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A PUZZLING ECLIPSING BINARY SYSTEM: EPSILON AURIGAE

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ABSTRACT

The purpose of the present paper is to report on our optical UBV photometry obtained during the recent 1982–1984 eclipse of εAur, and review the basic data and the model of the system deduced from the large sample of collected photometric spectroscopic and polarimetric observations.

1. INTRODUCTION

A third magnitude bright star ε Aur is one of the most extensively studied celestial objects since its discovery in 1700's. Although the eclipsing nature was discovered in 1921 (Fritsch 1924) its physical nature is still not understood properly. ε Aur undergoes a total eclipse of duration 647 days in every 27.1 years, and in every eclipse it is observed worldwide by many amateur and professional astronomers. During the recent 1982-1984 eclipse R.E. Stencel (NASA), D.S. Hall (Dyer Observatory) and R.M. Genet (Fairborn Observatory) have organized and coordinated an observational campaign. The results from the campaign have been discussed in a two days meeting held in Tucson Arizona (cf. Stencel, 1985). Ankara University Observatory (AUO) also joined the campaign to observe the binary photoelectrically in the UBV filters.

In the following section our observations are presented and in Section 3 the interpretations of the large sample of collected photometric, spectroscopic and polarimetric observations in terms of the physical nature of the system have been outlined. The collected basic parameters of the system are summarized in Table 2. A model of the system in as much as it was understood presently was also drawn (see Figure 1).

2. UBV OBSERVATIONS

We observed ε Aur in three colours (UBV) on 20 nights in 1982 and 2 nights in 1983 using EMI 6256S photomultiplier attached to the 30 cm Maksutov telescope of the Ankara University Observatory (AUO).

Since the binary has a quite long orbital period, only a few differential observations per night were obtained with respect to the suggested comparison star λ Aur. The instrumental differential magnitudes corrected for differential extinction are given in Table 1. together with Heliocentric Julian dates of observations.

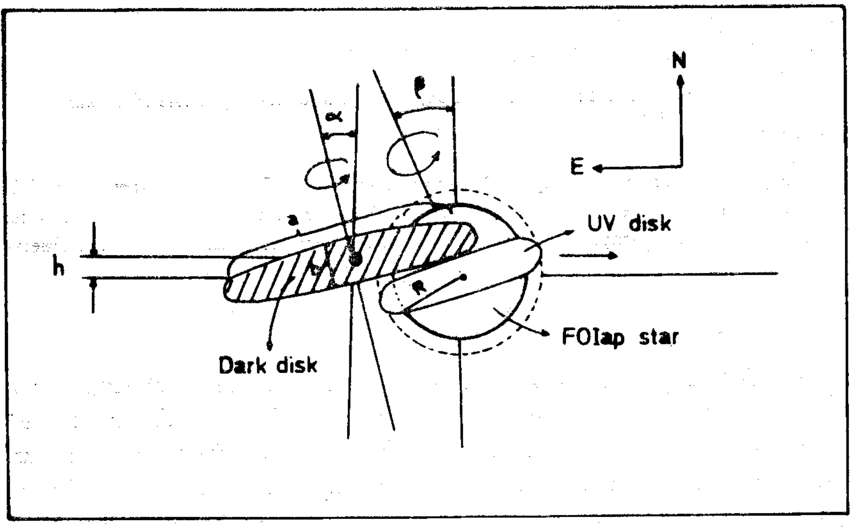

Figure 1. A model of ε Aur in as much as it was understood presently.

According to Gyldenkerne's (1970) prediction, our observations begin 123 days before the eclipse of ε Aur starts and well cover the ingress, second contact point and a part of the total phases. The light levels of the system in three colours drops steadily until the second contact point. Although the first contact point of the eclipse is not clear in our observations the total loss of lights due to the eclipse are estimated to be 0.8, 0.7 and 0.7 magnitudes in U, B and V filters. A deeper eclipse in the U filter was also observed by others (cf., e.g. Schmidtke, 1985). From ultraviolet data (cf. Ake, 1985) obtained with the international Ultraviolet Explorer Satellite, the depth of eclipse is known to increase for decreasing wavelength, down to about 1600 A. Below 1600 A the eclipse becomes shallower so that its depth is only 0.2 magnitudes at 1200 A. Our observations confirm that there is no significant U-B and B-V colour variation during the eclipse. This is in agreement with the finding that the spectral lines of primary component star are visible during all phases of the eclipse (cf., e.g. Hack, 1961). It means the invisible secondary component

Table. 1 UBV differential Observations of Epsilon Aur.

