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Evidence from infrared observations of circumstellar matter around chromospherically active binaries★

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ABSTRACT

We analyse a sample of 12 RS CVn-type systems for which accurate photometry exists, extending from optical to near-infrared and even to *IRAS* bandpasses in some cases. We reconstruct the energy distribution expected from the binaries, taking into account the radii and spectral types of the components, and we compare them with the observed fluxes. In five cases, an infrared excess (in the range 0.4–1.2 mag) is clearly present. Assuming that this is due to an absorbing shell, we estimate the required mass of dust, which turns out to be in the range 10^{-11}–$10^{-14}\ M_{\odot}$, corresponding to total shell masses (including gas) in the range 10^{-9}–$10^{-12}\ M_{\odot}$. We suggest that the circumstellar envelopes are built by mass loss in the form of stellar winds driven by magnetic activity.

Key words: stars: activity – binaries: close – binaries: eclipsing – circumstellar matter – infrared: stars.

1 INTRODUCTION

Among chromospherically active late-type stars, an important place is occupied by spectroscopic and photometric binary systems, such as RS CVn-type variables (Hall 1976; Rodonò 1986). As a result of extreme surface activity, signatures of the complex characteristics of these stars at different levels (corona, chromosphere, photosphere) can be recorded in any wavelength region (see, for example, Walter, Charles & Bowyer 1978; Walter & Bowyer 1981; Rodonò 1981, 1983; Catalano 1983; Mutel & Lestrade 1985; Mutel 1986; Busso, Scaltriti & Cellino 1986).

On the other hand, these complex and variable phenomena occurring in the external layers constitute a major difficulty for the clear and precise classification of RS CVn stars, because colours and spectra are affected either by contamination from spots and plages or by blending problems resulting from the similarity of the spectral types of the two components (Berriman et al. 1983). These facts ultimately influence our knowledge of the evolutionary status of these objects and our understanding of the general characteristics of the group (see e.g. Montesinos, Gimenez & Fernandez-Figueroa 1988).

In this respect, one of the most remarkable properties sometimes attributed to RS CVn binaries is the evidence of infrared (IR) excesses, which are related to the presence of diffuse circumstellar matter. The existence of this non-stellar component in the flux distribution of active binaries has been the object of controversy in recent years. Some studies discarded this possibility (Antonopoulou 1983; Berriman et al. 1983; Antonopoulou & Williams 1980, 1984), while others argued in favour of it (Hall, Montle & Atkins 1975; Milone 1976; Verma et al. 1983; Verma, Iyengar & Rengarajan 1987; Lazaro 1988). A review of the IR properties of RS CVn stars can be found in Scaltriti (1990). As has been clearly shown by Berriman et al. (1983), at IR wavelengths the observational effects of surface activity are strongly reduced or even completely cancelled. Hence the unambiguous detection of an IR excess would be a reliable indication of mass loss, being relatively free from contamination by photospheric perturbations. Conversely, when an IR excess is not present, the accurate reconstruction of the energy distribution from visible light to far-IR is a powerful tool for classification, and hence also for an understanding of the precise position of the binary components along their

★Based on observations collected at the T.IR.GO. telescope of the Italian Consiglio Nazionale delle Ricerche Gornergrat, Switzerland, and at the European Southern Observatory, La Silla, Chile.

evolutionary path above the main sequence of the Hertzsprung–Russell diagram.

The observations presented and analysed here are part of an ongoing effort aimed at a comprehensive study of active binaries at optical and IR wavelengths, in order to improve our knowledge of their evolutionary status and mass-loss phenomena. IR excesses have been detected for some RS CVn systems during previous stages of this work, either from near-IR photometry (Busso et al. 1987, hereafter Paper I) or from the data of the *IRAS* Point Source Catalog (PSC) (Busso et al. 1988).

Here, new *UBVRI* and near-IR photometry is presented for 10 further systems. These data are shown and briefly commented upon in Section 2. In Section 3 the main characteristics of our sources, as well as comparisons with previously published data, are discussed. In Section 4 we then try to fit the observed flux distributions with combinations of purely stellar spectra, following the procedure described in Paper I. For the sources for which this fit is not possible, and for which there is evidence of an IR excess of non-stellar origin, we try to interpret this excess by assuming the presence of a thin shell of absorbing material. This type of analysis is also performed for two further binaries (II Peg and CF Tuc), for which the energy distributions are taken from recently published simultaneous optical and near-IR observations (Lazaro, Arevalo & Fuensalida 1987; Lazaro 1988; Busso et al. 1988; Byrne et al. 1989).

Finally, Section 5 summarizes the main conclusions and briefly discusses the possibility of interpreting our results in the light of the evolutionary status of the sources.

2 THE OBSERVATIONS

The system of filters used to perform broad-band photometry at optical and near-IR wavelengths has been described by Busso et al. (1988), who have also reported zero-magnitude fluxes. That photometric system includes standard (Johnson) *UBV* filters, plus Cousins *R* and *I* passbands (Bessell 1979, 1983) and the *JHKL* (3.8 μm) system calibrated by Koornneef (1983a,b).

The near-IR observations were performed at the Italian T.IR.GO. telescope at Gornergrat (Zermatt, Switzerland), whereas the *UBVRI* data were obtained at the Astronomical Observatory of Torino and at the European Southern Observatory (La Silla, Chile), using at both sites a photometer equipped with a cooled RCA 31034 photomultiplier.

In both the optical and IR bands various measurements were made, distributed along the light curves of the sources. With the exceptions of the sources DK Dra and DH Leo, this allowed us to obtain contemporary (or at least phase-matched) optical and near-IR observations, thus avoiding possible systematic errors related to the variability in time of the sources. The spectral energy distribution can then be estimated using data near maximum emission, i.e. for conditions during which the photospheric disturbances due to dark spots are minimal. This caution is a posteriori found to be not strictly necessary at IR wavelengths, where the light curves are flatter; however, this is not a priori guaranteed, and is indeed not valid in some cases [see for example UX Ari (Hall et al. 1975)]. Hence, in order to be sure about the reliability of the data, care in the phase-matching of the observations is essential.

For the sources CQ Aur, RZ Cnc and RW UMa, we also made observations at the bottom of the primary minimum where, due to the total eclipse of the hot component, only the cool star is seen. This allows us to determine unambiguously the spectral type of the secondary component, which in its turn becomes a useful constraint for the reconstruction of the flux distribution of the whole binary.

