The origin of the infrared light of cataclysmic variable stars

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Summary. This paper presents a model-independent overview of the origin of the near infrared (1–2\,$\mu$m) light of a sample of 28 cataclysmic binary stars, largely dwarf novae in quiescence. The infrared light comes from the red dwarf that supplies matter to the white dwarf companion and the accretion disc around the white dwarf. The complex nature of the disc prevents near-infrared photometry from being a good probe of the red dwarfs, even in those systems where they are seen in the visual. All that can be found reliably is an upper limit to the proportion of light that the red dwarfs supply, and consequently lower limits to the distances to the systems.

The infrared light of the discs comes from opaque material and from the optically thin gas that gives rise to the visual and UV emission lines. The proportion of light supplied by each differs widely from system to system.

10-\,$\mu$m observations of five systems of cataclysmic binary stars show that they contain $<10^{-7}\ M_\odot$ of dust at 300 K, and $<7\times10^{-10}\ M_\odot$ at 1000 K. Such grains are are present most likely form in the plane of the orbit, from material carried away from the red star by flares.

1 Introduction

Despite much study in the past 5 yr, there is as yet no consensus on the origin of the infrared light of the accretion discs in cataclysmic variable stars (hereafter, CVs). The work of Sherrington \textit{et al.}

\textsuperscript{*} Based in part on observations made at Mount Wilson Observatory, as part of a collaborative agreement between the Carnegie Institution of Washington and the California Institute of Technology.

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(1980) appeared to support the theoretical notion that the light comes from an opaque steady state disc (Shakura & Sunyaev 1973). But subsequent work has shown that accretion discs exhibit a wide range of infrared colours, many differing from those expected in the steady state model (Szkody 1981; Sherrington & Jameson 1983).

This paper presents a model-independent overview of the origin of the infrared light (1–2 μm) of a large sample of CVs. The analysis takes account of the fact that both opaque and optically thin gas may give rise to the infrared continuum. Optically thin gas has scarcely been considered in other analyses. Yet CVs commonly show visual and ultraviolet emission lines, and the continuum radiation of the material producing them supplies much of the infrared light in the ultra-short-period CV OY Car (Berriman 1984); it may also be important in the visual in other systems (e.g. Kippenberger 1979; Schwarzenberg-Czerny 1981).

The infrared light comes not only from the accretion disc, but also from the red dwarf that supplies matter to it: the ellipsoidal light curves of these stars, tidally distorted by the white dwarf companion at the centre of the disc, have been seen in the infrared light curves of some highly inclined systems (e.g. Bailey et al. 1981). The analysis divides naturally into two parts: (i) how much light comes from the red star (which bears on the question of the distances, securely known for only a few systems); and (ii) how much of the light of the disc comes from opaque and optically thin gas, and what are the properties of each.

This paper also presents the first 10-μm measurements of CVs excluding AM Her stars. These data are a probe of thermal emission from dust grains. Sherrington & Jameson (1983) and Frank et al. (1981) have suggested that this is important in the near-infrared in some systems.

2 Observations

2.1 JHK photometry

Infrared observations of the variability of CVs over several years are useful in understanding the origin of their infrared light. For a sample of CVs consisting largely of dwarf novae in quiescence, Table 1 presents a compilation of published and unpublished JHK observations made between 1975 and 1982, together with V magnitudes. The 1σ uncertainties in the infrared data are ±0.04 mag, except where otherwise stated. The visible data are generally only accurate to at most 0.1 mag, except the 1981 data of Sherrington & Jameson (1983; hereafter SJ), which were obtained simultaneously with the infrared data and are accurate to several hundredths of a magnitude or better.

None of the observations have been corrected for interstellar reddening. Where determined from UV measurements, the reddenings are generally small, E(B–V)<0.1–0.15 (e.g. Verbunt et al. 1984; Szkody 1981). Such reddenings do not alter the conclusions of this paper.

Table 1 states the sources of the published data, which include some of those of SJ. The unpublished data were obtained in 1978–82 with cooled InSb detectors at the 1.3-m telescope at Kitt Peak National Observatory (the detector package ‘Otto’) and at the 1.5-m telescope at Mount Wilson Observatory. The measurements were calibrated by hourly observations of Johnson and CIT standards (Neugebauer 1978, private communication), and placed on the CIT system (Frogel et al. 1978).

The magnitudes quoted are the averages of several observations, each of which were generally reproducible within their 2σ uncertainties. This procedure minimizes the effects of intrinsic variability of the accretion disc, long seen in the visual. Such variability may have been seen in some of SJ’s colours, which are successive measurements of 10 min duration in each filter (Jameson 1984, private communication). In the sense that they are bluer than a Rayleigh–Jeans
tail, the $J-H$ colour of V603 Aql and the $H-K$ colour of TW Vir are unphysical. The variability required to do this in V603 Aql, and 0.3 mag in 30 mins, has been seen in the visual (Slovak 1980). The $P\beta$ (1.28 $\mu$m) and $B\gamma$ (2.17 $\mu$m) lines are too weak to significantly affect the colours. A spectrum of V603 Aql kindly obtained by Dr T. Geballe at UKIRT shows that the $B\gamma$ line supplies only a few per cent of the total light at 2 $\mu$m. This is expected to be generally true of the $P\beta$ and $B\gamma$ lines in CVs on the basis of an extrapolation from Balmer line ratios with Drake & Ulrich's (1980) theoretical line ratios. The $JHK$ data of TW Vir and V603 Aql are not considered further.

2.2 10-$\mu$m OBSERVATIONS

At 10 $\mu$m, the faintness of the objects and the high thermal background prevents observations of high accuracy. Table 2 presents 2σ upper limits to the 10-$\mu$m flux densities of several systems. The data were obtained at the 2.2-m Infrared Telescope Facility at Mauna Kea Observatory, Hawaii on 1980 June 8–12 UT. All measurements were calibrated by hourly measurements of CIT standard stars. On the CIT system, Vega has $N=0.00$ mag, and its flux density through the 10-$\mu$m filter is $F_\nu=43.5$ Jy.

3 The red stars

Bailey (1981) stated that the disc and red star supply the infrared light in short-period systems ($P<5.5$ hr), but the red dwarf alone is likely to supply it in the longer period ones. Such systems are large enough to accommodate $K$ dwarfs, luminous enough to be seen in the visual and red spectrum (e.g. Stover et al. 1980; Wade 1982). But Figs 1 and 2 show that the disc is an important source of infrared light in both long- and short-period systems, and so it must always be taken into account whatever the orbital period.

