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ULTRAVIOLET FLUX VARIATION OF EPSILON AURIGAE*

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Abstract

The eighteen ultraviolet light curves of Epsilon Aurigae have been plotted using the integrated fluxes reduced from the 233 IUE low dispersion spectra taken between 1978 and 1986. The times of contacts and depth of eclipse have been determined from the light curves at the wavelength from 2550 Å to 3050 Å. The UV light curves show two brightenings during the totality, the downward slope of the variation from the second to the third contacts, and asymmetry of the eclipse light curve. The two selected spectra note that the energy density distribution is not changed between the totality of the eclipse and out-of-eclipse.

1. Introduction

Epsilon Aurigae is a long period eclipsing binary system that undergoes a two-year eclipse every 27.1 years. The system has been observed at every eclipse phase since 1821. Fritsch (1824) recognized it as a variable and discussed the minimum light of 1821. Ludendorff(1903) found the system to have an Algol type light curve. Payne(1928) analyzed the low dispersion spectrum and concluded it a supergiant. At the 1928-30 eclipse the many photometric and spectroscopic observation of the system were made by various observers. Huffer(1932) found irregular fluctuations as large as 0.2 magnitude and a decrease in the brightness of the system of 0.06 magnitude during totality. For the 1955-57 eclipse there had been organized a comparative campaign by Wood(1958). Hack(1959) discussed about shell surrounded an invisible star with spectra taken at the eclipse phase. Numerous observers have observed Epsilon Aurigae at the 1982-84 eclipse based on the International Observing Campaign organized by NASA and Inter-

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national Amateur Professional Photoelectric Photometry(IAPPP). Nha and Lee(1983) reported the flare activity of Epsilon Aurigae between the second contact and mid-eclipse. During the 1982-84 eclipse, multispectral observations were made in the ultraviolet and infrared regions as well as optical region. Especially the system has been observed intensively in the UV region by the International Ultraviolet Explorer(IUE). Chapman *et al.*(1983), Parthasarathy and Lambert (1983), Boehm *et al.*(1984) and other many investigators have discussed the IUE spectra of Epsilon Aurigae. Several models have been proposed by Kuiper. Struve, and Strongrem(1937), Struve(1956), Hack(1961), and Kopal(1954, 1971). The system consists of a F supergiant star and a questionable so called I star. Its period and separation are 9885 days and 26 A. U.. The primary star, F supergiant star is known as non-radial pulsating star with 90 ± 20 day period. The secondary star has a gaseous envelope or disk ring and a temperature of 500 K measured at 5, 10, and 20 micrometers(Backman 1984). In this paper all IUE spectra for Epsilon Aurigae were collected. The low dispersion spectra between 1978 and 1986 were analyzed for the flux variation at the ultraviolet region.

2. Data Reduction of IUE Spectra

Ultraviolet spectra of Epsilon Aurigae have been taken since 1978, with the IUE by many observers. A total of 535 spectra for Epsilon Aurigae was collected in the IUE Merged Log as of June 1989. Our Photometry study is based on the analysis of 233 low dispersion spectra only. The low dispersion spectra consist of 127 spectra taken by the Short Wavelength Prime(SWP) camera, 78 spectra taken by the Long Wavelength Redundant(LWR) camera, and 28 spectra taken by the Long Wavelength Prime(LWP) camera. The IUE raw data have been converted to the wavelength vs. absolute flux(erg/㎠/sec/Å) using the Regional Data Analysis Facility (RDAF) software of the IUE Observatory. The absolute calibration also included camera temperature sensitivity and sensitivity degradation(Bohlin and Grillmair 1988). Since we collected the IUE spectra taken in the time span of 8 years, we paid attention to the sensitivity degradation of each camera system. We integrated the fluxes at the wavelength interval of 100 angstroms for each spectrum so that 8 integrated fluxes between 1150 angstroms and 1950 angstroms for the SWP spectra and 10 integrated fluxes between 2050 angstroms and 3050 angstroms for the LWP and LWR spectra. The integrated fluxes were converted to the instrumental magnitude scale to plot the light curves at the different wavelength regions. Therefore, for example. a light curve of the wavelength 2100 Å was plotted using flux(converted to magnitude scale) integrated from the wavelengths 2050 Å to 2150 Å. The quality flag for the data, epsilon value, was used to justify if the each integrated flux is real. Therefore the bad data, which have low epsilon value, could be omitted in the plotting of the light curves and analysis. The quality flag of the data was made by each observer based on the extrapolated intensity transfer function, microphonic noise, bright spot, saturated pixel, and pixel outside target ring.

