THE OPTICAL POLARIZATION OF EPSILON AURIGAE THROUGH THE 1982-84 ECLIPSE

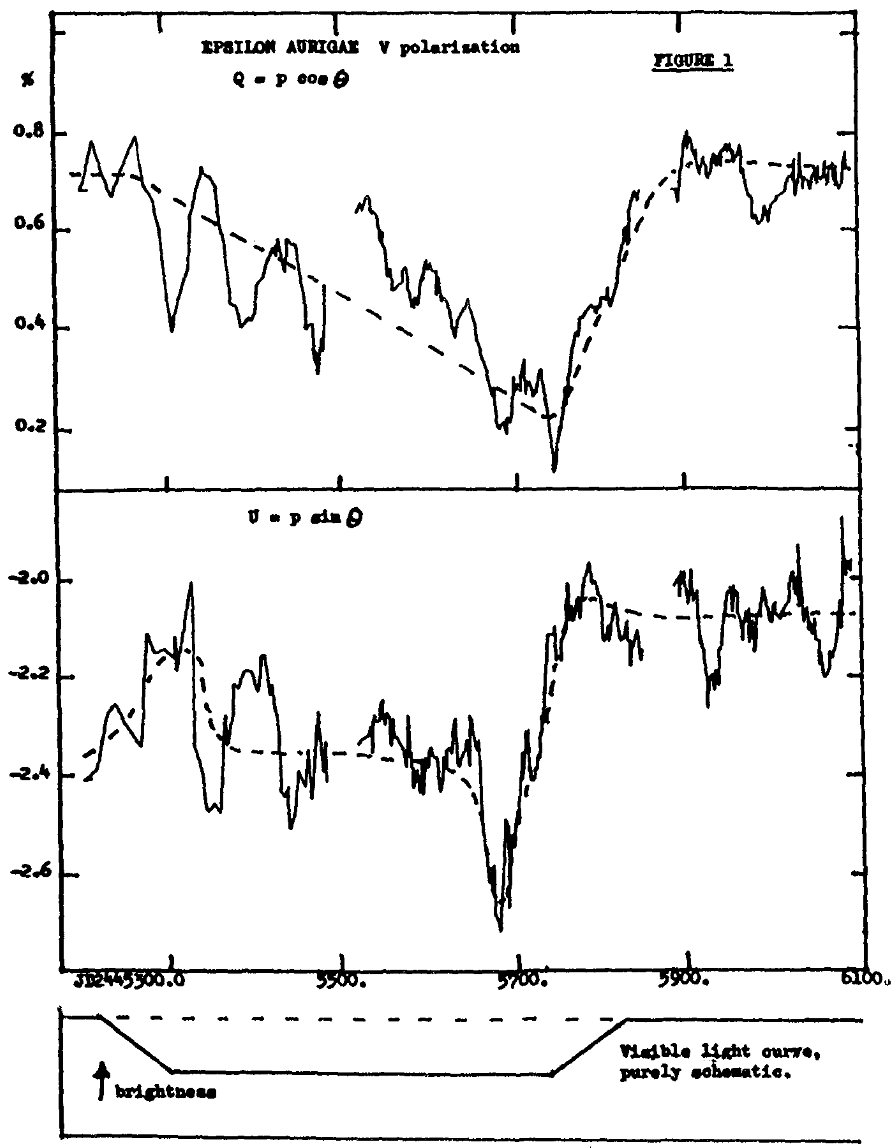
J.C. Kemp, G.D. Henson, D.J. Kraus, and I.S. Beardsley, Physics Dept., Univ. of Oregon, Eugene OR 97403.

About 350 nights' observations on the 61-cm telescope at Pine Mt. Observatory were made of the variable polarization of Eps. Aurigae during 1982-85, in the U, B, and V color bands. The V data are the most complete and are shown in Figure 1. In terms of the overall features the curves in all three colors are quite similar. The typical errors per nightly point in the V curves are about 0.015% for either of the two normalized, equatorial Stokes parameters Q and U. Note that there is a large background or constant component of some 2.5%, position angle around 135°. This is presumably largely interstellar, and the intrinsic polarization probably does not much exceed the amplitude of the variable component, $\sim$0.5%. We measured a few field-star polarizations but we did not get a very clear pattern in this part of the sky. (The stars closeby in direction, within $\sim$30 arcmin, seemed mostly to be in the foreground, with small polarizations. A deeper study is needed.)

We see two major variation patterns: (1) An overall pattern on the 1-year time scale of the eclipse. Aided by a model, we indicate this by dashed curves in the Figure. And (2) somewhat erratic oscillations on a 100-day time scale.

