the primary, but only our absorption component has an observed velocity closest to that predicted for the primary.

The third option is to calculate the average velocity of the peaks and use the result as our kinematic tracer of the secondary. For this we assume that the source of the emission must be distributed symmetrically around the secondary companion. We first compute the average velocity of the two peaks for each transition and then derive the final global average of kinematic tracers. Seven pairs of red and blue emission peaks are available from Tables 1 and 2 after rejecting N I at 1199.55 Å due to severe blending. From these emission pairs the global average of  $v_2$  is  $+13.4 \pm 4.9 \text{ km s}^{-1}$ . Finally, as mentioned before, our radial velocity scale includes a  $4 \text{ km s}^{-1}$  redshift as demonstrated by the Ly $\alpha$  Geo-coronal line. When we correct the velocities above for this shift, the tracer velocity is  $+9.4 \pm 4.9 \text{ km s}^{-1}$ , or  $v_2 = +10.8 \pm 4.9 \text{ km s}^{-1}$  after removal of the  $\gamma$ -velocity. This yields a mass ratio of  $q = 1.2 \pm 0.6$ , i.e., two binary components of almost equal mass, but with the primary as the slightly heavier object. Indeed, component masses are  $19 \pm 14$  and  $16 \pm 9 M_{\odot}$  for the primary and

secondary, respectively. These masses correspond to the absorption case with  $p = v_K/v_{rot} = 1.5$  as prescribed by Lambert and Sawyer (1986), although they preferred eventually to adopt  $p \leq 1.2$  and  $q \leq 0.4$ , leading to mass limits of  $M_1 \leq 3$  and  $M_2 \leq 6 M_\odot$ , i.e, values that are just below the one  $\sigma$  level of our results.

The masses just derived are reminiscent of the “high-mass” models in the literature, pertaining to a massive F0 Ia supergiant and a very under-luminous secondary. Our near-infrared spectroscopy shows that the pulsating primary of  $\epsilon$  Aur is spectroscopically indistinguishable from other massive yellow supergiants such as  $\phi$  Cas. But the secondary poses an enigma. Lissauer and Backman (1984) have suggested the presence of a binary star at the center of the disk, thus reducing the luminosity requirements. First, a reduction by a factor of  $\sim 10$  is due to the smaller mass of the (new) components; then, another reduction by a factor of  $\sim 10$  is suggested by radiation escaping through the poles of the disk. Carroll et al. (1991) prefer the high-mass scenario (using  $M_2 \sim 14M_\odot$ ) for their model of a proto-planetary disk around  $\epsilon$  Aur. More recently, Lissauer et al. (1996) modeled the disk hydrostatically and concluded that its height to radius ratio of  $\lesssim 0.03$  favors the presence of a massive secondary with  $M_2 \sim 15M_\odot$ .

## 6.2. Discussing the Disk

From the separation of blue and red emission peaks we derive a rotational velocity of  $103 \pm 20 \text{ km s}^{-1}$  under the assumption of a circum-secondary orbital motion. A Keplerian orbit for the gas implies a radius vector of  $1.4 \pm 1.0 \text{ AU}$  away from a central point of  $16 \pm 9 M_\odot$ . This result is consistent with previous size estimates of the inner transparent region of the disk. Carroll et al. (1991) model the hole in the disk and find that its radius is  $1.65 R_{\text{primary}} = 1.54 \text{ AU}$ . Furthermore, for a semi-major axis of  $a = 13.35 \text{ AU}$  (Webbink 1985) we derive an annulus radius of  $0.11(\pm 0.07)a$ , again a value very consistent with the model

by Wilson (1971) who found an inner disk radius of  $0.1a$ . Obviously the supported picture is of an opaque disk with an inner edge irradiated and ionized by hot central source(s), thus producing emission lines, while the cooler regions toward the outer edge are detectable via absorption lines during primary eclipse.

One recalls the observations performed during primary eclipse of absorption lines that changed from red shift to blue shift by  $\sim 66\text{--}84 \text{ km s}^{-1}$  in a manner consistent with a rotating disk (Lambert and Sawyer 1986, Saitō et al. 1987). Here we find from emission peak separation a radial velocity difference of  $206 \text{ km s}^{-1}$ , which under Keplerian rotation shows that the radius vector of the emitting region is approximately 6 to 10 times smaller than the annulus responsible for the absorption lines. (Lambert and Sawyer gave  $v_{\text{rot}} = 33 \text{ km s}^{-1}$ , Saitō et al. gave  $42 \text{ km s}^{-1}$ .) This purely spectroscopic deduction is consistent with photometric models. For example, the outer edge of the disk has been modeled to be 6.1 times greater than its inner edge by Carrol et al. (1991). This modeled ratio is derived from primary eclipse photometry in general and from the mid-eclipse brightening in particular.