3. Light Curves from the IUE Photometry

The UV light curves reduced from the IUE photometry were plotted in Fig. 1 and 2. Due to its steep spectral gradient, the magnitude from Epsilon Aurigae drops over 2 orders over the IUE wavelength range, i.e. the mean magnitude of the totality at 3000 angstrom band is approximately 6th magnitude(instrumental) while that at 1200 angstrom band is 11th magnitude(instrumental). Epsilon Aurigae has been continuously observed by the IUE from pre-eclipse to post-eclipse. However the IUE observation did not cover the three time spans during eclipse of Epsilon Aurigae, i.e. at the first contact, mid-eclipse, and just before the fourth contact, because Epsilon Aurigae was very close to the Sun. The light curve shows less scatter in the longer wavelength region. The depth of the eclipse is more shallow from 1400 angstrom to 1200 angstrom regions so that the shape of eclipse is not seen in those region. The light curves from 2600 Å to 3000 Å show less scatter and nice eclipse shapes compared to those in other regions. The light curves in UV region generally follows that found in the optical region except asymmetry of the eclipse shape. The six light curves between 2400 Å and 3000 Å were selected to determine the dates of contacts. The light curves in the shorter wavelength regions were not used for the analysis because of their scatters and shallow eclipses. To avoid subjective method, the observations were divided into four group(outside, ingress, totality, and egress) and fitted to the straight line in each group. The dates of contacts are tabulated in Table 1. There are not enough spectra available at the pre-eclipse phase to determine the dates of the first contact accurately. The Cepheid-like pulsation of the primary also introduces uncertainty in the determination of times of contacts. There is no observations even at the shoulder of ingress. Thus the date of first contact has not been determined in this paper. There are enough data near the second contact to determine the time of the second contact. The date of the second contact is determined to be in the range of JD 2445303~2445308, which depends on the wavelength region. The range of the date is well agreed with the dates(*JD 2445300~2445302) determined by Nha(1990) in the opti-*

