A&A 412, 405–416 (2003)
DOI: 10.1051/0004-6361:20031271

Astronomy & Astrophysics

Polarimetry of evolved stars

III. RV Tau and R CrB stars*,**

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Received 25 February 2002 / Accepted 5 August 2003

Abstract. We present broadband optical polarimetry, and broadband optical and infrared photometry, of eight RV Tau-type and five R CrB-type stars; much of the photometry and polarimetry was obtained simultaneously. For nine of the objects polarimetric data is reported for the first time. We have estimated and subtracted the interstellar component of polarization, allowing us to determine the level of intrinsic polarization. In some cases this is ≃1%–2% even when the star is in a bright photometric state. We consider this to be evidence for the presence of permanent clumpy non-spherical dust shells around the RV Tau and R CrB-type stars we observed. Our polarimetric and photometric data lead us to conclude that, for most of our programme stars, neutral extinction must be significant in their circumstellar envelopes. Apart from the brightness variations due to pulsations and changes in the effective temperature of stars, there is clear evidence of wavelength-independent flux variations – with amplitude from $0\overset{m}{.}5$ to $1\overset{m}{.}0$ – implying the presence of large ($a \gtrsim 0.15\,\mu$m) dust particles. Rapid (~2 hours) evolution of the infrared flux distribution at the level of $\sim 0\overset{m}{.}6$ in the *JHKL* bands was detected in the RV Tau star R Sct.

Key words. polarization – stars: circumstellar matter – stars: variable: general

1. Introduction

It is well-known that evolved stars, mainly OH/IR stars, carbon stars and Miras, are the major source of dust grains in the interstellar medium (e.g. Gehrz 1985). However some types of evolved stars, although not major contributors to the interstellar dust population because of their relative scarcity, may individually be prolific producers of dust. These include the R Coronae Borealis (R CrB) stars (e.g. Clayton 1996; Clayton et al. 1999) and the RV Tauri (RV) stars (Lloyd Evans 1985). Indeed in some of these objects (specifically the R CrBs) the formation of dust may be seen in real time.

In this paper we present new polarization measurements, together with quasi-simultaneous broadband optical and IR photometry, for 13 RV and R CrB stars. We supplement these data with polarimetric data from the literature, with the aims of (i) investigating the presence of intrinsic polarization, (ii) relating the polarimetric characteristics to the photometric properties of the stars and (iii) discussing the level of intrinsic polarization in the context of the distance of our programme stars.

1.1. The RV stars

The RV stars are post-Asymptotic Giant Branch (post-AGB), pulsationally variable stars with spectral types in the range F–K (e.g. Preston et al. 1963; see also Shenton et al. 1992, 1994a,b,c). The light curves show characteristic alternate deep and shallow minima, with periods (the time between deep minima) in the range 30–150 days.

Many RV stars have large IR excesses due to emission by circumstellar (CS) dust shells (e.g. Gehrz 1972; Lloyd Evans 1985; Goldsmith et al. 1987a) although not all have this property. Although about 100 objects are currently classified as RV type according to the SIMBAD database, only a few have been observed and studied polarimetrically in any detail (see Nook et al. 1990 and references therein). Only recently have the results of polarimetric measurements for 17 RV stars been presented by Yoshioka et al. (1997, 2000).

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* Table 2 is only available in electronic form at the CDS via anomymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/412/405

** Tables 3–6 are only available in electronic form at http://www.edpsciences.org

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Gehrz (1972), on the basis of the visual and IR lightcurves, first suggested that RV stars pulsate in non-radial modes. More recently Henson et al. (1985) have presented polarimetric evidence for non-radial pulsations in the carbon-rich RV star AC Her. Shenton et al. (1992, 1994b), again on the basis of optical and IR variations, have further argued in favour of non-radial pulsations in the RV stars AC Her and R Sct; however they suggested that SX Cen pulsates in purely radial modes (Shenton et al. 1994c).

1.2. The R CrB stars

The R CrB stars are a rare (fewer than 50 known) carbon-rich subset of the extreme hydrogen-deficient stars. Their evolutionary status is extremely unclear, with coalescing white dwarfs and final helium flash scenarios being invoked to account for the extreme abundances (e.g. Iben et al. 1996). They show unpredictable and frequent fading in visual light (by several magnitudes), and this behaviour is attributed to obscuration of the stellar photosphere by carbon dust grains condensing in carbon-rich material ejected from the stellar photosphere (see Clayton 1996 for a review). Their photometric behaviour is also characterized by small-amplitude periodic variability and indeed it is suspected that all R CrB stars may show pulsational behaviour (Clayton 1996).

That the IR flux is not greatly affected when the visual light goes into decline suggests that the carbon grain-forming material is ejected in the form of discrete clouds of gas rather then over the entire stellar surface. Presumably as a result of the accumulation of the ejected dust R CrB stars usually have an IR excess (indeed this is a defining property of the class, as is the episodic mass ejection and condensation of new dust particles).

Among this group the number of stars studied polarimetrically is also not large; we note the work of Serkowski & Kruszewski (1969); Stanford et al. (1988); Clayton et al. (1995); Rosenbush & Rosenbush (1990); a more detailed reference list may be found in Clayton (1996).

1.3. Motivation for present work

Most objects, in both classes, are luminous giants/supergiants, with clear evidence for radial and/or non-radial pulsations and, on the basis of their characteristics, may be considered as intermediate between the Cepheids and the long period Mira Ceti variables (Pollard et al. 1996). Both class of objects show variability of polarimetric parameters on different time-scales (days to months, cf. Clayton et al. 1995; Yoshioka et al. 1997, 2000), and which usually (but not always) correlates with photometric changes (Serkowski & Kruszewski 1969).

As discussed above, there is substantial evidence that the mass ejection in R CrB and RV stars is generally highly anisotropic. In such cases scattering of the stellar radiation by the ejected material will result in polarization. Consequently any optical evidence for mass loss (e.g. in the form of visual light declines for R CrB stars) may be expected to be accompanied by changes in polarization. Furthermore, pulsational variability, particularly if (as in the case of RV stars) pulsations are non-radial, may give rise to variations in polarization, arising from (for example) Rayleigh scattering by molecules close to the stellar photosphere, or Thomson scattering by electrons in the chromosphere. In many or all of these cases, therefore co-ordinated variations in photometry and polarization might be expected.

IR photometry has been obtained for many RV and R CrB stars (cf. Lloyd Evans 1985; Goldsmith et al. 1987a, 1990). In the case of R CrB stars it has been noted by Clayton (1996) that a correlation between IR flux and decline activity is not obvious. Some objects show relatively stable IR fluxes during several decline phases (Feast 1990), or incoherent variations of IR and optical fluxes on a time-scale a few hundred days (see Fig. 1 of Rosenbush 1995), while for others IR flux and decline activity are correlated (Glass 1994).

It is of interest to study possible correlations between optical and IR fluxes on a short (~1 day) time-scale in order help distinguish between different mechanisms of photometric variability (see below). This can be investigated by carrying out simultaneous optical-IR photometric measurements. Such data are unfortunately not numerous (at least for the stars in our programme). The two papers by Goldsmith et al. (1987a, 1990) contain synchronous optical-IR photometry for 23 RV stars and 10 R CrB stars; however for most of the stars only a few measurements, usually at a similar brightness level, were obtained. In a series of papers by Shenton et al. (1992, 1994a,b,c) four RV stars (AC Her, U Mon, R Sct and SX Cen) were studied more intensively, but not in enough detail to draw any conclusion about correlated (or otherwise) photometric behaviour.

2. Observations and analysis

The stars observed are listed in Table 1, which includes their alternative names, spectral types, distances, photometric periods and epochs of maximum or minimum light. Eight of the programme stars were included previously in the list of RV pulsating variables, four are R CrB stars, and one is a W Vir type object. Note that, for many of our programme stars, the pulsation periods are not stable (cf. Lawson & Cotterell 1990). Even a small difference in the period value leads to significant uncertainties in phase determination over a long timebase. Therefore where necessary we will refer to published light curves close to the dates of our observations.

Most of the observations were carried out in 1987 and 1988 on the 0.5 m telescope (and for U Aqr in 1994 on the 1 m telescope) at the South African Astronomical Observatory (SAAO) with the University of Cape Town photometer-polarimeter module (Cropper 1985). Full details of data reduction are given in Shenton et al. (1992, 1994a), Clarke et al. (1998) and Yudin & Evans (2002). Most polarimetric observations were taken through a "clear filter" (3000 Å–9200 Å) (indicated by "C" in Table 2), although on a few occasions $UBVR_CI_C$ filters were used. Photometric data were obtained at SAAO in the BVR_CI_C and *JHKLMNQ* bands, and at the Cerro Tololo InterAmerican Observatory (CTIO) in the *JHKLM* bands (see Shenton et al. 1992, 1994a for details).

Table 1. List of program stars.