Fig. 1 shows that the $K$ magnitudes of those objects measured more than once vary from epoch to epoch. This is as true of short-period systems, e.g. TT Ari ($P=0.14$ day), as it is of long-period ones, e.g. EM Cyg ($P=0.29$ day). The variability of the disc, long seen in the visual, is a natural explanation of this.

Fig. 2a is a flux ratio diagram based on the flux ratios $F_\nu(J)/F_\nu(K)$ and $F_\nu(H)/F_\nu(K)$ (hereafter, $J/K$ and $H/K$ for simplicity). It shows that the colours of CVs generally differ from those of red dwarfs alone (identified separately for clarity on frame (b), along with opaque gas and optically thin gas); this includes three systems thought by SJ to contain $K$ dwarfs, on the basis of their $J-K$ colours: V841 Oph, KT Per and TZ Per. Again this is as true of short-period systems as it is of long-period ones: e.g. AH Her and SU UMa have the same colours, but their periods differ by more than 4 hr.

U Gem has the colours of an M4–M5 dwarf, but only measurements of its ellipsoidal variations establish that it supplies all the infrared light (Panek & Eaton 1982; Berriman et al. 1983). Such measurements are necessary because there is no a priori reason why the light cannot come from an optically thin disc and an earlier type star than indicated by the colours, or an opaque disc and a later type one. This is borne out in V426 Oph and AE Aqr. V426 Oph contains a $K$ dwarf (Hessmann 1984, private communication), yet has the colours of an M dwarf. AE Aqr has the colours of an early $K$ dwarf, but its infrared light curves show variations not readily accounted for by the ellipsoidal variations of this star or heating of it by the accretion disc (Tanzi, Chincarini & Tarenghi 1981), so that the disc itself may supply some of the light. Infrared light curves should therefore be obtained for the other two systems which have the colours of red dwarfs: TT Ari and X Leo.
Table 1. Compilation of infrared photometry of cataclysmic variable stars.

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<th>J</th>
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Notes:

Column (2): DN = dwarf nova, NL = nova-like, N = nova
Column (3): Orbital period, where known
Column (5): Outburst phase of dwarf novae
  m = minimum (quiescent)
  max = maximum
  s = standstill
  mid = decline to minimum
Column (6): Source of V magnitude
  1 Measured within a few days of JHK
  2 Supplied by American Association of Variable Star Observers
  3 eye estimate
  4 measured simultaneously with JHK
Column (10): Source of published infrared magnitudes
Table 2. Upper limits (2σ) to the 10-μm flux densities of cataclysmic variable stars.

<table>
<thead>
<tr>
<th>Object</th>
<th>Flux Density (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V603 Aql</td>
<td>&lt;10</td>
</tr>
<tr>
<td>AE Aqr</td>
<td>&lt;27</td>
</tr>
<tr>
<td>SS Cyg</td>
<td>&lt;36</td>
</tr>
<tr>
<td>AH Her</td>
<td>&lt;32</td>
</tr>
<tr>
<td>EX Hya</td>
<td>&lt;33</td>
</tr>
</tbody>
</table>

3.1 FRACTION OF LIGHT SUPPLIED BY THE RED STARS, AND DISTANCES

The K dwarfs in the longer period systems, listed in Table 3a, Column 1, do not supply all the infrared light, but the very fact that they are important in the visual (see, e.g. Wade 1982; Stover et al. 1980) indicates that they are important in the infrared too.

How much of the light they supply is easily seen from the flux ratio diagram. In Fig. 2b, the flux ratios of an object O consisting of two components P and Q, lie along the straight line between them. The proportion of light coming from P at the ‘reference wavelength’, the denominator of each axis, is given simply by a ‘lever rule’ to be (1-QQ/PQ), and from Q, (1-OP/PQ). This lever rule was derived formally by Wade (1982) and Rabin (1981).

A disc consists in the most general case of an arbitrary combination of light from opaque and optically thin gas at any temperature, and so lies anywhere inside area ABCD. A disc in a given CV lies anywhere along the extension of the line from the red dwarf through the observations, to where it intersects the boundary of this area. According to the lever rule, as the disc approaches this intersection, it supplies less of the light, and the K dwarf supplies more.

Because the long-period systems lie close to the main sequence, their K dwarfs may supply as much as ~50 per cent of the light at K in AH Her in 1975 and up to 80 per cent in the others.

Figure 1. The year-to-year variability of the K magnitudes of cataclysmic variable stars with their J–K colours. H–K is shown for SY Cnc rather than J–K.
proportions cannot be specified any more exactly than this upper limit, because there is no reason to prefer one disc ratio over another. The upper limits themselves are approximately independent of the spectral type of the star. The observations lie intermediate between very hot opaque gas and very cool optically thin gas, where line AB is approximately parallel to the main sequence. Therefore an early K dwarf and a red disc account for the observations just as well as a later K dwarf and a bluer disc in the same proportions.

A consequence of the above discussion is that it is only possible to obtain a secure lower limit to the distances of these systems, but that they do not seriously underestimate their true distances. Column (3) of Table 3a lists the lower limits, as found from Bailey’s (1981) empirical result that the surface brightness at $K$ of a red star is insensitive to its spectral type. The distances, $d$, are given by

$$\log d = \frac{K}{5} + 1 - \frac{S_K}{5} + \log \left( \frac{R_*}{R_\odot} \right)$$

where $S_K$ is the surface brightness at $K$ ($S_K = 4.1$ for K dwarfs). When several measurements of a system have been made, only the most accurate ones have been used to determine the $K$ magnitude of the red dwarf, $R_*$ is its radius, determined largely by the orbital period (Warner 1976):

$$R_* = 1.8 P(d)^{2/3} M_*(M_\odot)^{1/3} R_\odot.$$ 

The masses of these stars are not well known. In order to be secure lower limits, the entries in Table 3 are for $M_r \sim 0.5 M_\odot$, the lowest mass a K dwarf can have. This is to be preferred to Warner’s (1976) period–mass relation; it strictly applies to stars that lie exactly on the main sequence mass–radius relation, which is not necessarily the case for the red dwarfs in CVs (Wade 1981; Young & Schneider 1981). The case of SS Cyg indicates that the true distances may be underestimated by as much as 25–50 per cent: we find it to be more than 95 pc away, but Kiplinger (1979) finds $d = 110–143$ pc, based on a decomposition of the visual spectrum.