Another observational result is the unequal brightness of the two peaks, a ratio of 3.7:1 in favor of the average red peak. Theoretical disks with rotational symmetry should produce two peaks of equal strength. In our case we already know about the central absorption, and perhaps there is stronger absorption overlapping the blue peak but which cannot be resolved in our spectrum. Another possibility may involve a hot spot on the redshifted side of the disk, i.e., a stream of gas that comes from the primary supergiant impacts onto the disk side that is rotating away from us and the increased amount of matter and gravitational energy result in a more pronounced red emission peak. Unfortunately, the difficulty with this scenario would be the formation of a hot spot by the *outer* edge of the disk, where the Keplerian rotational velocity is much lower than our derived velocity.

### 6.3. Eclipse Geometry

As remarked earlier, the eclipse of the secondary object is due very soon, unless it has started already! From the orbital solution we find that the 1<sup>st</sup> and 4<sup>th</sup> contacts will occur on ca. 1999 June 29 and 2000 December 11, respectively, pending orbit-to-orbit variations in both eclipse length and its mid-time. During secondary eclipse the optical brightness of  $\epsilon$  Aur will not change, being solely determined by the primary star. Only in the UV can observers hope to detect the secondary eclipse, perhaps in a most dramatic way when the emission lines we detected should weaken in the spectrum of the system during ingress and then, perhaps, vanish altogether during total secondary eclipse. Such a remarkable transformation would greatly benefit the confirmation and/or update of orbital elements and the determination of shapes and sizes for the components in this unique binary star system. It is interesting to note that had the orbital eccentricity been merely 0.0, there would have been a secondary eclipse in progress already at the end of 1996 January, i.e., ca. three weeks prior to the acquisition date of our GHRS spectrum. Furthermore, if the F0 supergiant happened to support a chromosphere with appreciable UV-continuum attenuation, secondary eclipse would start earlier and last longer than contact times calculated according to the photospheric size of the primary. Incredibly, then, the relative weakness of the blue side of the emission profiles can be explained also in terms of some eclipsing effect by the primary star. The latter's atmosphere could also be invoked as one of the possible sources for the central absorption, because the two differ by about  $10 \text{ km s}^{-1}$ , which is smaller than the observational error. Such a possibility is exciting for the option it offers to probe the outer atmosphere of the F0 supergiant. Of course, as the secondary moves closer to the line of sight of the primary, this effect should become stronger and easier to observe.

Secondary eclipse phases should be followed closely at higher resolution with the STIS

on board the *HST*, to provide better separation of emission and absorption components and to measure the systemic velocity of the gas more accurately. Later on, following secondary eclipse, the opportunity to inspect the secondary on the far side of the orbit would still be viable for a while, until  $\epsilon$  Aur starts heading towards its next primary eclipse, centered on about 2010 August 05. We note that using *HST* is the only way available for obtaining the radial velocity curve of the secondary and hence for finally determining the long-sought masses in this system.

## 7. CONCLUSIONS

In this paper we reported the detection of 17 optically-thick emission lines in the *HST* spectrum of  $\epsilon$  Aur, which belong to low-excitation transitions in common atomic species. With a mean radial velocity of  $\simeq +108$  km s $^{-1}$ , these lines happen to be red peaks as part of wider emission profiles. Weaker blue peaks give a mean radial velocity of  $\simeq -92$  km s $^{-1}$ . The flux depression between the two peaks has a contribution from an absorption component at  $\simeq -20$  km s $^{-1}$ .

