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X-RAY EMISSION FROM THE WEAK-LINED T TAURI BINARY SYSTEM KH 15D

William Herbst and Edward C. Moran
Astronomy Department, Wesleyan University, Middletown, CT 06459; bill@astro.wesleyan.edu, ecm@astro.wesleyan.edu
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ABSTRACT

The unique eclipsing, weak-lined T Tauri star KH 15D has been detected as an X-ray source in a 95.7 ks exposure from the *Chandra X-Ray Observatory* archives. A maximum X-ray luminosity of 1.5×10^{29} ergs s^{-1} is derived in the 0.5–8 keV band, corresponding to $L_X/L_{bol} = 7.5\times10^{-5}$. Comparison with samples of stars of similar effective temperature in NGC 2264 and in the Orion Nebula cluster shows that this value is about an order of magnitude lower than that for a typical star of its mass and age. We argue that the relatively low luminosity cannot be attributed to absorption along the line of sight but implies a real deficiency in X-ray production. Possible causes for this are considered in the context of a recently proposed eccentric binary model for KH 15D. In particular, we note that the visible component rotates rather slowly for a weak-lined T Tauri star and has possibly been pseudosynchronized by tidal interaction with the primary near periastron.

Subject headings: stars: individual (KH 15D) — stars: pre–main-sequence — stars: rotation — X-rays: stars

1. INTRODUCTION

KH 15D is a unique eclipsing pre–main-sequence (PMS) system near the Cone Nebula in NGC 2264 (Kearns et al. 1997; Kearns & Herbst 1998). The visible star is of K6 or K7 spectral class (Hamilton et al. 2001; Agol et al. 2004) and has an Hα equivalent width of ~2 Å, typical of a weak-lined T Tauri star (WTTS). Its mass and age are ~0.6 $M_{\odot}$ and 2 Myr, respectively (Hamilton et al. 2001). At high spectral resolution the star reveals broad wings on its hydrogen emission lines, and during eclipse one clearly sees forbidden emission lines (Hamilton et al. 2003). These features signify that accretion and outflow are still active in the system, but not at the level of a typical classical T Tauri star (CTTS). While the star has no measured infrared excess, an apparent disk and jet in H_2 have been detected by Deming et al. (2004) and Tokunaga et al. (2004), respectively.

The extremely long duration of the eclipse, currently about one-half of the period, clearly shows that the eclipsing body is not a companion star. Rather, it appears to be part of a circumstellar or circumbinary disk (Herbst et al. 2002). During eclipse the system becomes both bluer and more highly polarized (Herbst et al. 2002; Agol et al. 2004), suggesting that we are seeing it primarily or entirely in scattered light. There are two timescales associated with the eclipse, a 48.37 day cycle for the main eclipse and a secular increase in the eclipse duration of about 1 day yr^{-1} (Herbst et al. 2002; Winn et al. 2003; Hamilton 2004). Two recent models based on the historic light curve (Winn et al. 2003; Johnson & Winn 2004) have proposed that the 48 day eclipse cycle is the orbital period of a binary system, while the secular variation is caused by precession of the circumbinary disk (Winn et al. 2004; Chiang & Murray-Clay 2004). If this is correct it means that, for the first time, we can probe the structure of a disk on length scales as small or smaller than a stellar diameter and monitor events in a possibly planet-forming disk on human timescales! Clearly it is important to understand as much as possible about this unique PMS stellar system and to exploit its fortuitous geometry while the opportunity lasts.