In Table 1 the behaviour of our sources at IR wavelengths is summarized, using both our photometric observations and data from the *IRAS* PSC, Version II (see Busso et al. 1988 for an analysis of *IRAS* measurements). In the table we also indicate the site and epoch at which the data were obtained; each near-IR measurement derives from the average of a number of single observations in the same filter. We have also included the data on the two sources II Peg and CF Tuc, taken from the previously quoted papers by Lazaro et al. (1987), Busso et al. (1988) and Byrne et al. (1989).

Regarding the accuracy of the data, we shall briefly discuss each source separately in Section 3. As a general rule, however, we remember that, as discussed in Paper I and Busso et al. (1988), the calibration of the photometric system in the near-IR has an intrinsic uncertainty of several hundredths of a magnitude, while observational errors on individual measurements on good nights are smaller (at most 0.05 mag). Taking into account the possible residual presence of a wave distortion, in the infrared we generally estimate an average uncertainty of the order of 0.08–0.1 mag for the binaries for which synchronization between optical and near-IR observations was possible; the uncertainty is higher for the other cases (DK Dra and DH Leo). In *UBVRI* bands, the statistical accuracy of each observation is of the order of 0.02 mag, although possible systematic effects resulting from the calibration of the photometric system, small displacements of the effective wavelengths of filters for different spectral types (Bessell 1979) and extinction can increase it to roughly 0.05 mag (see also the discussion in Section 5). The further uncertainty arising from the wave-like distortion is summarized in Section 3, where the general properties of each source are discussed.

Table 2 shows the data at optical wavelengths that we use to supplement our IR observations in order to derive the spectral distributions of the fluxes. In this table also, information on the epoch and site at which the observations were obtained is presented. Again, information on II Peg and CF Tuc from the quoted references is included. The table also gives the estimated value (and the corresponding error, ε) of $k^2(=r_2^2/r_1^2)$, where r_1 and r_2 are the radii of the larger and smaller stellar components, respectively. A 'C' in the last column of the table indicates that the optical and IR observations of that source are contemporary.

3 OBSERVED CHARACTERISTICS OF THE SOURCES

In the following, we describe some of the features of the sample stars, paying attention to those that are relevant to our study. For more information, a very useful general reference is the catalogue by Strassmeier et al. (1988).

(i) **CQ Aurigae.** The spectral types suggested by Popper (1980) are G2 and early K; the rather small radius of the hot component suggests that it is near the main sequence, whereas the possibility that the cool companion is larger is not excluded (Cerruti-Sola et al. 1980). Our measurements, made at the bottom of primary minimum in the optical and near-IR, are in agreement with these suggestions, giving a best-fitting classification of K3V–IV for the cool component, with only a few hundredths of a magnitude of uncertainty. Our values of $B-V$ and $U-B$ (0.88 and 0.38) are comparable with those given by O'Connell (1978) (0.86 and 0.41) and by Popper & Dumont (1977) (0.87 and 0.41); we may infer that the colour curves are very stable in time and rather flat. The distortion wave during the period of our observations was about 0.04 mag around the mean level. For the above reasons, we estimate that the uncertainty in the colours should be limited to a few hundredths of a magnitude in the optical and to less than 0.08 mag in the IR.

(ii) **SS Camelopardalis.** Arnold et al. (1979) reported spectral types of F5V–IV+K0IV–III. The colours appear to be very stable [with less than 0.03-mag difference between our values and those by Popper & Dumont (1977) and Arnold et al. (1979)]. During the period of our observations the distortion wave was also small ($\leq$0.04 mag in V), so we can assume an uncertainty of about 0.05 mag in *UBV* (we have no *R* and *I* observations) and of about 0.1 mag in the infrared.

(iii) **RZ Cancri.** Popper (1976) suggested spectral types of K1III+K3–4III. At the photospheric level, the amplitude of the distortion wave reaches 0.05 mag at most (Hall 1980); despite a rather strong ellipticity effect [$A_2=-0.08$, and average value from *UBV* observations by Broglia & Conconi (1973) and Popper (1976)], the colour curves are flat and our $B-V$ and $U-B$ colours agree with the mean values given by Broglia & Conconi (1973) and by Popper (1976) within 0.06 mag. Hence the uncertainty in the distribution of the colour indices should not be greater than 0.06–0.08 mag throughout the spectral range considered. Within this error, our observations at the bottom of primary minimum in the near-IR are compatible with the energy distribution of a K4III–IV secondary component.

(iv) **WY Cancri.** Spectral types are uncertain: Awadalla & Budding (1979) suggested a G5 dwarf with a very red companion. The distortion wave is very small ($\leq$0.02 mag: see Milano 1981). There is a close agreement (within 0.03 mag) between our $B-V$ colour and those given by Chambliss (1975) and Popper & Dumont (1977), whereas a somewhat higher dispersion (0.06 mag) exists in the $U-B$ values. In the short time interval during which we made both optical and near-IR observations, the precision should be essentially limited by the accuracy of the photometric system.

(v) **DK Draconis.** The spectral type of both components is K0III (Fekel, Moffett & Henry 1986). The distortion wave is very large (0.28 mag: see Eaton et al. 1982) but the colour curve is flat, thus reducing the uncertainty in the optical filters. We were not able to achieve simultaneity between the optical and IR photometry, so that in this case the error bars could be a priori large; as in the case of DH Leo, however, the fit that we achieve with stellar energy distributions is very good up to rather long wavelengths, indicating that the colour curves are probably also very flat in the infrared.

(vi) **RZ Eridani.** Sarma (1986) suggests spectral types of F6V+K2IV. The distortion wave is small ($\leq$0.04 mag: see Caton 1986), and a comparison of our $B-V$ and $U-B$ values (0.63 and 0.30) with those by Popper & Dumont (1977) (0.66 and 0.36) shows a dispersion of less than 0.06 over several years. Hence the uncertainty in the colours should not exceed 0.06–0.08 mag throughout the energy distribution.

(vii) **GK Hydrae.** Spectral types in the range F8–G0 and G7–8IV have been suggested (Hall 1980; Popper 1980). Our colours agree with those by Popper (1980) within 0.03 mag,

Table 1. Infrared and *IRAS* observations.

