The Eclipsing Radio Emission of the Precataclysmic Binary V471 Tau

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ABSTRACT

We present strong evidence confirming the presence of eclipses in the centimeter radio emission of the eclipsing binary V471 Tau, comprising a K2 dwarf and a white dwarf. In observations spanning 2 complete orbital periods, we detected one eclipse per orbit: in all we observed one near–complete radio eclipse, the ingress phase of two other radio eclipses, and the egress phase of yet another radio eclipse. The minimum of the near–complete radio eclipse observed is centered at the orbital phase $\phi = 0$ when the white dwarf is eclipsed and directly behind the K dwarf, and has a full width of $\Delta\phi \approx 0.3$; by comparison, the optical eclipse of the white dwarf occupies only $\Delta\phi = 0.066$. Inside eclipse the total flux density of V471 Tau falls to a level $\sim$20% of that outside eclipse, implying that a large fraction of the radio emission originates from the region between the two stars. Outside eclipse the radio emission varies slowly and follows, in large part, the same phase dependence over the two observed orbits (separated by one orbit). This suggests that much of the modulation observed outside eclipse may be due to an apparent change in the observed radiation pattern of the source with orbital revolution, rather than intrinsic variability in the radio emission process. From the data, we place constraints on the physical parameters of both the occulter and the occulted radio source; we find that the radio source is most probably radiating by nonthermal gyrosynchrotron emission. We favour a model where the radio–emitting electrons are accelerated by the interaction (collision) between the magnetospheres of the K dwarf and the white dwarf. This region of interaction is likely to be located very close to the surface of the white dwarf, leading naturally to a picture where the radio emission originates from large magnetic structures associated with the K dwarf. Such a model can qualitatively explain many of the features observed in the radio light-curve. The proposed magnetic structures may provide the means by which mass is transferred from the K dwarf to the white dwarf, accounting partly or wholly for the inferred accretion of the white dwarf.

Subject headings: stars: binaries: eclipsing - radio continuum: stars - stars: coronae - stars: magnetic fields - stars: late–type - stars: white dwarfs

1. INTRODUCTION

V471 Tau, a member of the Hyades cluster, is a binary system comprising a (degenerate) white dwarf and a (main sequence) K2 dwarf in a very close, eclipsing orbit. It belongs to a class of detached binaries known as precataclysmic binaries, the presumed progenitors of cataclysmic variables. The companion stars in this system are separated by only $3.1R_{\odot}$, and orbit each other every 12.5 hrs. The K dwarf companion has started to fill its Roche lobe, and is distorted into an ellipsoidal shape by tidal forces from its white dwarf companion. When the K dwarf overfills its Roche lobe, direct mass transfer (i.e., along the gravitational potential well of the system) to the white dwarf will become possible, turning the system into a cataclysmic variable. Study of precataclysmic binaries is therefore important for our understanding of the evolution of close binary systems, and of the progenitors of cataclysmic variables. Among the known precataclysmic binaries, so far only V471 Tau has been found to exhibit detectable radio emission.

Until recently, radio observations of V471 Tau were restricted to short periods spanning much less than one orbital period. The system was first detected in radio by Crain et al. (1986), who observed a flare at 6 cm with a peak flux density of 1 mJy. The transient nature of this event was further confirmed by Morris & Mutel (1988), who did not detect V471 Tau at 6 cm with an upper limit of 0.4 mJy. By contrast, White, Jackson, & Kundu (1993) detected the system as an apparently nonimpulsive source at 20 cm with a flux density of 0.4 mJy. In the first extensive radio observations of V471 Tau, Patterson, Caillault, & Skillman (1993) reported broad dips in the 6 cm radio emission of V471 Tau centered close to, but not always at, the eclipse of the white dwarf. They suggested that the dips were caused by the eclipse of a radio–emitting region situated between the two stars, but were careful to point out that the evidence for eclipses was far from conclusive. This was due in part to the occurrence of several strong flares during the observations, with peak flux densities up to ∼8 mJy. As a consequence, the phase dependence in intensity during radio eclipse (if real) was poorly constrained, and the phase dependence outside of radio eclipse unconstrained. Knowledge of the orbital phase dependence in radio intensity both during and outside eclipse can provide valuable information on the structure of the occulter, as well as of the occulted radio source.