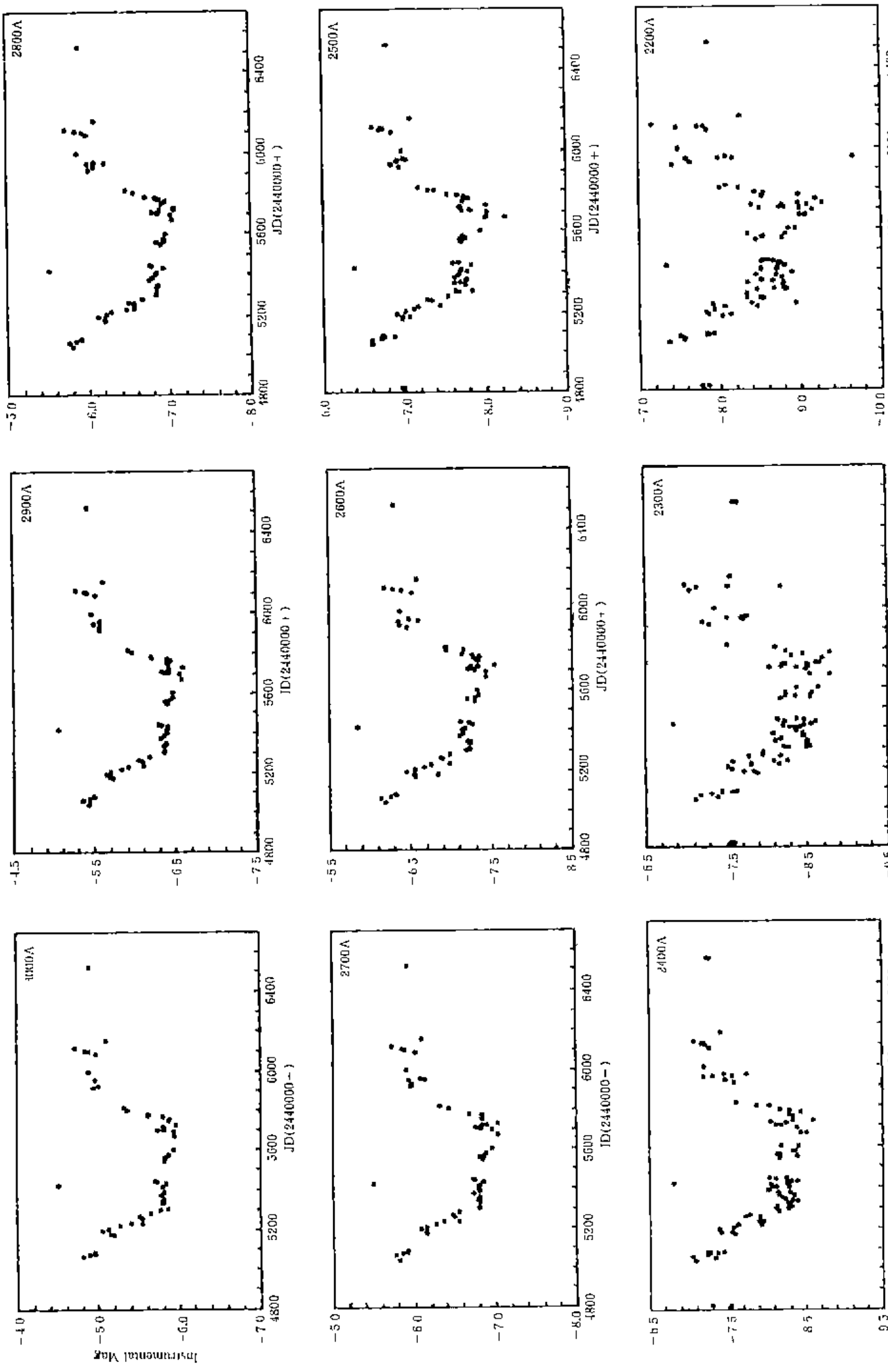

Fig. 1. Ultraviolet light curves of Epsilon Aurigae for long wavelength. The nine light curves are plotted using the integrated fluxes reduced from the 233 IUE low dispersion spectra taken between 1978 and 1986.