Star	J	H	K	L	M	[12]	[25]	Epoch Month – Year/Int. JD 2440000+	Observatory or Source
CQ Aur	7.23	6.64	6.66	6.51				Feb-Mar 1987/6835-67	TIRGO
* CQ Aur	7.50	6.87	6.74	6.52				January 1987/6820	TIRGO
SS Cam	8.37	7.84	7.84					March 1987/6863-7	TIRGO
RZ Cnc	6.55	5.88	5.81	5.77				Jan 86 - Mar 87/6447-867	TIRGO
* RZ Cnc	7.32	6.60	6.42	6.30				January 1987/6816	TIRGO
WY Cnc	7.89	7.49	7.43	7.42				Jan-Mar 1986/6451-98	TIRGO
DK Dra	4.41	3.94	3.76	3.42		3.35	3.34	Jan-Apr 86/6448-525	TIRGO+IRAS
RZ Eri	6.32	5.80	5.67	5.53				January 1987/6820-1	TIRGO
GK Hya	7.91	7.47	7.47	7.40				March 1987/6835-67	TIRGO
DH Leo	5.98	5.57	5.37	5.37				January 1986/6448-57	TIRGO
AR Mon	6.63	6.00	5.98	5.86				March 1987/6863	TIRGO
II Peg	5.39	4.78	4.61	4.43	4.45	4.05		August-September 1984	(1)
CF Tuc	5.99	5.46	5.33	5.20		5.13		December 1984/6063-8	(2)
RW UMa	8.61	8.21	8.10	7.95				Jan 86- Feb 87/6448-851	TIRGO
* RW UMa	9.18	8.82	8.62					February 1987/6827	TIRGO

References: (1) Lazaro et al. (1987); (2) Busso et al. (1988). An asterisk (*) means that the star was observed at the bottom of primary minimum.

Table 2. *UBVRI* observations and information on k^2.

Star	U	B	V	R	I	Epoch Month – Year/Int. JD 2440000+	Observatory or Source	k^2	ε	#
CQ Aur	10.31	9.93	9.05	8.56	8.02	Jan-Apr 1987/6766-881	ESO+TURIN	0.05	0.01	C
* CQ Aur	11.24	10.51	9.43	8.85	8.26	December 1986/6767-88	TURIN	-		
SS Cam	11.17	10.88	10.11			Dec 86-Feb 87/6766-828	TURIN	0.07	0.01	C
RZ Cnc	11.06	10.00	8.79	7.89	7.19	Dec 86-Feb 87/6767-827	TURIN	0.70	0.11	C
WY Cnc	10.25	10.11	9.40	8.85	8.43	December 1986/6769-92	TURIN	0.14	0.02	C
DK Dra		7.26	6.14	5.25	4.69	June 1980	(1)	1.00	0.10	
RZ Eri	8.71	8.41	7.78	7.39	6.86	Dec 86-Mar 87/6767-883	ESO+TURIN	0.16	0.03	C
GK Hya	10.19	10.06	9.38			Dec 86-Mar 87/6767-82	ESO+TURIN	0.22	0.01	C
DH Leo	9.27	8.76	7.89	7.32	6.81	Dec 86-Mar 87/6769-882	ESO+TURIN	0.48	0.05	
AR Mon	10.39	9.73	8.70	8.08	7.51	Dec 86-Mar 87/6767-883	ESO+TURIN	0.58	0.16	C
II Peg	9.16	8.47	7.47	6.86	6.22	August-September 1984	(2)	-		C
CF Tuc	8.37	8.21	7.50	7.06	6.60	December 1984/6058-62	(3)	0.27	0.04	C
RW UMa	10.83	10.75	10.11			Dec 86-Feb 87/6767-828	TURIN	0.28	0.02	C
* RW UMa	13.35	12.71	11.65	10.86	10.29	December 1986/6768	TURIN	-		

References: (1) Fekel et al. (1986); (2) Nations & Ramsey (1981); Rondonò et al. (1986); Byrne et al. (1989); (3) Busso et al. (1988).
An asterisk (*) means that the star was observed at the bottom of primary minimum.
For the stars CQ Aur (minimum), RZ Cnc, WY Cnc and DK Dra, *R* and *I* magnitudes were obtained in the Johnson system and the $V-R$ and $V-I$ colours have been transformed according to the formulae given by Bessell (1979, 1983).
The $U-B$ colour of DK Dra is from Strassmeier et al. (1988).
A 'C' in the last column indicates that *UBVRIJHKLM* are contemporary observations; it means that optical and IR runs have been carried out within few weeks during the same season.
The following list gives information on the sources of the adopted k^2.
CQ Aur: Cerruti-Sola et al. (1980); SS Cam: Arnold et al. (1979); RZ Cnc: Popper (1976); WY Cnc: the value is the average of the radii given by Awadalla & Budding (1979), Budding & Zeilik (1987) and Naftilan (1987); DK Dra: Bopp et al. (1979); RZ Eri: Popper (1988); GK Hya: Sarma (1986); DH Leo: Barden (1985); AR Mon: Popper (1976); CF Tuc: Budding & McLaughlin (1987); RW UMa: Popper & Dumont (1977).

and appear to be constant throughout the light curve; the amplitude of the distortion wave attains some hundredths of a magnitude (Caton 1986). Because of this colour stability, the errors are rather small (less than 0.06 mag and about 0.1 mag at optical and near-IR wavelengths, respectively).

(viii) **DH Leonis.** This is a triple spectroscopic system with no eclipses (Barden et al. 1986). Indications for the spectral types are K0V+late-K or early-M secondary and distant, red companion (Barden 1984). This system is known to have a rather large-amplitude distortion wave (about 0.08 mag). All of our colours differ from published ones (Eggen 1978, 1984; Barden et al. 1986) by less than 0.08 mag, so we can estimate that the uncertainty is lower than about 0.1 mag in the optical filters. Because it was not possible to achieve simultaneity with IR photometry, the error in the near-IR colours could in principle be higher (up to 0.15 mag); we find, however, that the colour distribution can be fitted quite well (see Section 4), so maybe in this case the uncertainty has been overestimated.