One characteristic of T Tauri stars, especially WTTSs, is that they are prodigious sources of X-ray emission, although for still largely unknown reasons (Feigelson & Montmerle 1999; Feigelson et al. 2003). We hoped to use the periodic eclipse of the K6–K7 star behind an optically thick and presumably X-ray opaque circumstellar disk to allow us to map the structure of the coronal plasma in this WTTS. As a prelude to this intended study, we searched for archival X-ray data on NGC 2264 and found a long exposure in the archives of the *Chandra X-Ray Observatory* that includes KH 15D. It was obtained during a time interval when the star was out of eclipse, so we expected a relatively strong signal, characteristic of a WTTS. Instead, we found that the total X-ray count out of eclipse is so small that it may not be possible to learn much by monitoring it during an eclipse cycle. This in turn has prompted us to consider the extent to which KH 15D is unusual in yet another way, namely, as a remarkably faint X-ray source for a WTTS. In this paper we present the case that it is, indeed, an unusually weak source of X-ray emission and discuss possible implications of this for the system and for the broader question of X-ray production in solar-like PMS stars.

2. X-RAY DATA

2.1. *The X-Ray Luminosity of KH 15D*

The southern portion of NGC 2264, containing KH 15D, was observed with the Advanced CCD Imaging Spectrometer Imager (ACIS-I) array on board the *Chandra X-Ray Observatory* for 95.74 ks on 2002 October 28–29 (UT). The instrument was operated in its nominal mode, with a frame time of 3.2 s and a focal plane temperature of −120°C. We reprocessed the data using the CIAO software, version 3.2.1, to correct for charge transfer inefficiency of the front-illuminated CCDs and to apply a time-dependent gain correction to the data. In addition, we improved the original afterglow correction and removed the 0.5 pixel randomization applied during the standard processing of the data. The screened data used for analysis consist of events with grades 0, 2, 3, 4, and 6 and energies between 0.5 and 8.0 keV.

The J2000.0 coordinates of the instrument aim point for the observation are $\alpha = 06^{h}40^{m}58\overset{s}{.}10$, $\delta = +09^{\circ}34'00\overset{''}{.}40$; thus, KH 15D, at $\alpha = 06^{h}41^{m}10\overset{s}{.}27$, $\delta = +09^{\circ}28'33\overset{''}{.}40$, is included within the $17'\times17'$ ACIS-I field of view at an off-axis angle of $6\overset{'}{.}35$. A weak source at the location of KH 15D is faintly visible in the image. We used bright nearby sources to determine the appropriate size of the source aperture (12 pixels, or ~6″, in radius), which was centered on the optical position of KH 15D. The background level was estimated in a concentric,

TABLE 1

Optical and X-Ray Properties of K1–K7 PMS Stars in NGC 2264

Star	I	$V-I$	Spectral Type	Counts	H/S	kT (keV)	F_X (ergs cm^{-2} s^{-1})	L_X (ergs s^{-1})
3748	14.4	1.64	K1	192.1	1.261	>10	3.0×10^{-14}	2.0×10^{30}
3778	13.8	1.61	K7	503.6	0.106	0.6, 2.7	4.6×10^{-14}	3.2×10^{30}
5143	13.8	1.56	K4	114.3	0.141	1.8	7.5×10^{-15}	5.2×10^{29}
5274	14.3	1.63	K4	256.3	0.089	0.7, 3.0	2.0×10^{-14}	1.4×10^{30}
5653	14.2	1.64	K7	211.0	0.060	0.6, 3.7	1.9×10^{-14}	1.3×10^{30}
KH 15D	14.5	1.60	K6–K7	22.5	<0.264	2.7	2.2×10^{-15}	1.5×10^{29}

source-free annulus with inner and outer radii of 20 and 60 pixels, respectively. A total of 22.5 net counts were detected in the full 0.5–8.0 keV band, corresponding to a signal-to-noise ratio of 3.5. The spectrum of KH 15D is soft, with ~80% of the net counts falling below 2 keV. The implied band ratio (i.e., the ratio of counts detected in the hard 2–8 keV and soft 0.5–2 keV ranges) is 0.264, although because KH 15D is not formally detected in the hard band, this should be considered an upper limit.