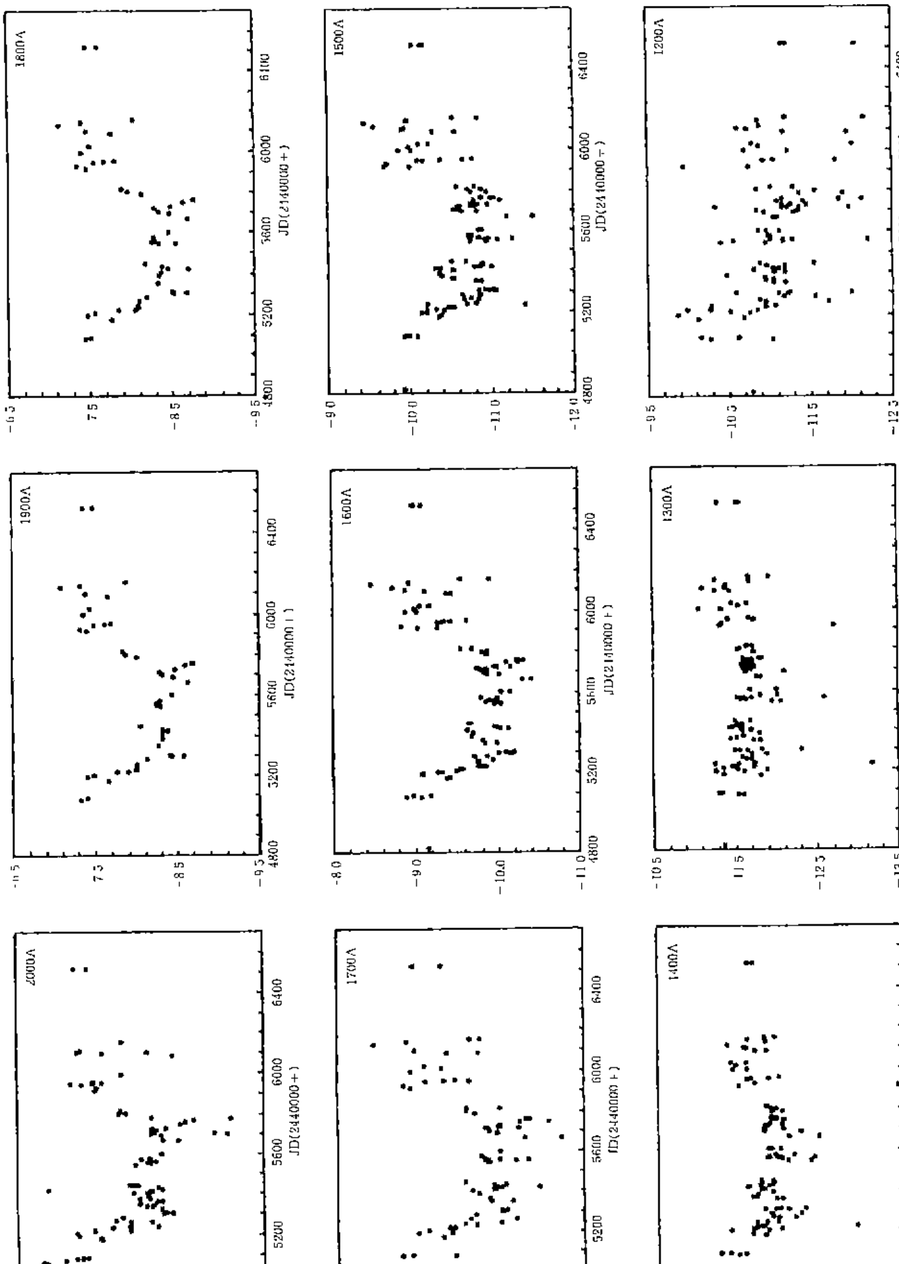

Fig. 2. Ultraviolet light curves of Epsilon Aurigae for short wavelength. The nine light curves are plotted using the integrated fluxes reduced from the 233 IUE low dispersion spectra taken between 1978 and 1986.

Table 1. Dates of Contacts at Different Wavelengths

Wavelength	2nd Contact	3rd Contact	4th Contact
3000 Å	JD 2445306	JD 2445761	JD 2445940
2900 Å	303	765	946
2800 Å	303	766	942
2700 Å	308	768	940
2600 Å	304	772	943

cal region. The third contact is determined to be in the range of JD 2445761-2445772. The dates of the third contact in UV region took place approximately 20 days later than those in the optical region. Therefore the length of totality and duration of the eclipse in the UV region is longer than those in the optical region. The times of mid-eclipses were determined as the middle between the third and fourth contact. The mid-eclipses and durations of eclipse are tabulated in Table 2.

Table 2. Mid-eclipse and Duration of Eclipse

Wavelength	Mid-eclipse	Duration of Totality	Duration of Egress
3000 Å	JD 2445534	455 days	179 days
2900 Å	534	462	181
2800 Å	535	463	176
2700 Å	538	460	172
2600 Å	538	468	171

The selected light curves of the wavelength 2600 Å, 2700 Å, 2800 Å, and 3000 Å are plotted in Fig. 3. In the Figure, instead of whole eclipse light curve only totality phase is displayed to investigate the variations during totality. The light variations of Epsilon Aurigae during the totality in the IUE wavelength region is not exactly same as those found in the optical region. There are two brightenings during totality except the mid-eclipse brightening in Fig. 3. The first brightening during totality occured at the JD 2445400(after second contact) with maximum amplitude $0^{m}.16$. The amplitudes of the brightenings are tabulated in Table 3. In the optical light curve, the light variation shows different way. At the JD 2445400 the optical light decreases instead of brightening in the UV curves. The second brightening during the totality occured at the

