

AN OCCULTATION ANGULAR DIAMETER IN H-ALPHA LIGHT

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ABSTRACT

The lunar occultation of 119 Tauri, spectral type M2 Ib, was observed in continuum light and in the light of the H α absorption line. The restored strip-brightness distributions indicate that the H α light comes from a region having at least twice the diameter of that producing the continuum light.

Subject headings: occultations — stars: chromospheres — stars: diameters — stars: late-type — stars: supergiants

I. INTRODUCTION

Red giants and supergiants are known to be surrounded by expanding envelopes of gas and dust which extend to distances of many stellar radii. The best-studied object of this kind is α Ori, in which K I line emission has been detected to a radius $\approx 50''$ (Honeycutt *et al.* 1980), CO line emission to $R \lesssim 10''$ (Knapp, Phillips, and Huggins 1980), and dust emission as far out as $R \sim 90''$ (McMillan and Tapia 1978). Holographic measurements of α Ori (Roddiier and Roddiier 1981), recorded with a rotation-shearing interferometer (Roddiier 1979) at 10 optical wavelengths with bandwidths down to 50 Å, also reveal an optical halo extending to about 7 stellar radii ($\sim 0''.14$). Taylor (1966) derived a one-dimensional brightness distribution from a series of published occultation measurements of α Sco made with broad-band filters and found a halo extending to $0''.028$ surrounding a bright, central component of radius $0''.019$. The angular diameter of α Ori shows a wavelength dependence in blue to yellow continuum light (summarized in White 1980). The continuous emission observed in the envelopes around α Ori and α Sco could arise from the scattering of photospheric radiation, either by dust (Faÿ and Johnson 1973; Tsuji 1978) or by free electrons in a warm chromosphere. Although it seems well established that in many stars the flow begins in the chromosphere (cf. Dupree 1976; Goldberg 1979), most investigators have assumed that the expansion velocity is constant throughout the greater part of the shell, which makes possible the use of the radius at

which the flow reaches its terminal velocity as a key parameter in the estimation of the mass loss rate. Unfortunately, there is no reliable way to determine this radius with any accuracy (cf. Castor 1981), and largely for this reason mass loss rates derived by different investigators for the same star can differ by more than an order of magnitude.

It would clearly be of considerable importance to be able to measure the heights and thicknesses of the chromospheric regions in which the flows are accelerating. There are both theoretical (Hartmann and McGregor 1980) and observational (Goldberg 1981) reasons for supposing that in red supergiants, e.g., α Ori, the chromospheres may extend to distances of as much as several radii above the photospheres. Observations through narrow-band filters centered on, say, H α or the 8542 Å line of Ca II during lunar occultations or with the technique of speckle interferometry have been suggested (Goldberg 1981) as a means of detecting these extended envelopes. Such observations may be expected to yield important information on the structures as well as the diameters of red giant chromospheres.

The importance of observing stellar diameters in monochromatic light was pointed out over 10 years ago by Hanbury Brown *et al.* (1970), who found that the diameter of the Wolf-Rayet star γ^2 Vel, when measured with the intensity interferometer through a filter of 25 Å bandwidth centered on the C III-IV emission at 4650 Å, was about 5 times as large as that measured with a bandwidth of 100 Å in the continuum at 4430 Å.

This paper presents data obtained from a lunar occultation observation in H α of 119 Tauri (M2 Iab, $m_v = 4.33$), an M supergiant similar in spectral type to α Ori but much more stable in its spectroscopic and photometric properties (White 1980). Despite some con-

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tamination by continuum light in the $H\alpha$ passband, the angular diameter of the $H\alpha$ source derived from the restored strip-brightness distribution was found to be at least $0''.019$. Nearly simultaneous continuum light observations fixed the photospheric angular diameter at $0''.010$.

II. OBSERVATIONS AND REDUCTIONS

The emersion of 119 Tauri occurred during morning twilight on 1980 August 6 UT. The waning moon was 19% illuminated, with the Sun 10° below the horizon and the star about 35° above the horizon. The event occurred at a predicted lunar position angle of $317^\circ 9'$ and contact angle of $118^\circ 1'$, yielding a rate of emersion of $0''.2214 \text{ s}^{-1}$ (404 m s^{-1} with the lunar distance at 376,883 km).