(ix) **AR Monocerotis.** The spectral types suggested by Popper (1976) are G8+K2–3, with radii sufficiently large to justify the luminosity class III. No clear indication of a distortion wave is available. The maximum of the light curve shows a large ellipticity effect, with $A_2=-0.1$ (average value from the *UBV* observations by Popper 1976). The agreement of our $B-V$ and $U-B$ values (1.03 and 0.66) with those by Popper (1976) (1.07 and 0.72) is within 0.06 mag. Taking into account the lack of data on the wave, we will assume a cautious value for the uncertainty, in the range 0.08–0.1 mag, in the optical filters also.

(x) **II Pegasi.** This is a very active and well-studied binary. Recently, studies of the UV, optical and IR fluxes of this binary (Lazaro et al. 1987; Doyle et al. 1988, 1989; Lazaro 1988) have pointed out the concentration of spotted regions in a single active hemisphere. From the literature, it was possible to extract a set of colours taken in the same period and extending from the *U* to *M* bands. Because these colours were not observed with the same filters as used for the other sources analysed here, and because the distortion wave is large (about 0.1 mag), we shall assume a cautious value for the uncertainty (0.1 mag in the optical filters, 0.12 mag in the infrared). A nearly complete polarization curve (in the *V* band) has been obtained by Koch et al. (1991). It shows a possible phase-lock in the linear polarization; its dependence on wavelength indicates small dust particles as a possible cause, thus increasing our interest in analysing the emission from this star.

(xi) **CF Tucanae.** Our coordinated observations from *U* to *K* have already been presented by Busso et al. (1988). They show a very small distortion wave (≤ 0.04 mag) and no colour variation along the light curve, so the error should be limited to the minimum allowed by the system of filters in use. The existence of an IR excess was ascertained by Busso et al. (1988), so we have included this source in the analysis of Section 4 in order to look for the presence of circumstellar matter.

(xii) **RW Ursae Majoris.** We succeeded in obtaining observations at the bottom of primary minimum in *UBVRIJHK*, finding colours in agreement with a mid-K spectrum (class V or IV) for the red component (K4V–IV is our best fit). This is somewhat redder than previous observations (F8–9V–IV + K1IV: see Popper 1980 and Hall 1976). The wave amplitude was about 0.05 mag during our observations, and the colours agree with those of Popper & Dumont (1977) within 0.04 mag. Small errors in the flux distribution are hence expected, typically at the level of accuracy of the system of filters.

4 ENERGY DISTRIBUTION AND INFRARED EXCESSES

As done during previous stages of this work (see Paper I and Busso et al. 1988), we try here to reproduce the observed colour distributions using *typical* colour sequences, derived from superpositions of normal stellar components, weighted by the values of k^2 reported in Table 2.

For this purpose, we have supplemented the standard colour distributions of normal stars used in Paper I (see references therein) with the detailed sequences published by Bell & Gustafsson (1989). A very good agreement between the two sets of data is found for classes V, IV and III. Moreover, from the accurate calibration of the spectral distributions as functions of $T_{\rm eff}$ and log g, carried out by Bell & Gustafsson, we have also derived standard colours for a class intermediate between main-sequence stars and subgiants (class V–IV). The use of *normal* stellar spectra to fit the energy distributions of RS CVn stars may appear to be a critical point, because of their surface activity and hence spot coverage. However, it has been shown by Berriman et al. (1983) that, even when spots cover a huge area, this has only minor effects on colours, especially at IR wavelengths.

Once the colours of standard spectral types have been derived for the various luminosity classes, they can be used to estimate the total flux expected from a particular binary source. Let $F_1(\lambda)$ and $F_2(\lambda)$ be the intrinsic flux distributions corresponding to the spectral types and luminosity classes of the large and small components, respectively, of a binary system. The total flux at a distance D is then

$$f(\lambda)=F(\lambda)/D^2=\frac{r_1^2}{D^2}[F_1(\lambda)+k^2F_2(\lambda)], \qquad (1)$$

where k is the ratio of the radii. From the flux of equation (1), the integrated colours of the binary can be computed.

Since the spectral classification of RS CVn components is uncertain, the total flux $f(\lambda)$ has to be evaluated for all possible combinations of *normal* spectral types, looking for the pairs that allow the best fit to the observations. In practice, for our sources we spanned the range from late A to early M, for the above-mentioned luminosity classes III, IV, IV–V and V.

4.1 Systems for which no infrared excess is found

The application of the above procedure yields the conclusion that, for seven out of the 12 sources studied, the observed colour distributions can be fitted, within the error bars discussed in Section 3, by purely stellar components. For these seven systems Table 3 shows the 'best-fitting' sequences with their uncertainties as derived from the errors on k^2 (see the column labelled ε in Table 2), compared to the observed colours. We must emphasize that the fit is always very good; in fact, for sources like DK Dra and DH Leo, for which simultaneous observations in the various filters were not available, it is even better than one would a priori expect. In the cases of CQ Aur, RZ Cnc and RW UMa, our data from the bottom of primary minimum fully confirm the findings of Table 3, since the secondary components suggested in the table match the colours observed at the minimum, within the experimental uncertainty. We also note that DH Leo is fitted with a three-component combination, in accordance with indications that the source is a triple star (Barden et al. 1986). In Table 3 we also give the 'improved' spectral combination for the binaries in which no IR excess has been detected.

4.2 Systems for which an infrared excess is found

For the remaining five binaries (SS Cam, WY Cnc, GK Hya, II Peg and CF Tuc), fits based only on stellar energy distributions appear to be impossible: no combination of spectral types with luminosity classes from III to V can reproduce the observed colours within the errors indicated in Section 3. In the absence of a better criterion, Table 4 gives the spectral combinations that are found to minimize the discrepancy. They always imply an infrared excess of non-stellar origin, hence requiring the presence of some sort of circumstellar material. In this respect, for II Peg our analysis confirms the findings of Lazaro (1988). In Table 4 we give the maximum 'measured' excess found in the analysis, and the corresponding wavelength at which it occurred.