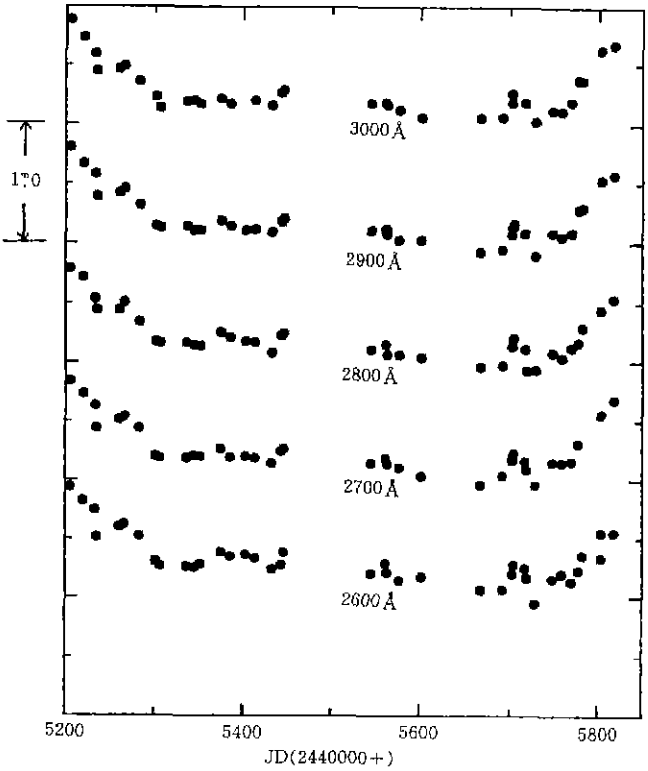

Fig. 3 Five selected light curves of Epsilon Aurigae from the wavelength 2600 Å to 3000 Å.

JD 2445710(before third contact), where the light is up to $0^m.3$ brighter than those at the third contact. This amplitude($0^m.3$) is much large compared to the amplitudes of $0^m.03$(U), $0^m.18$(B), and $0^m.11$ (V) determined by Kim(1989) in the UBV light curves. Thus the second brightening in the UV light curve is well matched with that in the optical light curve except the amplitude. Even if the wave like variations are seen during the totality, the distinctive variation during the totatlity in the UV light curve is the downward slope of the variation from the second to the third contacts. The downward slope is much clear in the IUE light curves. The brightness at the third contact is approximately 0.2–0.3 magnitude dimmer than that at the second contact in the IUE light curves. This downward slope at the totality phase introduces the longer totality than that in the optical region. In light curves of the wavelength 2600 Å, 2700 Å, 2800 Å, 2900 Å, and 3000 Å, the brightness drops suddenly after mid–

Table 3. Amplitudes of Brightenings during totality

Wavelenth	1st Brightening (JD 2445400)	2nd Brightening (JD 2445700)
3000 Å		0.23 mag.
2900 Å	0.10 mag.	0.26
2800 Å	0.13	0.28
2700 Å	0.13	0.30
2600 Å	0.16	0.30

eclipse. The IUE spectra did not cover the phase of the mid-eclipse so that the mid-eclipse brightening in the optical region could not be confirmed in the IUE spectra. But the mid-eclipse brightening can be easily inferred from the IUE observations at the vicinity of the mid-eclipse. The duration and shape of ingress is not same as those of egress in the IUE light curves. This notes that the eclipse light curves in the UV region are asymmetry. It was not possible to determine the fourth contact accurately, because the IUE observation was not made just before the fourth contact and there is a fluctuation near the expected fourth contact. Therefore it was determined by interpolating the observations. The date of the fourth contact is in the range of JD 2445940-2445946. Determination of the eclipse depth can differ substantially, since they depend on the choice of the out-of-eclipse reference spectra. This is a delicated choice because of the primary's Cepheid-like variability(Feruga and Hack 1985). We fit a straight line to the observation pre-and post-eclipse as an out-of-eclipse reference line. From the reference line the depths of the eclipse at the second contact and the third contact were determined in the five IUE light curves and are tabulated in Table 4.