The "100-day" structure is almost surely connected with the primary star's pulsations --since, for example, these fluctuations continue outside eclipse. The eclipse process evidently interacts in some way with the pulsational polarization structure and we cannot completely separate the two effects. But the 1-year interval between 2nd and 3rd contacts covers about three pulsation cycles, thus the slow, long drop in the Q Stokes parameter, at least, is surely due to the eclipse itself.

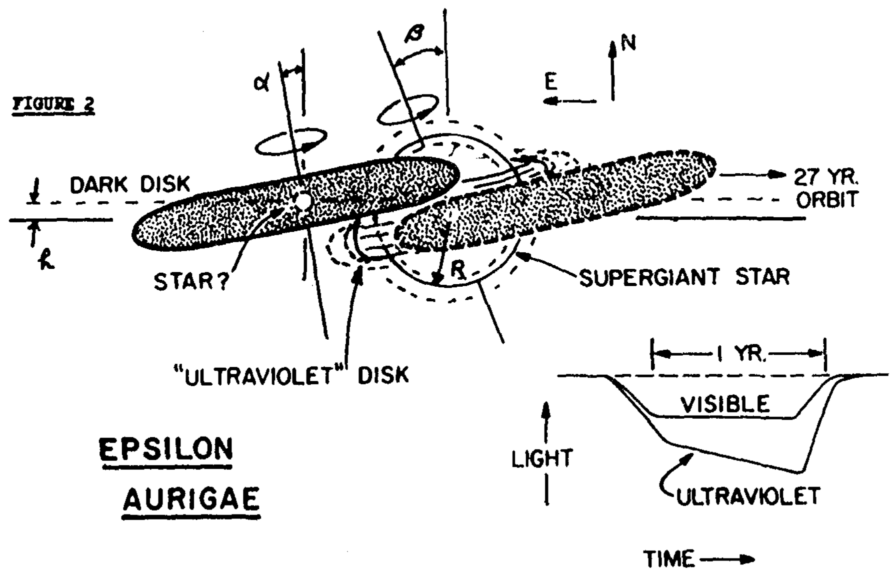
Some rapid changes on time scales of 1-5 days are also seen. While there are a few cases of large errors, this structure is mostly real, and suggests stochastic activity. The minimum time scale seems to be $\sim$ 0.5 day.



On at least 6 nights we followed the object for up to 7 hours and found no changes larger than $\Delta Q \sim \Delta U \sim 0.03\%$ over such time spans.

Models. We model the eclipse polarization in terms of limb polarization in the primary star, modulated by the passing dark cloud. For this we ignore pulsation and consider the star as spherical. See Figure 2. The star is assumed to emit polarized light concentrated strongly on the limb, due to internal scattering, with the E vector parallel to the limb. During partial eclipse this mechanism gives a non-vanishing net polarization (see e.g. Kemp et al 1983, Ap.J., 273, L85).

FIGURE 2



EPSILON AURIGAE

The asymmetrical changes in the observed polarization during the eclipse, especially the slope in the Q parameter, require that the disk must be tilted out of the orbital plane; and the orbit of the system cannot be exactly edge on, i.e. we must have $i < 90^{\circ}$. In Fig. 2 we indicate the non edge-on inclination by an upward displacement h, of the disk on the sky, relative to a line parallel to the orbit plane passing through the star's center. For our modelling the relevant parameter is h/R, the fractional displacement of the disk (at mid eclipse) from the star center. The disk is tipped by an angle α. The astrometric orbit (van de Kamp 1978, A.J., 83, 975) indicates that the system is oriented on the sky essentially east-west ($\theta \simeq 95^{\circ}$), and that the disk passes from east to west across the star, as drawn in Fig. 2. Note that some of our qualitative conclusions, mainly that the disk is tilted relative to the orbit and that $i \neq 90^{\circ}$, do not depend on the astrometric information.