Object	HD	Sp class	Type	Distance* (kpc)	Distance† (kpc)	Epoch, JDs	Periods	Ref.
RU Cen	105578	A7Ib–G2pe	RV	3.9[a], 2.2[b], 1.0[c]	1.639 (0.575–∞)	2 448 124.57+	64.ᵈ6	3
SX Cen	107439	F5–G3/5Vp	RV	5.2[a], 5.5[b], 2.5[d]		2 447 324.97+	32.ᵈ8642	2
BU Cen			RV				85.ᵈ50	1
R Sct	173819	G0Ia–K0Ibe	RV	0.4[a]	0.43 (0.318–0.667)	2 444 872.0+	146.ᵈ5	1
R Sge	192388	G0Ib–G8Ib	RV	2.9[a], 3.2[b]		2 443 830.0+	70.ᵈ770	1
DS Aqr	216457	F2II	RV	0.45 – 0.69[e]	0.467 (0.249–3.850)	2 433 862.50+	78.ᵈ213	1
UY Ara		G	RV	9.6[a]		2 426 868.40+	57.ᵈ220	1
AI Sco	320921	G0–K2	RV	2.4[a], 3.6[b]		2 448 373.93+	71.ᵈ03	3
UW Cen		K	R CrB	(2.83, 4.25)[f], 5.5[g], 1.0[c]	0.787 (0.245–∞)		≈43ᵈ	5
RY Sgr	180093	G0Iep	R CrB	(1.32, 4.1)[f], 1.5[h], 1.7[g]	2.78 (0.676–∞)		≈38ᵈ	6
DY Cen		early BI	R CrB	4.8[i]			3.ᵈ8–5.ᵈ5	7
U Aqr		C	R CrB	13.2[g]	0.279 (0.163–0.970)	2 446 662.0+	81.ᵈ3	4,8
V1711 Sgr		F4–F6	W Vir	5.4[j]	0.427 (0.212–∞)	2 444 151.11+	28.ᵈ55	1

*Distances mainly from absolute magnitude-reddening calibrations; †distances from Hipparcos parallaxes; (a) Alcolea & Bujarrabal (1991); (b) Jura (1986); (c) Eggen (1986); (d) data from Shenton et al. (1994b); (e) derived from z-distance from Wahlgren (1992); (f) distances from radial velocities and reddening calibrations from Trimble & Kundu (1997); (g) Lawson et al. (1990); (h) data from Clayton & Ayres (2001); (i) Rao & Raveendran (1993); (j) distance from period–luminosity relation by Harris & Wallerstein (1984). (1) epoch of maximum light taken from Kholopov et al. (1998); (2) epoch of primary minima from Shenton et al. (1994b); (3) epoch of primary minima from Pollard et al. (1997); (4) period from Lawson & Cotterell (1990); (5) period from Jurcsik (1996); (6) Menzies & Feast (1997); (7) data from Pollacco & Hill (1991); (8) JD of a photometric minimum determined here from the light curve of Lawson & Cotterell (1990).

The complete polarimetric and photometric data are listed in Tables 2–6, in which the Julian days are the time of mid-observation. Unless otherwise noted in the Tables, photometric errors are ±0.ᵐ01 in $UBVR_CI_C$, ±0.ᵐ03 for the SAAO *JHKL* photometry, ±0.ᵐ1 for the SAAO *MNQ* photometry, ±0.ᵐ05 and ±0.ᵐ1 for the CTIO *JHK* and *LM* photometry respectively. The SAAO bolometer also provides a measurement in the *H* band; however this *H* filter has a red leak, and a measurement with this filter is indicated in Table 6 by [*H*] (for further details see Hutchinson et al. 1994). Note that although some (but not all) photometric data for R Sct and SX Cen were published previously by Shenton et al. (1994b,c) we repeat them here partly for comparison purposes.

We tested for the presence of polarization using the *z*-statistic described in Clarke & Stewart (1986); where polarization was detected at the 99% (∼3σ) confidence level the values of the degree of polarization P and equatorial position angle (PA) θ are given in Table 2. The values of the normalized Stokes parameters (NSP) were also used to test for variability, using the Welch test (see Clarke & Stewart 1986).

3. Polarization

3.1. Circumstellar vs. interstellar polarization

A major problem in modelling the polarimetric behaviour of these stars is the large uncertainty in their distances so that allowance can not straightforwardly be made for interstellar (IS) polarization. As noted by Trimble & Kundu (1997), none of the Hipparcos parallax measurements for R CrB stars differ significantly from zero. The same is true of the RV stars, for most of which the parallaxes also do not differ significantly from zero, or are non-existent. This problem also impacts the interpretation of polarimetric data, as without knowledge of the *IS* component of polarization we are unable to estimate the level of *intrinsic* polarization. Moreover, there is reason to believe that (with a few exceptions) most RV and R CrB stars are distant (≳1 kpc) objects, for which the IS component of polarization can be very significant.

To avoid these difficulties Serkowski (1970) suggested that the average value of the observed polarization be considered as the value of the *IS* polarization for the two RV stars U Mon and R Sct, on the assumption that the average *intrinsic* polarization is zero. This procedure was also later applied by Stanford et al. (1988) to R CrB itself. However, that this method is inappropriate for most stars is evident, bearing in mind the ubiquitous presence of dust in their CS environments, either in the form of shells or clumps. More detailed discussion on this point can be found in Nook et al. (1990). For a few cases these authors used the so-called "field star method" (e.g. Bastien 1985; Yudin 2001), whereby the local growth of IS polarization $P_{\rm is}(D)$ with distance D is first obtained from the data for field stars in a small projected area around the target star. At that time, however, such a procedure was unfeasible for many objects due to the lack of polarimetric catalogues and distance determinations for field stars. However such data are now available (cf. Heiles 2000).

A closely linked (and unresolved) problem is the separation of the IS and CS extinction for these stars. In some cases the values of $A_V^{\rm is}$ adopted in the literature are not justified and can be underestimated if there is a contribution from non-selective extinction in the CS environment.

Most of the objects in our programme show a level of observed polarization ∼1% or less. This level seems very small, bearing in mind well-established presence of CS dust shells around most of the stars investigated. There are two possible explanations: (i) an essentially uniform and spherically symmetric distribution of scattering material in the CS environment and/or (ii) a compensation of the level of intrinsic polarization by the IS component.

Regarding the first possibility, the existence of a preferred plane for the dust ejection has been considered by several authors (e.g. Stanford et al. 1988; Clayton et al. 1995; Clayton 1996; Feast et al. 1997). Clayton et al. (1997), from consideration of polarimetric data, deduced that there is a preferred direction for dust ejections in R CrB itself. A similar conclusion was reached by Rao & Raveendran (1993) for the R CrB star V854 Cen. It is likely therefore that other R CrB stars have equatorial dust tori and/or bipolar dust ejection. There is no information on this topic in the case of RV stars due to lack of polarimetric data. However Lloyd Evans (1999) recently noted that the colours of RV stars may possibly indicate the presence of dusty CS discs. The existence of an edge-on CS dust disc around AC Her was recently suggested by Jura et al. (2000; see also van Winckel et al. 1998).

Note that an explanation for an increase in polarization (up to 14%, as observed in R CrB; Efimov 1980) near deep minima requires a priori extremely non-spherical geometry for dust ejection. In addition, it is well established that the CS environment around R CrB and RV stars is highly clumped, and that the dust forms close to the star. For example, in R CrB stars dust formation may occur over giant convection cells in the stellar atmosphere (Clayton 1996; Feast et al. 1997), or above the cool magnetic spots (Soker & Clayton 1999), rather than in an isotropic flow. All the above, together with the large IR excesses in many of these objects, suggests that the mean level of intrinsic polarization should in principle be relatively large at least in some cases. Of course the level of intrinsic polarization can be reduced if the CS discs (if such exist) are face-on, and/or the optical depths of the CS shells are small ($\lesssim$0.1).

3.2. The interstellar polarization

We now consider the effect of the IS component of polarization on the data. Although the distances for the stars in our programme are very uncertain (see Table 1), on average most are located at distances at least 1–2 kpc. It was shown recently by Fosalba et al. (2002) that, beyond ∼2 kpc, the interstellar polarization $P_{\rm is} \approx 2\%$. These authors found empirical relations for the IS polarization, which we first use to estimate the expected level of $P_{\rm is}$ for our programme stars:

$$P_1^{\rm is}(\%) \approx 1.3 + 0.9 \sin(2l + 180^\circ) \quad (1)$$

$$P_2^{\rm is}(\%) \approx 0.1 + 0.0067 \csc(0.05\,|b|) \quad (2)$$

$$P_3^{\rm is}(\%) \approx 3.5\, E(B-V)^{0.8} \quad (3)$$

$$P_4^{\rm is}(\%) \approx 0.13 + 1.81D - 0.47D^2 + 0.036D^3\,; \quad (4)$$

here D is the distance in kpc, l, b are the Galactic co-ordinates and $E(B-V)$ (obtained from the literature) is the colour excess; these have been obtained be a variety of methods, such as the reddening along the same line of sight as the programme star, removal of the interstellar "2175" feature, etc. Where possible we have taken several independent estimates of $E(B-V)$ and taken the mean, $\overline{E(B-V)}_{\rm is}$. The resultant values of $P^{\rm is}$ are presented in Table 7. Note that, for most of the programme stars, the level of IS polarization is non-negligible.

