

Letters

Fine Structure in the Circumstellar Environment of a Young, Solar-like Star: The Unique Eclipses of KH 15D

WILLIAM HERBST AND CATRINA M. HAMILTON¹

Astronomy Department, Wesleyan University, Middletown, CT 06459

FREDERICK J. VRBA

US Naval Observatory, Flagstaff Station, Box 1149, Flagstaff, AZ 86002-1149

MANSUR A. IBRAHIMOV

Ulugh Beg Astronomical Institute of the Uzbek Academy of Sciences, Astronomicheskaya 33, 700052 Tashkent, Uzbekistan

CORYN A. L. BAILER-JONES, REINHARD MUNDT, AND MARKUS LAMM

Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

TSEVI MAZEH

School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv, Israel

ZODIAC T. WEBSTER

Astronomy Department, 601 Campbell Hall, University of California, Berkeley, CA 94720-3411

KARL E. HAISCH

NASA Ames Research Center, Mail Stop 245-6, Moffett Field, CA 94035-1000

ERIC C. WILLIAMS AND ANDREW H. RHODES

Astronomy Department, Wesleyan University, Middletown, CT 06459

THOMAS J. BALONEK

Department of Physics and Astronomy, Colgate University, 13 Oak Drive, Hamilton, NY 13346-1398

ALEXANDER SCHOLZ

Thüringer Landessternwarte Tautenburg, Sternwarte 5, D-07778 Tautenburg, Germany

AND

ARNO RIFFESER

Universitäts-Sternwarte München, Scheinerstrasse 1, D-81679 Munich, Germany

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ABSTRACT. Results of an international campaign to photometrically monitor the unique pre-main-sequence eclipsing object KH 15D are reported. An updated ephemeris for the eclipse is derived that incorporates a slightly revised period of 48.36 days. There is some evidence that the orbital period is actually twice that value, with two eclipses occurring per cycle. The extraordinary depth (~ 3.5 mag) and duration (~ 18 days) of the eclipse indicate that it is caused by circumstellar matter, presumably the inner portion of a disk. The eclipse has continued to lengthen with time, and the central brightness reversals are not as extreme as they once were. $V-R$ and $V-I$ colors indicate that the system is slightly bluer near minimum light. Ingress and egress are remarkably well modeled by the passage of a knife edge across a limb-darkened star. Possible models for the system are briefly discussed.

1. INTRODUCTION

Planets are believed to form during the first ~ 100 Myr of a star's life from matter in a circumstellar disk (Chambers &

Wetherill 1998). The initial stages of that process have been viewed with increasing clarity in high-resolution images of young stars obtained with the *Hubble Space Telescope*. These have revealed complex disk structures on scales of tens to hundreds of AU around ~ 1 Myr old objects (O'Dell 2001; Krist, Stapelfeldt, & Watson 2002). Probing the inner parts of

¹ Physics Department, Connecticut College, Box 5424, New London, CT 06320.

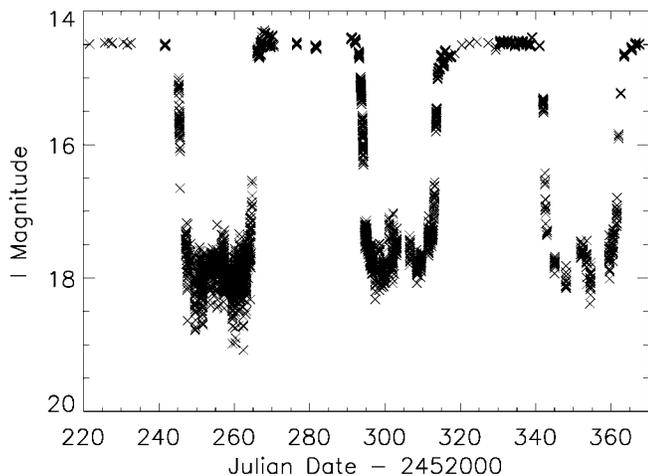


FIG. 1.—Portion of the light curve of KH 15D during the 2001–2002 observing season showing three eclipses. The last eclipse displayed above was centered at JD 2,452,352.26. On the basis of these data we predict that future eclipses will occur at intervals of 48.36 days. The current width of the eclipses, measured at the 16.25 mag level, is almost exactly 0.4 in phase, or 19.3 days. Ingress and egress begin approximately 1.5 and 1.9 days before or after the 16.25 mag level, respectively. The rate of decline becomes much shallower about 0.5 day after that level is reached, and the deepest minimum may not occur until many days later.