In this paper we present compelling evidence for the occurrence of periodic eclipses in the radio emission of V471 Tau. During our observations V471 Tau appeared to be in a quasi–steady (quiescent) state, and hence its phase dependence in intensity both during and outside eclipse could be studied in detail. In §2 we present our observations and results. In §3 we discuss the orbital phase dependence of the radio emission, and the constraints it places on the physical parameters of the occulter and the occulted radio source. In §4 we examine two models for the radio emission of V471 Tau, and discuss their consequences for the structure of the radio–emitting region. In §5 we present a new hypothesis for the method of mass transfer from the K dwarf to the white dwarf. Finally, in §6 we summarize our conclusions.

2. OBSERVATIONS and RESULTS

We observed V471 Tau for nearly 12 hrs on two consecutive days, 1994 Dec 2 and 3, with the VLA[1]. These observations were carried out as part of a multi–wavelength campaign involving the *EUVE* satellite observatory and ground–based optical telescopes; a preliminary report of this campaign has been presented by Cully et al. (1995). Here, we will confine our attention to the radio results. In the observations we switched between 20 and 3.6 cm consecutively with a duty cycle of ∼1:2, and a period of ∼7 mins. At the beginning of every 5 cycles we observed a secondary calibrator, 0336+323. At 2–3 hr intervals, we also observed the system briefly at 6 and 2 cm. We used 3C48 as our primary flux calibrator.

We detected V471 Tau at every wavelength. Although the presence of a very strong (peak flux density of ∼0.3 Jy) confusing source at 20 cm prevented a detailed time analysis for flux variability at this wavelength, this was not a problem at shorter wavelengths. Thus, we confine our attention largely to the observations at 6, 3.6, and 2 cm. In Figure 1 we

[1]The Very Large Array is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

plot the flux density of V471 Tau as a function of orbital phase for the two days of our observations, with the different wavelengths represented by different symbols. At 20 cm, the integrated map showed that V471 Tau had a flux density of $\sim$0.5 mJy on Dec 2, and was only slightly weaker on Dec 3. We have phased our data according to the ephemeris of Skillman & Patterson (1988), based on observations spanning 16 yrs.

3. RADIO PROPERTIES OF V471 TAU

3.1. Orbital Phase Dependence of the Radio Emission

The radio emission of V471 Tau varies slowly with orbital phase and, unlike in the observations of Patterson et al. (1993), showed no obvious impulsive variations. On 1994 Dec 3 a broad and apparently symmetrical dip in the 3.6 cm intensity can be seen centered at orbital phase 0.0; this drop in flux also is detectable at 6 cm, and apparently also at 2 cm with 2σ significance. On both 1994 Dec 2 and 3 the beginning of corresponding dips are visible near orbital phase 0.8, and on 1994 Dec 2 the end of such a dip is visible near orbital phase 0.2. These repeating, periodic dips provide strong evidence for eclipses in the radio emission of V471 Tau.

The shape of the near complete radio eclipse observed (the third eclipse) can well be described by a U–shape with an approximately flat bottom and slightly inclined vertical arms. The flux density at mid–eclipse is $\sim$0.2 mJy. The ingress and egress phases appear to be quite short, each spanning only $\sim$0.05 orbital phase. By comparison, the full width of the eclipse spans $\sim$0.3 orbital phase, identical to that found by Patterson et al. (1993). The ingress and egress phases of the remaining eclipses observed, however, appear to be less sharp, and at these times the full width of the eclipse may be wider in orbital phase. If this reflects the true character of the radio eclipse, then one would have to conclude that the intrinsic shape of the radio eclipse varies with time. In support (but not proof) of this statement, Patterson et al. (1993) found that the minimum of the radio eclipse was centered at slightly different orbital phases (0.9 and 1.0 respectively) in two observations taken nearly 2 yrs apart. On the other hand, our data are not inconsistent with a stronger contribution from non–eclipsed radio emission on Dec 2 than Dec 3, modifying the shape of the eclipse light–curve on the first day. Specifically, both eclipses on Dec 2 appear to have a shallower bottom than the near–complete eclipse observed on Dec 3, and furthermore outside eclipse the flux density on Dec 2 is elevated on average by comparison with the following day; consistent with this argument, the mean flux density of V471 Tau at 20 cm is slightly higher on Dec 2 than on Dec 3. This hypothesis requires the extra contributing emission to be either larger than the occulter (which is at least the size of the K dwarf optical disk; see §3.2), or, probably more likely, to be distributed more or less homogeneously over the surface of the K dwarf. On Dec 3, the ingress phase of the final dip appears to occur at a much earlier orbital phase than expected based on the previous eclipse. Given that the early ingress phase of the previous eclipse was not observed, it may be that the eclipse shape is actually asymmetrical with a much longer ingress than egress phase.