Table 4. Depths of Eclipse

Wavelength	Depth at 2nd Contact	Depth at 3rd Contact	Difference
3000 Å	0.97 mag.	1.17 mag.	0.20 mag.
2900 Å	0.97	1.22	0.25
2800 Å	0.97	1.23	0.26
2700 Å	0.94	1.19	0.25
2600 Å	0.95	1.26	0.31

4. Color Curves

One of the puzzling problems of Epsilon Aurigae is no change of the spectral type and no color variation between eclipse and outside eclipse. However some color variations during eclipse have been reported based on the more accurate observation from the more broad wavelength regions. If the eclipsing dusty disk is uniform and composed of material with neutral extinction properties the color variations within totality and outside the eclipse should be the same. However, if there is an extended gaseous envelope around the disk, and material with some kind of selective extinction properties in the disk, then the primary star(F supergiant star) will undergo color variations when the disk causes an eclipse(Parthasarathy and Frueh 1986)

In this paper, only 5 selective light curves in the long wavelength region were used to produce the color curves. To concentrate the variation during totality, the second and third contacts, the four color curves were plotted only between JD 2445200 and JD 2445850 in Fig. 4. During this phase there are enough IUE observations except the mid-eclipse for analysis of the color variation. Since there is no systematic color variation between totality and outside eclipse, the outside eclipse part was not included in the color curves.

The color curves in Fig. 4 show puzzling results. The color variations in each color curve occur at the vicinity of JD 2445400(before mid-eclipse) and JD 2445800(after third contact), where the light curves in Fig. 3 show slight brightening and egress. Two color curves of wavelengths 2800Å-2900Å and 2600Å-2700Å show that the color index decreases at the vicinity of JD 2445400 and increase(become redder) at the vicinity of JD 2445800. However the color curve of wavelengths 2700Å-2800Å shows opposite sense, and the color curve of wavelengths 2900Å-3000Å shows no variation for the whole phase. We notice that the amplitudes of the variation at the JD 2445400 might attribute to the observational scatters in the top three color curves in the Fig. 4. At the bottom curve in Fig. 4, the color index at the JD 2445400 clearly decrease approximately 0.1 magnitude compared to those during the early totality phase. This color variation occurs at the same phase of the first brightening during the totality.

The color curves at the vicinity of the JD 2445800 show variations in the bottom three color curves in Fig. 4, while the top color curve shows no variation during the whole observation period. The opposite sense of the color variation, between the second and fourth curves, and the third curve from the top, might be explained by the Doppler shift of the spectral lines. The IUE photometry in this study was made by integrating the fluxes at 100 Å bandpass intervals. Thus

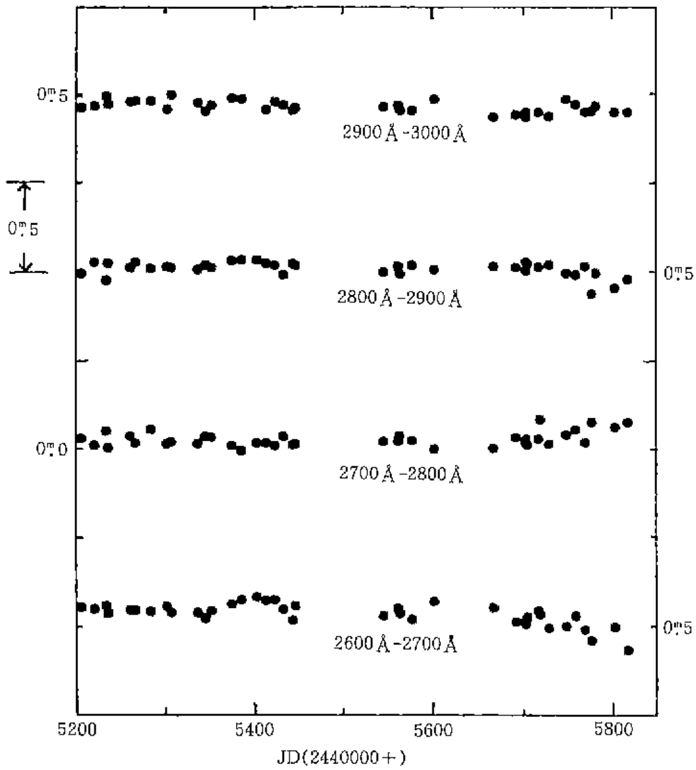

Fig. 4. Color curves of Epsilon Aurigae. The color index is reduced from the five selected light curves