disks, where terrestrial planets formed in our solar system and where giant planets are found in many exosolar systems (Marcy & Butler 2000; Vogt et al. 2002), however, is still well beyond the reach of the current generation of telescopes. Here we report observations of a remarkable eclipsing solar-like star at an age of ~ 3 Myr, which provides a glimpse of the structure and possibly evolution of circumstellar matter on scales as fine as 0.01 AU. This is possible because of its unique geometry that results in the star being periodically eclipsed by extended non-luminous matter in its vicinity. No other object in the history of astronomy has been found to behave in quite the same way.

The star in question, KH 15D ($\alpha = 6^{\text{h}}41^{\text{m}}10^{\text{s}}.18$, $\delta = 9^{\circ}28'35''.5$, epoch J2000; see Hamilton et al. 2001 for an identification chart), was first noticed in 1997 as a unique and potentially important object during a photometric monitoring program of young clusters undertaken with a small telescope at Van Vleck Observatory (VVO) on the campus of Wesleyan University in Middletown, Connecticut (Kearns et al. 1997; Kearns & Herbst 1998). It undergoes a very deep (~ 3.5 mag) eclipse every 48.3 days and remains in the faint state for about 18 days, suggesting that the eclipsing body is nonluminous circumstellar matter. Remarkably, there is a central reversal of variable height that sometimes returns the star to its out-of-eclipse level (and once to an even brighter level) for a brief time near mideclipse. A follow-up study by Hamilton et al. (2001) revealed that the star has a mass of $0.5\text{--}1 M_{\odot}$ and a radius of about 1.3 solar radii, indicating that it is still in its contraction phase toward the main sequence and has not yet

initiated hydrogen burning in its core. Its pre-main-sequence status is confirmed by the presence of Li I in its spectrum and its membership in the young open cluster NGC 2264, which has an age of 2–4 Myr and a distance of 760 pc (Sung, Bessel, & Lee 1997). No other star among the thousands monitored in the VVO program or elsewhere over more than a decade (Stassun et al. 1999; Herbst et al. 2000; Rebull 2001; Herbst, Bailer-Jones, & Mundt 2001) has behaved in similar fashion. The closest analogs we can find in the astronomical literature are ϵ Aur, an F-type supergiant that is eclipsed every 27 yr by dark circumstellar matter (Lissauer et al. 1996), and BM Ori, an early B star that is eclipsed every 6.5 days by something dark orbiting it (Popper & Plavec 1976). Neither star is solar-like, nor are the eclipses even remotely similar to those of KH 15D.

2. OBSERVATIONS

To investigate this phenomenon in more detail, we organized, during the 2001–2002 observing season, an international campaign aimed at obtaining precision photometry with the highest possible time resolution over the longest possible time interval. A full report on this effort will be given elsewhere (C. M. Hamilton et al. 2002, in preparation). Here we provide a brief overview of the phenomena and an ephemeris to facilitate observations. The principal sources of optical photometric data were telescopes of 0.6–1.5 m aperture at the US Naval Observatory’s (USNO) Flagstaff Observing Station in Arizona, Maidanak Observatory in Uzbekistan, Wise Observatory in Israel, Kitt Peak National Observatory (KPNO), and VVO. Additional contributions, some at earlier epochs, came from Calar Alto Observatory in Spain, the European Southern Observatory in Chile, and a campus telescope at Colgate University in New York. Differential photometry relative to a grid of local comparison stars was used to establish zero points and combine the data. Photometric accuracy is ~ 0.02 mag out of eclipse but, because of the faintness of the star and its proximity to a much brighter cluster member, declines to ~ 0.1 mag during eclipse. Most observations were obtained in the *I* band of the Cousins system but some other filters were used, as discussed below. We obtained some data on all five eclipses that occurred during the observing interval 2001 September 11 to 2002 April 3; excellent coverage was obtained on the last three eclipses, in December, January–February, and March, respectively.