We interpret the double-peaked emission lines as rotational signatures of the circum-secondary disk. From the average velocity of seven pairs of emission peaks we derived a secondary radial velocity of  $\approx +10.8$  km s $^{-1}$ , a value which corresponds to a binary mass ratio of  $q \approx 1.2$ , and stellar masses of  $M_1 \approx 19$  and  $M_2 \approx 16 M_\odot$ . (All our derived values are accompanied by appreciable error bars, as explicitly described above.) These are consistent with the “high mass” models of  $\epsilon$  Aur—see, for example, Lissauer et al. (1996) who model a disk surrounding a  $15 M_\odot$  secondary. “Low-mass” models (Saitō et al. 1987, Lambert and Sawyer 1986) are formally excluded by our results but the quoted uncertainties do not include two likely key sources of additional uncertainty: our untested assumptions that (i) the emission is centered on the secondary’s orbital velocity, and (ii)

the appropriate velocity is the mean of red and blue emission peak velocities. Therefore, we caution that the indication that “high-mass” models are preferred should not be accepted as ending a long debate over  $\epsilon$  Aur’s mass and evolutionary status. We offer the results as an indication that the secondary mass is possibly obtainable from these emission lines if they are observed at the higher resolution of STIS and observed sufficiently often that an adequate segment of the secondary’s velocity curve can be defined.

From the velocity separation between seven pairs of emission peaks we derived an average disk rotational velocity of  $\simeq 103 \text{ km s}^{-1}$ , which corresponds to an inner disk radius of  $\approx 1.4 \text{ AU}$ , or about six times smaller than the outer regions of the disk as detected via absorption lines. Not surprisingly, the emission is generated in a more energetic medium much closer to the high-temperature secondary, at a disk radius which is also about 10 times smaller than the primary’s orbital semi-major axis. Both the orbital and the rotational kinematic methods agree with each other and point to a moderately massive binary system for  $\epsilon$  Aur.

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Fig. 1.— The fully-reduced GHRs spectrum of  $\epsilon$  Aur, after correction for a reddening of  $E(B - V) = 0.3$ . Emission lines and strong absorption features are labeled in a higher and lower labels, respectively. We do not show the reddest part of the spectrum (1350–1461 Å) where the photospheric absorption spectrum of the primary is dominant. The lower dotted curve depicts the error in the observed flux level, as derived by the calibration at STScI. Note the Ly $\alpha$  emission line of H I which serves as an excellent standard for profile shape and position for this spectrum.

Fig. 2.— A closer view of nine emission line profiles in  $\epsilon$  Aur reveals their construction as a stronger red peak with a weaker blue bump and a middle absorption feature. The average radial velocities of these three components are marked by vertical lines. All emission lines have been normalized by a continuum subtraction (base at 0.0) and a division by their peak value (top at 1.0). The left and center panels show common-multiplet transitions. In the right panel, C II exhibits a very strong absorption feature and a red peak that is more redshifted than the average radial velocity of +108 km s<sup>-1</sup>. Note that the red wings of the lines at 1193, 1259, and 1334 Å are affected by some blending with their redder neighbors, i.e.,  $\lambda\lambda$  1194, 1260, and 1335.

Fig. 3.— A comparison of our GHRs spectrum, degraded to lower resolution of 5 Å by a 35-pixel box smoothing, and the *IUE* exposure SWP 29696 from ten years earlier. The latter has been re-scaled by  $\times 0.63$  for proper alignment. Both spectra have been corrected for interstellar reddening.

Fig. 4.— Three F0 supergiants observed by the *IUE* are compared here after combining their SWP and LWP spectra. Panel *a* shows the shorter wavelength region that corresponds to the coverage of our GHRs exposure. In panel *b* the longer wavelength region is shown. The match is very good below 2900 Å. A small region around 1900 Å suffers from a mis-match between the SWP and LWP independent exposures.