To obtain further (independent) estimates of the interstellar polarization parameters and to determine $\theta_{\rm is}$ we also apply the "field star method" (see above), using the catalogue of Heiles (2000). The deduced values of $P_{\rm is}$ and $\theta_{\rm is}$, together with estimates of intrinsic polarization parameters for selected objects at two reasonable values of distance, are presented in Table 8. Note that estimates of $P_{\rm is}$ derived by the "field star method" agree well with a weighted mean value of $\overline{P}_{\rm is}$ from Table 7.

Having removed the IS polarization we conclude the following: first, the mean level of the *observed* polarization for 12 of the programme stars is 0.7%, whereas the mean level of the *intrinsic* polarization is significantly higher, 1.1%. Second, the values of $P_3^{\rm IS}$ derived using the adopted values of $E(B-V)_{\rm is}$ (or $A_V^{\rm is}$) are significantly smaller for many cases than the values of $P_{\rm is}$ determined by the "field star method". This is clear indication that the $A_V^{\rm is}$ is *underestimated*, due to incorrect separation of the IS and CS components. If non-selective CS extinction were taken into account, the values of $A_V^{\rm is}$ would be higher, which would be more in line with our results.

3.3. Presence of intrinsic polarization

We demonstrated in the previous section that the intrinsic polarization for all the stars in our programme can be large. An alternative means of determining whether or not an intrinsic component of polarization is present is to check for polarimetric variations. This is preferably done using the NSP rather than the degree of polarization and PA, and establishes the presence of an intrinsic component irrespective of the IS contribution to the polarization.

For all programme stars for which two or more measurements in the same pass-band were made, polarimetric variability has been detected at the 95% (or higher) level of significance on a time-scale of several days, either in both NSPs (for R Sct, DS Aqr, AI Sco) or in one of the NSPs (RU Cen, SX Cen, BU Cen, UY Ara, UW Cen; see Table 2). A typical amplitude for these variations is about 0.2%–0.5%. A comparison of our data for UW Cen and DY Cen with those obtained in a "clear" filter by Rosenbush & Rosenbush (1990) also indicates polarimetric variability on a longer time-scale. Thus we strongly confirm the conclusions of Yoshioka et al. (1997, 2000) that, in general, RV stars are polarimetric variables.

Conclusions about the intrinsic polarization can also been drawn if $P_{\rm obs}$ shows a wavelength-dependence which is significantly different from the Serkowski et al. (1975) law for

Table 7. Estimates of P_{is} for programme stars.

Object	l (deg.)	P_1^{is} (%)	b (deg.)	P_2^{is} (%)	$E(B-V)$ (Ref.)	$\overline{E(B-V)}_{is}$	P_3^{is} (%)	d (kpc)	P_4^{is} (%)	$\overline{P}_{is}$ (%)
RY Sgr	4.43	1.2	−19.45	0.5	2,6,13,14	0.12	0.6	1.3;4.0	1.8;2.1	1.1
V1711 Sgr	10.81	1.0	−27.46	0.4	7,8,9	0.12	0.6	0.43	0.8	0.7
R Sct	27.40	0.6	−1.72	…	1,4,11,12	0.21	1.0	0.43	0.8	0.8
U Aqr	39.15	0.4	−49.81	0.3	13,14	0.03	0.3	0.16–0.93	0.4–1.5	0.3–1.3
DS Aqr	44.10	0.4	−61.56	0.2	1	0	0	0.5	0.9	0.4
R Sge	57.53	0.5	− 9.75	0.9	1,4,10	0.25	1.2	2.9–3.2	2.3	1.2
RU Cen	295.25	2.0	+16.82	0.6	1,4,5,11	0.16	0.8	1.6–3.9	2.3	1.4
SX Cen	297.87	2.0	+13.36	0.7	1,4,11	0.20	1.0	2.5–5.5	2.3–1.9	1.5
UW Cen	301.74	2.1	+ 8.32	1.0	2,3,6,14	0.25	1.2	0.79;2.8–5.5	1.3;2.3–1.9	1.5
DY Cen	307.95	2.2	+ 8.29	1.0	2	0.10	0.6	4.8	2.0	1.5
BU Cen	309.20	2.2	+12.41	0.7	1,4	0.20	1.0	…	…	1.3
UY Ara	331.86	2.1	−13.78	0.7	1,11	0.17	0.8	…	…	1.2
AI Sco	356.97	1.4	−4.45	1.8	1,5,11	0.35	1.5	2.4–3.6	2.3–2.2	1.8

(1) Goldsmith et al. (1987a); (2) Goldsmith et al. (1990); (3) Lawson & Cotterell (1990); (4) Dawson (1979); (5) Jura (1986); (6) Trimble & Kundu (1997); (7) Beers et al. (2000); (8) Fernie (1990); (9) McAlary & Welch (1986); (10) Gonzalez et al. (1997); (11) Alcolea & Bujarrabal (1991); (12) Baird & Cardelli (1985); (13) Bergeat et al. (1999); (14) Asplund et al. (1997). $P^{is}_{1,2,3,4}$ calculated using Eqs. (1)–(4); $\overline{P}_{is}$ is a weighted mean value of IS polarization.

Table 8. Parameters of interstellar polarization (P_{is}; θ_{is}) derived by the "field star method" and values of intrinsic polarization (P_*; θ_*) of programme stars.

	RU Cen		SX Cen		UW Cen		DY Cen
D (kpc)	2.0	4.0	2.5	5.2	2.8	3.3	5.0
P_{is}; θ_{is}	1.0% ; 85°	1.5% ; 85°	1.3% ; 85°	1.8% ; 80°	1.4% ; 83°	1.5% ; 80°	2.0% ; 80°
P_*; θ_*	1.5% ; 15°	1.7% ; 8°	1.0% ; 3°	1.4% ; 173°	1.0% ; *	1.1% ; *	2.0% ; 158°
	V1711 Sgr		**DS Aqr**		**UY Ara**		**RY Sgr**
D (kpc)	0.5	1.0	0.47	3.0	10	3-5	2.0
P_{is}; θ_{is}	0.5% ; 5°	0.8% ; 15°	0.05% ; 140°	0.2% ; 120°	1.5% ; 35°	2.0% ; 55°	0.90 ± 0.12% ; 82°
P_*; θ_*	0.55% ; 65°	0.6% ; 85°	0.26% ; 74°	0.25% ; 168°	1.0% ; 103°	1.0% ; 145°	1.0% ; 170°
	R Sct		**AI Sco**		**BU Cen**		**R Sge**
D (kpc)	0.43		3.0		1.5	3.0	3.0
P_{is}; θ_{is}	0.65 ± 0.05% ; 50° ± 5°		1.8 ± 0.2% ; 5°		0.9% ; 70°	1.4% ; 80°	1.8% ; 30°
P_*; θ_*	0.63% ; 18°		0.9% ; 120°		1.0% ; 150°	1.2% ; 163°	1.5% ; 213°

* For two measurements on JD6991 and JD7000, the values of θ_* differ significantly: ≈140° and ≈5° respectively.

IS polarization. Observations in all $UBVR_CI_C$ bands were conducted for only one object, U Aqr. Although the errors in all bands are large, the object possibly shows an increase of polarization to the ultraviolet, up to the value ≈6% (see Fig. 1). This high level of polarization, and the wavelength-dependence ($P \propto \lambda^{-3}$) sometimes observed in cool stars of this type (see Serkowski & Shawl 2001), can be attributed to scattering by small dust grains in the CS environment of U Aqr; there is certainly evidence that U Aqr has a near-IR excess due to dust emission (e.g. Feast et al. 1997; Bergeat et al. 1999).

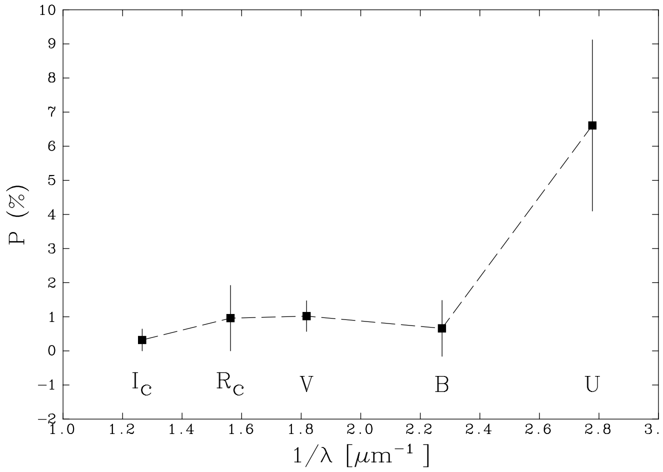

Fig. 1. Wavelength-dependence of polarization in U Aqr.