A portion of the light curve, including the three well-sampled eclipses of last season, is shown in Figure 1. The basic features, including a rapid ingress and egress phase, a deep, structured minimum with central reversal, and an eclipse duration of about 40% of each cycle, are evident. Combining these data with what has been observed over the 6 yr interval since its discovery, we have derived a new ephemeris for mideclipse:

$$\text{JD}(\text{mideclipse}) = 2,452,352.26 + 48.36E.$$

The current width of the eclipses, measured at the 16.25 mag

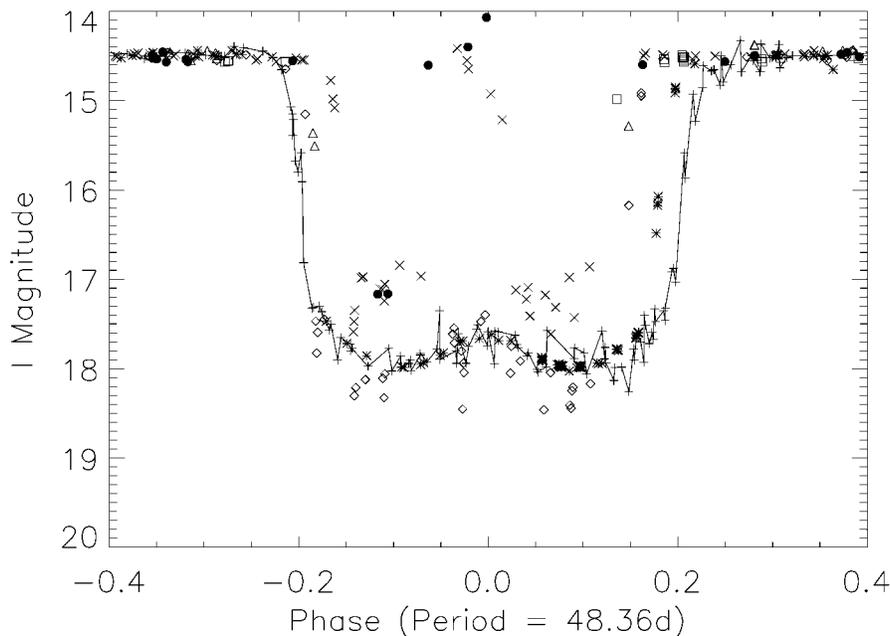


FIG. 2.—Eclipses of KH 15D since its discovery in 1995, phased with the period 48.36 days. Different symbols refer to different years, as follows. *Filled circle*: 1995/1996; *cross*: 1996/1997; *square*: 1997/1998; *triangle*: 1998/1999; *diamond*: 1999/2000; *asterisk*: 2000/2001; *pluses connected by lines*: 2001/2002. The data, averaged by day, from the 2001/2002 season and connected by the solid line clearly define the outer limits of the observed points in phase. This shows that the eclipse has been widening with time. It is also noticeable that the central reversals have declined in brightness with time.

level, is almost exactly 0.4 in phase, or 19.3 days. Ingress and egress begin approximately 1.5 and 1.9 days before or after the 16.25 mag level, respectively. The rate of decline becomes much shallower about 0.5 day after that level is reached, and the deepest minimum may not occur until many days later. There were also subtle variations from eclipse to eclipse last season, as may be noticed by close inspection of Figure 1. In fact, while this requires verification, it appears quite possible that the true period for this star is not the average interval between eclipses (48.36 days), but twice that, 96.72 days. In particular, the “central” reversals of alternate eclipses are slightly offset from mideclipse by similar amounts but in opposite direction, while the adjacent minima are symmetric, but in mirror-image fashion.