The flux density outside eclipse on Dec 3 is $\sim$1.0 mJy, implying that $\sim$80% of the radio emission of the system is blocked by the occulter during eclipse. The radio emission outside eclipse varies slowly with orbital phase, but appears to repeat in part. On both days, it displays local maxima at or near orbital phase quadrature, namely $\phi \approx 0.25$ and $\phi \approx 0.65$. The radio emission appears to show a local minima at or near the transit of the white dwarf, at $\phi \approx 0.4$ on Dec 2 and $\phi \approx 0.5$ on Dec 3. Both inside and outside eclipse, and indeed where sampled over the entire orbit, the radio spectrum appears to be flat between 6 and 2 cm. Between 20 and 6 cm, however, the radio emission appears to have a rising spectrum.

3.2. Physical Parameters of the Occulter and the Occulted Radio Source

The width and shape of the eclipse constrain the physical parameters of both the occulting source and the occulted radio source. For the purpose of this discussion, we shall assume that the width and shape of the near complete eclipse observed is characteristic of the properties of the eclipsed radio emission of V471 Tau. Even if these properties change with time, we still have to explain why the eclipse sometimes assumes the characteristics seen in the near–complete eclipse observed. In the following, we shall assume (as is very likely to be the case) that the rotation axis of the K dwarf is (nearly) perpendicular to the orbital plane, which of course is aligned close to our line–of–sight (inclination of $\sim 80°$; Skillman & Patterson 1988). Figure 2 illustrates the geometry of the system.

Let us initially make the obvious assumption that the occulter is the K dwarf, i.e., the size of the occulter is that of the K dwarf's optical disk, which has a (mean) radius of $R_K \approx 0.8 R_\odot$. There are two obvious limits for the location of the radio source: just above the surface of the K dwarf, or coincident with the white dwarf. If the latter, the radio source must be significantly larger than the white dwarf in order for the eclipse width to significantly exceed $\Delta\phi = 0.066$, the photospheric eclipse width of the white dwarf; in fact, the radio source has to have a radius of at least $3.6 R_\odot$, 4.5 times the radius of the K dwarf. Such a large source at the distance of the white dwarf from the K dwarf, however, can only produce a gradual and shallow eclipse, contrary to the actual observed shape of the eclipse. In the opposite limit, the radio source may be located just above the surface of the K dwarf, situated on the side of the star facing the white dwarf and centered (almost) exactly on a line joining the two stars. For a thin emitting slab, the maximum longitudinal extent of the occulted radio source is then one–third of the stellar circumference. A thicker slab, or a source located at a greater height, must necessarily have a smaller longitudinal extent.

On the other hand, the occulter may be substantially larger than the K dwarf's optical disk. One can cite here evidence from the soft X–ray light–curve of V471 Tau, which is dominated by the photospheric emission of the white dwarf. Apart from the eclipse caused by the K dwarf, strong absorption in soft X–rays also is seen at certain narrow phases near eclipse (Jensen et al. 1986); between these absorption dips and the white dwarf eclipse, the soft X–ray light curve returns to (nearly) its uneclipsed level. These absorption dips are attributed to ionized gas trapped at the relevant Lagrangian points of the system, located at orbital phases 0.83 (ingress side) and 0.17 (egress side) along the line of sight to the white dwarf (see Fig. 2). Interestingly, these are the approximate orbital phases where the radio eclipse begins and ends. In this model, the radio source is identified with the white dwarf, and material at the abovementioned Lagrangian points only partially absorbs the white dwarf's radio emission. Because, unlike the soft X–ray light curve, the radio light–curve does not return to its uneclipsed level between the hypothesized absorption dips and the eclipse of the white dwarf, once again the radio source has to be significantly larger than the white dwarf; in this case, it has to have a radius of at least $1.9R_{\odot}$ (the Lagrangian points L_4 and L_5 are located at a perpendicular distance of $\sim 2.7R_{\odot}$ from a line joining the two stars), more than twice the radius of the K dwarf. Once again, such a large source can only produce a rather gradual eclipse.