The wavelength-dependence of polarization would be consistent with the above suggestion.

Four programme stars (RU Cen, R Sct, AI Sco and R Sge) were observed through B and I_C filters, allowing us at least to compare the level of polarization between the blue and red regions of the spectrum. For RU Cen and R Sge polarization in the B and I_C bands shows the same level (within the errors). The difference in polarization in the V and I_C bands detected for AI Sco, in principle, is close to that expected for IS polarization but, as noted above, the polarization is variable. Spectropolarimetric data for R Sct in the 3300 Å–11 000 Å range, from a single night (Landstreet & Angel 1977), also indicate a flat wavelength-dependence of polarization. Although the polarization of R Sct is variable in magnitude, three pairs of our BI_C measurements show similar behaviour, in that polarization in the I_C band is even larger than in B. The PA for the polarization in the I_C band from our measurements is consistent with the values reported by Serkowski (1970). However, our values of θ_B for two of the three measurements are significantly different ($\approx$60°–70° compared with $\overline{\theta}_B \approx 32°$ for the Serkowski data). The same behaviour (i.e. rotation of the PA) was noted for R Sct by Landstreet & Angel (1977) ($\theta_{UBVRI} \approx 80°, 65°, 40°, 35°, 35°$ respectively) from observations in 1973, (which also points unambiguously to the intrinsic polarization of the star).

Our data for RY Sgr do not allow us to determine the wavelength-dependence of polarization. However mean values (over about a 100^d period) of $UBVR$ polarization reported by Rosenbush & Rosenbush (1990) show a remarkably flat $P(\lambda)$ dependence [$P_{UBVR} \approx 0.50 \pm 0.05\%$ at $\theta \approx 178° \pm 2°$; see Fig. 2]. This behaviour is also evident from individual $UBVR$ measurements in Rosenbush (1995).

Photometric variability may arise as a result of changes in the star itself (e.g. by virtue of pulsation or the presence of starspots) or by the effect of changes in the CS environment. For intrinsic changes, we would expect changes in the effective temperature (and hence consequent changes in observed flux and colours) to occur on timescales comparable with the pulsation (i.e. photometric) period (cf. Table 1), while changes due to starspots should occur on timescales comparable with the stellar rotation periods. Extrinsic changes will be governed by, for example, the timescales for changes in the "clumpiness" of the CS environment, as condensations of material form and disperse. The variability timescales in this case will clearly depend on the mechanism involved. Alternatively, if photometric and polarimetric changes are attributed to changes in the CS environment, the timescales may provide constraints on variability mechanisms. Table 9 gives the amplitude of variations in the various pass-bands as determined from synchronous optical and IR data. The data in Table 9 suggest that changes in the star (pulsation or rotation) as a cause of variability are unlikely in most cases (see below) for the following reasons:

1. To a good approximation for the stars in our study, changes ΔT in the effective stellar temperature T give rise to flux changes of

$$\Delta m(\lambda) \simeq -15615 \, \frac{1}{\lambda_{\mu m} T} \, \frac{\Delta T}{T} \times \left[1 - \exp\left\{-14382/(\lambda_{\mu m} T)\right\}\right]^{-1}, \quad (5)$$

in the near IR, where $\lambda_{\mu m}$ is the wavelength in μm.

4. Simultaneous optical and IR photometry

While reasonable changes in the effective temperature give rise to flux changes in the optical that are comparable, and have similar wavelength-dependence, to some of the Δm values in Table 9, the amplitudes of the changes in the IR, their wavelength-dependence and the time-scale (~1 day) over which variations occur, suggest that this mechanism is not responsible for the variations.
In some cases however (e.g. BU Cen, DS Aqr and possibly SX Cen) the amplitudes of variability seem consistent with the changes in effective temperature that accompany stellar pulsation (see Fig. 3, in which the data in Table 9 have been plotted along with Eq. (5)).

2. Stars of spectral type G → M are not known to have high rotational velocities, neither are supergiants (Allen 1973). The rotational periods are

$$\mathcal{P} \simeq 51 \left(\frac{R_\star}{100\,R_\odot}\right)\left(\frac{\mathcal{V}}{100\,\mathrm{km\,s^{-1}}}\right)^{-1} \text{ days}$$

where $\mathcal{P}$ is the rotational period and $\mathcal{V}$ the rotational velocity. Again we see that the observed changes are in general far too rapid to be due to stellar rotation.

Accordingly, unless the observed variations are due to flaring activity, their origin must in general be in the CS environment, for example by virtue of variable extinction by CS dust in the optical-IR, or by changes in the dust emission in the mid-IR. In particular, we can compare the photometric variability in Table 9 with the canonical IS extinction law (Cardelli et al. 1989), from which the values of the ratio A_λ/A_V are included in Table 9. Where the wavelength-dependence of the amplitude of variation is similar to that for IS grains, this as an indication that the observed variation is caused by variable extinction by IS-like grains; a flatter (steeper) dependence suggests extinction by grains that are larger (smaller) than IS-like grains.

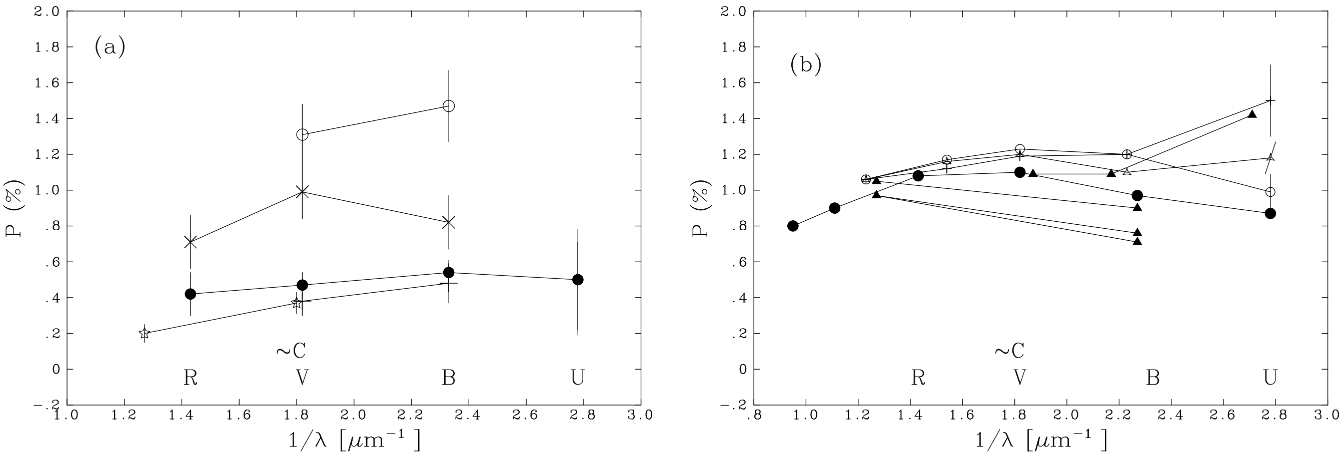

Fig. 2. a) Wavelength-dependence of polarization for RY Sgr from Rosenbush & Rosenbush (1990) (•, +, ×); Serkowski & Kruszewski (1969) (○); data from this paper (★). **b)** Wavelength-dependence of polarization for R Sct from HPOL (○, ×, △); Landstreet & Angel (1977) (•); Shawl (1975) (×); data from this paper (filled triangles). Lines are included to guide the eye.

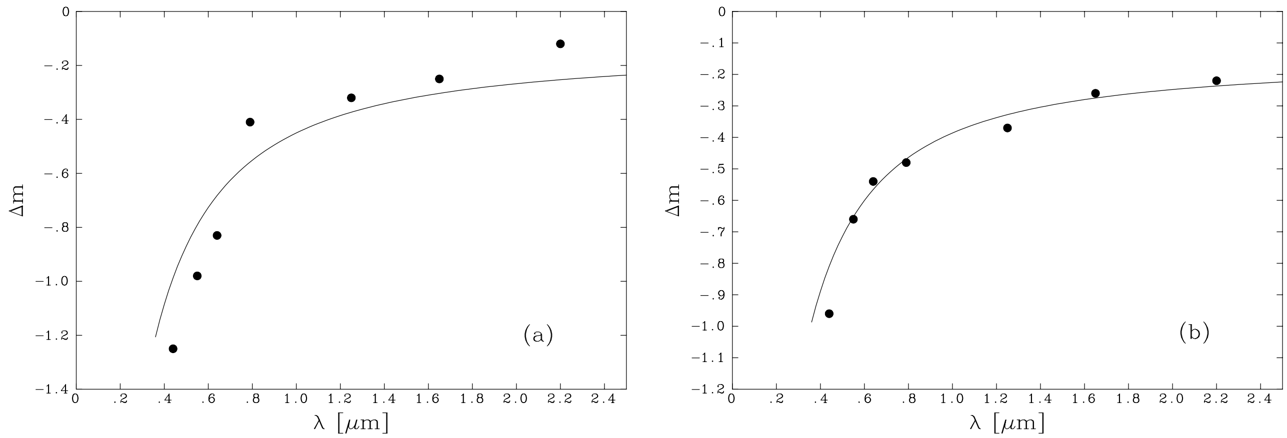

Fig. 3. a) Dependence of amplitude variation on wavelength for BU Cen. Points are from Table 9 for JD6991–6248; curve is Eq. (5) with $T = 4300$ K and $\Delta T/T = 12\%$. **b)** as **a)** but for DS Aqr for JD7040–7048; $T = 5700$ K, $\Delta T/T = 13\%$.