These underestimates may be much larger for the remaining systems, generally short-period objects containing less luminous dwarfs or systems of unknown period. For example, a secure minimum distance for HR Del is 175 pc, if the surface brightness of its red star is that appropriate to M dwarfs, $S_r = 4.6$, and its mass is that of a very late type star, $M_r = 0.2 M_\odot$. It is actually two and a half times further away, at $\sim 400$ pc (Hutchings 1969).

Table 3b presents distances for all the remaining systems, deduced in the same way as for HR Del, except when the period is unknown, when $R_* = 0.2 R_\odot$ has been used. The proportions of the light supplied by the red dwarf differ widely from system to system, from as little as 10 per cent in T Leo, to possibly all the light in TT Ari. X Leo has been excluded from Table 3b, as its position in the flux ratio diagram and the uncertainties in its measurements do not allow the proportion of the light from its red dwarf to be found accurately.

 Measurements of absorption lines in red spectra thus remain the best method of measuring the spectral types and apparent magnitudes of the red dwarfs, but this has so far proven difficult to do because the disc still supplies much of the light there (Young & Schneider 1981). Infrared light curves of highly inclined CVs show not only an eclipse of the disc by the red star, but also the ellipsoidal variations of the tidally distorted red dwarf and its eclipse by the outer disc, half a cycle later. Berriman (1984) has shown that the depths of these minima give useful constraints on the apparent magnitude of the red dwarf, but this method has so far been applied only to OY Car. Until such time as these two types of measurements have been made for many systems, accurate distances will be difficult to determine. The minimum distances presented here are the most secure distances available to date for a large sample of object. They will be compared with distances determined by other methods in a future paper (Berriman 1985, in preparation).
G. Berriman, P. Szkody and R. W. Capps

Figure 2. A flux ratio diagram based on the ratios $F_v (J)/F_v (K)$ and $F_v (H)/F_v (K)$. Frame (a) identifies the loci of the lower main sequence, of hot and cool optically thick spectra, and of recombination spectra; H is a hypothetical object used to explain the application of the diagram; see text. Frame (b) gives comparison with observations. The inset to (b) compares the observations with those of steady state discs, which have the mass loss rates indicated in $M_0$ yr$^{-1}$; the ticks along each track denote the radius of the disc: from left to right, it increases from $10^{10}$ cm to $6 \times 10^{10}$ cm in increments of $10^{10}$ cm for $M=10^{-9}$ and $10^{-10} M_0$ yr$^{-1}$, and 3 to $6 \times 10^{10}$ cm for the others.

The lower main sequence is taken from Johnson (1966), Frogel et al. (1978) and Young & Schneider (1981). M dwarfs are in the classification scheme of Boeshaar (1976); VB 10 is one of the coolest M dwarfs known (Reid & Gilmore 1984). The colours of opaque gases come from three sources, depending on their temperature: at $T>6000$ K, the colours are those of upper main sequence stars (Bohm-Vitense 1981), and at $2500<T<6000$ K, those of lower main sequence stars; their temperatures are: K0, 5200 K; K5, 4400 K; M0, 3650 K; M2, 3400 K; M4, 3250 K; M6, 2900 K. Below 2500 K, the colours are those of blackbodies.

The colours if optically thin gas, of solar abundance, are from two sources. At $2500<T<6000$ K, where $H^-$ is the principal source of opacity, the colours have been found from Stilley & Callaway (1970) and Geltman (1962). Below 2500 K there are too few free electrons for $H^-$ to be important, and above 6000 K the ion is destroyed; their colours are from Ferland (1980), who considered gases hotter than 500 K. The optically thin gas in a CV is unlikely to be cooler than this because the mass stream heats the disc.

4 The accretion discs

The first detailed infrared study of a CV, EX Hya, used $J-K$ to conclude that it contained a steady state disc having a radial temperature gradient of $T \propto R^{-3/4} M^{1/4}$ ($M$=mass transfer rate) and a spectrum $F_v \propto \nu^{1/3}$ (Sherrington et al. 1980). Yet, as these authors state, the disc would have to be as big as the orbital separation to have such a spectrum. At the same time, its $J-K$ colour of 0.9 is similar to that of optically thin gas and of red dwarfs, so that this colour is not a good probe of an accretion disc. Berriman's (1984) analysis of the disc of OY Car bears this out. It is similar in $J-K$ to EX Hya in 1980, but its $H-K$ and $J-K$ colours of $\sim 0.6$ and $\sim 0.9$ differ from those of a $F_v \propto \nu^{1/3}$ spectrum. Much of the light actually comes from optically thin gas: $H-K$
measures the slope of the Pfund continuum of optically thin gas, and is always redder than opaque gas hotter than 2500 K. $J-K$ and $H-K$ together are thus more useful probes of the accretion disc than $J-K$ alone.

A study of the properties of the optically thin gas in quiescent discs may prove of fundamental importance, for thermal instabilities in it may give rise to the outbursts which give CVs their name (e.g. Canizzo & Wheeler 1984; Papaloizou, Lin & Faulkner 1983). Whether it is generally an important source of continuum emission in quiescent discs has yet to be established, and will be addressed in this preliminary study of accretion discs in the infrared. The objects are distributed throughout Fig. 2b, but quiescent ones are generally redder than $H/K \sim 1.35$. Bluer ones are nova-like systems, thought to be dwarf novae in permanent outburst. UX UMa and H2215–086, though, are nova-like objects, but are as red as quiescent systems.

The origin of the infrared light of each disc is given in a simple, model-independent way by the flux ratio diagram, as illustrated by reference to the hypothetical object, H, in Fig. 2a. If the
Table 3. Lower limits to the distance of cataclysmic variable stars.

<table>
<thead>
<tr>
<th>Object</th>
<th>$K$ (star)</th>
<th>$R(\Omega)$</th>
<th>d(pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE Aqr</td>
<td>8.7</td>
<td>0.9</td>
<td>90</td>
</tr>
<tr>
<td>RX And</td>
<td>11.5</td>
<td>0.6</td>
<td>180</td>
</tr>
<tr>
<td>Z Cam</td>
<td>11.1</td>
<td>0.7</td>
<td>190</td>
</tr>
<tr>
<td>SS Cyg</td>
<td>9.6</td>
<td>0.7</td>
<td>95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Object</th>
<th>$K$ (star)</th>
<th>$R(\Omega)$</th>
<th>d(pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE Herc</td>
<td>12.4</td>
<td>0.7</td>
<td>180</td>
</tr>
<tr>
<td>Lanning 10</td>
<td>13.2</td>
<td>0.6</td>
<td>450</td>
</tr>
<tr>
<td>V426 Oph</td>
<td>10.5</td>
<td>0.7</td>
<td>80</td>
</tr>
</tbody>
</table>

b. Systems not known to contain K dwarfs.