The observations were made with the Lowell 1.1 m and the Perkins 1.8 m telescopes. At the 1.1 m telescope, the spectral bandpass was 46 \AA centered on 6563 \AA . Though centered on $H\alpha$, the bandwidth is nearly 30 times the equivalent width of the absorption line and is therefore considered to be continuum. The sampling rate was 1000 integrations per second. A second color observation was attempted at 4100 \AA but was too noisy to use because of the low contrast in the morning twilight.

The Perkins 1.8 m was used in a one-color mode with an $H\alpha$ temperature-controlled interference filter. The only filter available to us at the time had a half-power bandpass of about 6.5 \AA centered at 6563 \AA (several angstroms wider than had been specified). In consequence of the fairly bright twilight, the filter transmitted a noisy background that set a limit on the faintness of the detectable circumstellar envelope. The sampling rate was 500 integrations per second. The differential radial velocity between observing site and star was less than 2 km s^{-1} so that the narrow filter was centered on the 2 \AA wide $H\alpha$ absorption line of 119 Tauri. Of the total photons passed by the filter and spectral feature combination, about 50% originated within $\pm 2 \text{ \AA}$ of 6563 \AA and 15% within $\pm 1 \text{ \AA}$ of 6563 \AA . All data were recorded digitally using small computers.

The occultation traces are shown in Figure 1. The intensity scale is normalized to the star intensity long before occultation. The individual traces are shifted vertically for display purposes. The abscissa is in units of time and encompasses 0.2 s.

Both a nonlinear least-squares fitting procedure (e.g., White 1978) and a deconvolution technique were used to determine the angular diameter. Deconvolution yields both a strip-brightness distribution (SBD) and an estimate of the angular diameter. The least-squares model-fitting routine converged quickly, but the shape of the star's SBD had to be assumed. Since very different diameters were found for the two observations, the deconvolution technique was applied to verify the dif-

ference and to provide some information on the SBD. If a radically incorrect SBD is assumed in the application of the model-fitting technique, the convergence may be excellent, even though the angular diameter may be incorrect.

Scheuer (1962) showed that a restoration function can be calculated which, when convolved with the observed occultation trace, will yield the SBD of the object. The restoration function is the second derivative of the point-source diffraction pattern convolved with the filter transmission curve (nearly monochromatic). This function is again convolved with a symmetric function chosen to limit the restoration function to a practical length. The width of the symmetric function is related to the angular resolution of the restored SBD. The limit in angular resolution for these data is due first to the signal-to-noise ratio and second to the telescope aperture.

As suggested by Scheuer (1962) and von Hoerner (1964), several restoration functions of increasing resolving power were tried as a means of empirically determining the limit of resolution dictated by the signal-to-noise. The restored SBD from the narrowband data became ill-defined due to signal rms noise for resolution less than $0''.002$ and showed a resolution-dependent angular diameter for a resolution greater than $0''.009$. The restoring function used for these results was equivalent to scanning the star with a beam of about $0''.003$ half-power full-width. The useful range for the wide-band data was

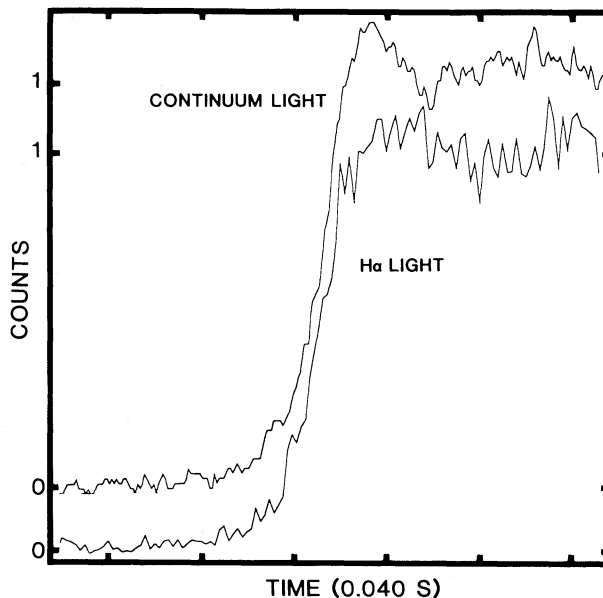


FIG. 1.—The observed occultation traces normalized to the star's intensity are plotted against time in units of 0.040 s. The integration time per point was 0.001 s for the continuum trace (upper) and 0.002 s for the $H\alpha$ trace (lower).

0''.002 to 0''.004. The restoring function applied was about 0''.002 half-power full-width beam.

