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LIMITS ON ECLIPSES OF THE PRE–MAIN-SEQUENCE STAR KH 15D IN THE FIRST HALF OF THE 20TH CENTURY

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ABSTRACT

Over the last decade, the pre–main-sequence star KH 15D has exhibited periodic eclipses that are surprisingly deep (∼3 mag) and long-lasting (∼40% of the 48.4 day period). The cause of the eclipses is unknown, but it could be a feature in a nearly edge-on protoplanetary disk. Here we report on an analysis of archival photographs of KH 15D from the Harvard College Observatory plate collection, most of which were taken during the years 1913–1951. During this time range, the data are consistent with no eclipses; the duty cycle of 1 mag eclipses was less than 20%. The decadal timescale of this change in eclipse behavior is compatible with the expected timescale of protoplanet/disk interactions. Archival images from more recent epochs should reveal the onset of the eclipses.

Subject headings: open clusters and associations: individual (NGC 2264) — planetary systems: protoplanetary disks — stars: individual (KH 15D) — stars: pre–main-sequence

On-line material: color figures

1. INTRODUCTION

The unique eclipses of the pre–main-sequence star KH 15D have recently gained attention because of the possibility that they are related to processes of planet formation. The eclipses were discovered by Kearns & Herbst (1998)[4] during a variability study of the young cluster NGC 2264. The optical spectrum of KH 15D is that of a T Tauri star (Hamilton et al. 2001, 2003), a category believed to represent a late stage in the accretion and dispersal of circumstellar material and the condensation of planets (Bertout 1989). Hamilton et al. (2001) estimated the age of the star to be 2–10 Myr, from its position on a color-magnitude diagram.

During the eclipses, which recur every 48.36 days and last ≈20 days, the star plummets in brightness by over 3 mag in a manner consistent with a knife edge crossing the face of the star (see Herbst et al. 2002 for a striking presentation and discussion of the light curves). The obscuring matter must be composed of large dust grains or macroscopic objects, because small dust grains would cause reddening of the starlight that is not observed. If the obscuring material is orbiting the star, it must be spread out over a large fraction of the orbit in order to explain the long duration of the eclipses. Strangely, the star rebrightens near mideclipse, as if the obscuring material is distributed symmetrically about a central opening.

The eclipses are sufficiently dramatic that it appeared possible to investigate their history in photographic plate archives, despite the poor sensitivity and resolution of old photographs compared to modern detectors. In § 2, we describe our findings from the Harvard College Observatory plate collection. In § 3 we use the data to place limits on the eclipse properties of KH 15D in the first half of the 20th century. Finally, in § 4, we place our results in the context of previous measurements and previously offered theories for the origin of the eclipses.

2. DATA

We searched the collection of the Harvard College Observatory, one of the world's largest archives (Hazen 1994), for plates of NGC 2264. The most useful part of the archive was the "MC series," one of the highest-quality plate series in the collection. It was obtained with the 16 inch f/5.2 Metcalf Doublet refracting telescope, in Cambridge and Oak Ridge, Massachusetts, between 1909 and 1988. We found 66 suitable plates in the MC series. In each case we digitized a $30' \times 30'$ region surrounding the expected position of KH 15D, using an optical scanner with a resolution of 3000 pixels inch^{-1} and 14 bits pixel^{-1}.

We also found one suitable plate in the "A series," taken with the 24 inch f/5.6 Bruce Doublet in Bloemfontein, South Africa, on 1936 January 24. This plate could not be digitized because of its large physical size (14 × 17 inches). However, the A plate was of much higher quality than any of the MC plates, allowing the analysis described below to be performed visually.