<table>
<thead>
<tr>
<th>Object</th>
<th>$K$ (star)</th>
<th>$R(\Omega)$</th>
<th>d(pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FO Aql</td>
<td>13.0</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>TT Ari</td>
<td>13.2</td>
<td>0.3</td>
<td>180</td>
</tr>
<tr>
<td>SY Cnc</td>
<td>13.3</td>
<td>0.2</td>
<td>110</td>
</tr>
<tr>
<td>YZ Cnc</td>
<td>15.2</td>
<td>0.2</td>
<td>260</td>
</tr>
<tr>
<td>CPD-48 1577</td>
<td>9.7</td>
<td>0.4</td>
<td>50</td>
</tr>
<tr>
<td>CM Del</td>
<td>13.7</td>
<td>0.2</td>
<td>130</td>
</tr>
<tr>
<td>HR Del</td>
<td>13.1</td>
<td>0.35</td>
<td>175</td>
</tr>
<tr>
<td>H2215-086</td>
<td>13.6</td>
<td>0.35</td>
<td>200</td>
</tr>
<tr>
<td>EX Hya</td>
<td>13.6</td>
<td>0.2</td>
<td>130</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Object</th>
<th>$K$ (star)</th>
<th>$R(\Omega)$</th>
<th>d(pc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T Leo</td>
<td>15.7</td>
<td>0.2</td>
<td>400</td>
</tr>
<tr>
<td>CY Lyr</td>
<td>13.2</td>
<td>0.2</td>
<td>105</td>
</tr>
<tr>
<td>VB41 Oph</td>
<td>11.9</td>
<td>0.2</td>
<td>60</td>
</tr>
<tr>
<td>KT Per</td>
<td>12.2</td>
<td>0.2</td>
<td>70</td>
</tr>
<tr>
<td>TZ Per</td>
<td>12.5</td>
<td>0.2</td>
<td>80</td>
</tr>
<tr>
<td>UV Per</td>
<td>13.0</td>
<td>0.2</td>
<td>100</td>
</tr>
<tr>
<td>SU U Ma</td>
<td>15.5</td>
<td>0.25</td>
<td>350</td>
</tr>
<tr>
<td>UX U Ma</td>
<td>13.4</td>
<td>0.4</td>
<td>270</td>
</tr>
<tr>
<td>TW Vir</td>
<td>14.5</td>
<td>0.35</td>
<td>340</td>
</tr>
</tbody>
</table>

Notes:
- Column (2): bright limit to $K$ mag of red dwarf
- Column (3): radius of red dwarf
- Column (4): minimum distance.

spectral type of the red star is unknown, the disc lies anywhere inside hatched area HXAY, and so consists largely of opaque gas hotter than 6000 K.

4.1 OPAQUE DISCS IN QUIESCENT SYSTEMS

4.1.1 Gross properties of the opaque material

The general location of quiescent discs in between hot and cool gas requires that, if they are opaque, they contain a wide range of temperatures: cooler than $\sim 3000$ K to account for $H/K$ and hotter than $\sim 15000$ K in some cases to account for $J/K$.

The coolest matter would have to supply as much as one-half to two-thirds of the total light. Yet to be this important, it would have to more than fill even a face-on disc, as shown in Table 4a. It compares the radii such cool discs would have with those expected. These expected radii are those of tidally limited viscous discs, estimated from those radii measured directly by, e.g., Sulkanen, Brasure & Patterson (1981), and scaled according to orbital period.
The radius, $R_{\text{cool}}$, of the cool material is given by

$$R_{\text{cool}}^2 = 8.1 \times 10^{14} d (\text{pc})^2 F_\nu (\text{mJy}) \exp(6545/T) - 1 \text{ cm}^2$$

where $F_\nu$ is the flux density of the material at 2.2 $\mu$m, and $d$ is its distance. These two quantities have been found under the assumption that the disc is redder in $H/K$ by the 1σ uncertainties and bluer in $J/K$ by the same amount; that is, under the assumption that the disc supplies the bulk of the light. This requires that (i) the cool matter is typically at $\sim 3000$ K in objects close to the main sequence ($J/K \sim 1-1.2$), but somewhat cooler in the remaining systems; and (ii) the systems are further away than the minimum distances given in Section 3.1, typically by a factor of 2; those given correspond to a late K or early M star (as is appropriate to the orbital period). If these stars are in reality earlier than this, they make a conclusion that is clear from Table 4a still stronger: only in TT Ari and SY Cnc is the cool matter able to fit into the disc. It is worthwhile repeating that this applies to a face-on disc: the discrepancy becomes greater for a more highly inclined one.

Essentially the same general results apply whatever the proportion of light from the red dwarf. If it supplies more light, the system moves nearer, but the cool matter becomes still cooler and less luminous. If it supplies less, the cool matter becomes hotter, but the system moves further away. The same results apply to all systems, and Table 4b makes this clear for one illustrative example, RX And. It shows that the radius of the disc declines somewhat with the fraction of light, $F$, supplied by the red dwarf, but nevertheless remains larger than its expected radius.

This conclusion holds whether the cool material radiates as a blackbody or as a stellar atmosphere, or intermediate between the two (Wade 1984). A stellar atmosphere only radiates more than a blackbody of the same temperature for $T \approx 4000-6000$ K, by 20–30 per cent (e.g. Mould 1976). The light comes from deeper, hotter layers than at other wavelengths because the H$^+$ opacity has abroad minimum centred at 1.6 $\mu$m. Below 3500 K, the increasing importance of H$_2$O bands in the $K$ bandpass offsets this effect. An excess of 20–30 per cent at 3500 K makes the radius of the disc decline by only 10–15 per cent, as indicated in Table 4b. The entry for this temperature has used $L_{\nu}(\mu = 0) = 8.2 \times 10^{-6} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$, deduced by integrating those fluxes in Mould's tabulation that lie in the $K$ bandpass.