On the other hand, a decline at short wavelengths accompanied by an increase longward of the *K* band suggests obscuration by grains which reradiate in the IR.

Evidently, investigation of photometric variability using colour indices is not always meaningful, as colour indices may not be sensitive to variations in optical/IR flux. If photometric variability is due to neutral CS extinction, the colours indices remain constant while the fluxes *in* individual bands vary. We illustrate this by considering the spectral energy distributions (SED) of our programme stars (Figs. 4 and 5), which show evidence for non-selective extinction. These SEDs have been corrected for interstellar reddening (see below), but different values of $E(B-V)_{\rm is}$, or uncertainties in $E(B-V)_{\rm is}$ for individual objects, have no effect on our comparison of the SEDs obtained on different dates.

Despite the fact that our data set is limited, some conclusions for individual objects can be drawn by considering our data in combination with previously published results. We briefly discuss individual objects:

DS Aqr. On an 8-day time-scale (JD…7040–7048; see Table 9), the change of flux in the different pass-bands is more extreme than expected for an IS-like extinction law, indicating the presence of particles smaller than those typical of IS grains. However later, on a 4-day time-scale (7048–7052), variations in flux in the optical and IR are anti-correlated in the sense that, when the star became brighter in the IR, the fluxes in optical pass-bands decreased. A change of a sign in flux variations occurs between the $I_{\rm C}$ and *J* bands.

UY Ara shows more complex behaviour. On a 2-day time-scale and longer, the change of flux deviated strongly from the IS law in the *BV* filters and in the IR pass-bands. Changes in *BV* seem to correspond to extinction by very small dust grains, whereas in the IR the presence of large particles is required to explain the variations. On a 40-day time-scale the flux in the *BV* and other bands are clearly anti-correlated. A change of sign in the flux variations takes place between the *V* and $R_{\rm C}$ bands.

R Sct shows clear anti-correlation between flux changes in the UV and in the IR, on time-scales ≃9 and 40 days. For the first dates for which we have data an increase of flux in *BV* coincides with a decrease in the red/IR; the contrary behaviour, but more extreme, was observed for the second period. A change of sign in the flux variations takes place around the *J* band. On JD6991 three *JHKL* measurements were obtained

Table 9. Amplitude of variations from synchronous optical-IR photometry of programme stars. Values of A_λ/A_V from Cardelli et al. (1989).

Object	JD[a]	ΔU	ΔB	ΔV	$\Delta R_{\rm C}$	$\Delta I_{\rm C}$	ΔJ	ΔH	ΔK	ΔL	ΔM	ΔN	ΔQ
RU Cen	6991–7000	...	$-0^{\rm m}.42$	$-0^{\rm m}.12$	$-0^{\rm m}.02$	$0^{\rm m}.10$	...	...	...	...	...	...	...
	6244–6245§	$0^{\rm m}.13$	$0^{\rm m}.13$	$0^{\rm m}.10$	$0^{\rm m}.09$	$0^{\rm m}.09$	...	...	...	...	...	...	...
BU Cen	6991–6248§	...	$-1^{\rm m}.25$	$-0^{\rm m}.98$	$-0^{\rm m}.83$	$-0^{\rm m}.41$	$-0^{\rm m}.32$	$-0^{\rm m}.25$	$-0^{\rm m}.12$	...	...	...	...
DS Aqr	7040–7048	...	$-0^{\rm m}.96$	$-0^{\rm m}.66$	$-0^{\rm m}.54$	$-0^{\rm m}.48$	$-0^{\rm m}.37$	$-0^{\rm m}.26$	$-0^{\rm m}.22$	...	...	...	...
	7048–7052	...	$0^{\rm m}.65$	$0^{\rm m}.51$	$0^{\rm m}.43$	$0^{\rm m}.38$	$-0^{\rm m}.07$	$-0^{\rm m}.10$	$-0^{\rm m}.10$	...	...	...	...
UY Ara	6998–7000	...	$-0^{\rm m}.39$	$-0^{\rm m}.24$	$-0^{\rm m}.18$	$-0^{\rm m}.13$	$-0^{\rm m}.30$	$-0^{\rm m}.82$	$-0^{\rm m}.18$	...	...	...	...
	7000–7040	...	$0^{\rm m}.41$	$0^{\rm m}.05$	$-0^{\rm m}.10$	$-0^{\rm m}.20$	$-0^{\rm m}.14$	$-0^{\rm m}.36$	$-0^{\rm m}.47$	...	...	...	...
	7000–6244§	...	$1^{\rm m}.13$	$0^{\rm m}.67$	$0^{\rm m}.47$	$0^{\rm m}.34$	$0^{\rm m}.34$	$0^{\rm m}.18$	...	...	...	...	...
SX Cen*	6999–7353	...	$-0^{\rm m}.78$	$-0^{\rm m}.72$	$-0^{\rm m}.65$	$-0^{\rm m}.58$	$-0^{\rm m}.57$	$-0^{\rm m}.53$	$-0^{\rm m}.63$	$-0^{\rm m}.63$	...	...	...
	6243–6248§	$0^{\rm m}.51$	$0^{\rm m}.44$	$0^{\rm m}.34$	$0^{\rm m}.30$	$0^{\rm m}.28$	$0^{\rm m}.26$	$0^{\rm m}.26$	$0^{\rm m}.38$	$0^{\rm m}.45$	$0^{\rm m}.43$	...	...
R Sct†	6991–7000	...	$-0^{\rm m}.48$	$-0^{\rm m}.47$	$0^{\rm m}.02$	$0^{\rm m}.12$	0	$0^{\rm m}.03$	$0^{\rm m}.04$	$0^{\rm m}.08$	...	...	...
	7000–7040	...	$0^{\rm m}.55$	$0^{\rm m}.30$	$-0^{\rm m}.22$	$-0^{\rm m}.30$	0	$-0^{\rm m}.08$	$-0^{\rm m}.14$	$-0^{\rm m}.26$	...	...	...
	1.45–1.48¶	...	...	...	...	...	$-0^{\rm m}.43$	$-0^{\rm m}.39$	$-0^{\rm m}.24$	...	...	...	...
	1.48–1.53¶	...	...	...	...	...	$-0^{\rm m}.17$	$-0^{\rm m}.22$	$-0^{\rm m}.26$	$-0^{\rm m}.38$	...	...	...
AI Sco	7000–7042	...	$3^{\rm m}.57$	$3^{\rm m}.16$	$2^{\rm m}.99$	$2^{\rm m}.85$	$0^{\rm m}.38$	$0^{\rm m}.40$	$0^{\rm m}.44$	$0^{\rm m}.38$	$-1^{\rm m}.00$	$-0^{\rm m}.64$	$0^{\rm m}.05$
	7041–7042	...	$0^{\rm m}.50$	$0^{\rm m}.39$	$0^{\rm m}.40$	$0^{\rm m}.40$	...	...	...	...	$-1^{\rm m}.35$	$0^{\rm m}.26$	$0^{\rm m}.22$
UW Cen	6243‡–7000	...	$3^{\rm m}.27$	$2^{\rm m}.71$	$2^{\rm m}.41$	$2^{\rm m}.05$	$1^{\rm m}.44$	$0^{\rm m}.81$	$0^{\rm m}.26$	...	...	...	...
RY Sgr	6991–6999	...	$0^{\rm m}.03$	$-0^{\rm m}.11$	$-0^{\rm m}.20$	$-0^{\rm m}.36$	...	...	...	...	...	...	...
	6991–7042	...	$0^{\rm m}.20$	0	$-0^{\rm m}.10$	$-0^{\rm m}.25$	$-0^{\rm m}.22$	$-0^{\rm m}.22$	$-0^{\rm m}.16$	$-0^{\rm m}.07$	...	...	...
1711 Sgr	6999–7040	...	$0^{\rm m}.93$	$0^{\rm m}.50$	$0^{\rm m}.67$	$0^{\rm m}.19$	$-0^{\rm m}.03$	$-0^{\rm m}.09$	$-0^{\rm m}.11$	$-0^{\rm m}.14$	...	...	...
DY Cen	6999–7000	...	0	$0^{\rm m}.03$	$0^{\rm m}.16$	$0^{\rm m}.12$	...	...	...	...	...	...	...
	6999–6248‡	...	$0^{\rm m}.08$	$0^{\rm m}.20$	$0^{\rm m}.25$	$0^{\rm m}.36$	...	...	...	...	...	...	...
R Sge	6998–6999	...	$0^{\rm m}.07$	$0^{\rm m}.07$	$0^{\rm m}.06$	$0^{\rm m}.07$	$0^{\rm m}.02$	$0^{\rm m}.02$	$-0^{\rm m}.02$	$-0^{\rm m}.01$	...	...	...
A_λ/A_V		1.569	1.337	1.000	0.843	0.612	0.282	0.190	0.114	0.056	–	–	–