There is another strong argument against (significant) radio emission from the white dwarf. The detection of rotational modulation in the optical and soft X–ray photospheric emission of the white dwarf has been attributed to the accretion of heavy elements at the white dwarf's magnetic poles (Jensen et al. 1986; Clemens et al. 1992; Barstow et al. 1992). From the lack of detectable π and σ Zeeman sub–components in its Lyman α photospheric absorption line, an upper limit of a few kilogauss can be placed on the dipole field of the white dwarf (Sion 1995, personal communication). If we assume a dipole field of $\sim$5 kG, then the radius at which the field reaches, say 10 G, is only about $\sim 8R_{wd}$, where $R_{wd} \approx 0.01R_{\odot}$; at or much beyond this point, the radio emission becomes optically thin. Such a small optically thick source is contrary to the large dimensions required to explain the shape of the radio eclipse if the emission originates from the white dwarf. Also, in this picture the brightness temperature of the radio source would have to be $\sim 5 \times 10^{12}$ K (for a distance of 45 pc), above the limit imposed by inverse Compton losses.

From the above discussion, it appears much more likely that the radio emission is located closer to the surface of the K dwarf rather than the white dwarf, and that it has a cross–sectional radius smaller than that of the K dwarf's optical disk. For a source of circular cross–section, the depth of the eclipse implies an average brightness temperature of $T_b \geq 8.2 \times 10^9$ K. The radio emission must therefore be nonthermal in nature, and this remains true even if we invoke the above less acceptable models where the radio source size can be as large as 4.5 times the radius of the K dwarf. The inferred minimum brightness temperature is near the upper limit expected for nonthermal gyrosynchrotron emission (which requires mildly–relativistic electrons), and, if the source is significantly smaller than the inferred upper limit, may involve synchrotron emission (which requires relativistic electrons). The radio spectrum implied by Figure 1 is remarkably flat at all orbital phases. An optically thick homogeneous (constant magnetic field) nonthermal gyrosynchrotron source of fixed size would have a spectrum rising roughly as $\nu^{2.7}$; the observed flat spectrum is more consistent with an optically thick source whose effective size increases dramatically as the frequency decreases (source size $\propto \nu^{<-2}$; e.g., White, Kundu & Jackson 1989). The alternative is optically–thin emission by a very hard ($E^{-1.3}$) electron energy distribution, which is not borne out by the X–ray spectrum.

We can think of two possible physical origins for the nonthermal electrons producing the radio emission of V471 Tau. One is simply enhanced solar–like activity in the corona of the K dwarf; the ratio of its soft X–ray to bolometric luminosity is at the observed saturation limit for active late–type stars (e.g., Barstow et al. 1992). In this case, the K dwarf's radio luminosity of $\sim 2 \times 10^{15}$ ergs s^{-1} Hz^{-1} (based on a flux density of 1.0 mJy) would place it at the upper end of the quiescent radio luminosity distribution of K dwarfs (Güdel 1992), but consistent with that of the most rapidly–rotating and active K dwarfs. It, however, would be unique among these active K dwarfs in that it is the only one so far to show strong rotational modulation in its quiescent emission (AB Dor can show strong rotational modulation of its strong, semi–continuous flaring emission; Lim et al. 1992; 1994). The second possibility is that the nonthermal electrons are directly associated with the binary nature of V471 Tau, and specifically with the region of interaction between the magnetospheres of the two stars. The white dwarf is apparently rotating with a period of 9.25 minutes (Jensen et al. 1986), and consequently its magnetic field must be whipping rapidly past the coronal field lines of the K dwarf. The region where this takes place is an obvious plausible source of energy release, and hence acceleration of nonthermal electrons. We now investigate how each of these models compares with the observational data.