We used the XSPEC software, along with the response matrix and effective area files generated by CIAO, to estimate the X-ray flux of KH 15D. A spectral model consisting of a single-temperature, optically thin (MEKAL) plasma was adopted (Feigelson et al. 2002). Solar abundances were assumed for the plasma, and based on the maximum possible reddening of KH 15D of $E(B-V) = 0.1$ (Hamilton et al. 2001), an absorption column density of 2×10^{20} atoms cm^{-2} was included in the model. We adjusted the temperature of the plasma until the above band ratio was obtained, which suggests $kT = 2.7$ keV. Using the model normalization required to match the observed count rate of the source, we obtain a 0.5–8 keV flux of 2.2×10^{-15} ergs cm^{-2} s^{-1}. For a distance of 760 pc (Sung et al. 1997; Hamilton et al. 2001), this corresponds to an unabsorbed X-ray luminosity of 1.5×10^{29} ergs s^{-1}. Given that the maximum values of the band ratio and column density were assumed, this should be taken as an upper limit.

2.2. *Comparison with Other Pre–Main-Sequence Stars*

Our derived total X-ray luminosity for KH 15D may be compared with other PMS stars of similar effective temperature in NGC 2264 and in the Orion Nebula cluster (ONC). The most direct comparison is with stars in the same archival *Chandra* image as KH 15D. We used the photometric and spectroscopic surveys of Rebull et al. (2002) and Lamm et al. (2004) to search for K stars within that field that had comparable magnitude (within 0.7 mag in I) and color (within 0.04 mag in $V-I$). Since the reddening in NGC 2264 is relatively small [$E(B-V) \sim 0.1$ or less] and uniform, this procedure should result in a reasonable comparison set. Five stars meeting the photometric conditions were found, and all five were firmly detected in the *Chandra* image. Their source counts and X-ray spectra were extracted in the same manner as described above for KH 15D.

Because of the strength of the detections of the comparison stars, we were able to estimate their X-ray fluxes directly via spectral modeling. We began by fitting single-temperature plasma models to each of the spectra. However, good fits were obtained in just two of the cases. For the remaining three objects, we employed two-temperature plasma models, which are frequently required to fit the X-ray spectra of PMS stars (Feigelson et al. 2002). The fitted column densities for four of the five objects are consistent with zero. The fit of other object, star 3748, suggests a column density of $\sim 4 \times 10^{21}$ cm^{-2}. This absorption was not corrected for when calculating the star's X-ray flux, so the X-ray luminosity that we derive for it is a lower limit.

Table 1 summarizes the optical and X-ray properties of the five comparison stars and KH 15D. Listed for each object are the source number from Rebull et al. (2002), the I-band magnitude, the $V-I$ color, the spectral type, the net counts detected in the 0.5–8 keV band, the hard-to-soft band counts ratio H/S, the plasma temperature(s) in keV, the 0.5–8 keV flux (in ergs cm^{-2} s^{-1}), and the X-ray luminosity (in ergs s^{-1}) in the same band. As the table indicates, KH 15D is significantly underluminous relative to this set of comparison stars. Moreover, it is evident that the weakness of its X-ray emission is *not* a result of a greater amount of soft X-ray absorption; the upper limit to its band ratio and the inferred plasma temperature are consistent with those of the comparison stars. We also calculated X-ray fluxes for the comparison stars using exactly the same spectral model as for KH 15D, with resulting fluxes that differed by only 3%–25% (with an average deviation of 17%) from what is shown in Table 1.

To expand the comparison set, we have also employed observations of K3–K7 stars in the northern part of NGC 2264, whose X-ray luminosities were calculated by Ramirez et al. (2004) based on a *Chandra* ACIS-I image. They detected 37 likely cluster members in this spectral range, as well as five nonmembers (L. M. Rebull and J. Stauffer 2005, private communication), and their exposure time of 48.1 ks is long enough to have reached sources close to the luminosity of KH 15D, if not below it. The X-ray luminosity of their cluster members is derived in a manner similar to what we have used and is based on the same assumed distance. In Figure 1 we compare the X-ray