A second remarkable result from last season’s intensive monitoring effort is that the breadth of the eclipse and height of the central reversal have continued to evolve in secular fashion (see Fig. 2). Phasing all of the photometry obtained over the 6 yr interval since its discovery with the 48.36 day period, we see that the most recent data define the outer limits of the eclipse in phase. That is, at earlier epochs, eclipses were clearly of shorter duration and the central reversals often reached much brighter levels, sometimes climbing to the out-of-eclipse level or, in one case, slightly brighter. Figure 2 may represent the first detection of changing structure in the circumstellar disk of a young star and provides a serious challenge to models of the system. It is currently impossible to predict how the eclipses

will evolve with time, but the fact that they are changing so dramatically on human timescales underscores the necessity to keep monitoring this star.

Ingress and egress are remarkably smooth and have shapes that are well represented by the steady advance or retreat of a “knife edge” across a limb-darkened star. In the case of ingress this takes ~ 1.9 days, while for egress it is slightly longer, ~ 2.4 days. A comparison between the knife-edge models and the data, phased with the 48.36 day period, is shown in Figure 3. A standard limb-darkening law,

$$I(\theta) = I(0) - \mu + \mu \cos \theta,$$

with $\mu = 0.3$, appropriate to a star with effective temperature of 4000 K, was assumed (Dorren 1987). The shape of the model light curve is quite insensitive to the value of μ . It derives primarily from the geometric feature that near the halfway point the edge is cutting longer chords of the star. It is important to note that the durations of ingress and egress are much longer than the expected transit time (~ 0.5 day) of an object on a Keplerian orbit about the star with a period of 48 or 97 days.

During totality, which lasts about 18 days, the system is still visible, but at about 5% of its out-of-eclipse intensity. The spectrum and color (Fig. 4) during this time indicate that we are seeing reflected starlight from the circumstellar matter. The knife-edge model (Fig. 3) includes this component as a constant addition at all phases. In fact, the “central” reversals and short

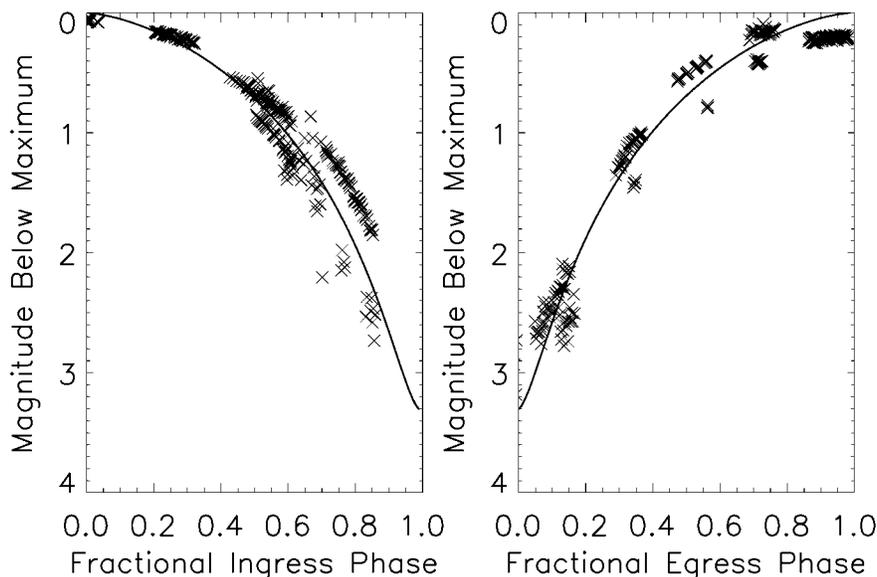


FIG. 3.—Ingress and egress of all eclipses observed in 2001/2002 compared with a knife-edge model. The model assumes a perfectly straight, sharp edge cutting across a limb-darkened star over a 1.9 day period for ingress and 2.4 day period for egress. It includes a 5% addition for scattered light in the system, which becomes important only near minimum light. Clearly the models are a reasonable representation of the data.