The radial brightness distribution can be derived from the SBD if the geometry of the source is known. We assumed circular symmetry and calculated the radial distribution by differencing the area-weighted portions of the annuli and strips defined by the number of points in the radial distribution and SBD, respectively. This procedure begins with the outermost strip and works inward; therefore, the errors of the individual points of the radial brightness distribution increase with decreasing radial distance. The center point will have approximately 2.4 times the standard error of the outermost point if all strip-brightness values have the same standard errors.

III. RESULTS

The angular diameter determined by the nonlinear least-squares model-fitting method applied to the wide-band observation (6563 Å, 46 Å bandpass) was $0''.0090 \pm 0''.0002$ (uniform-disk assumption). This is in excellent agreement with five earlier observations (White 1980) whose mean was $0''.0096 \pm 0''.00075$. The observed rate of occultation was $459 \pm 7 \text{ m s}^{-1}$, 13% faster than predicted. The signal-to-rms-noise ratio for the trace was 43.

The same method applied to the narrow-band observation (6563 Å, 6.5 Å bandpass) yielded a uniform disk angular diameter of $0''.014 \pm 0''.001$, nearly 50% larger than the results of the wide-band observation. Assuming a total limb-darkened distribution, the angular diameter value increased to about 0''.017. Because of

the lower signal-to-rms-noise ratio (18) and the subtle fringe pattern due to the larger diameter, the observed rate of occultation, $510 \pm 30 \text{ m s}^{-1}$, was not as well defined (see Fig. 1).

The SBDs derived by the restoration method of Scheuer (1962) are plotted in Figure 2. The scatter about the zero flux level is indicative of the rms noise. The angular diameters inferred from the restored SBDs are $0''.010 \pm 0''.001$ and $0''.019 \pm 0''.002$ for the wide and narrow bandpasses, respectively. These values are slightly larger than those determined above by the model-fitting method. However, the restoration technique makes no assumptions as to geometry or flux distribution across the stellar disk. Although the lack of restricting assumptions causes the technique to fail for data with relatively poor signal-to-noise ratio, it is a valuable tool in cases where the validity of the usual assumptions of circular symmetry and smooth radial light distribution may be suspect.

Both limb-darkened and uniform-disk SBDs have been plotted on the restored distributions in Figure 2. The models were normalized to the estimated peak flux and angular diameter of the restored distributions. The differences between the wide-band (continuum) result and the models are small. However, the narrow-band restored distribution falls off more rapidly than the models. There is also some indication of asymmetry.

The radial brightness distributions derived from the restored SBDs on the assumption of circular symmetry are shown in Figure 3. As mentioned previously, each point of the radial distribution depends upon all points defined at greater radial distances; therefore, the errors

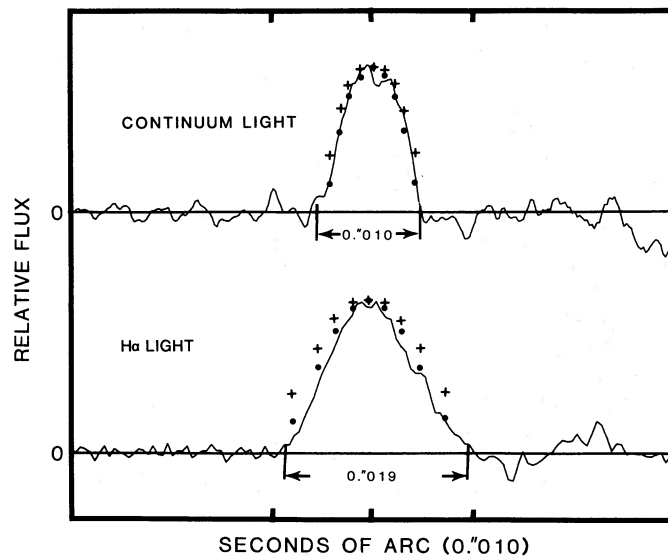


FIG. 2.—The restored strip brightness distributions (SBDs) are indicated by solid lines. For comparison, two theoretical SBDs are plotted: +, the distribution expected for a uniformly illuminated disk; ●, the distribution assuming full limb darkening. The angular resolution of the restored SBDs is about 0''.002.