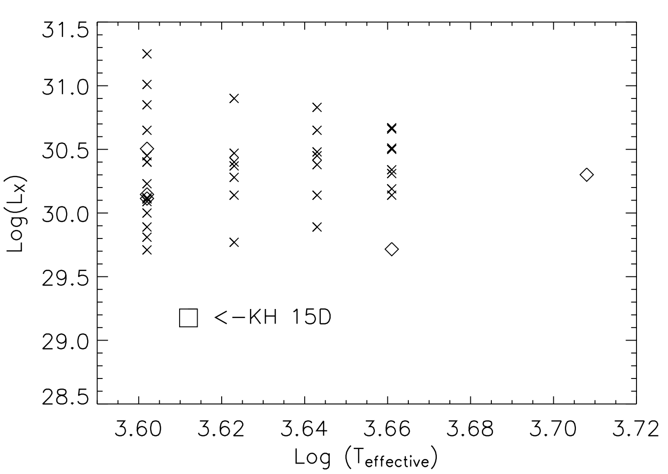

Fig. 1.—X-ray luminosity of mid-K spectral class members of the northern part of NGC 2264 from Ramirez et al. (2004; *crosses*) and from Table 1 (*diamonds*), compared with KH 15D (*square*). Obviously, KH 15D is about an order of magnitude fainter in X-rays than is typical of cluster members of similar effective temperature.

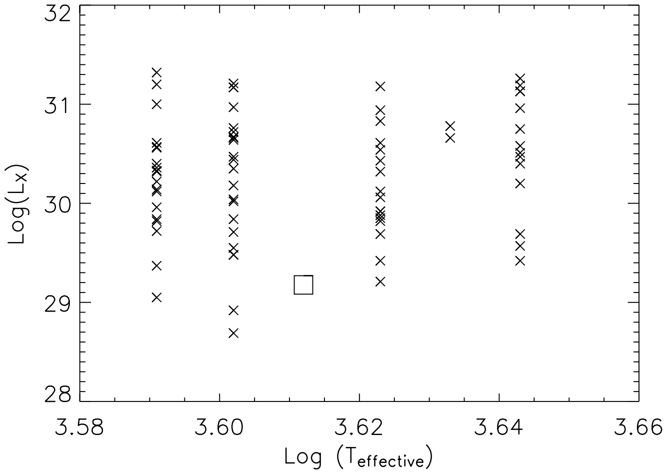

FIG. 2.—X-ray luminosity of KH 15D (*square*) compared to the K5–K8 stars in the ONC (*crosses*) from Feigelson et al. (2005). Extinction corrections have been made for the Orion data and are negligible in the case of KH 15D, as discussed in the text. It is clear that KH 15D is deficient in its X-ray production by about an order of magnitude compared to stars of similar effective temperature in the ONC. Note that two of the three stars in the ONC with smaller X-ray luminosity than KH 15D also have visual extinctions exceeding 5 mag.

luminosity of KH 15D (*square*) to the stars in the northern part of the cluster (*crosses*) and to those in the southern part from Table 1 (*diamonds*). It is clear from this comparison that KH 15D has a lower than typical X-ray luminosity for mid-K stars in both parts of NGC 2264. It lies about an order of magnitude below the median value of both samples and is more than a factor of 3 fainter than the next faintest detected object.

As a further test of the degree to which KH 15D is anomalously weak in X-rays, we compare it to stars of similar spectral class in the ONC. This cluster is slightly younger than and about half the distance of NGC 2264. The optical data come from the extensive photometric and spectroscopic survey by Hillenbrand (1997). Total X-ray luminosities in the *Chandra* band of 0.5–8 keV have been derived by Feigelson et al. (2005) for more than a thousand sources in the ONC, based on an extraordinarily long exposure of 850 ks. Figure 2 shows a comparison of our result for KH 15D with the 74 ONC members having spectral types between K5 and K8, inclusive. The inferred plasma temperatures of these stars are comparable to the value of 2.7 keV that we infer for KH 15D, which is typical of PMS stars in general (Feigelson et al. 2002). Note that this X-ray survey detected every optically known ONC member in this spectral range, so the comparison sample is as complete as possible. It is clear from this figure that KH 15D is a very weak X-ray source compared to the ONC stars of similar effective temperature.