5 ON THE POSSIBLE ORIGIN OF THE EXCESSES

Since the sample stars are active and should therefore possess hot coronae (see for example AR Lac: Walter, Gibson & Basri 1983) and hence stellar winds, one could presume that the source of IR excess is free–free emission from ionized plasmas. A homogeneous, isothermal, ionized wind, however, is expected to produce an IR spectrum of the form $S(\nu)\simeq\nu^{-0.6}$ (Wright & Barlow 1975), very different from any of the observed energy distributions or excesses. Moreover, even the possible existence of inhomogeneous structures, such as blobs and clumps in the presence of high mass-loss rates, has been shown to generate distortions in the spectrum only in the far-IR or radio regions (Lamers & Waters 1984). We can conclude that free–free emission is not a suitable explanation for the observed excesses.

We have also examined interstellar extinction as a possible source of a wavelength-dependent IR excess. In general, one knows that RS CVn stars are nearby objects (Strassmeier et al. 1988), and that the Sun is at the centre of a clear area with negligible reddening (Eggen 1963; FitzGerald 1968), the

Table 3. 'Best-fitting' spectral types for the systems for which no IR excess was detected.

	CQ AUR		RZ CNC		DK DRA	
Colour	Obs. values	K3V-IV+F2V	Obs. values	K4III+K1III	Obs. values	K3III+K0III
U-B	0.38±0.05	0.52±0.09	1.06±0.08	1.20±0.04	1.00±0.10	1.03±0.02
B-V	0.88±0.05	0.90±0.07	1.21±0.05	1.20±0.02	1.12±0.10	1.12±0.01
V-R	0.49±0.05	0.50±0.02	0.62±0.05	0.65±0.01	0.62±0.10	0.60±0.01
V-I	1.03±0.05	0.97±0.04	1.25±0.05	1.24±0.03	1.13±0.10	1.13±0.01
V-J	1.82±0.08	1.73±0.06	2.24±0.10	2.10±0.04	1.73±0.15	1.89±0.02
V-H	2.41±0.08	2.28±0.07	2.91±0.10	2.74±0.06	2.20±0.15	2.46±0.03
V-K	2.39±0.08	2.46±0.08	2.98±0.10	2.89±0.06	2.38±0.15	2.61±0.03
V-L	2.54±0.08	2.45±0.08	3.02±0.10	2.98±0.06	2.72±0.15	2.70±0.03
V-[12]					2.79±0.15	2.76±0.02
V-[25]					2.80±0.15	2.82±0.02

	RW UMA		RZ ERI		AR MON	
Colour	Obs. values	K4V-IV+F5V	Obs. values	K3IV+F2V	Obs. values	G7III+K4III
U-B	0.08±0.08	0.18±0.03	0.30±0.05	0.27±0.07	0.66±0.08	0.83±0.06
B-V	0.64±0.05	0.66±0.02	0.63±0.05	0.72±0.09	1.03±0.08	1.05±0.04
V-R			0.39±0.05	0.41±0.04	0.61±0.08	0.60±0.02
V-I			0.92±0.05	0.83±0.06	1.19±0.08	1.15±0.04
V-J	1.50±0.08	1.46±0.04	1.46±0.08	1.50±0.11	2.07±0.10	1.96±0.07
V-H	1.90±0.08	1.96±0.04	1.98±0.08	2.00±0.13	2.70±0.10	2.57±0.09
V-K	2.01±0.08	2.09±0.05	2.11±0.08	2.21±0.14	2.72±0.10	2.72±0.09
V-L	2.16±0.08	2.14±0.06	2.25±0.10	2.18±0.14	3.84±0.10	2.80±0.10

	DH LEO	
Colour	Obs. values	K2V+M2V+M2V
U-B	0.46±0.10	0.70±0.03
B-V	0.87±0.10	0.92±0.02
V-R	0.57±0.10	0.55±0.02
V-I	1.08±0.10	1.04±0.02
V-J	1.91±0.15	1.83±0.04
V-H	2.32±0.15	2.24±0.02
V-K	2.52±0.15	2.54±0.02
V-L	2.52±0.15	2.62±0.03

Table 4. Suggested spectral types, physical and geometrical parameters of the shell and the value of the maximum 'measured' IR excess (and corresponding wavelength) for SS Cam, WY Cnc, GK Hya, II Peg and CF Tuc.

Star	Suggested spectral types	D/r_1	T(°K)	$\tau_{10\mu m}$	$M_d/M_\odot$	Maximum IR excess and corresponding λ
SS Cam	G8IV+F2V-IV	60	1600	0.005	$1.63\ 10^{-11}$	0.73^m - H
WY Cnc	G5V+K4V-IV	40	1500	0.005	$2.94\ 10^{-12}$	0.37^m - H
GK Hya	G3IV+F8V	55	1600	0.0045	$1.03\ 10^{-11}$	0.57^m - H
II Peg	K0V-IV	60	1750	0.004	$3.99\ 10^{-12}$	1.17^m - [12]
CF Tuc	G5V+K5V	35	1700	0.004	$5.60\ 10^{-14}$	0.51^m - L

radius of which is between 100 and 200 pc. This is well confirmed by CQ Aur and RZ Eri (with distances of 200 and 150 pc, respectively), whose colours at primary minimum (where only the cool star is visible) fit our spectral classification very well, without indications of errors (from extinction) larger than the uncertainty that we have adopted. Among the analysed sources, three are at larger distances and could hence be affected by interstellar extinction with colour excesses of greater than few hundredths of a magnitude: they are RZ Cnc, AR Mon and SS Cam. The first two of these do not show IR excesses; this means that the possible effects of interstellar reddening are within the limits of the estimated uncertainty (0.08 and 0.10 mag, respectively). Since for SS Cam we claim that the excess exists, we have repeated the fits for this source using the dereddened colours, assuming a reddening of $E(B-V)=0.07$ according to the model by Knude (1979), who infers a value of $E(b-y)$ (in the Strömgren filters) of about 0.02 mag $(100\ \text{pc})^{-1}$. We recognize that the problem is not changed, since no spectral combination can reproduce the whole energy distribution. Considering the fact that optical colours are surely more reliable than IR ones, we prefer solutions that correctly fit the photosphere in the optical range; they invariably imply an IR excess. Moreover, the largest IR excess we find (more than 1 mag) corresponds to II Peg, a source whose distance is only 29 pc and for which the standard extinction law would give colour variations of less than 0.01 mag in the optical bands and 0.02–0.03 mag in the infrared. We therefore conclude that interstellar extinction cannot account for the detected IR excesses.