timescale fluctuations during minima indicate that variable amounts of reflected light are present. More detailed modeling and, in particular, polarization measurements should ultimately provide important constraints on the detailed distribution of circumstellar matter. The fact that successive ingress and egress data do not match precisely indicates that there are fine-scale opacity variations in the edge itself. It is also likely that the

stellar surface is inhomogeneous to some extent, since stars of this mass and age commonly have dark (magnetic) or bright (accretion) spots. Detailed photometric and spectroscopic monitoring during ingress or egress should reveal much about the structural and optical properties of the obscuring matter and perhaps also the stellar surface.

Optical photometry in bluer bands (B , V , and R) was obtained at a number of phases, permitting us to study the color behavior of the star. These data indicate, remarkably, that there is no reddening of the star, even as it fades by more than 3 mag (see Fig. 4). This means that the eclipsing object is, indeed, a very sharp knife edge with no detectable optically thin transition zone or that the optically thin “atmosphere” is devoid of small dust grains (which invariably produce reddening in the interstellar medium). During minimum there is large scatter in the color data, owing to the faintness of the star, but the median color is bluer by ~ 0.1 mag than when out of eclipse. This presumably indicates that at least some small dust grains are present in the circumstellar matter and that we are seeing the star partly or entirely by scattered radiation near minimum light. There are real variations by up to 20% in the brightness of the star that occur on timescales as short as 1 hr during minima, indicative of changing orientations of the star and scattering clouds. The short timescales imply length scales for the variable features of less than 0.01 AU, or 1 solar diameter, assuming that they are in Keplerian orbits with periods of 48 or 97 days.

In an attempt to detect the circumstellar matter of KH 15D by its emission, we have obtained near-infrared and millimeter-wavelength observations of the star at the Infrared Telescope Facility in Hawaii and the Owens Valley Radio Observatory

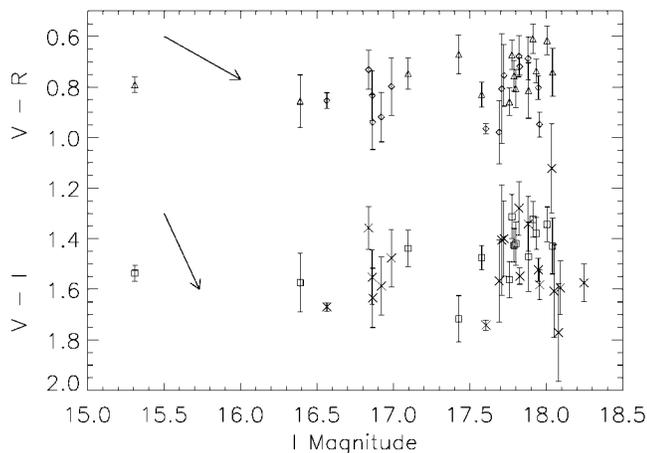


FIG. 4.—Color vs. brightness. In $V-R$, triangles indicate data obtained at the Flagstaff station of the USNO and diamonds indicate data obtained at KPNO. In $V-I$, squares indicate USNO data and crosses indicate KPNO data. Normal interstellar reddening vectors are shown for both colors. Clearly, the star does not follow these lines but maintains a nearly uniform color while fading by more than 3 mag. At minimum light, the median color appears to be bluer by ~ 0.1 mag than its out-of-eclipse value.

millimeter-wave array in California, respectively. The near-infrared (*JHKL*) colors both in and out of eclipse are consistent with an unreddened K7 star exhibiting no infrared excess attributable to a disk. The millimeter-wavelength observations did not detect a source at the optical position. Unfortunately, neither of these results provides a strong constraint on the possible mass of a disk. The upper limit on the millimeter emission translates to a mass limit of about 7 Earth masses of dust at a temperature of about 500 K, while the lack of detectable infrared excess may simply reflect the fact that the putative disk is practically edge-on and opaque at these wavelengths.