We further note that KH 15D is likely to be even more anomalously weak as an X-ray emitter than is evident from Figure 2. There are two reasons for this. First, the extinction in the ONC is much higher in general than in NGC 2264 and is also highly variable. For example, two of the three ONC stars in Figure 2 with cited X-ray luminosity less than KH 15D have visual extinction estimates exceeding 5 mag. This suggests to us that some of the apparent scatter in X-ray luminosity in the cluster, especially the scatter to low values, is due to extinction, not lack of X-ray production. Second, we note that the ONC is slightly younger and therefore probably has a higher percentage of CTTSs compared to WTTSs. This is hard to verify because of the strong nebulosity in which the ONC is embedded. If true, however, it means that there may be more low-luminosity X-ray sources in the ONC because of this difference.

To summarize this section, we find that KH 15D is the weakest X-ray emitter known for stars of its spectral class in NGC 2264 and lies about 1 order of magnitude below the median value for the cluster. It is also a weaker X-ray source than all but 3 of the 74 known mid-K star members of the ONC, and two of them have visual extinctions exceeding 5 mag. Again, it lies about an order of magnitude below the median of the cluster. It is possible, of course, that the *Chandra* exposure we analyzed was obtained, by chance, at a time when KH 15D was at or near the bottom of its range of X-ray variability. It is believed that much of the scatter seen in PMS X-ray luminosity is caused by actual time variations associated with flaring (Feigelson & Montmerle 1999; Feigelson et al. 2003). This would be an extraordinarily unlucky circumstance, of course, since it is such an extreme outlier, and we consider instead, in the remainder of the paper, whether some aspect of the properties of this star that makes it unique in other ways could also account for its unusually low X-ray luminosity.

3. DISCUSSION

Can the low X-ray luminosity of KH 15D be attributed to some sort of extinction effect, perhaps within the circumbinary disk that surrounds it? We find this difficult to support for two reasons. First, there is essentially no reddening or obscuration evident in the light of the K6–K7 star during maximum brightness, when the X-ray data were obtained. The star has a color excess of $E(B-V) = 0.1$ mag if it is a K6 star and less if it is K7. This is consistent with what is found for other members of NGC 2264, in which the reddening is known to be small (Rebull et al. 2002; Lamm et al. 2004). If there is any local extinction associated with circumstellar matter, it must be very small. Out of eclipse the star also shows very small photometric variations (less than 0.1 mag in I) and no detectable color variations (Hamilton et al. 2005). In addition, there is no evidence in the X-ray data for a deficiency of soft X-rays, which would be most susceptible to absorption. The hard-to-soft ratio is typical of what is found for lightly reddened T Tauri stars such as those in the ONC. We conclude that KH 15D is almost certainly an intrinsically weak X-ray source because of an anomalously low production rate, not because of absorption.

Since the cause of X-ray emission in PMS stars is not fully established, it is not immediately evident how to interpret the low luminosity of KH 15D. Here we discuss two possible explanations, neither of which is without difficulty. It seems likely that, in some way, the binary nature of the star is an important element, so we begin there. An attractive unifying paradigm for the unique and, in some cases, anomalous properties of this WTTS is provided by the eccentric binary model of Winn et al. (2004). It is shown by these authors that constraints on the system from the historic and current light curves can be understood if KH 15D is a roughly equal luminosity binary system with a highly eccentric ($e \sim 0.5$–0.8) orbit and period of 48.4 days. The orbit is, at present, slightly inclined to the plane of a circumbinary disk so that one (and only one) of the stars periodically rises above it. Precession of the disk plane is plausibly responsible for the secular variation in the eclipse duration. This compelling model implies a separation of the components at periastron of only about 0.08 AU, close enough to consider possible tidal effects or other influences that such a close approach could have on the system and, in particular, on X-ray production.