To determine the threshold of detectability of each plate, we chose 10 stars with a range in brightness of roughly 2 mag bracketing the magnitude of KH 15D in its uneclipsed state and searched for those 10 stars in each image. These reference stars are identified by KH number in Figure 1*a*, which is an image of the field from the Palomar Observatory Sky Survey (POSS).[5]

Next, we looked for KH 15D. This was not a trivial task because its uneclipsed magnitude was usually close to the limiting magnitude. In addition, a nearby bright star (HD 47887) was often overexposed to such a degree that its "halo" of scattered light enveloped the expected position of KH 15D. This was a particular problem in blue-light observations (which formed the majority of cases) because the bright star is very

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[4] The name KH 15D was derived from their initials and the star's catalog number in field D of Kearns et al. (1997).

[5] The National Geographic Society—Palomar Observatory Sky Atlas (POSS-I) was made by the California Institute of Technology with grants from the National Geographic Society.

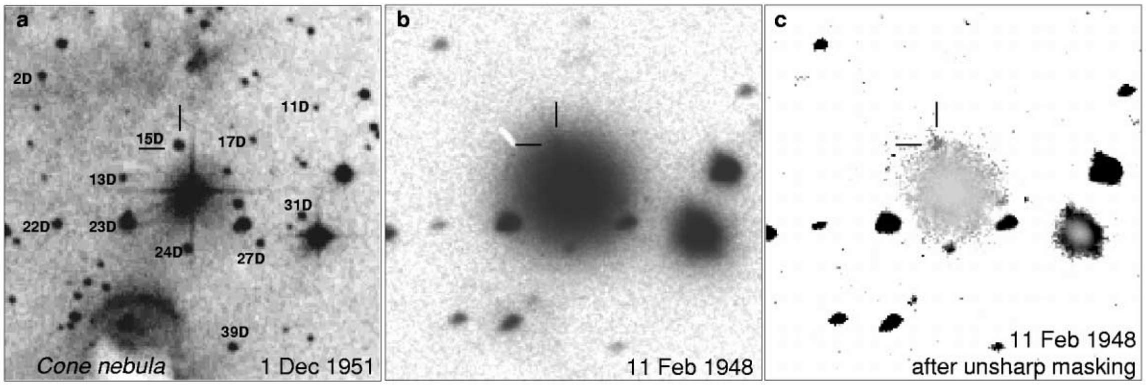

FIG. 1.—The 4′.8 region surrounding HD 47887 from (*a*) the POSS, (*b*) a typical blue plate, and (*c*) the same plate after unsharp masking. In all cases, north is up and east is left. [*See the electronic edition of the Journal for a color version of this figure.*]

blue. In those cases, we employed the technique of "unsharp masking" commonly used in astrophotography (see, e.g., Malin & Zealey 1979). In this technique, one produces a blurred image by convolving the original with a circular Gaussian tapering function and then subtracts a scaled version of the blurred image from the original image. This enhances contrast by removing low spatial frequencies, at the expense of an increased noise level. The width of the Gaussian function and the scaling of the blurred image are adjusted to achieve optimal results. Here the method works because the image of HD 47887 is very broad and flat-topped, whereas images of fainter stars such as KH 15D are more sharply peaked (see Figs. 1*b* and 1*c*). Star KH 24D, being brighter than KH 15D and slightly farther away from HD 47887, provided a useful test of our ability to detect stars close to the bright central star: if KH 24D could not be detected, surely no useful information about KH 15D could be obtained from that plate.

In this manner we determined that 40 of the plates had sufficient sensitivity and resolution for KH 15D to have been detected when uneclipsed. Among these, we securely detected KH 15D in 36 cases. In the other four cases, we believe that KH 15D is present, but we are not as confident in the detection because it is right at the plate limit (i.e., brighter comparison stars were detected, but fainter comparison stars were not detected). We summarize the results as follows: in 90% of the cases for which detection of KH 15D was possible, it was securely detected, and there were no secure nondetections.

We have not attempted accurate photometry because of the contaminating influence of HD 47887. However, judging from the comparison stars, we conclude that the detection of KH 15D on a given plate rules out an eclipse deeper than 1 mag at that epoch. Thus, the data are consistent with no eclipses deeper than 1 mag.