4. MODELS FOR RADIO EMISSION

4.1. Active solar–like K dwarf corona

In this model the radio activity is not directly associated with the white dwarf. It is, however, indirectly associated in that the white dwarf forces the K dwarf into rapid corotation, and the enhanced stellar activity of the K dwarf is at least partly due to its rapid rotation and hence strong dynamo–generated magnetic fields. Two other effects of the white dwarf are also potentially significant: the distortion of the K dwarf's surface by the white dwarf's gravitational field, and the irradiation of the K dwarf by the ultraviolet flux from the white dwarf.

In this model we would expect radio emission from regions of the corona containing strong, structurally complex magnetic fields. A difficulty for the stellar–activity model is that the form of the radio light curve requires the side of the K dwarf facing the white dwarf to be preferentially active. There is no obvious reason for such a preference in simple dynamo action of a rotating star, unless the white dwarf's gravitational field also affects convection in the K dwarf in such a way that magnetic flux emerges preferentially on the side facing the white dwarf. We note that a large starspot ocassionally dominates the optical light curve of the K dwarf, but Skillman & Patterson (1988) find no evidence that it forms preferentially on the side facing the white dwarf. The one advantage that this model offers is a simple way to explain the broad eclipses of the radio emission. If the radio source has a relatively small radial scale height but is extended in stellar longitude, eclipses of duration up to half an orbital period can be explained. There are, however, at least two difficultes with this model. First, outside eclipse one would expect the radio emission to be strongest at phase 0.5, contrary to what is actually observed. Second, the sharp egress of the radio source from eclipse requires a rapid change in the visible area of the (optically thick) radio source, and this is difficult to achieve with a small radial scale height but wide longitudinal distribution of radio–emitting material. The alternative, that the electrons are in extended loops well above the surface of the K dwarf, is a characteristic of the interacting stellar magnetospheres model discussed next.

4.2. Interacting Stellar Magnetospheres

Patterson et al. (1993) suggest that collisional interactions between the magnetospheres of the white dwarf and the K dwarf may result in the acceleration of electrons responsible for the radio emission of V471 Tau. This provides a natural explanation for why the (strong) radio–emitting region is located preferentially between the K dwarf and the white dwarf. Although the white dwarf's magnetic field has not been detected directly, as mentioned earlier the periodically pulsed nature of its photospheric optical and soft X–ray emission indicates the presence of a strong, probably dipolar–like, magnetic field. Likewise the K dwarf's magnetic field has not been directly detected, but its strong soft X–ray emission indicates the presence of a magnetically structured corona.

To investigate the possible location of the magnetically interacting region, we shall initially assume that the K dwarf is completely covered by $\sim$4 kG photospheric magnetic fields. This we estimate from the empirical relationship between the photospheric magnetic fluxes and the rotation periods of active late–type dwarfs, as derived by Saar (1987) and Linsky & Saar (1987). As mentioned in §3.2, the magnetic field of the white dwarf cannot exceed a few kG, and for illustrative purposes we shall again assume a dipolar magnetic field with a surface strength of 5 kG. In this picture, the magnetic field strength of the white dwarf decreases from the stellar surface with a r^{-3} dependence (where r is the radial distance from the stellar center), whereas the magnetic field of the K dwarf (which we assume expands homogeneously to fill the entire volume above the stellar surface) decreases with a r^{-2}–r^{-3} dependence depending on the height at which magnetic field lines close. Because of the very much smaller radius of the white dwarf, the magnetic field strengths of the two stars are expected to balance much closer to the surface of the white dwarf than the K dwarf. For a r^{-2} dependence in the K dwarf's magnetic field strength, the fields of the two stars balance in strength at a radial distance of only $\sim$3 R_{wd} from the white dwarf; for a r^{-3} dependence in the K dwarf field, their field strengths balance at a radial distance of only $\sim$4 R_{wd}. Even if we assume a surface field of only 100 G for the K dwarf, and a r^{-3} dependence, the field strength of the two stars still balances at a radial distance of only $\sim$14 R_{wd} from the white dwarf. Thus, any magnetic interaction almost certainly occurs very close to the surface of the white dwarf, probably at a height of order its radius, where the field strength is likely to be of order several tens of gauss.