Thus if cool opaque material does fill the outer disc, it alone will not be able to explain why the objects are red in $H/K$, a conclusion that is independent of any model of the disc. A scaling of the radii in Table 4a indicates that it may supply no more than $\sim$ one-quarter of the light responsible for these colours.

### 4.1.2 Steady state opaque discs

A corollary to the statement immediately above is that steady state discs will not account for the observations either. The properties of such discs are well established (Shakura & Sunyaev 1973). Their radial temperature gradient is $T \propto R^{-3/4} \dot{M}(1/4)$ ($\dot{M}$-mass transfer rate), and the inset to Fig. 2b compares their colours with the observations for the mass transfer rates thought to be typical of CVs. The Appendix describes the calculation of these model discs.

At mass transfer rates of $\dot{M} \sim 10^{-11}$–$5 \times 10^{-11} \text{ M}_\odot \text{ yr}^{-1}$, the discs are cool enough to explain the colours of systems close to the main sequence ($J/K \sim 1-1.2$), but are usually at least 1 mag too faint to be able to supply the light. This is apparent in Table 4c. The entries in it are obtained in a similar fashion to those in Table 4a; the flux ratio diagram gives the mass transfer rate of a disc of a given size needed to account for the bulk of the infrared light; the exact ratios of object and disc determine the $K$ magnitude of the disc and the distance to the system. The $K$ magnitudes the discs would be expected to have at this distance are found from a scaling of Fig. A1, which gives the variation with radius of the $K$ magnitude of a face-on disc at an arbitrary distance is 150 pc. The blackbody approximation underestimates these magnitudes by only 0.15 mag at most (as described in the Appendix).
Many of these objects close to the main sequence are long-period ones containing K stars, which are likely to supply much of the light. Thus their discs will resemble those of the systems bluest in \(J/K\). Clearly steady state discs cannot supply all their infrared light: Fig. 2b shows that the discs are in reality much redder in \(H/K\) than steady state discs having these values of \(J/K\).

Kiplinger (1979) found that in SS Cyg, the steady state model does not account for visual light in quiescence. But the model does apply in outburst, as it does in other systems (e.g. Kiplinger 1980; Horne & Cook 1985; Mayo, Wickramasinghe & Whelan 1980). The present work extends this result into the infrared. Kiplinger (1980) has proposed that Z Cam at standstill contains a disc of radius \(~5\times10^{-10}\) cm, a mass transfer rate of \(M\sim5\times10^{-9}\) \(M_\odot\) yr\(^{-1}\), and is inclined at 54\(^\circ\). Such a disc would have to supply half the total light at \(K\) and be 240 pc away, and a scaling of Fig. A1

**Table 4.** The properties of accretion discs at 2.2 \(\mu\)m. (a) Cool matter in quiescent discs. (b) Cool matter in RX And. (c) \(K\) magnitudes of quiescent, steady state discs. (d) \(K\) magnitudes of steady state discs above quiescence.

<table>
<thead>
<tr>
<th>Object</th>
<th>(d (\text{pc}))</th>
<th>(T (\text{K}))</th>
<th>(F_v (\text{nJy}))</th>
<th>(R_{\text{cool}} \left(\times10^{10} \text{cm}\right))</th>
<th>(R_{\text{disc}} \left(\times10^{10} \text{cm}\right))</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX And</td>
<td>300</td>
<td>3000</td>
<td>7</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>TT Ari</td>
<td>570</td>
<td>3000</td>
<td>0.2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Z Cam</td>
<td>270</td>
<td>3000</td>
<td>19</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>SY Cnc</td>
<td>130</td>
<td>2500</td>
<td>10</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>SS Cyg(76)</td>
<td>270</td>
<td>3000</td>
<td>86</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>SS Cyg(79)</td>
<td>270</td>
<td>3800</td>
<td>95</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>CM Del</td>
<td>300</td>
<td>2000</td>
<td>1.6</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>AH Her</td>
<td>400</td>
<td>2000</td>
<td>10</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>T Leo(82)</td>
<td>580</td>
<td>3000</td>
<td>2.5</td>
<td>13</td>
<td>2</td>
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<tr>
<td>T Leo(81)</td>
<td>400</td>
<td>2000</td>
<td>0.8</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>V 426 Gph</td>
<td>230</td>
<td>3000</td>
<td>40</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>SU UMa</td>
<td>410</td>
<td>2000</td>
<td>2.6</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>TW Vir</td>
<td>440</td>
<td>3000</td>
<td>1.2</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

Notes: Column (5) gives the radius of a disc occupied by cool material having the temperature and flux density inCols (3) and (4) at the distance in Col (2). Col (6) compares this radius with the expected radius of the disc.

Only the most accurate data of AH Her and SU UMa are included.

<table>
<thead>
<tr>
<th>(F)</th>
<th>(d (\text{pc}))</th>
<th>(T (\text{K}))</th>
<th>(R_{\text{cool}} \left(\times10^{10} \text{cm}\right))</th>
<th>(R_{\text{disc}} \left(\times10^{10} \text{cm}\right))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
</tr>
<tr>
<td>0.10</td>
<td>340</td>
<td>3500</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>0.10*</td>
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<td>3500</td>
<td>8</td>
<td>5</td>
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<tr>
<td>0.30</td>
<td>300</td>
<td>3000</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>0.70</td>
<td>210</td>
<td>1500</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

Notes: Cols (3) and (4) show the variation of the temperature and radius of the cool matter with the fraction, \(F\), of light supplied by the red dwarf.

* Radius computed for model atmosphere at 3500K.

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indicates that it will have the required brightness of \( K \sim 11.7 \). The entries in Table 4d (deduced in the same way as those in Table 4c immediately above it) show the same result for CPD-48°1577, RX And at standstill and Lanning 10. Discs having \( M \sim 10^{-8} \) to \( 10^{-9} \) M\(_\odot\) yr\(^{-1}\) are at least as bright as required by the observations; the model is clearly consistent with the data, and can be made to agree more precisely if the discs are not face-on (as will be the case in the eclipsing system Lanning 10), or the mass transfer rate is a little less.

The magnetic systems TT Ari, UX UMa and H2215-086 have been excluded from this table, as has HR Del. These four objects are somewhat redder than the models in H/K. This may arise in the magnetic systems because some of the light comes from cyclotron emission from the magnetic field that disrupts the disc near the white dwarf (as first suggested in H2215-086 by Sherrington, Jameson & Bailey 1984). But in HR Del, optically thin gas giving rise to its emission lines (not usually seen in nova-like systems) most likely supplies the additional light, as it does in the quiescent systems discussed in the next section.