JD (Hel.)	D (V)	D (B)	D (U)	D (B-V)	D (U-B)
45057.23224	−1.740	−1.881	−1.621	−0.078	0.197
45057.23849	−1.724	−1.804	−1.615	−0.080	0.189
45068.29172	−1.667	−1.747	−1.619	−0.081	0.128
45068.30769	−1.550	−1.684	−1.435	−0.134	0.249
45224.57951	−1.347	−1.423	−1.182	−0.076	0.241
45224.58847	−1.383	−1.453	−1.208	−0.070	0.244
45224.59708	−1.375	−1.444	−1.212	−0.069	0.232
45265.59356	−1.179	−1.256	−0.986	−0.077	0.270
45265.60258	−1.166	−1.254	−0.988	−0.088	0.266
45267.40445	−1.172	−1.253	−1.029	−0.081	0.224
45267.41347	−1.165	−1.248	−1.022	−0.082	0.225
45271.32179	−1.204	−1.248	−1.069	−0.044	0.180
45271.33075	−1.153	−1.244	−1.062	−0.092	0.182
45283.39652	−1.027	−1.146	−0.705	−0.120	0.442
45283.40707	−1.053	−1.150	−0.728	−0.096	0.422
45286.33130	−1.058	−1.138	−0.905	−0.079	0.232
45286.34137	−1.072	−1.141	−0.901	−0.070	0.241
45289.32572	−1.064	−1.123	−0.888	−0.059	0.235
45289.33572	−1.036	−1.111	−0.904	−0.075	0.207
45298.36592	−1.020	−1.062	−0.812	−0.042	0.250
45298.37654	−0.991	−1.054	−0.783	−0.063	0.271
45298.38390	−0.976	−1.055	−0.770	−0.079	0.285
45298.39418	−0.999	−1.058	−0.784	−0.059	0.274
45298.40175	−0.991	−1.052	−0.783	−0.061	0.269
45298.41099	−0.989	−1.041	−0.733	−0.052	0.308
45298.41981	−0.970	−1.038	−0.731	−0.068	0.307
45298.43487	−1.005	−1.065	−0.796	−0.060	0.269
45298.44460	−1.008	−1.028	−0.777	−0.020	0.251
45298.45751	−1.004	−1.042	−0.779	−0.038	0.263
45298.47397	−0.985	−1.051	−0.775	−0.066	0.277
45298.48626	−1.006	−1.043	−0.774	−0.038	0.269
45298.49904	−0.981	−1.030	−0.755	−0.049	0.274
45298.51161	−0.996	−1.036	−0.762	−0.040	0.273
45298.52078	−0.990	−1.035	−0.748	−0.045	0.287
45298.53217	−0.987	−1.045	−0.763	−0.058	0.282
45298.54092	−0.996	−1.035	−0.752	−0.039	0.283
45298.55175	−0.973	−1.032	−0.735	−0.060	0.297
45299.30795	−1.014	−1.084	−0.847	−0.070	0.237
45299.31774	−1.011	−1.059	−0.825	−0.049	0.234
45300.41179	−0.986	−1.038	−0.784	−0.052	0.254
45300.42283	−1.037	−0.034	−0.754	−0.003	0.280
45302.34058	−1.105	−1.038	−0.685	−0.066	0.353
45302.37273	−0.965	−1.090	−0.679	−0.125	0.411
45311.26684	−0.974	−1.028	−0.779	−0.055	0.249
45311.27677	−0.960	−1.016	−0.770	−0.056	0.246
45313.25080	−0.920	−0.956	−0.755	−0.035	0.201
45313.26393	−0.892	−0.973	−0.752	−0.080	0.220
45314.40080	−0.925	−0.915	−0.839	−0.010	0.076
45320.28992	−0.934	−1.012	−0.755	−0.079	0.257
45320.30242	−0.961	−1.031	−0.770	−0.069	0.261
45321.24039	−0.966	−1.002	−0.770	−0.036	0.232
45321.24525	−0.973	−1.039	−0.785	−0.066	0.254
45321.25463	−0.923	−1.027	−0.774	−0.104	0.253
45326.26440	−0.997	−1.040	−0.777	−0.043	0.264
45326.27454	−0.956	−0.015	−0.760	−0.059	0.255
45328.28007	−0.968	−1.028	−0.774	−0.060	0.254
45327.28917	−0.976	−1.027	−0.766	−0.051	0.262
45360.45609	−0.922	−0.975	−0.706	−0.053	0.269
45360.47088	−0.910	−0.949	−0.684	−0.040	0.265
45305.26339	−0.929	−0.997	−0.717	−0.068	0.280
45405.27110	−0.914	−0.970	−0.742	−0.056	0.228