(a) Magnitude differences Δ mag calculated between Julian Dates indicated in this column; negative Δ mag indicates that the flux in the passband *increased*; † data from Shenton et al. (1994b); * data from Shenton et al. (1994c); ‡ data from Goldsmith et al. (1990); § data from Goldsmith et al. (1987a); ¶ three *JHKLM* measurements at JD6991 separated by 43 and 72 min. Values of A_λ/A_V from Cardelli et al. (1989).

within intervals of 43 and 72 min. As indicated in Table 4 the brightness of R Sct increased synchronously in all *JHKL* bands by about $0^{\rm m}.6$ over a very short period, less than 2 hours. This is the shortest time-scale observed for IR photometric variability in RV and R CrB stars. Prior to this IR variability in SX Cen was detected by Shenton et al. (1994c) at the of level about $0^{\rm m}.3$–$0^{\rm m}.4$ during a three-day period (see also our Table 4).

AI Sco: was unexpectedly bright ($6^{\rm m}.8$) during the period JD6998–7000, or $\approx 2^{\rm m}.5$ brighter than observed previously; the range of photometric variability for AI Sco is given as $9^{\rm m}.3$ to $12^{\rm m}.9$ by Kholopov et al. (1998), and $8^{\rm m}.87$ to $11^{\rm m}.42$ by Pollard et al. (1996). Clearly we can not exclude mis-identification but this is highly unlikely for a star normally at $V \simeq 10^{\rm m}$. From JD6998–7000 to JD7041–7042 the flux in the V band decreased by more than $3^{\rm m}$. Although the amplitude of flux variations is smaller in the IR compared to the optical, the A_λ dependence is flatter than that for the IS law.

It is interesting to note that the decrease in the optical fluxes on JD7042 was accompanied by a strong surge (by $1^{\rm m}.35$) in the M band (see Fig. 5), which is again uncharacteristic (we note that the probability of mis-identification on two telescopes independently is essentially zero). This object clearly merits careful monitoring.

UW Cen and *RY Sgr.* The former shows an A_λ dependence close to the IS law. In the case of RY Sgr, for all dates on which we have multi-wavelength photometry, the fluxes in the UV and IR bands are anti-correlated, on time-scales 8 and 50 days. Changes of sign in the flux variations occur around the V band.

V1711 Sgr. There is a clear anti-correlation of flux variations in the UV-optical and IR regions (Table 9), and the change of sign in the flux variations occurs between the $I_{\rm C}$ and J bands. The IR fluxes on JD7000 were $\approx 1^{\rm m}.3$ and $\approx 2^{\rm m}.0$ brighter in the *MN* bands respectively than on JD7040 (see Tables 4, 6 and Fig. 4).

It has been noted by many authors that the IR excesses detected from *JHKLM* photometry arise from CS dust, whereas the fluxes at wavelengths shorter than 1 μm come from the star itself (Lloyd Evans 1985; Feast et al. 1997). A simple periodic dust extinction model, however, can not explain the detected anti-correlations of UV and IR fluxes.

It is more likely that, for the stars showing anti-correlated changes in flux in the UV and IR regions, this is due to the formation of small dust particles which scatter and absorb

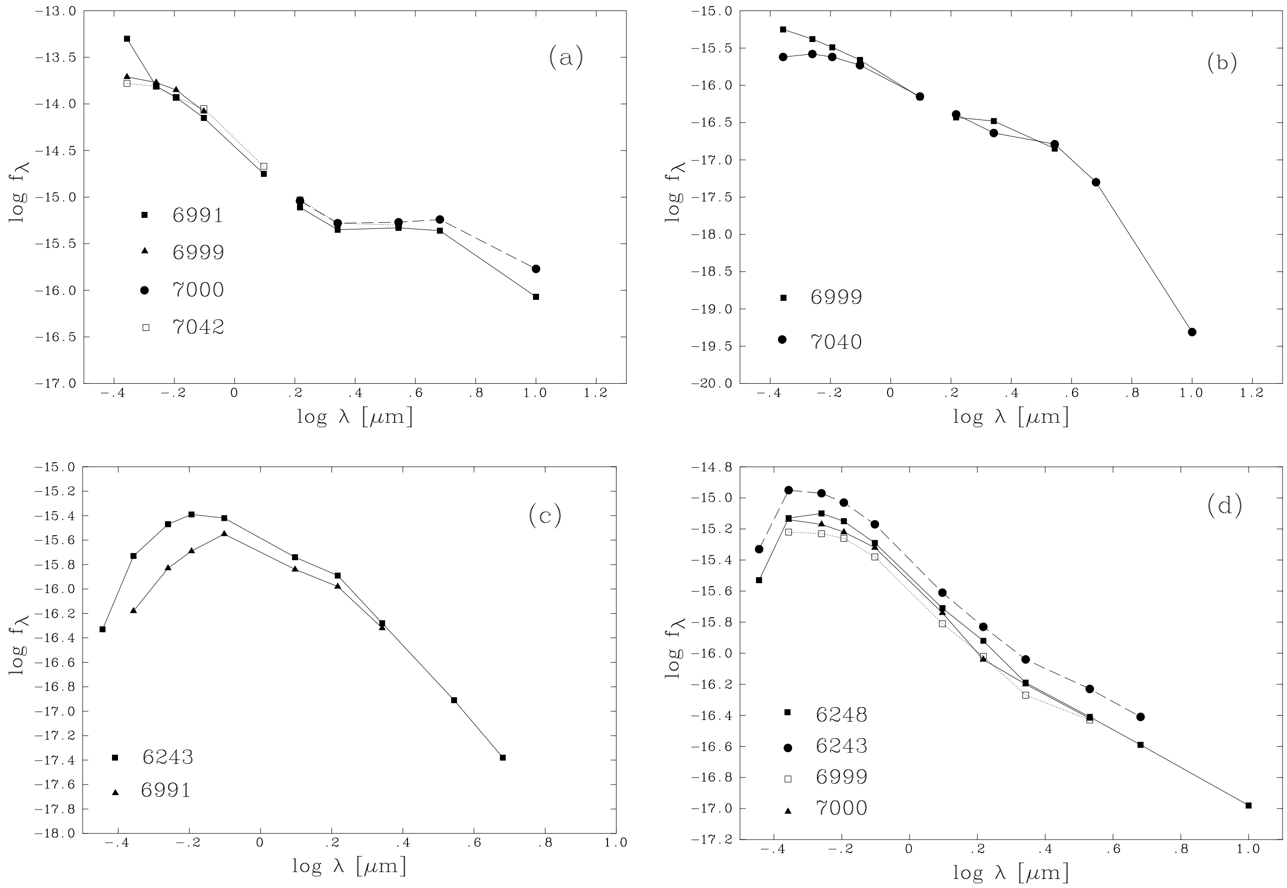

Fig. 4. Spectral energy distributions derived from synchronous optical-IR photometry; f_λ in W m^{-2} μm^{-1}. Data dereddened by the $E(B-V)$ indicated in brackets. **a)** RY Sgr (0.12); **b)** V1711 Sgr (0.12); **c)** BU Cen (0.20); **d)** SX Cen (0.20). Symbols are identified by JD − 2 440 000. Lines are included to guide the eye.

effectively at UV wavelengths and radiate in the IR. As noted by Goldsmith et al. (1987b), the process of dust formation can be very rapid and possibly detected on time-scales of days. From the above discussion, episodic appearance of small dust particles in the CS environment can be suggested for DS Aqr, UY Ara, R Sct, RY Sgr and V1711 Sgr.

5. Polarization and photometry

It is of interest to compare the polarimetric data with optical and IR photometry obtained simultaneously. Note, however, that a simple comparison of photometric changes with variations in the degree of observed polarization can be misleading. For example, if the IS component of polarization dominates, and the intrinsic and IS polarization vectors are orthogonal, the *observed* degree of polarization, being the vector sum of the two components, can *decrease* even if the intrinsic polarization *increases*. For this reason, if the IS polarization component is undetermined, it is possible to discuss only the correspondence between photometric and polarimetric variability, without drawing any conclusions regarding changes in the polarization.