We have therefore tried to explain the excesses using the same technique adopted in Paper I, i.e. by supposing that, at a distance D from the binary, a spherical shell of absorbing material at temperature T is present, the effects of which on the stellar flux are described by the function $\tau(\lambda)$, the so-called 'optical depth'. Let us assume that the main contributors to the extinction (absorption plus scattering) are dust grains having an effective cross-section $C_\lambda = GQ_{\text{ext},\lambda}$, where $G = \pi a^2$ is the geometrical cross-section and $Q_{\text{ext},\lambda}$ is the extinction coefficient (see e.g. Schaifers & Voigt 1982a). Regarding the absorption and scattering properties of dust grains, Jones & Merrill (1976) computed and tabulated Q_{ext} as a function of λ for three different types of dust. Here we have made use of their 'dirty silicates' model.

For a spherical shell of thickness ΔD at a distance D from the stellar source, one has

$$\tau_\lambda = \int_D^{D+\Delta D} NC_\lambda \, dz \simeq \langle N \rangle \pi a^2 Q_{\text{ext},\lambda} \int_D^{D+\Delta D} dz \simeq \frac{M_d a^2 Q_{\text{ext},\lambda}}{4 m_g D^2},$$

where $\langle N \rangle$ is the average number density of dust grains having radius a, M_d is the total mass of dust and m_g is the mass of a single grain. We assume a typical grain density of 3 g cm^{-3}, and $a = 0.1$ μm, $Q_{\text{ext}}(10\ \mu\text{m}) = 0.0908$ (see Jones & Merrill 1976). Hence one has $m_g \simeq 1.26 \times 10^{-14}$ g and

$$M_d/M_\odot = 1.35 \times 10^{-14} (D/R_\odot)^2 \tau_{10\ \mu\text{m}}. \qquad (2)$$

It should be noted that Jones & Merrill (1976) reported both the *total* extinction and the scattering term resulting from partial reflection along the line of sight of radiation emitted in other directions (see their table 1). The last term vanishes for a thin spherical shell, because of symmetry (Goldsmith et al. 1987). Hence the extinction coefficient Q_{ext} reduces to the absorption coefficient Q_{abs}. In this approximate treatment, we can further simplify our geometry by saying that the shell is equivalent to two planar sheets of dust, one in front of the star and the other behind it. It is easy to show that the emergent flux $g(\lambda)$ is then

$$g(\lambda) = \frac{F(\lambda)}{D^2} \exp[-\tau_{\text{abs}}(\lambda)] + B(\lambda, T)\{1 - \exp[-2\tau_{\text{abs}}(\lambda)]\}, \qquad (3)$$

where $B(\lambda, T)$ is the blackbody radiation from the circumstellar material. Here thermodynamic equilibrium is assumed for the shell emission. In case of a full spherical shell, the second term of $g(\lambda)$ would instead become

$$4B(\lambda, T)\{1 - \exp[-\tau_{\text{abs}}(\lambda)]\}.$$

Probably the best geometry to use is that of a toroid, since magnetic activity is expected to evacuate the polar regions. For our purposes, however, equation (3) is sufficient; in any case, it can be shown that the uncertainty arising from the geometry is limited to a factor of 2 or less. This results in an error on the dust temperature of a factor of $(2)^{1/4} \simeq 1.2$, which is always well inside the general uncertainties of our simple, semi-quantitative treatment. Thus we can try to fit the emergent energy distributions by adjusting the three parameters $\tau_{\text{abs}}(10\ \mu\text{m})$, T and D.

Although the approximation described above is a simple one, it is noticeable that it suffices to obtain a good reproduction of the observed data using reasonable combinations of the three parameters. Table 4 summarizes the values of these parameters in the various cases, and gives estimates for the mass of dust to be assumed in the circumstellar envelopes, in order to get the best fits to the observed data. These fits are

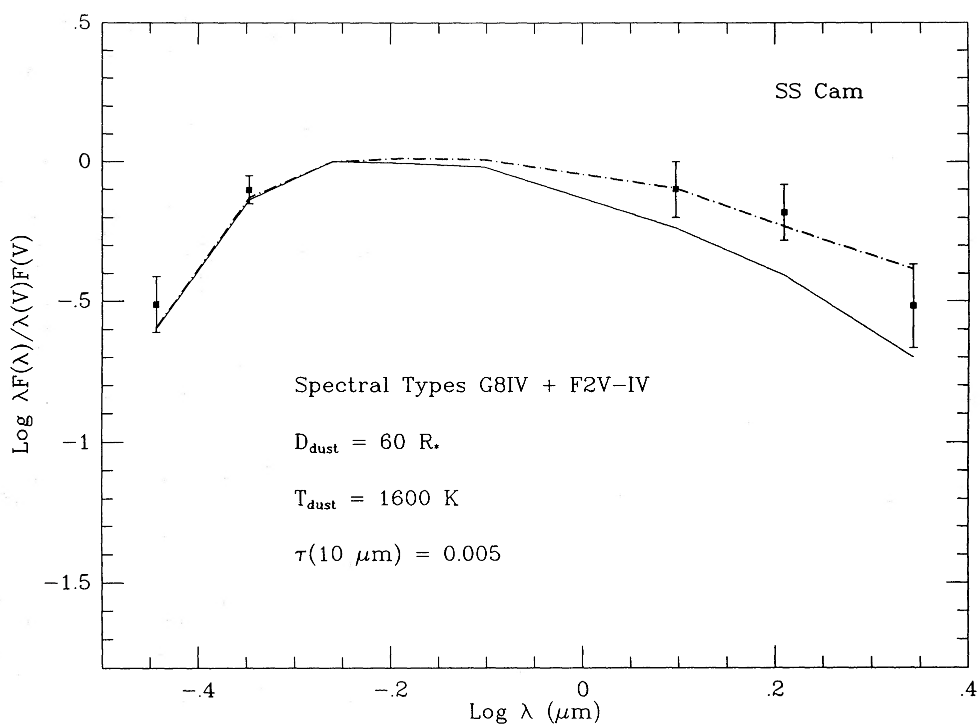

Figure 1. Model energy distribution of SS Cam compared with observations.

also shown in Figs 1–5. In the table, the distance is expressed in units of the radius of the larger stellar component in the binary system; to write it in units of the solar radius, as in equation (2), we have derived the radii of the observed stars from their spectral properties (see e.g. Schaifers & Voigt 1982b).