Table 2. Basic data of ε Aur (for the notations α, h / R, a, b see Figure 1).

Primary

Sp = F0Iap, $V = 3.00$, $E_{B-V} = 0.30$
$T_{ef} = 7650 \pm 150$°K
$T_0 = 2435629.0$, $P = 9892.0$ days ≈ 27.1 years.
$f(m) = 3.25 \pm 0.38\ M_0$
$A_1 \sin i = 13.37 \pm 0.53$ AU
$e = 0.200 \pm 0.034$
$a_1 = 0''.0227 \pm 0.0010$
$i = 89° \pm 3°$
$d = 578 \pm 51$ pc ≈ 1900 Ly.
$M_V = -6.74 \pm 0.30$
Ppuls. $= 90 \pm 20$ days
$\log L_1 / L_0 = 4.54 \pm 0.12$
$\log R_1 / R_0 = 2.02 \pm 0.06$
$\log M_1 / M_0 = 1.11 \pm 0.13$

Secondary

$10\ M_0 < M < 20\ M_0$
Tef $= 475 \pm 45$°K
$\alpha \approx 5°$
$h / R \approx 0.4$
$a = 8b$ (optical)
$a = 2b$ (infrared)

never eclipse the primary completely (see the model in Figure 1). The first contact point of the eclipse in our observations is not well covered and thus could not be estimated from the observations. Gyldenkerne's prediction for this point is 1982, Jul. 29. The second contact point of the eclipse was found to be 1982, Nov. 30; Dec. 6; and Dec. 8 in U, B and V filters, respectively, with a probable uncertainty of ± 5 days due to large scatter in the observations. Such wavelength dependence of the second contact point can not be accounted for in a simple manner.

The UBV observations of ε Aur, in and around second contact point, obtained in the Tjorn Island Astronomical Observatory (TIAO) in Sweden, the Hopkins Phoenix Observatory (HPO) in Arizona (cf. Hopkins, 1985), and in the Scalnate Pleso Observatory (SPO) in Czechoslovakia (cf. Chochol and Ziznovsky, 1987) have been compared with ours. An interesting aspect is that the shoulder seen especially in the BV observations from TIAO and HPO during the later portion of ingress is much less significant in our observations and in the observations from SPO.

The existence of such shoulder in the observations affects significantly the timing of the second contact point of the eclipse. Schmidtke (1985) found by using the observations from TIAO and HPO that the second contact was on the date 1982, Nov. 28 which is 13 days earlier than the predicted value (cf. Gyldenkerne, 1970). The mean second contact time (1982, Dec. 4). from our observations is 7 days earlier than the predicted value.

It should be noted that the pulsation-induced light variation of the visible star may also affect the timing of contact points. It is known, on the other hand, that the eclipse timing is important in determining both the physical and geometrical elements of the eclipsing and eclipsed celestial objects.

3. THE GEOMETRICAL AND PHYSICAL NATURE OF ε AUR

3.1. The Basic Facts

The light curves of ε Aur are of the Algol type displaying only one minimum that is about 0.7 magnitude deep in the visible. The duration of the entire eclipse is ≈ 714 days while the totality lasts for ≈ 330 days (Gyldenkerne, 1970). In spite of the existence of total phases in the eclipse the spectral lines of primary component are visible during all phases of the eclipse. Thus, the large secondary is far from being spherical in shape and do never cover the primary completely during the eclipse although the inclination i is close to 90° (see Figure 1). The absence of a secondary minimum indicates that secondary component has a very low temperature and is not observable in visible. Not all the observable properties of this system could be reproduced by any model. The mysterious secondary of the system has been described as a swarm of meteorites (Ludendorff, 1924), a giant infrared star (Kuiper, et al. 1937), a small infrared star plus an ionized gas stream (Struve, 1956), a hot B star surrounded by an ionized gas shell (Hack, 1961), a bar of optically thick material (Huang, 1965), a proto-planetary system (Kopal, 1971), a black hole plus a semitransparent disk (Cameron, 1971), a black hole within a thin, opaque disk with a central opening (Wilson, 1971), and an early type massive close binary system surrounded by an opaque thick disk (Lissauer and Backman, 1984), Thus, ε Aur, as Wilson (1971) commented, is the only binary system that can be described "with complete justification as mysterious".