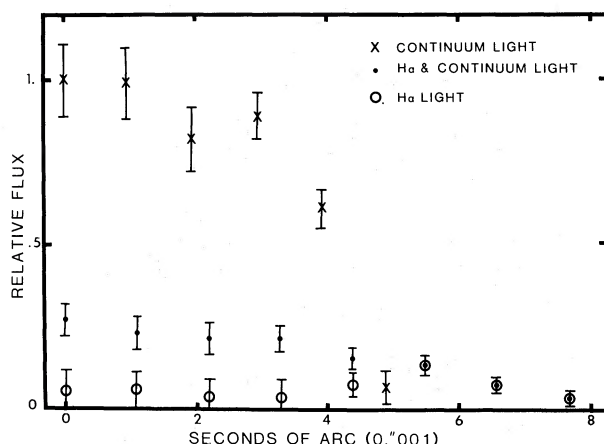


FIG. 3.—The radial brightness distributions, symbols \times and \bullet , were derived from the strip brightness distributions shown in Fig. 2. The zero for the abscissa is the center of the stellar disk. The photospheric radius defined by the continuum light observation is about $0''.005$. The open circles indicate the radial brightness distribution in H α light corrected for continuum light passed by the narrow passband filter.

increase toward the center of the distribution (stellar disk). The relative flux scale was determined from the relative sensitivity of each of the telescope-filter-photomultiplier combinations and a spectrophotometric tracing about the H α line from an echellogram obtained with the KPNO 4 m telescope.

The contamination of continuum light in the H α observation is estimated to be about $75\% \pm 10\%$ from a weighting of the H α spectrophotometric profile by the filter transmission curve. The radial brightness distribution was corrected for continuum light (\circ) by subtracting the properly weighted continuum radial brightness distribution (\times) from the contaminated H α distribution (\bullet). Figure 3 shows that the corrected H α radial brightness distribution is flat, within the errors, across the photospheric disk, increases to a maximum of more than twice this value just off the disk, and decreases into the background noise at about 1.8 stellar radii.

IV. DISCUSSION

Because of the high sky background, as well as continuum light contamination, we cannot draw any firm conclusion about the true size and shape of the radial brightness distribution of the H α source nor about the excitation mechanism. However, the observations confirm the continuum diameter previously measured by White (1980) and suggest that the source of light in the H α absorption line may extend out for several stellar radii. Taylor (1966) found a similar extension for α Sco; however, those occultation observations were all made with wide passband filters. It is not clear why only our narrow-band observations show the extended envelope of 119 Tau unless the B-type companion increases the

brightness of the envelope surrounding α Sco—e.g., by electron scattering.

Until we have better knowledge of the densities and temperatures in the H α -emitting region, we are unable to judge which atomic processes predominate in the excitation mechanism. We note, however, that the corrected H α radial brightness distribution is qualitatively similar to that expected from an optically thin envelope. It can be shown, for example, that if the density of neutral hydrogen falls off as $1/r^2$, the rate of emission per unit area at some projected distance ϕ from the star, relative to that at the center of the stellar disk, is

$$E = \frac{3\pi}{4} \phi^{-3} \left[1 - \frac{2\phi}{\pi} (1 - \phi^2)^{1/2} - \frac{2}{\pi} \tan^{-1} \left(\frac{1 - \phi^2}{\phi} \right)^{1/2} \right] \quad (1)$$

for $0 < \phi < 1$, and

$$E = \frac{3\pi}{2} \phi^{-3} \quad (2)$$

for $\phi \geq 1$. The distance ϕ is in units of the stellar radius. Notice that when $\phi = 1$, the emission intensity increases abruptly by a factor of 2 and then decreases rapidly with increasing distance. The rate at which the emission drops off is proportional to $\phi^{-(\alpha+1)}$, where $(-\alpha)$ is the exponent of r in the density distribution (see also Honeycutt *et al.* 1980).

For the present, the angular resolution ($0''.0014$) is too low and the error bars too large to permit any sure estimate of the value of α or the amount of the intensity increase. The magnitude of the error bars for the points at radial distances greater than $0''.005$ ($\phi = 1$) are due only to the rms noise of the narrow-band observations. For radial distances less than $0''.005$, the errors are larger due to the combination of rms noise from both traces. The significance of the intensity increase therefore depends equally on the narrow-band and continuum observations, although we believe the data do indicate a real intensity increase. Clearly, observations of this kind should be attempted again. For the study of both chromospheres and circumstellar shells, we suggest the use of filter passbands of about 2 \AA centered on one or more of the following wavelengths: 5890 \AA ; 5896 \AA of Na I; 6563 \AA of H I; 7699 \AA of K I; and 8542 \AA , 8662 \AA of Ca II. Resonance-line emission of the metals falls in the blue-violet region of the spectrum and probably could not be detected with existing telescopes. In Table 1 we give a representative list of relatively bright, cool giants in the zodiacal zone which will be occulted under favorable conditions during the period from late 1981 until the end of 1983. Unfortunately, 119 Tau will not be occulted again in this decade. The first two columns give the bright star and SAO catalog numbers of the