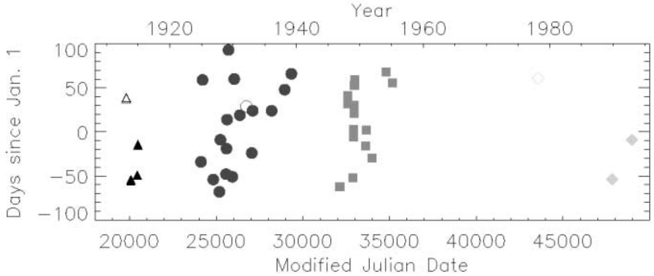

FIG. 2.—Time coverage of 40 high-quality plates and also the DPOSS and DPOSS-2 images. In order to separate the points vertically, the *y*-axis was taken to be the number of days since the nearest January 1. [*See the electronic edition of the Journal for a color version of this figure.*]

3. ANALYSIS

Figure 2 shows the time coverage of the 40 high-quality plates and also includes the POSS image (1951 December 1) and the two epochs of the DPOSS-2 images[6] (1989 November 7 and 1992 December 21), on which KH 15D appears uneclipsed. The data fall naturally into four groups in time, which we have distinguished by arbitrary colors and symbols: black triangles, for 1913–1915; red circles, for 1924–1939; green squares, for 1946–1955; and blue diamonds, for 1978–1992. Solid symbols are secure detections, and open symbols are the ambiguous cases.

We use these data to place limits on the "eclipse fraction" f, defined as the fraction of time that KH 15D is eclipsed by more than 1 mag. The simplest approach is to ignore the modern ephemeris and assume that the phase of each epoch is random. Then, using binomial statistics with a uniform prior on f, the observation that KH 15D is uneclipsed in at least 39/43 cases implies $f < 0.20$ with 95% confidence. The result changes to $f < 0.24$ when only the 1924–1939 data are used and $f < 0.17$ when only the 1946–1955 data are used.

A more sophisticated approach is to use the modern ephemeris to convert the time of each observation into ϕ, the phase of the photometric period. Hamilton et al. (2001) estimated the period to be 48.34 ± 0.02 days. After obtaining additional data, Herbst et al. (2002) revised the period to 48.36 days but did not give an error estimate. We adopt the ephemeris of Herbst et al. (2002),

$$\mathrm{JD(mideclipse)} = 2{,}452{,}352.26 + 48.36E, \qquad (1)$$

and an uncertainty of 0.02 days in the period. The phase coverage of our observations is shown in Figure 3, for the choices $P = 48.34$, 48.36, and 48.38 days. The dashed lines show the modern eclipse duration. The dotted lines show the approximate

[6] The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.

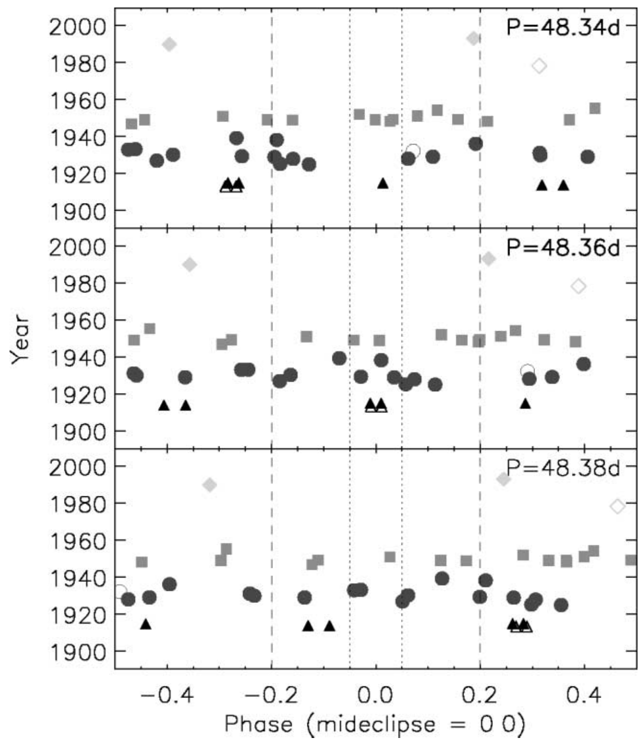

FIG. 3.—Phase coverage of detections of KH 15D, for three choices of period P. The symbols and color scheme are the same as in Fig. 2. [*See the electronic edition of the Journal for a color version of this figure.*]