With an upward (northward) displacement h, and a small tilt ($\alpha \lesssim 10^{\circ}$) in the direction shown in Fig. 2, just after second contact the disk covers mainly the upper hemisphere of the star, giving a relatively small net polarization. (Covering precisely a hemisphere gives zero polarization.) The disk then drifts downward. At third contact it covers, say, a central band on the star, with north and south poles exposed. This gives a maximum polarization, with E vector approximately EW, corresponding to a negative Q or ΔQ (relative to the interstellar value). This effective drifting of the eclipsed zone on the star thus accounts for the simplest feature of the eclipse polarization. During ingress and egress, the transient motions of the eclipsed zone produce relatively abrupt additional structure; positive and negative peaks occur in the U parameter. Assuming a diameter/thickness ratio of 6 for the disk, we generated a few model Q and U curves for several values of h/R and α. The best fits seemed to require $h/R \simeq 0.4$ and $\alpha \simeq 5^{\circ}$. With an orbit radius of 13 AU and a primary star radius of 1 AU, this h/R corresponds to $i \simeq 88^{\circ}$. The disk tilt angle α is small enough so that an almost flat light curve (between 2nd and 3rd contacts) comes out of the model. (Figure 2 is not drawn quite to scale. Deep in eclipse the disk should cover 50% of the star.)

Pulsational structure. In the light curve, a ~100-day "pulsation" pattern is well recognized, both inside and outside eclipse; see e.g. E.F. Guinan's paper at this Workshop. A polarimetric counterpart is not surprising. Because of possibly subtle interaction between the eclipse and the pulsation, we should first look at the outside-eclipse Q and U curves after fourth contact -- after approx. JD 2445850 in Figure 1. Clear ~100-day variation is seen in the U parameter, and a less-clear and perhaps weaker pattern is seen in Q. Since the U parameter measures polarization in $\pm 45^{\circ}$ directions (i.e. in NE or NW directions), we must have non-radial pulsations with an eigenaxis which is appreciably tipped from the orbit normal on the sky (approximately NS). We cannot say which direction the eigenaxis is tipped, i.e. toward NE or NW, without a complete model of the pulsation polarization which must include correlation with the photometric pulsation. In Figure 2 we have shown the primary star's spin axis, which we take to be the eigenaxis of the pulsation, as tilted in the NE direction. As will be seen, this choice is influenced by a connection with the IUE light curves.

The mechanism here is that the primary is a rotating pulsator, in which the pulsations produce an expanding and contracting equatorial belt or ring. Light from the star is scattered by this ring, producing the oscillating polarization. The ring is highly ionized with a large free-electron density, giving a high polarizing efficiency and almost color-independent polarization.

Connection with IUE light curves: A chromospheric belt? At this workshop, T. Ake has shown vacuum-ultraviolet light curves of Eps. Aurigae's eclipse, from IUE data. Over about the range 1600-3000 Å, these curves look schematically as we show at lower right in Figure 2. While the visible-light curve is flat (ignoring here the so-called mid-eclipse brightening), the UV curves slope downward. Here is strong evidence, separate from the polarization, for a pronounced asymmetry in the system!

We explain the sloping UV light curves in terms of an inclined, UV-emitting belt, or ring, encircling the primary star's equator -- the same tilted ring which we associate with the pulsational polarization. Because of the tilts of both the secondary disk and the primary star's spin axis, and the slightly non edge-on inclination, the eclipse of the chromospheric belt is somewhat delayed, relative to the eclipse of the star's approximately circular photosphere. The disk's shadow does not fully cover the belt until near third contact.

Epsilon Aurigae: A complex, gyrating system. The polarimetric properties of this system, combined with the asymmetrical IUE light curves, have shown it to be geometrically more complex than anyone had thought, even allowing for the Cepheid-like pulsations of the primary. For example, both the secondary disk and the primary star's spin axis must precess, because they are tilted. A rigid-body estimate for the disk precession time is around 1000 years. Note that the spin and disk directions of course lie in three dimensions, while in Fig. 2 we indicate basically just the projected directions on the sky. Precession would cause successive eclipses to differ, at least slightly. The 1928 eclipse had a quite flat-bottomed light curve, while the recent 1982-84 one had a strong special feature, a mid-eclipse brightening. Guinan (this Workshop) has suggested that the mid-eclipse brightening has to do with a kind of central gap in the secondary disk, which momentarily exposes the primary star. We can think of a precessing doughnut, which in 1928 was almost exactly edge on, so that no hole was exposed. By 1983 the disk may have precessed just enough so that we are beginning to see through the hole. Could we thus predict that in 2010 the eclipse will show an even stronger central brightening?

Continuing observations. We are extending our polarization observations for probably at least another year, with a view to defining the outside-eclipse pulsational structure. This is extremely important, and we issue a nenewed call to photometrists to continue their work as well! There is indication that the polarimetric changes do not reflect a simple "uniaxial" type of pulsation (as with some RV Tauri stars, for example); there may be multimode effects. Apart from the pulsation, in a couple of years the orbital phase will be such that we may be able to detect reflection polarization -- light from the primary scattered by the disk. For one thing that could help to check on the astrometric orientation of the system.