Spectra with a resolution of $\sim 40,000$ covering the range 478–690 nm were obtained on three nights with the Very Large Telescope (VLT) of the European Southern Observatory on Mount Paranal in Chile. Spectra were obtained on UT 2001 November 29 (just prior to ingress), December 14 (near central minimum), and December 20 (during the early part of egress). A full account of the information contained in these data will be given elsewhere (C. M. Hamilton et al. 2002, in preparation). They show, however, that the spectrum during eclipse is basically an attenuated version of the bright state, except for the emission lines. Near minimum and during egress, the H α equivalent width is substantially larger (~ 30 and 50 Å, respectively) than when the star is at maximum light (~ 2 Å). Essentially, the spectrum makes a transition from one characteristic of non-accreting or low accretion rate “weak-lined” T Tauri stars to one characteristic of “classical” T Tauri stars, objects with clear evidence for active accretion of gas from a circumstellar disk. In particular, broad wings extending to several hundred kilometers per second are seen on the H α (and H β) lines during minimum light and during egress, indicating that the star may still be in an active accretion stage.

A cross-correlation of the November 29 and December 20 spectra yields a radial velocity difference (in the sense November minus December) for the star between those two dates of $+3 \pm 1$ km s $^{-1}$. The interpretation of this result is complicated by the fact that the line profiles change shape during the eclipse, presumably because of the selective elimination of direct radiation from parts of the star’s surface as well as an increased contribution of scattered light to the spectrum. C. M. Hamilton et al. (2002, in preparation) will explore these issues further. Here we note that if the K7 star were orbiting the center of mass of the system with a 48.36 day period in response to a planet embedded in the obscuring matter, it would have yielded a *negative* value for the velocity difference on those dates. Therefore, assuming that the line-profile effects are small, we can place a limit of $\sim 10 M_J$ on any mass associated with a single obscuring clump orbiting with a 48 day period. With only three spectra currently available, we cannot, of course, rule out the possibility of additional significant mass(es) in the system orbiting with a 97 day (or other) period. However, there is no evidence in the spectrum for such a companion, so it is unlikely to be comparable in mass to the visible K7 star. A radial velocity study spanning at least one

season with a precision of at least 1 km s $^{-1}$ is clearly required and is underway in collaboration with G. Marcy of the University of California, Berkeley.

3. DISCUSSION

KH 15D is a unique and amazing object that promises to tell us much about conditions in the inner circumstellar region of a solar-like star of planet-forming age. The principal purpose of this contribution is to summarize the available observations of the star with the hope of stimulating additional observations and to support those by providing an updated ephemeris and description of the phenomena. However, a brief discussion of possible models is in order, based on the information currently available. These fall into two categories, depending on whether the K7 star is the dominant mass in the system or not. If it is, then the basic model involves occulting matter orbiting the star. If it is not (i.e., if KH 15D is a binary star system and the unseen component has a mass comparable to or larger than the K7 star), then the observed phenomena could be caused wholly or in part by the motion of the visible star with respect to a circumbinary disk. We discuss the “single-star” interpretation first, noting that it also applies to binary models in which the K7 star is the dominant mass.

Assuming that the eclipse is caused by a feature or features orbiting the K7 star with a period of 48 or 97 days, we can apply Kepler’s third law to derive a semimajor axis for the orbit of the occulting matter of 0.21 or 0.32 AU, respectively. Therefore, if this model is correct, we are probing a region of the circumstellar environment closer to the star than Mercury is to the Sun. The occulting feature appears to have a very sharp edge, such that a knife-edge model fits the data well. However, the transit time for an object orbiting at 0.2–0.3 AU from the K7 star is only ~ 0.5 day, much less than the time of ingress or egress (~ 2 – 2.5 days). Therefore, if the star is eclipsed by a sharp-edged orbiting feature, its occulting edge must be inclined by about 15° to its direction of motion. A sketch of what this would look like during the early stages of ingress is shown in Figure 5. Such an eclipsing structure could be caused by density waves or a corrugation of a disk driven by an embedded planet or brown dwarf, as Bryden et al. (2000), for example, have modeled. Alternatively, the features could be associated with a resonance of a yet undetected mass. During the eclipse, the system is seen primarily or entirely by reflected light from the circumstellar matter. Models such as these have many attractive features, including the potential to explain the central reversal as backscattering off the wave on the far side of the star or as a local minimum in the opacity near the location of an embedded planet or protoplanet.