The electrons accelerated in the interacting region should stream down magnetic field lines to the surface of both the white dwarf and the K dwarf. These electrons are presumably replenished continuously as new magnetic fields are continually brought into the interacting region by the 9.25 min rotation of the white dwarf. Also, the magnetic field of the K dwarf is presumably not static, but highly dynamic. Because the volume of the white dwarf magnetosphere is intrinsically small, the white dwarf is expected to contribute relatively little to the overall radio emission of the system. Instead, much of the radio emission is expected to originate from magnetic structures that extend from the K dwarf to the interaction region, that is those with heights of $\sim$2.3 $R_{\odot}$.

The above picture may explain qualitatively many of the characteristics seen in the orbital phase dependence of the radio emission of V471 Tau. An optically–thick radio–emitting structure that is much greater in height ($\sim$2.3 $R_{\odot}$) than the separation of its footpoints ($\ll$ 1.6 $R_{\odot}$, the diameter of the K dwarf) should have a relatively sharp ingress and egress phase to eclipse due in part to its rapidly changing projected area, and in part to geometrical eclipse by the stellar disk. The radio emission should peak at or near orbital phase quadrature when the projected area of the magnetic structure is largest, as is apparently observed. It also should show a local minimum at or near phase 0.5 when the projected area of the magnetic structure is smallest, as also is apparently observed. A broad radio eclipse, however, is difficult to understand in a model where the structure is uniformly bright in radio throughout its entire height. Such a broad eclipse is better explained by a source with a scale height smaller than the stellar diameter, which is feasible if — as is expected — the nonthermal electrons radiate preferentially in the stronger magnetic fields lower in the corona. We noted earlier that the spectrum requires the radio source to be much larger at low frequencies than at high frequencies, and this is consistent with the picture where the radio source is extended radially from the surface of the K star with the optically–thick area reaching greater heights at lower frequencies. This model implies that the higher–frequency source should be occulted longer than the lower–frequency source, a prediction that can be tested by multifrequency observations. In this picture, the active regions on the K dwarf which are magnetically connected to the interaction region are the site of the dominant radio emission, but not the only site. Other solar–like active regions on the K dwarf may also produce (weaker) radio emission, which could account for the uneclipsed radio emission of the system.

5. MAGNETICALLY–CHANNELED MASS TRANSFER?

The rotational modulation observed in the soft X–ray photospheric continuum emission of the white dwarf is attributed to the accretion of heavy elements (presumably from the K dwarf) at its magnetic poles (Clemens et al. 1992; Barstow et al. 1992). These elements lead to more efficient radiative losses at, and therefore cooling of, the poles, resulting in an enhancement of the photospheric optical emission but a decrement of the photospheric soft X–ray emission. Mullan et al. (1989) attribute the origin of these heavy elements to accretion from a massive stellar wind from the K dwarf companion. From observations of ultraviolet absorption lines, they infer a mass–loss rate for the wind of at least 10^{-11} $M_{\odot}$ yr^{-1}.

The wind properties inferred by Mullan et al. (1989) are uncomfortably close to — and may indeed exceed — the limit where radio emission originating from close to the K dwarf's surface cannot escape because of free–free absorption by the wind. This can be demonstrated by considering the radial distance at which the wind attains significant optical depth (specifically τ_{ν} = 0.244; as seen by an observer looking in from outside) (Wright &

Barlow 1975):

$$R(\nu) = 2.8 \times 10^{28}\ \gamma^{1/3}\ g_\nu{}^{1/3}\ Z^{2/3}\ T^{-1/2}(\frac{\dot{M}}{\mu\ v_\infty\ \nu})^{2/3} \quad \mathrm{cm} \quad , \tag{1}$$