RU Cen was observed polarimetrically around a secondary minimum (which occurs at phase $\phi = 0.5$; see Fig. 5 of Pollard et al. 1996) on JD6991 ($\phi = 0.46$) and on JD7000 ($\phi = 0.60$). Although the second measurement shows variation in the PA ($\Delta\theta \approx 40°$), variations in the degree of polarization were small. No other polarimetric data have been published for this object.

AI Sco. Taking into account the ephemeris of Pollard et al. (1997) we observed the star in its bright state ($\phi = 0.39$ for JD7000) and near a deep minimum ($\phi = 0.97, 0.99$ for JDs7041, 7042; see Fig. 18 of Pollard et al. 1996). The polarization behaviour was unusual. In spite of a large ($\approx 3^{\rm m}$) decrease of flux in the V band, changes in the degree of polarization were relatively small ($\Delta P \sim 0.7\%$ at constant PA $\sim 170°$). Moreover, a decrease in the V-band flux coincided with an *decrease* in polarization; however allowance for IS polarization results in an increase of P_* in the last measurement, corresponding to a decrease of visual flux (i.e. contrary to variations in the *observed* polarization).

RY Sgr. The photometric period for this object is well determined and an ephemeris is given by Lawson & Cotterell (1990); additional photometric data for the time of our observations are given by Manfroid et al. (1991). Using these data, and adding our V-band measurements, we re-construct a more detailed light curve for the period between JD6900–7200 (see Fig. 6). As is evident, our polarimetry was obtained close ($\phi \approx 0.9$ for JD7000, $\phi \approx 0.1$ for JD7042) to two consecutive light maxima. The level of polarization in both measurements

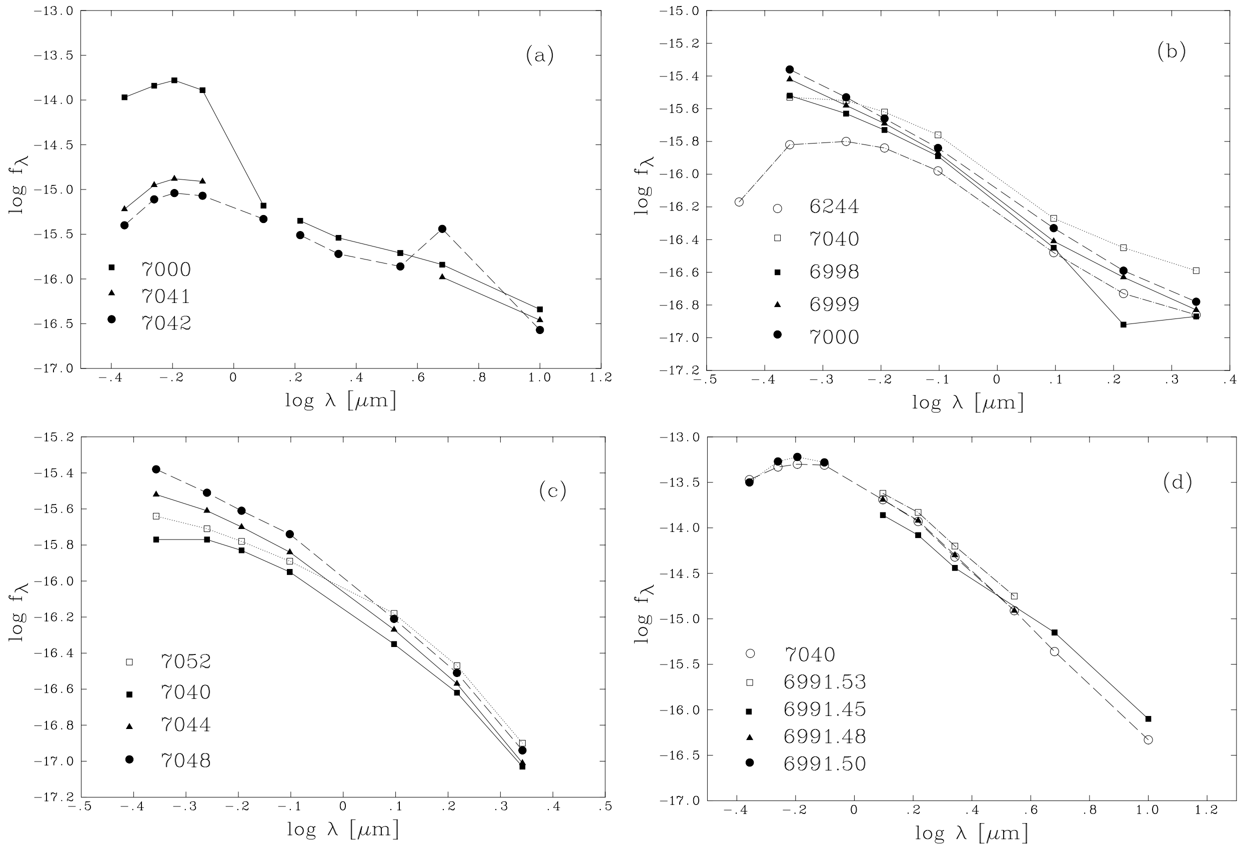

Fig. 5. Spectral energy distributions derived from synchronous optical-IR photometry; f_λ in W m^{-2} μm^{-1}. Data dereddened by the $E(B-V)$ indicated in brackets. **a)** AI Sco (0.35); **b)** UY Ara (0.17); **c)** DS Aqr (0.0); **d)** R Sct (0.25). Symbols are identified by JD – 2 440 000. Lines are included to guide the eye.

was small (≈0.2%–0.4%) but the PA between the observations changed by ≈90°. Note, however, that our data were obtained in different filters ($I_{\rm C}$ and "C"), so a direct comparison is almost certainly not justified. The *UBVR* polarimetry of RY Sgr published by Rosenbush (1995) show a higher level of polarization (∼0.5–0.8%, compared to our 0.2% in $I_{\rm C}$ and 0.37% in "C"), with PA $\theta = 178°$, close to our $\theta_{\rm C} = 171°$ obtained when the star was significantly fainter ($m_V \approx 7\overset{\rm m}{.}6$–$8\overset{\rm m}{.}3$). Strong polarimetric variability in RY Sgr was also detected by Serkowski & Kruszewski (1969) both in the degree of polarization ($\Delta p \sim 1\%$) and in PA ($\Delta\theta \approx 100°$) without, however, any obvious correlation with brightness variations.

The observed polarization values for RY Sgr differ by only 0.17%, but show a large difference in PA, ≃90°. After correction for the IS component we obtain $P_* = 0.64\%$ at $\theta = 166°$ for the first measurement, and $P_* = 1.26\%$ at $\theta = 172°$ for the second: the large difference in PA of the *observed* polarization disappears. Although both observations were made at exactly the same light curve level ($V = 6\overset{\rm m}{.}29$), on the second date the star was redder (by $\simeq 0\overset{\rm m}{.}2$; see colours in Table 3), accompanied by an increase of all the red/IR fluxes, from $R_{\rm C}$ to Q, by the same amount $\simeq 0\overset{\rm m}{.}2$.

U Aqr. The only polarimetric measurement of U Aqr, in one pass-band, was published previously by Rosenbush & Rosenbush (1990): $P_V = 0.5\pm0.2\%$, $\theta = 158°\pm8°$ at $V \approx 11\overset{\rm m}{.}0$, i.e. at maximum light ($\phi \approx 0.42$). Our $UBVR_{\rm C}I_{\rm C}$ measurements were made on one night only, at $V \approx 11\overset{\rm m}{.}8$ (phase $\phi \approx 0.85$) and they show a higher value of polarization in the V band (about 1%) at approximately the same PA (within the errors).

SX Cen. For this object a light curve covering the period of our observations is given by Shenton et al. (1994c). SX Cen was observed at phases 0.85 and 0.12, i.e. before and after the deep minimum. In the second measurement (after minimum) SX Cen was brighter by about $0\overset{\rm m}{.}2$ in the optical and the degree of polarization (in the "C" band) decreased by about 0.15–0.2%, without significant changes in PA. The observed polarization for SX Cen was larger *before* and smaller *after* minimum light. However the *intrinsic* polarization again shows the contrary behaviour, which is more typical for these stars and more easily understood.

R Sct. The mean level of polarization detected is about 0.5%. R Sct was also observed polarimetrically around deep minimum, at phases 0.80, 0.86 and 0.15 (see the light curve in Shenton et al. 1994b). Although both polarimetric and photometric variability are clearly seen in our data, no pronounced correlations between them were apparent. The polarization in both filters used ($BI_{\rm C}$) has a tendency to increase in magnitude, whereas the visual flux decreases by $0\overset{\rm m}{.}5$ from phases 0.8 to 0.85, and thereafter increases by $0\overset{\rm m}{.}3$.