We have found that temperatures and optical depths of the shell lie in the intervals 1500–1750 K and 0.004–0.005,

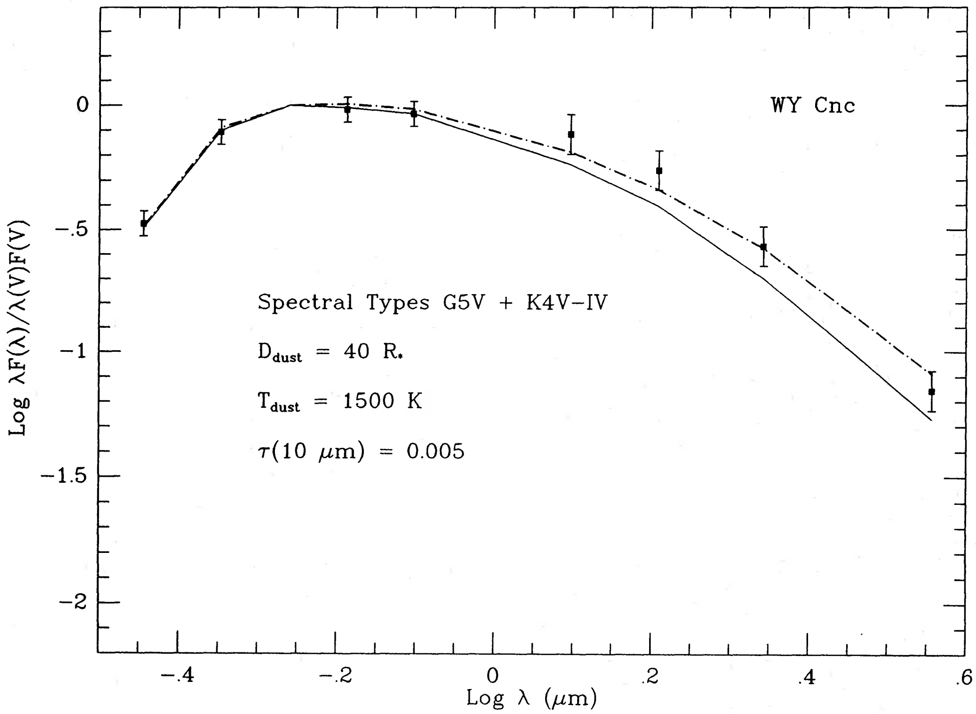

Figure 2. Model energy distribution of WY Cnc compared with observations.

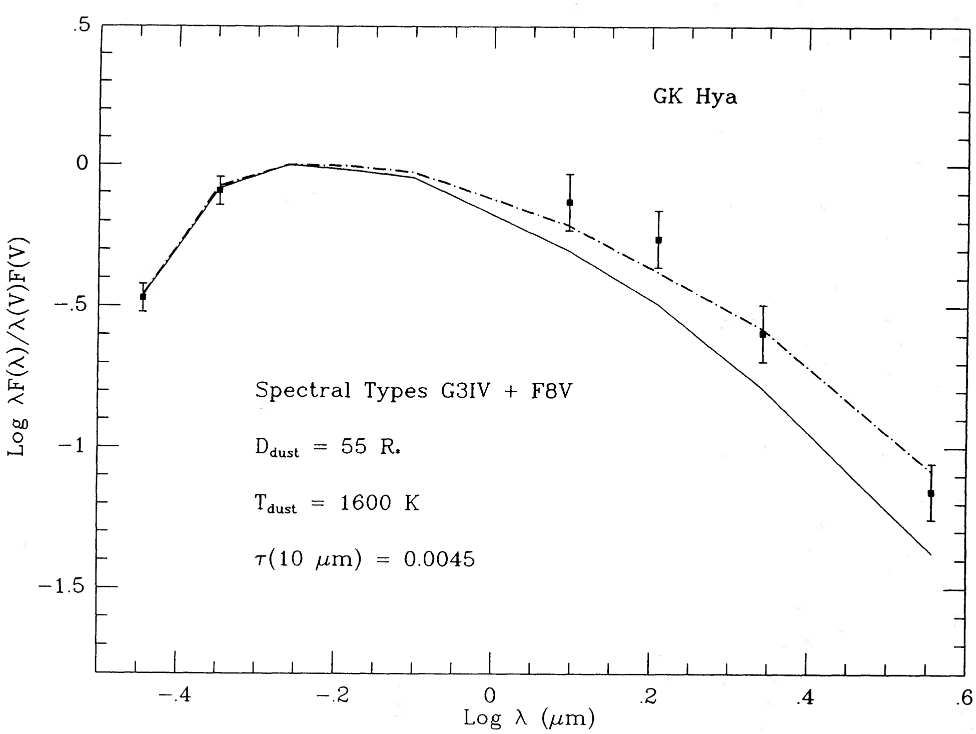

Figure 3. Model energy distribution of GK Hya compared with observations.

respectively. Taking into account the observational errors in the colours, we may estimate uncertainties of the order of 400 K in the derived temperatures. The temperatures appear rather high, being of the same order as those obtained by Goldsmith et al. (1987) for RV Tauri stars with IR excesses when the optical depth is similarly small. According to Goldsmith et al., for very low values of $\tau(\lambda)$ the IR excesses cannot be fitted with great accuracy, so our derived tempera-