4.2 A MODEL FOR QUIESCENT SYSTEMS

4.2.1 Origin of the infrared light

Berriman (1984) showed that optically thick gas hotter than 6000 K and optically thin gas give rise to the infrared continuum of the disc in the ultra-short-period system OY Car in quiescence. The discussion of Section 4.1 requires a similar model to apply throughout the sample, to long-period
objects as well as to short-period ones: it is the optically thin gas which is in large measure
responsible for making the objects red in $H/K$. It has a typical emission measure of
$N^2 V \sim 10^{52} \text{ cm}^{-3}$ at an electron temperature of $T_e = 10\,000 \text{ K}$ and at the minimum distances (with
the emission coefficients of Ferland 1980).

In the short-period object EX Hya and the long-period object AH Her, the optically thin gas
supplies up to half the light if it is hot as $T_e = 10\,000 \text{ K}$, and up to one third at $T_e = 5\,000 \text{ K}$. Thus the
simple notion that short-period systems contain more optically thin gas because their mass
transfer rate are lower can no longer be held to be valid (e.g. Ritter 1980).

Whatever the temperature of this gas, the wide differences in colour from system to system
indicate wide differences in the proportion of light it supplies, and in the temperature of the
opaque gas. In those objects close to the main sequence but bluer in $H/K$ than AH Her, optically
thin gas at 10000 K supplies up to one-quarter of the light of the disc, less at cooler temperatures.
In objects like AH Her, it may supply much more than this, e.g. 50 per cent at $T = 10\,000 \text{ K}$
in AH Her itself.

In those objects reddest in $J/K$, the bulk of the opaque gas supplying the rest of the light may be
as cool as $\sim 5\,000 \text{ K}$. Gas as cool as this fills the bulk of the disc, e.g. in RX And, its radius, $R$, is:

$$R = 3 \times 10^{10} \left( \frac{d}{300 \text{ pc}} \right) \left( \frac{F_2}{12 \text{ mJy}} \right)^{1/2} \left( \frac{B_v(T)}{B_v(5000 \text{ K})} \right)^{-1/2} \text{ cm}. $$

An important consequence of this result is that the outbursts which give CVs their names,
cannot arise from thermal instabilities in the disc for these instabilities require that the disc is
everywhere warm and optically thin ($T_{\text{eff}} \sim 6000 \text{ K}$; Faulkner, Lin & Papaloizou 1983) or cool
and opaque ($T_{\text{eff}} \sim 2500 \text{ K}$; Canizzo & Wheeler 1984).

The model remains plausible only if the systems are close to their minimum distances and the
opaque material is hotter than 15 – 20 000 K, a condition necessarily satisfied in those systems
bluest in $J/K$, like T Leo. The surface area of the material becomes small enough for it to be the
hotspot on the outer rim of the disc or the white dwarf at its centre; e.g. again RX And, material at
$> 25\,000 \text{ K}$ and close to the minimum distance has a radius of

$$R < 4.5 \times 10^9 \left( \frac{d}{180 \text{ pc}} \right) \left( \frac{F_v}{3 \text{ mJy}} \right)^{1/2} \left( \frac{B_v(T)}{B_v(25000 \text{ K})} \right)^{-1/2} \text{ cm}. $$

Exactly how much light the red dwarf supplies is therefore crucial to the question of whether
the thermal instability model is plausible. With the infrared arrays now under construction, it will
become possible to measure the red dwarfs in the infrared and therefore answer this question. It
gains importance because the brightness temperature of the optically thin material, for the
proportions of light and distances described above, is typically $T_B \sim 4000 – 6000 \text{ K}$, precisely that
required by the model.

4.2.2 Properties of the optically thin gas

The location of the opaque and optically thin gas can be found by multicolour visual and infrared
studies of the eclipses in highly inclined systems (see, e.g. Horne 1983). Simple considerations do,
however, indicate where the optically thin gas lies. Its emission measure is similar to that required
to support the Balmer lines (Oke & Wade 1982), and suggests the lines and continuum come from the
same plasma. If this is so, its electron temperatures is $\sim 7000 – 15\,000 \text{ K}$, and it may supply a
significant fraction of the visual continuum, e.g. up to 40 per cent at 10000 K in T Leo (as can be
seen from the colours in Ferland 1980). Schwarzenberg-Czerny (1981) has shown theoretically
that the optically thin continuum may be important in the visual.

The lines are very wide ($\sim 1500 \text{ km s}^{-1}$ in highly inclined systems), and thus most likely arise
from a chromosphere above the opaque material; unless the opaque material is hot enough to come entirely from the hot spot or white dwarf, when the disc itself can be everywhere optically thin. The flat decrements indicate that the material is denser than $10^{10} \text{cm}^{-3}$ (Oke & Wade 1982). Such a plasma can still be optically thin at $2 \mu m$, as is the case, for instance, if it has a density of $N \sim 10^{12} \text{cm}^{-3}$ and $T_{\text{el}} \sim 10^4 \text{K}$, and a radius of $\sim 1 \times 10^{10} \text{cm}$. Somewhat denser plasmas will become optically thick at $2 \mu m$ in discs this large – at $N \sim 10^{13} \text{cm}^{-3}$ and $T_{\text{el}} \sim 10^4 \text{K}$, this happens for path lengths as small as a few $\times 10^9 \text{cm}$ – and so such dense plasmas can thus only be found in low-inclination systems.

5 Dust grains in cataclysmic variable stars

$10 \mu m$ observations are a useful probe of dust grains in CVs. The red star and opaque matter in the disc radiate predominantly at shorter wavelengths, and the optically thin plasma will have become opaque this far into the infrared. The upper limits to the $10-\mu m$ flux densities presented in Table 1b are such that emission from dust grains may be important, in the sense that they will allow for an upturn in the $2-10 \mu m$ spectrum of as much as $F_v(10 \mu m) \sim 3F_v(2 \mu m)$.