Table 1. Red Emission Peaks of  $\epsilon$  Aur

| Atom  | Multiplet | $\lambda_0$<br>( $\text{\AA}$ ) | $\lambda_{\text{obs}}$<br>( $\text{\AA}$ ) | $v_{\text{rad}}$<br>( $\text{km s}^{-1}$ ) | $A_{ij}$<br>$\text{ns}^{-1}$ | Flux <sup>a</sup> | FWHM<br>( $\text{\AA}$ ) |
|-------|-----------|---------------------------------|--|--|------------------------------|-------------------|--------------------------|
| Si II | (5)       | 1190.42                         | 1190.83                                    | +114                                       | 1.539                        | 3.8±0.7           | 0.58                     |
| Si II | (5)       | 1193.29                         | 1193.81                                    | +131                                       | 6.103                        | 3.4±0.4           | 0.80                     |
| Si II | (5)       | 1194.50                         | 1194.98                                    | +121                                       | 7.652                        | 4.7±1.0           | 0.71                     |
| Si II | (5)       | 1197.39                         | 1197.85                                    | +115                                       | 3.038                        | 4.3±0.7           | 0.68                     |
| N I   | (1)       | 1199.55                         | 1199.93                                    | +86  | 0.399                        | 1.6±0.2           | 0.57                     |
| N I   | (1)       | 1200.71                         | 1201.09                                    | +92  | 0.398                        | 1.5±0.2           | 0.57                     |
| H I   | (1)       | 1215.67                         | 1215.58                                    | −22  | 0.939                        | 2.8±2.5           | 0.65                     |
| S II  | (1)       | 1250.58                         | 1251.00                                    | +101                                       | 0.047                        | 4.1±0.5           | 0.58                     |
| S II  | (1)       | 1253.81                         | 1254.26                                    | +108                                       | 0.042                        | 7.2±0.7           | 0.55                     |
| S II  | (1)       | 1259.52                         | 1259.95                                    | +102                                       | 0.034                        | 2.1±0.4           | 0.51                     |
| Si II | (4)       | 1260.42                         | 1261.07                                    | +155                                       | 2.066                        | 1.0±0.2           | 0.47                     |
| Si II | (4)       | 1264.74                         | 1265.37                                    | +150                                       | 2.489                        | 6.8±1.0           | 0.93                     |
| O I   | (2)       | 1302.17                         | 1302.66                                    | +112                                       | 0.315                        | 19.2±1.9          | 0.72                     |
| Si II | (3)       | 1304.37                         | ...  | ...  | 0.741                        | ...               | ...                      |
| O I   | (2)       | 1304.86                         | 1305.23                                    | +90  | 0.188                        | 35.8±2.4          | 0.82                     |
| O I   | (2)       | 1306.03                         | 1306.38                                    | +78  | 0.063                        | 32.3±2.1          | 0.77                     |
| Si II | (3)       | 1309.28                         | 1309.72                                    | +101                                       | 1.467                        | 19.3±1.2          | 0.71                     |
| C II  | (1)       | 1334.53                         | 1335.00                                    | +106                                       | 0.225                        | 1.2±0.3           | 0.63                     |
| C II  | (1)       | 1335.71                         | 1336.26                                    | +123                                       | 0.273                        | 3.7±0.4           | 0.65                     |

<sup>a</sup>in units of  $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$

Table 2. Blue Emission Peaks and Central Absorption of  $\epsilon$  Aur

| Atom  | $E_j$<br>(eV) | $\lambda_0$<br>(Å) | $v_{\text{rad}}^{\text{Blue}}$<br>(km s <sup>-1</sup> ) | $\frac{F(\text{Blue})}{F(\text{Red})}$ | FWHM<br>(Å) | $v_{\text{rad}}^{\text{Abs}}$<br>(km s <sup>-1</sup> ) | $W_\lambda$<br>(mÅ) | FWHM<br>(Å) |
|-------|---------------|--------------------|---|--|-------------|--|---------------------|-------------|
| Si II | 0.00          | 1190.42            | -85   | 0.26                                   | 0.58        | -11  | 100                 | 0.58        |
| Si II | 0.00          | 1193.29            | -121  | 0.14                                   | 0.41        | -33  | 180                 | 0.44        |
| Si II | 0.04          | 1197.39            | ...   | ...                                    | ...         | -40  | 69                  | 0.19        |
| N I   | 0.00          | 1199.55            | -110  | 0.34                                   | 0.57        | -27  | 153                 | 0.57        |
| S II  | 0.00          | 1250.58            | -62   | 0.52                                   | 0.57        | -28  | 34                  | 0.43        |
| Si II | 0.04          | 1264.74            | -118  | 0.07                                   | 0.63        | ...  | ...                 | ...         |
| O I   | 0.00          | 1302.17            | -84   | 0.28                                   | 0.56        | -3   | 320                 | 0.58        |
| Si II | 0.00          | 1304.37            | -87   | ...                                    | 0.47        | ...  | ...                 | ...         |
| Si II | 0.04          | 1309.28            | -69   | 0.21                                   | 0.71        | ...  | ...                 | ...         |
| C II  | 0.00          | 1334.53            | -89   | 0.31                                   | 0.54        | 0  | 320                 | 0.61        |
| C II  | 0.01          | 1335.71            | ...   | ...                                    | ...         | -16  | 210                 | 0.62        |