3.1. *Interacting Magnetospheres at Periastron?*

The radius of the only currently visible star is about 1.3 $R_\odot$, based on its luminosity and effective temperature (Hamilton et al. 2005). The currently invisible companion was last seen in 1995 and measured to be brighter by several tenths of a magnitude than the K7 star. The historical light curve of the system also demonstrates that the unseen companion is slightly more luminous than the visible star. Assuming the stars are coeval, which seems inescapable, simple theoretical considerations demand that the unseen star be slightly more massive and larger than the K7 star. Hence, its radius is probably a little larger than 1.3 $R_\odot$ but not much larger. The separation of the two components at periastron is about 15 stellar radii. Since magnetospheres of WTTSs are typically believed to extend 5–10 stellar radii from the surfaces (Ostriker & Shu 1995; Preibisch et al. 2005), disruption of the magnetosphere by interactions with matter (or magnetic fields) inside this point could play a role in lessening X-ray luminosity either by cooling or by lack of confinement of hot gas.

Unfortunately, there is little evidence to support (or refute) this hypothesis in the observed X-ray luminosity of other PMS binaries. Perhaps the most similar system known is DQ Tau, which is a CTTS with nearly equal mass mid-K components in an orbit of eccentricity $e = 0.56$, which brings the stars within about 8 stellar radii of each other at periastron (Mathieu et al. 1997). The star is not detected in the *Röntgensatellit* (*ROSAT*) All-Sky Survey (König et al. 2001), which means it is weaker than many PMS stars in Taurus. However, since it is a CTTS it is possible that its low X-ray luminosity is due to absorption in circumstellar matter. Another reasonably eccentric ($e = 0.24$) PMS binary is UZ Tau E (Martin et al. 2005). Unfortunately, it is only a few arcseconds from UZ Tau W (also a binary), and so the X-ray luminosity of this binary is not measured. Its separation at periastron is also a little larger (about 25 solar radii), it has a much smaller mass ratio ($q = 0.2$), and it is also a CTTS, so there are potentially important differences with KH 15D.

One WTTS spectroscopic binary with a K7 primary, circular orbit, and separation of 12.6 stellar radii, V826 Tau, is observed to be roughly normal in its X-ray luminosity, with a quiescent luminosity of around 2×10^{30} ergs s^{-1} (Reipurth et al. 1990; Carkner et al. 1996). This shows that proximity of stars, by itself, may not be sufficient to disrupt X-ray emission. However, it may be the variation of the magnetic influence caused by an eccentric orbit that is the key to disrupting a dynamo, so V826 Tau may also not be the best analog. Since there is no observational evidence that proximity of magnetospheres is a sufficient cause to reduce X-ray emission, we consider another aspect of close periastron passages, namely, tidal interactions and possible rotational synchronization.

3.2. *Tidally Influenced Rotation?*

Rotation is a factor in the X-ray luminosity of stars as young as 30 Myr, but it has not been proven to be important in T Tauri stars; evidence to date suggests that it is not. Several authors find no correlation between rotation and X-ray emission for PMS stars in the ONC (Gagne & Caillault 1994; Feigelson et al. 2003). Perhaps the large and variable extinction effects, as well as the difficulty of discriminating between WTTSs and CTTSs in that cluster, cause problems with the interpretation. In this regard it will be interesting to see what studies in slightly older and less highly obscured regions, such as the Orion flanking fields and NGC 2264, will reveal about the role of rotation in X-ray production (Ramirez et al. 2004). Since X-ray emission in T Tauri stars is not yet fully understood, and since rotation could be a factor in at least some stars, we inquire whether the rotation of the visible star in the KH 15D system is unusual in any way.