5.1 Mass of the dust grains

The total mass $M_g$ of dust grains at temperature $T_g$ and density $\rho_g$ giving rise to the $10-\mu m$ flux density is (Gehrz et al. 1980)

$$M_g = \frac{1}{3} \frac{L_{1\mu m} \rho_g}{\sigma T_g^4 Q_c/a}$$

where $Q_c/a$ is the Planck averaged emission coefficient, and $L_{1\mu m}$ is the total luminosity of the grains, related to the $10-\mu m$ flux density $F_v$ by

$$L_{1\mu m} = 4\pi d^2 F_v c \Delta \lambda / f(T_g) \lambda^2$$

where $f(T_g)$ is the fraction of the light transmitted by the $10-\mu m$ filter (of bandwidth $\Delta \lambda = 5 \mu m$), and $d$ is the distance to the system. Table 2 gives the minimum distances, except for V603 Aql, which is 300 pc away (Dreschel et al. 1981). Each object has roughly the same value of $d^2 F_v$ (to within a factor of 4) and thus roughly the same total luminosity in the grains – $\sim 1.5 \times 10^{32} \text{erg s}^{-1}$ at 1000 K and $\sim 6 \times 10^{31} \text{erg s}^{-2}$ at 300 K – and hence the same total mass in the grains. The actual mass depends upon their composition. For silicate grains, it is

$$M_g < 1.6 \times 10^{-7} M_\odot \text{ at } 300 \text{ K}$$

$$< 3 \times 10^{-9} M_\odot \text{ at } 1000 \text{ K},$$

independent of grain size for an approximate emission coefficient of $Q \sim 0.4 a (\mu m)$ (deduced from Draine & Mok Lee 1984).

For graphite grains this mass is:

$$M_g < 3 \times 10^{-7} M_\odot \left( \frac{a}{0.1 \mu m} \right)^{-0.25} \text{ at } 300 \text{ K}$$

$$< 7 \times 10^{-10} M_\odot \left( \frac{a}{0.1 \mu m} \right)^{-0.25} \text{ at } 1000 \text{ K}$$

for

$$Q_c = 8.5 \times 10^{-5} a^{1.25(\mu m)} T_g^{1.4},$$

again deduced from Draine & Mok Lee.
5.2 FORMATION AND LOCATION OF DUST GRAINS

Elementary considerations of dust formation show that dust grains can only form in CVs under special conditions. They cannot condense from material ejected from the system in the high-velocity winds \((V=2500 \text{ km s}^{-1}; \text{ Cordova \\& Mason 1985})\) occasionally seen in CVs. The grains would start to form far from the disc, where the condensation nuclei on to which they condense are in equilibrium with its radiation field. This condensation radius is, for silicate grains that are black on the ultraviolet (Clayton \\& Wickramasinghe 1976)

\[
R_0^2 = \frac{L}{16\pi\sigma T_\text{e}^4 Q_e(T_e, a_0)}
\]

\[
R_0 \approx 10^{11}(L/4.10^{32} \text{ erg s}^{-1})^{1/2} (T_e/1500 \text{ K})^{-2} \text{ cm}
\]

where \(L=4\times10^{32} \text{ erg s}^{-1}\) is a typical disc luminosity (Cordova \\& Mason 1984).

But to allow even small grains to condense, the density has to be high, just as it is in the dust-forming shells in novae and Wolf–Rayet stars, and so the mass loss rate must also be high. For the grains as small as \(a<0.005 \mu\text{m}\), the density of condensable material has to be, for perfectly efficient dust formation (Gehrz et al. 1980)

\[
\varrho_0 = 4a\varrho_{\text{gr}}V/\dot{b}R_0
\]

\[
= 7.5 \times 10^{-17} (a/0.005 \mu\text{m}) (V/2500 \text{ km s}^{-1})
\]

\[
\times (\dot{b}/5 \times 10^5 \text{ cm s}^{-1})^{-1} (R_0/10^{13} \text{ cm})^{-1} \text{ g cm}^{-3}
\]

which corresponds to a total mass loss rate (condensable and non-condensable material) of

\[
\dot{M} = 4\pi R_0^2 V\varrho_{\text{total}}
\]

\[
= 1.5 \times 10^{-4} (R_0/10^{13} \text{ cm}) (V/2500 \text{ km s}^{-1}) M_\odot \text{ yr}^{-1}
\]

for a solar-abundance wind. Essentially the same result applies to graphite grains.

Here, \(\dot{b}\) is the thermal velocity of the atoms, \(\sim 5\times10^5 \text{ cm s}^{-1}\) at a few thousand degrees (to which the initially hot wind will have cooled by the time it reaches \(R_0\); Drew 1985, private communication); \(\varrho_{\text{gr}}\) is the density of matter in the solid phase, \(\sim 3 \text{ g cm}^{-3}\).

Even under the generous assumptions of black absorbing grains and perfectly efficient grain formation, this is still six orders of magnitude less than this, at \(\sim 10^{-10} M_\odot \text{ yr}^{-1}\) (Drew \\& Verbunt 1984). Any grains present now in a shell must therefore have formed in a prehistoric nova explosion. The luminosity of the disc now is several orders of magnitude too small to heat them up to 300 K or more so that they can be seen at 10\(\mu\)m (if they are more than 10\(^{14}\) cm from the disc, the distance where grains in novae usually form; Clayton \\& Wickramasinghe 1976). That novae have the required luminosity has led Bode \\& Evans (1982) to propose that this may be the origin of the infrared emission seen in recent novae.

The grains form instead in the plane of the orbit, from mass lost from the red dwarf and the outer disc. Protected from the high-energy photons originating in the inner disc, the grains can form as close as \(R_0 \approx 10^{11} \text{ cm}\) from a late M dwarf \((T \sim 3000 \text{ K}, L \sim 0.005 L_\odot)\). The critical density of \(\varrho_0 \approx 3 \times 10^{-16} \text{ g cm}^{-3}\) corresponds to a total mass rate of \(\dot{M} \sim 3 \times 10^{-6} M_\odot \text{ yr}^{-1}\) at \(V = 300 \text{ km s}^{-1}\), the velocity of the solar wind. This very high mass loss rate cannot be sustained continually, for the
star loses mass on a time-scale $\tau_M$,
\[ \tau_M = \frac{M}{\dot{M}} \sim 1.3 \times 10^3 (M/0.4 \, M_\odot) \text{ yr} \]

that is two orders of magnitude higher than the Kelvin time-scale. It would be driven far out of thermal equilibrium and expand rapidly. This cannot be the case, for the red stars are at most only slightly larger than main sequence stars of similar mass (Wade 1981; Young & Schneider 1981).