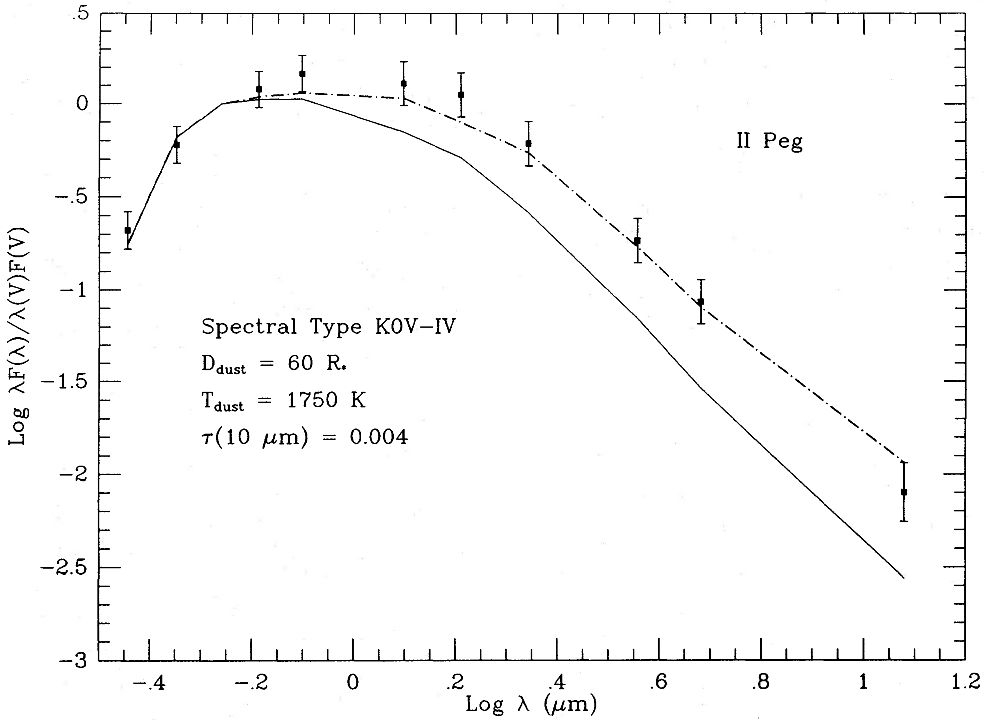

Figure 4. Model energy distribution of II Peg compared with observations.

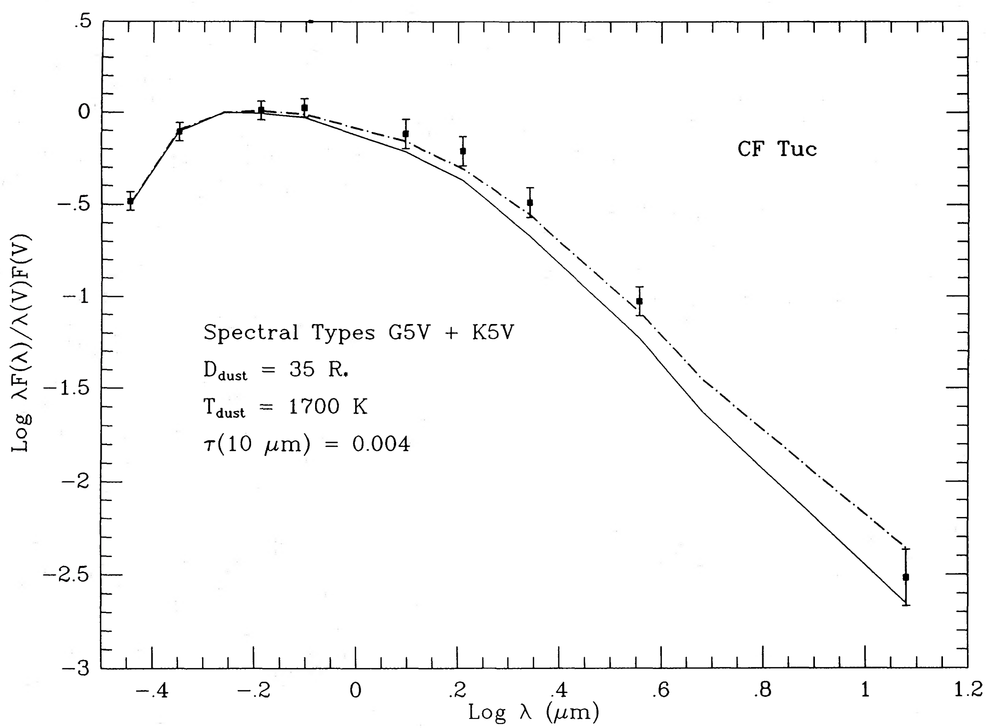

Figure 5. Model energy distribution of CF Tuc compared with observations.

tures should be considered only as first-order approximations. We simply underline here that, according to the analysis performed in this section, an explanation of the IR excesses in terms of dust shells remains the only plausible one, despite the crudity of the above approach.

The resulting dust masses span a rather wide interval. They are smaller than those found around T Tauri stars (e.g. $5 \times 10^{-10}\,M_{\odot}$ for HL Tau: see Cohen 1983) by factors ranging from 10 up to 10^4. With a standard gas-to-dust ratio (100–200: see Schaifers & Voigt 1982a), the dust masses imply total shell masses in the range 10^{-9}–$10^{-12}\,M_{\odot}$. These masses appear to be rather well correlated with the present evolutionary status of the sources, so we suggest that the circumstellar envelopes are built by the integrated mass lost in the form of stellar winds driven by magnetic activity.

Hence we can speculate that the sources with a detectable IR excess were in the past somewhat more active than were the other binaries of our sample for which the excess is not present.

6 CONCLUSIONS

The sample of 12 RS CVn-type binaries that we have studied in this paper through optical and infrared photometry clearly shows that a fraction of them (about 40 per cent) have infrared excesses that are not modulated by the spot activity, suggesting the presence of circumstellar shells. A detailed analysis of the energy distributions quantitatively confirms this conclusion, and allows us to evaluate the mass of the absorbing material, which is supposed to be in the form of silicate grains. Among the sources showing an excess, the masses of the dust shells are larger for those sources that appear slightly more evolved, so a tentative hypothesis is that the circumstellar material now seen is the result of continuous mass-loss episodes and hence depends on all the previous magnetic activity.

As far as we know, the technique based on the reconstruction of the energy distribution has been used on 20 objects so far (Paper I; Busso et al. 1988; Gimenez, Reglero & Fabregat 1990; present paper). Among these, for two binaries the IR excess is uncertain, while for seven systems the presence of the excess has been clearly ascertained. Estimated maximum IR excesses span the interval 0.4–1.2 mag.

We are currently performing (Busso & Scaltriti, in preparation) a similar analysis on several other binaries (about 20) for which the flux can be reconstructed from optical–infrared bands. In this way, we shall achieve a fairly good statistical basis (40 of the ≃100 presently known RS CVn systems) in order to explore the hypothesis that the IR excess is a common feature of this type of star.

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