phases of the mideclipse rebrightenings, during which the star has sometimes been observed at its uneclipsed brightness (or even slightly brighter).

The phase coverage is fairly complete and can be used to rule out eclipses with the present characteristics. Suppose, for example, that the past eclipses were nearly symmetric about mideclipse, as they are today. We define the "eclipse duty cycle" f' as the fraction of the photometric period between the 1 mag levels of ingress and egress. In general, $f' \geq f$ because of the possibility of mideclipse rebrightenings. We determine the maximum phase of the eclipses, $\phi_{\max}$, as the minimum $|\phi|$ among all the secure detections, not counting detections with $|\phi| < 0.05$ (where rebrightenings are expected). The resulting limit on the eclipse duty cycle is $f' < 2\phi_{\max}$. To deal with the period uncertainty, we determine $\phi_{\max}$ for all possible values of P and then compute a weighted histogram of the results, using a weighting function that is Gaussian in P with mean 48.36 days and $\sigma = 0.02$ days.

Using all the data, the result is $f' < 0.14$ with 95% confidence. Using only the data from 1924–1939, the result is $f' < 0.18$. With only the 1946–1955 data, the result is $f' <$ 0.24. Neither the earliest data nor the most recent data are constraining by themselves.

4. SUMMARY AND DISCUSSION

We conclude that the deep eclipses of KH 15D observed today did not occur in the first half of the 20th century with their present characteristics. The eclipses may have been shorter in duration or shallower than 1 mag, or perhaps the mideclipse rebrightenings extended to larger phases. Of course, a combination of these effects or a more complex time history are also possible.

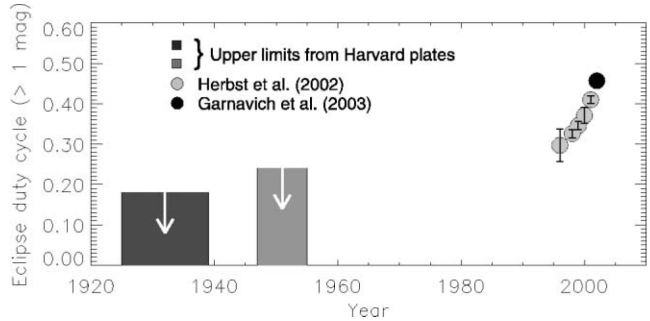

FIG. 4.—Determinations of the eclipse duty cycle (f') from this work, from our estimates using the light curves of Herbst et al. (2002) and from unpublished data by P. Garnavich et al. (2003). [*See the electronic edition of the Journal for a color version of this figure.*]

The simplest explanation is that the eclipses have grown in duration, as has been observed over the last decade. Figure 4 shows the upper limits on the eclipse duty cycle derived at the end of § 3, along with modern values that we estimated from the light curves of Herbst et al. (2002) and from unpublished data from 2002–2003 obtained by a group led by one of the authors (P. G.). Apparently a change is occurring on decadal timescales, either in the features of the obscuring material surrounding the KH 15D system or in the alignment of those features with our viewing angle.

What could explain both the eclipses and their recent onset? Hamilton et al. (2001) and Herbst et al. (2002) offered two hypotheses to explain the eclipses: (1) KH 15D has a nearly edge-on protoplanetary disk, and a warp or ridge in the disk periodically blocks the star, and (2) KH 15D has a higher mass companion that is hidden by an edge-on circumstellar disk. The observed star is eclipsed as its orbit carries it through the projected plane of the disk. Grinin & Tambovtseva (2002) offered another hypothesis: (3) KH 15D has a low-mass companion, and the resulting accretion and outflow of circumstellar material create an asymmetric common envelope, with a large and dense region near the low-mass companion. The orbital motion of the secondary causes periodic occultations of the primary.