The mass must be lost in flares whose recurrence time is longer than the thermal time-scale, so that the energy expended in driving them does not force the stars out of thermal equilibrium. Flares carrying away $\sim 10^{-6} - 10^{-7} M_\odot$ into an arbitrary solid angle of $\Omega \sim 0.1$ sr would have the required density at $R_0$ (for $V \sim 300 \, \text{km s}^{-1}$) and would support $\sim 10^{-9} - 10^{-10} M_\odot$ of grains, intermediate between the upper bounds presented above. Such flares would give rise to abrupt period changes of a few seconds at most, as they are thought to do in other semi-detached binaries (e.g. Batten 1973), and measurements of the eclipse timings in CVs are such that these changes cannot be ruled out (Pringle 1975).

5.3 Near-infrared emission from dust grains

Thermal emission from grains has been suggested as being the cause of the near-infrared spectral upturns reported in V603 Aql. EX Hya, SU UMa and AH Her (Frank et al. 1981; SJ). This is, however, unlikely to be the explanation. Even a massive shell ($10^{-7} M_\odot$) at 300 K is too cool to be important there: it would give rise to a $K$ magnitude of $\sim 18$ in V603 Aql, compared to 11.8 observed by SJ. Furthermore the grains cool too quickly once they have formed for enough hot grains to be sustained. For example, silicate grains follow a cooling law $T^{-1} \propto 1/\dot{Q}$, and cool to below 800 K in $10^4$ s. Thus even if the star continually lost mass at $M \sim 3 \times 10^{-6} M_\odot \text{ yr}^{-1}$, it would still only sustain $10^{-13} M_\odot$ of grains at above 800 K, which would again give rise to $K = 18$ in V603 Aql.

In all four systems, there is an alternative explanation for the near-infrared observations. SU UMa and AH Her are red in $H - K$ because optically thin emission is important in them (Section 4), V603 Aql is probably affected by variability of the source (Section 2) and the upturn in EX Hya is only at the level at $1\sigma$.

5 Conclusions

We have discussed the origin of the infrared light of cataclysmic variable stars. Our principal conclusions are:

(i) $JHK$ photometry is not a good probe of the red dwarfs, even in those long-period systems where they are seen in the visual. Such observations give only the maximum proportion of the light that they supply, and therefore a lower limit to the distance of the system.

(ii) The infrared light of the discs in quiescent systems comes from opaque gas and from the optically thin plasma that gives rise to $B$ emission lines. The proportion of light supplied by each differs widely from system to system.

(iii) 10-$\mu$m observations show that the total mass of dust grains present in CVs is $<10^{-7} M_\odot$ at 300 K and $<7 \times 10^{-10} M_\odot$ at 1000 K. Such grains as are present in a CV most likely condense in the plane of the orbit, out of matter lost from flares on the surface of the red dwarf.

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References


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Origin of IR light from CVs


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Appendix: Computation of steady state discs

A steady state disc has a temperature gradient of

\[
T(R) = 36.510 \left( \frac{\dot{M}}{10^{10} M_\odot \text{ yr}^{-1}} \right)^{1/4} \left( \frac{M_{\text{WD}}}{M_\odot} \right)^{1/4} \left( \frac{R_{\text{WD}}}{10^9 \text{ cm}} \right)^{-3/4} \left( \frac{R}{R_{\text{WD}}} \right)^{-3/4} \left( 1 - \left( \frac{R}{R_{\text{WD}}} \right)^{-1/2} \right)^{1/4}
\]

Discs having this temperature gradient were computed for the mass transfer rates and disc radii thought to be typical of CVs: \( \dot{M} \approx 10^{-9} - 10^{-11} M_\odot \text{ yr}^{-1} \) (Paczynski 1981; Verbunt 1984); the radii of the discs are tidally limited to \( \sim 70 \) per cent of the Roche lobes of the white dwarfs; of the systems considered here, \( R_d \) may be as small as \( 1 - 2 \times 10^{10} \text{ cm} \) in the shortest period and \( 5 - 6 \times 10^{10} \text{ cm} \) in the longest period systems.

Each disc was divided into annuli \( 10^6 \text{ cm} \) wide, each considered to have a constant temperature and to act as a blackbody. The flux ratios at two frequencies \( \nu_1 \) and \( \nu_2 \) are given simply by

\[
\frac{F_{\nu_1}}{F_{\nu_2}} = \frac{\sum_i B_{\nu_1}(T_i) A_i}{\sum_i B_{\nu_2}(T_i) A_i}
\]

where \( B_\nu \) is the Planck function, and \( T_i \) is the temperature of the \( i \)th annulus of area \( A_i \).

Discs are in reality intermediate between blackbodies and stellar atmospheres. Infrared model atmospheres have not been computed over the wide range of temperatures considered here, but the blackbody approximation only introduces small errors into the flux ratios even for the coolest discs, where much of the light comes from material hotter than 2500 and 6000 K, when the H\(^-\) opacity is important. Numerical experiments with the model atmospheres of Mould (1976) indicates that even at \( M \approx 10^{-11} M_\odot \text{ yr}^{-1} \) and \( R_d \approx 5 \times 10^{10} \text{ cm} \), the disc is redder in \( H/K \) by only \( \sim 10 \) per cent and bluer in \( J/K \) by \( \sim 5 \) per cent.

The \( K \) magnitude of a disc at inclination \( i \) is given by

\[
K = 2.5 \left[ \log_{10} \left( \sum_i B_\nu(T_i) A_i \right) \cos^2 i \right] - K_0,
\]

\( K_0 = 617 \text{ mJy} \).
Fig. A1 gives the $K$ magnitudes of face-on discs for an arbitrary distance of $\sim 150$ pc, which can be simply scaled to any distance or inclination, such as those presented in Table 4. At small radii, the discs become rapidly brighter as they become bigger. This increase gradually falls off, because the emissivity of the cool opaque matter in the exterior is lower than that of the hot material in the interior.

The blackbody approximation systematically underestimates the $K$ magnitudes by up to $\sim 0.1$ mag and, as described in Section 4.1, arises principally because the $\mathrm{H}^-$ opacity, important below 6000 K, is a minimum near 1.6$\mu$m. A stellar atmosphere at $4000 < T < 6000$ is 20–30 per cent brighter than a blackbody at the same temperature (Mould 1976): such material produces 30 per cent of the total light in the lower mass transfer rates considered here.

The same uncertainties apply to all inclinations, for limb darkening it changes the emergent flux by only a few per cent in the infrared, as shown by the quadratic coefficients of Rucinski & Wade (1985) for $T > 5500$ K and the linear ones of Carbon & Gingerich (1969) for $T < 5500$ K.