where γ is the number of electrons per ion, g_ν the free–free Gaunt factor, Z the rms ionic charge, T the temperature, $\dot{M}$ the mass–loss rate (in $M_\odot$ yr^{-1}), μ the mean molecular weight, ν_∞ the terminal velocity of the wind (in km s^{-1}), and ν the observing frequency (in Hz). For simplicity we assume $\mu = Z = \gamma = 1$, with $g_\nu \approx 6$, and we use the wind properties inferred by Mullan et al. (1989) of $T \approx 10^4$ K, $v_\infty \approx 800$ km s^{-1}, and $\dot{M} \geq 10^{-11} M_\odot$ yr^{-1}. One then finds that $R(\nu) \geq 4.0\ R_K$ at 20 cm, $R(\nu) \geq 1.7\ R_K$ at 6 cm, and $R(\nu) \geq 0.8\ R_K$ at 3.6 cm. Thus, (nonthermal) radio emission from close to the K dwarf's surface at 20 cm is unlikely to escape, and that at 6 cm and shorter wavelengths may just escape depending on the actual height of the emitting structure (and the actual mass–loss rate).

As subsequently pointed out by Mullan et al. (1991), the accretion rate of the white dwarf is surprisingly small if the mass–loss rate from the K dwarf is as high as inferred. They found that, given the rapid rotation of the white dwarf, the propeller mechanism may be able to prevent efficient accretion on the white dwarf, provided that the surface field is in excess of 2–6 kG. Such field strengths, however, are already uncomfortably close to the upper limit for the white dwarf communicated to us by Sion (1995).

Given the above situation, we suggest here an alternative method by which mass may be transferred from the K dwarf to the white dwarf. The following picture follows naturally from our interpretation that interacting stellar magnetospheres can explain the nature of the radio emission of the system. Mass from the K dwarf may be channeled directly to the white dwarf through the large–scale magnetic fields that interact with the magnetosphere of the white dwarf. The transferred material may be ablated from the chromosphere of the K dwarf by the precipitation of the radio–emitting electrons. From the point of view of energetics, this material is more likely to be supplied (perhaps also through ablation of chromospheric material) by more compact flares occuring at the surface of the K dwarf, and which have (at least some) field lines connected to the proposed large–scale magnetic structures. Ionized material transferred to the magnetosphere of the white dwarf will naturally flow down magnetic field lines to the poles of the star. The accretion rate is determined solely by the amount of material injected into the large–scale magnetic structures associated with the K dwarf, independent of any stellar wind.

6. CONCLUSIONS

We presented strong evidence that the radio emission of the precataclysmic binary V471 Tau suffers an eclipse during each orbital period. The eclipse minima appears to be centered at the orbital phase where the white dwarf is eclipsed and directly behind the K dwarf ($\phi \approx 0.0$), and has a full width of $\Delta\phi \approx 0.3$. By comparison, the ingress and egress of the eclipse can be quite sharp, with a width of only $\Delta\phi \approx 0.05$. The shape of the eclipse — both the width of the ingress and egress phases, as well as the overall width of the eclipse — may be time variable. Approximately 80% of the radio emission of the system is eclipsed, implying that much of the radio emission of V471 Tau originates from the region between the two stars. Outside eclipse, the radio emission of the system appears to peak at $\phi \approx 0.25$ and $\phi \approx 0.65$, that is at or near orbital phase quadrature. The radio light–curve shows a local minima at $\phi = 0.4$–0.5, at or near the transit of the white dwarf.

A model in which the radio emission is due only to enhanced stellar dynamo–associated activity on the K dwarf has several drawbacks. Instead, we favor the model suggested by Patterson et al. (1993) in which the radio–emitting electrons are accelerated in the region where the magnetospheres of the two stars, rotating at different rates, interact. For a range of magnetic parameters likely to apply to these two stars, we find that the interaction region is likely to be located very close to the white dwarf. This leads naturally to a picture where much of the radio emission originates from magnetic structures rooted in the K dwarf that have heights nearly comparable to the orbital separation. Such an optically–thick radio–emitting structure may be able to qualitatively explain the observed orbital phase dependence in the radio emission of V471 Tau. The channeling of material from the K dwarf to the white dwarf through the proposed magnetic field structures may provide, partly or wholly, the material accreted by the white dwarf.

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Figure Legends

Figure 1

Radio Emission of V471 Tau plotted as a function of orbital phase in (a) 1994 Dec 2 and (b) 1994 Dec 3. Data points at 3.6 cm are plotted as open circles, 6 cm as filled squares, and 2 cm as filled diamonds. Each point represents an individual scan, and has an error bar of length $\pm 1\sigma$.