There are two methods for determining the rotation rate of a WTTS, and both have been employed in the case of KH 15D. Most directly, one can search for periodic fluctuations in the stellar brightness associated with the rotation of a spotted surface. This has been done by Hamilton et al. (2005), and they have detected two clearly significant peaks in the periodogram of out-of-eclipse data at two separate epochs. In both cases, the period was 9.6 days, strongly suggesting that this is, in fact, the rotation period of the visible component of the binary. Confirmation of that comes from a new measurement of $v \sin i$, based on high-resolution spectra taken out of eclipse at the Keck and McDonald observatories by the same group. Hamilton et al. (2005) find a value of $v \sin i = 6.9 \pm 0.3$ km s^{-1} (replacing an earlier estimate of $v \sin i < 5$ km s^{-1} by Hamilton et al. [2003] that did not take proper account of macroscopic turbulence in the comparison star). Combining the new $v \sin i$ measurement with the known radius of the star, $R = 1.3\ R_\odot$, yields an expected rotation period (P) of $P \sin i = 9.4 \pm 0.3$ days (Hamilton et al. 2001, 2003). Since $\sin i \sim 1$ for this eclipsing system, we conclude that KH 15D has a rotation period of 9.6 ± 0.1 days.

This rotation period of KH 15D is somewhat long for a WTTS of its mass in NGC 2264, where the (bi)modal values are near 1 and 4 days (Lamm et al. 2004). It is not, however, the slowest rotator in the cluster. Of the 184 stars with $R - I < 1.84$ (roughly corresponding to mass $>0.25\ M_\odot$) in the study by Lamm et al. (2005), 22 (12%) have periods of 9.6 days or longer. If no correlation between rotation period and X-ray emission exists among NGC 2264 stars in general, then the significance of KH 15D's slower than usual rotation for the problem discussed here is obscure. We note, however, that because it is a member of a relatively close binary, the rotation of the visible component may have been affected by tidal interaction with its primary and could be tidally synchronized (or, rather, pseudosynchronized), as discussed by Hamilton et al. (2005).

Hut (1981) has shown that the pseudosynchronization angular rotation frequency is a nearly constant fraction (f) of the orbital angular frequency at periastron for orbits in the eccentricity range $e = 0.3$–0.8. Therefore, one may write

$$P_{\rm ps} = \frac{P_{\rm orb}}{f} \frac{(1 - e^2)^{3/2}}{(1 + e)^2}.$$

Identifying $P_{\rm ps}$ as the measured rotation period and $P_{\rm orb}$ as the orbital period and taking $f = 0.81$, as appropriate to the plausible eccentricity range of KH 15D (Johnson et al. 2004), we find that the equation is satisfied for $e = 0.65 \pm 0.01$. This is slightly outside the range of solutions ($e = 0.68$–0.8) favored by Johnson et al. (2004) based on astrophysical grounds (primarily the system's total mass and mass ratio), but it is well within the plausible range based on the radial velocity curve. It is also consistent with the best-fit eccentricity that comes from modeling the historical and modern light curves (J. N. Winn et al. 2005, in preparation). An estimate of the timescale for pseudosynchronization based on the work of Zahn (1977) suggests that this could have been achieved within a couple of million years, as would be required by the inferred age of the KH 15D system.

To summarize, we have found that KH 15D is an unusual stellar system in a new way—it is a very weak source of X-ray emission for its mass and age. It seems likely to us that its eccentric binary nature and close periastron approach are probably involved in this. One possible mechanism is disruption of the magnetosphere of the visible star (and probably both stars) during repeated periastron passages due to magnetic reconnection events. Another, perhaps more likely, possibility is disruption of the usual magnetic dynamo through tidal interactions, which could also be implicated in the slower than normal rotation of the visible component. Of course, these are not mutually exclusive mechanisms. Further observations are needed to establish the degree to which KH 15D is in fact anomalous in its X-ray properties for a WTTS and whether either proposed mechanism, or perhaps both, can indeed account for the dearth of X-ray emission.

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