TABLE I
OCCULTATIONS OF COOL GIANTS

Bright Star No. (1)	SAO (2)	Spectral Type (3)	<i>V</i> (4)	UT Date (5)	Place ^a (6)	Object (7)
3	128572	K0 IIIb	4.6	1982 Jul 12 1982 Aug 8 1982 Sep 4 1982 Nov 26 1982 Dec 23 1983 Jul 2 1983 Aug 26	T MS J CT MS MK J	33 Psc
489	110065	K3 IIIb	4.4	1983 Aug 28 1983 Sep 24 1983 Nov 18 1983 Dec 15	CT MK CT MS	ν Psc
649	110408	G6 II-III	4.4	1983 Sep 25 1983 Dec 16	CT T	ξ' Cet
1739	77097 77915	G8 III gG5	5.0 4.2	1983 Feb 22 1982 Dec 2 1983 Jan 26 1983 Mar 22	CT, T MK MK CT	109 Tau 1 Gem
2216	78135	M3 III	3.2	1982 Sep 11 1982 Oct 8-9 1982 Nov 5	MS J J, T	η Gem
2286	78297	M3 IIIab	3.0	1982 Aug 15 1982 Oct 9	MK J	μ Gem
2473	78682	G8 Ib	3.1	1983 Oct 27 1983 Nov 23	CT MK	ϵ Gem
2630	78999	G5 II	5.2	1983 Apr 19 1983 Sep 30	MK T	ω Gem
2985	79653	G8 IIIa	3.6	1983 Oct 28 1983 Nov 24	CT MK	κ Gem
4517	119035		4.0	1982 Jan 14 1982 May 31 1982 Jun 27 1982 Dec 8 1983 Jan 31 1983 Feb 28 1983 Apr 24 1983 Dec 25	T CT MK J J T T, CT J	ν Vir
5908	159563	K0 III-IV	4.1	1982 Mar 15	T	θ Lib
6104	159892	K0 II-III	4.5	1983 Feb 6 1983 Apr 2	T CT	ψ Oph
7120	187445	K3 IIIa	5.0	1982 Feb 19	MK	ν^2 Sgr
7217	187643	gG8	3.8	1981 Sep 9	CT, T	\circ Sgr
8288	164593	G8 III	4.7	1983 Jul 26 1983 Sep 19	MS CT	
8679	165321	M0+ III	4.0	1983 Aug 24 1983 Oct 17 1983 Nov 14	T J MK	τ Aqr
8841	146598	K0 III	4.2	1981 Aug 17 1981 Oct 11	T CT	ψ^1 Aqr
9089	147042	M3 III	4.4	1982 Jul 12 1982 Aug 8 1982 Nov 25 1983 Jul 29 1983 Aug 25 1983 Oct 19 1983 Nov 15 1983 Dec 13	T, CT MS CT MS J MS J MK	30 Psc

^aT=Tucson; MS=Mitaka-Shi; J=Jungfrauoch; CT=Cerro Tololo; MK=Mauna Kea.

star, columns (3) and (4) the visual magnitude and spectral class, respectively, and columns (5) and (6) the date and place for which the occultation was predicted.

If the H α -emitting region in 119 Tau is as large as 3 stellar radii, it would be resolvable by speckle interferometry at the largest telescopes. Other bright giants and supergiants, whose stellar disks have already been resolved by speckle interferometry (Gezari, Labeyrie, and Stachnik 1972)—e.g., α Sco, β Peg, β Tau, α Boo, α Aur, β Cep, μ Cas, α Ori, and o Cet—would be of particular interest to observe with narrow bands. Still other stars, such as μ Cep and indeed all M supergiants with $I(104)$ magnitudes brighter than 2 in the list given by White and Wing (1978), may have H α and Ca II

8542 Å diameters resolvable by speckle techniques. It is important to note that the spatial resolution attainable with the occultation technique, in most cases, exceeds that of the speckle method by an order of magnitude.

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