Hypothesis 2 seemed unlikely even before this work, because Herbst et al. (2002) and Hamilton et al. (2003) measured only a small radial velocity shift (3.3 ± 0.6 km s^{-1}) between widely separated phases. Those authors also expressed concern about systematic effects that may allow the true radial velocity shift to be zero. In addition, we do not know how to make this hypothesis compatible with the recent onset of the eclipses.

The low-mass companion of hypothesis 3 could be small enough to be allowed by the current radial velocity measurements. Grinin & Tambovtseva (2002) do not make any specific statements regarding the expected timescale of changes in eclipse duration, but they do claim that their model can explain decadal variations seen in other young photometrically active stars such as UX Ori stars. This makes hypothesis 3 viable and worthy of further investigation.

Hypothesis 1 is not only consistent with a small radial velocity shift but also naturally involves a physical timescale that is compatible with our result. The viscous timescale at the orbital distance of 0.2 AU (corresponding to the 48 day period) is 10–100 years. If protoplanet/disk interactions cause perturbations in the disk, then one would expect these perturbations to evolve on this timescale. All other timescales in the disk at 0.2 AU are much shorter: the dynamical and cooling timescales are ∼2 days, while a single-impulse perturbation would be damped in less than 1 month (D'Alessio et al. 1999). Thus, protoplanet/disk interactions are an appealing explanation of the KH 15D phenomenon and the observed evolution.

For the sake of providing a concrete and falsifiable example of such an interaction, we indulge in further speculation, elaborating on a suggestion by Herbst et al. (2002). Models of planet formation at larger orbital distances predict density perturbations in the form of two spiral waves: a leading wave extending to smaller orbital distances, and a lagging wave extending to larger distances (see, e.g., Bate et al. 2003). The spiral waves extend more than a radian in azimuth, and for a Jupiter-mass planet the density is enhanced by a factor of 3–5 even at 1 pressure scale height, h, above the midplane. For a typical T Tauri disk, the optically thick portion of the disk extends to a height of $H_s \approx 4h$ above the midplane (D'Alessio et al. 1999; Jang-Condell & Sasselov 2003), corresponding to 0.02 AU at the estimated orbital distance (0.2 AU) of the occulting feature. This thickness is approximately equal to the diameter of the young star ($2R_s \approx 4\,R_\odot = 0.02$ AU). The spiral shock waves induced by a Jupiter-sized protoplanet are capable of increasing H_s by more than a factor of 2 and creating an elongated ridge along our line of sight that is thick enough to block the central star entirely. Moreover, as previously suggested (Herbst et al. 2002) and recently demonstrated with three-dimensional computational models (Bate et al. 2003), the ridge will have a local depression at the position of the protoplanet, which would explain the mideclipse rebrightenings.

If this is correct, our naïve prediction is that the eclipse duty cycle will increase to ≈0.75 and remain there for the next decade, because in the simulations, the spiral waves cover a maximum of ≈75% of the orbit. Furthermore, if the true period is actually 97 days, as suggested by Herbst et al. (2002) on the basis of small differences between alternate eclipses, this scenario would be wrong. We emphasize that this speculation was inspired by simulations at much larger orbital distances; we are not aware of any detailed simulations of protoplanet/disk interactions at 0.2 AU.

Finally, we note that although the Harvard collection does not happen to include many photographs of this field after 1960, many such photographs undoubtedly exist. Because of its placement in a scientifically interesting young cluster and near a photogenic nebula, there should be many images from 1960 onward that are of sufficient quality to measure KH 15D. A compilation of these data should reveal the onset of the modern eclipse behavior.

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