3.2. Summary of The Results From Last Observational Campaign

The large amount of photometric data at different passbands revealed that F supergiant primary pulsates with a period of 105-120 days (Guinan, 1982). Such cepheid like pulsations (0.1-0.2 mag. variations outside as well as inside the eclipses) were first suggested by Krat (1936). The UV and polarization data also support the nonradial pulsations of primary. The UV continuum variations are cepheid like.

The primary star is a FO Iap type supergiant whose spectrum is also visible during the eclipse. Thus, the eclipsing cool object should be highly flattened disc not to eclipse primary completely (see Figure 1).

The eclipse depth is significantly less at $\lambda > 5$ micrometer suggesting an opaque and very cool eclipsing disk. IRAS observations gave a temperature of $T = 475 \pm 50°K$ for the secondary. It was found by Backman (1985) that side of the secondary facing the primary is heated up to $\sim 1100°K$. According to Ferluga and Hack (1985) dusty opaque disk must be made of particles much larger than those present in the interstellar dust, because no additional reddening is observed at 2200 A during the eclipse. A more extended gas envelope around disk is responsible from the additional spectrum appearing during the eclipse. Ferluga and Hack claims also that an extended envelope surrounds the whole system.

A faint hot object which is not eclipsing and whose radiation dominates at $\lambda = 1500$ A. In fact the depth of the eclipse tends to zero at $\lambda = 1200$ A (Ake, 1985) thus indicating that the excess in the UV is real and not due simply to scattered light from longer wavelengths in the spectrum of the primary. This hot body may be a star (cf. Hack, 1971; Hack and Selvelli, 1979) or a massive binary (cf. Lissauer and Backman 1984, and Eggleton and Pringle, 1985) in the center of the disk. Backman (1985) found that the projected width is about half the length for the eclipsing disk in IR. Such large thickness could be due to agitation of the disk material by the embedded object (s), e.g. a rapidly revolving close massive (B type) binary. The radiation of the embedded hot object should escape from the poles of the disc, excites and ionizes the gaseous envelope, producing the shell spectrum. The variable light of the hot body in the UV region is supported by close binary model.

A mid-eclipse brightening of over 0.2 magnitude is seen in UV and optical light curves. However the brightening is not present in the colour curves. The gray nature of this phenomenon argues against a pulsation induced light variation as the cause. Less obvious mid-eclipse brightenings were also observed in the earlier eclipses. Such brightening is thought to be related to hot object embedded in thick disk which is required to be not exactly edge on (i.e. $i < 90°$). The increasing amplitude of this brightening may be due to a possible precession of the disk. An other possible explanation of this brightening has been suggested as due to a gravitational lensing effect (cf. Hopkins 1984, and Schmidtke, 1985).

Kemp et al. (1985) observed asymmetrical changes in the polarization during the eclipse and they interpreted this as the tilted disc effect. They also claimed slightly northward displacement of the tilted disc. The negative slope in the UV total eclipse phases (cf. Ake, 1985) were also interpreted by Kemp et al. (1985) in terms of an inclined UV emitting ring, encircling the primary star's equator. Because they are tilted both the secondary disk and the primary star's spin axis must precess. Kemp et al. estimated a 1000 years for the disk precession time.

The evolutionary status of the primary is interpreted by Webbink (1985) in terms of a massive post MS star in a state of shell helium burning or, one in which the supergiant is contracting toward WD state, having been stripped of most of its hydrogen rich envelope by a combination of tidal mass transfer to the secondary component and mass loss in a stellar wind. A fossil accretion disk around secondary which is probably a massive binary is found not implausible by Webbink.

The collected basic data concerning ε Aur are summarized in Table 2 and the model is drown in Figure 1.

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