If KH 15D is a binary in which the K7 star moves substantially with respect to the center of mass of the system, then an entirely different explanation of the observed phenomena is possible. Namely, one could imagine the K7 star passing above (and, possibly, alternately below) the plane of an oc-

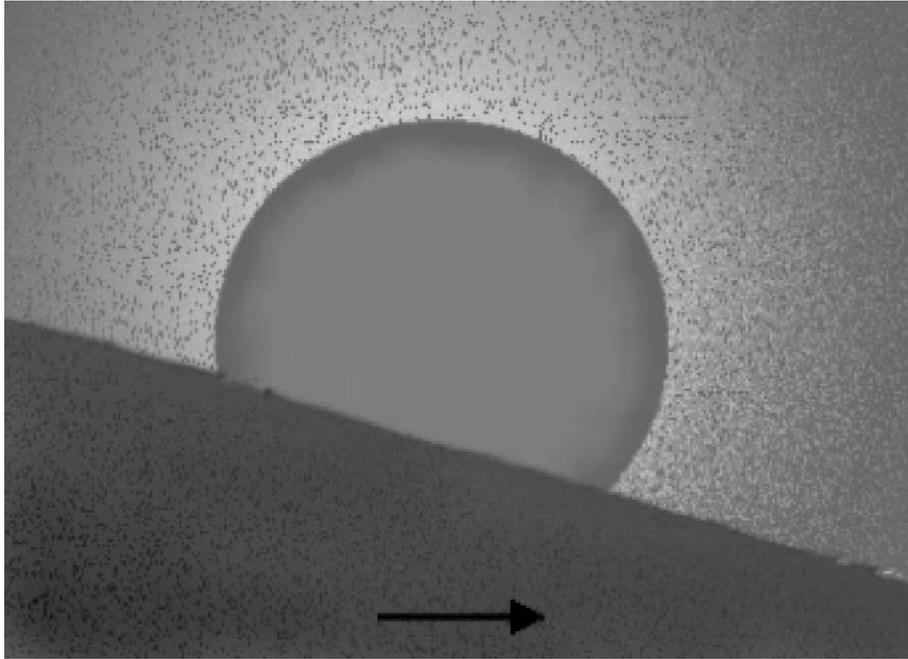


FIG. 5.—Sketch of the knife-edge model during ingress. The top of the occulting material is inclined by $\sim 15^\circ$ to its direction of motion, which is horizontal in this figure. The star is cooler (and, therefore, redder) than the Sun and exhibits limb darkening appropriate to its spectral class. Scattered light arises from the visible portion of the circumstellar matter and (possibly) a second occulting feature on the opposite side of the star. The scattered light, which is bluer than direct sunlight, becomes increasingly important as the star's photosphere is occulted.

culding (presumably circumbinary) disk. In other words, it would be primarily the motion of the star, in this model, that was causing the eclipse, not the motion of the occulting matter. As noted previously, this appears less likely at present for two reasons. First, there is evidence for only a single stellar spectrum from the system at any phase, even when the photosphere of the K7 star is completely occulted. Second, there is very little difference in the radial velocity of the K7 stars on two dates separated by 21 days. Neither of these arguments is sufficient, however, to rule out a binary model. For example, if the visible K7 star were on an eccentric orbit about a slightly more massive star and the orbit was properly inclined to the plane of a circumbinary disk, one could reproduce most or all

of the observations, including the central peaks and the ingress/egress timescales. A comprehensive radial velocity study, as is under way, is clearly required to make progress. We note that, regardless of whether KH 15D proves to be a single or binary star, its unique orientation provides us with a powerful tool for studying the structure and evolution of circumstellar matter close to a young star on an unprecedented fine scale.

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