if there is an absorption or emission feature at the boundary between bandpasses and the feature is shifted, the shifted feature would cause such a puzzling color variation. Another possible answer to the puzzling result is the variation of the line profile due to the UV sensitive material in the extented gaseous envelope around the secondary star. This UV sensitive material might affect the light and spectral lines during totality and egress. If such effect is maximum near the third contact instead of mid-eclipse, the result would be the downward slope during the totality and asymmetry of the eclipse shape.

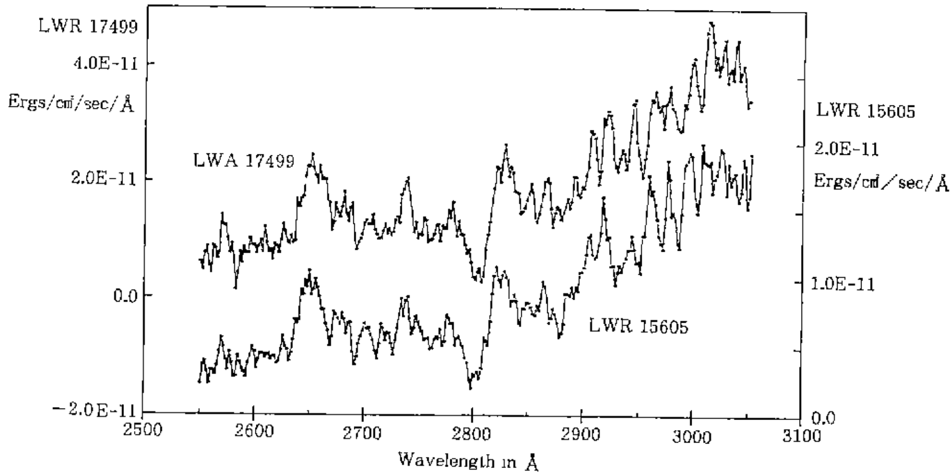

Fig. 5. Energe density distribution of Epsilon Aurigae between the wavelength 2550 Å and 3050 Å.

5. Energy Density Distribution

A comparison between totality and post-eclipse spectra is shown in Fig. 5. The energy density distribution of Epsilon Aurigae in the wavelength range from 2550Å to 3050 Å for two selected spectra are plotted with different scales. The LWR 15605 was taken on March 29, 1983 (JD 2445422) during the totality of eclipse and the LWR 17499 taken on August 16, 1984(JD 2445928) out-of-eclipse. Even if it is not possible to dentify each line profile because of low resolution spectra, the two spectra show nearly same features. This notes that the energy density distribution has not been changed between totality and out-of-eclipse. However the absorption feature at the vicinity of 2800 Å in the LWR 17499 has been red-shifted compared to that in the LWR 15605. Other features show the same shift. This might cause the color variation when we integrate the fluxes at every 100 Å interval regardless where the line profile is.

6. Conclusion

From the UV light curves of Epsilon Aurigae based on the IUE photometry, we determined the characteristics of the eclipse shape and may say the following points as conclusions.

(1) The two brightenings during the totality were shown in the UV light curves. The first brightening is not confirmed in the optical region. The amplitude of the second brightening is much larger than that in optical region. These brightenings might be due to the Cepheid-like variation of the primary star.

(2) The downward slope of the variation is shown from the second contact to the third contact. This variation caused the longer totality of the eclipse.

(3) The UV sensitive material in the extended envelpe of the secondary star gives the maximum effect near the third contact. Thus the effect causes the downward slope of variation during totality and asymmetry of the eclipse.

(4) The energy density distribution in the wavelength range 2550Å-3050Å is not changed between the totality of the eclipse and post-eclipse.

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