Although *UY Ara* has been observed at different phases (0.84 and 0.53), no significant variations in brightness or in polarization occur. Taking into account the $85^{\rm d}$ photometric

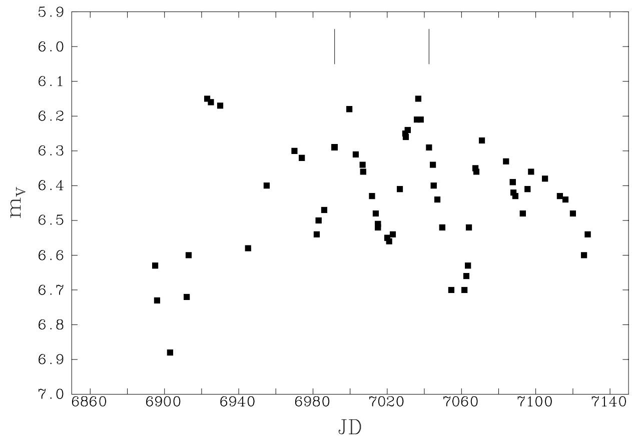

Fig. 6. Light curve of RY Sgr; the times of our polarimetry are indicated.

period of *BU Cen*, we observed it at the same phase. A relatively small increase (≈$0^{\rm m}.15$) in the visual flux was accompanied by a decrease of polarization, by about 0.5%, with a possible rotation in the PA. The small variations in brightness and polarization in R Sge do not enable us to draw any conclusions about the link between them.

DS Aqr. Photometric variations in brightness were large in the optical and IR regions ($0^{\rm m}.96$, $0^{\rm m}.66$ in *BV* and $0^{\rm m}.45$ in *JHK*). Changes in the polarization parameters also reach values of 0.4% and 40°, but no correlations between P and optical-IR magnitudes were found.

UW Cen. Although the increase of V by $0^{\rm m}.13$ corresponds to a decrease of polarization, the error in the first P measurement is too large to enable us to draw any conclusions. Note that our polarimetric data are in agreement with the single "clear filter" datum of Rosenbush & Rosenbush (1990) [1.2 ± 0.4% and 56° ± 10°].

As noted in Sect. 3.3, at least 5 objects (RU Cen, R Sge, AI Sco, R Sct, RY Sgr) show flat $P(\lambda)$ dependence (see Fig. 2). The same conclusion can be drawn from previously-published polarimetric data for other RV stars: AC Her, U Mon, V Vul, SS Gem (Serkowski 1970; Raveendran et al. 1989; Nook et al. 1990). Our conclusion regarding large particle size as inferred from the variations in the SEDs (see Sect. 3.2) are consistent with the wavelength-dependence of polarization.

To account for the flat wavelength-dependence of polarization, dust particles of any reasonable composition (e.g. silicate, magnetite, graphite) can not have radii $\lesssim 0.1\,\mu$m (see e.g. Kruszewski et al. 1968; Zickgraf & Schulte-Ladbeck 1989). For most of our programme stars, the dimensions of the dust particles would be even larger if subtraction of an IS component of polarization is taken into account (see above). This is consistent with our multi-colour photometry, and supports the view that non-selective extinction is permanently present in the CS environments of these stars. In fact, for only a few stars (R CrB itself, TW Cam, AR Pup) does the detected $P(\lambda)$ dependence (occasionally steeper than λ^{-2}) indicate Rayleigh scattering by particles of sizes 0.05 to $0.1\,\mu$m (Coyne & Shawl 1973; Nook et al. 1990; Raveendran 1999).

6. Concluding remarks

We have presented optical polarimetry, and optical/IR photometry, of a number of RV and R CrB stars.

In a few cases we detect wavelength-independent flux variations, with amplitude from $0^{\rm m}.5$ to $1^{\rm m}.0$: it seems that neutral extinction, caused by large dust particles with dimension $a \gtrsim 0.15\,\mu$m likely plays an important rôle in the dusty CS envelopes responsible for the observed IR excesses.

Determination and subtraction of the IS component of polarization allowed us to determine the level of intrinsic polarization to be about 1%, but in some cases it is on the order of 1.5%–2% even in the bright photometric state. We consider this to be evidence for the presence of permanent optically thin ($\tau < 0.5$), non-spherical dust shells viewed at different inclination angles around selected RV and R CrB stars.

Unfortunately, none of the 150 or so objects of the RV and R CrB classes have been observed polarimetrically in IR. We stress the importance of conducting IR polarimetry of these stars, as such observations can be a very simple test of the presence of the large dust grains suggested by the neutral CS extinction.

Acknowledgements. We thank Dr S. Trammell for her helpful comments on an earlier version of this paper. RVY was supported by a Royal Society Grant, the Program of Prezidium of RAN No.4 and GNTP "Astronomy". This paper uses observations made at the South African Astronomical Observatory (SAAO). This work made use of the *SIMBAD* database.

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Online Material

Table 3. SAAO optical (BVR_CI_C) photometry.

Object	JD 2 440 000+	V	$B-V$	$V-R_C$	$V-I_C$
RU Cen	6991.289	9.14	0.83	0.45	0.98
	7000.902	9.02	0.53	0.35	0.76
BU Cen	6991.361	11.59	1.75	0.96	2.11
	6995.323	11.43	1.67	0.91	1.99
DS Aqr	6991.627	10.69	0.69	0.39	0.84
	7040.465	10.82	0.65	0.36	0.74
	7041.775	10.78	0.56	0.39	0.73
	7042.490	10.72	0.53	0.32	0.71
	7044.485	10.42	0.44	0.29	0.61
	7048.494	10.16	0.35	0.25	0.60
	7052.618	10.67	0.49	0.33	0.73
UY Ara	6998.459	10.93	0.55	0.33	0.69
	6999.444	10.82	0.41	0.32	0.64
	7000.436	10.69	0.40	0.27	0.58
	7040.346	10.74	0.76	0.42	0.83
AI Sco	6998.512	6.77	1.28	0.67	1.28
	6999.454	6.79	1.29	0.69	1.30
	7000.500	6.90	1.27	0.66	1.30
	7041.338	9.67	1.62	0.84	1.62
	7042.359	10.06	1.68	0.83	1.61
R Sge	6994.516	8.90	0.96	0.51	1.04
	6998.476	8.78	1.01	0.54	1.06
	6999.483	8.85	1.01	0.55	1.06
	7000.465	8.91	1.41	0.51	1.06
R Sct	6991.500	5.34	1.50	0.74	1.45
	7000.483	5.81	1.51	0.76	1.65
	7040.372	5.51	1.26	0.71	1.54
SX Cen	6991.318	10.15	1.09	0.58	1.23
	6995.299	10.58	1.10	0.60	1.22
	6999.294	10.04	0.86	0.52	1.04
	7000.284	9.94	0.81	0.49	1.04
UW Cen	6991.339	11.78	1.22	0.68	1.40
	7000.300	11.65	1.26	0.69	1.40
RY Sgr	6991.607	6.29	0.50	0.27	0.48
	6999.595	6.18	0.64	0.36	0.54
	7042.460	6.29	0.70	0.37	0.73
DY Cen	6999.307	12.61	0.34	0.25	0.56
	7000.322	12.64	0.31	0.21	0.47
V1711 Sgr	6999.611	10.22	0.45	0.30	0.63
	7040.434	10.72	0.88	0.47	0.94
U Aqr	9575.550	11.8*	…	…	…

* Error = ±0.1 mag.

Table 4. SAAO infrared ($JHKL$) photometry.

Star	JD 2 440 000+	J	H	K	L
DS Aqr	7040.45	9.55	9.13	9.04	…
	7044.46	9.35	9.02	8.98	…
	7048.48	9.18	8.87	8.82	…
	7052.46	9.11	8.77	8.72	…
UY Ara	6998.32	9.92	9.97	8.68	>6.5
	6999.29	9.82	9.26	8.58	>6.5
	7000.36	9.62	9.15	8.46	>6.5
	7040.28	9.48	8.79	7.99	6.50*
BU Cen	6991.27	8.43	7.66	7.34	>6.5
DY Cen	7000.32	12.17*	12.06*	11.72	>6.5
RU Cen	7000.24	7.68	7.19	6.89*	6.36*
SX Cen	6998.23	8.55	7.92	7.42	5.84
	6999.23	8.37	7.75	7.20	5.71
	7000.25	8.19	7.80	7.02	5.67
UW Cen	7000.27	9.21	8.29	6.90	>6.5
R Sge	6998.46	7.11	6.54	5.99	4.60
	6999.54	7.13	6.56	5.97	4.59
	7041.44	8.02	7.51	7.44	…
RY Sgr	6991.55	5.65	5.44	4.87	2.93
	7000.50	5.46	5.25	4.70	2.78
	7042.47	5.43	5.22	4.71	2.86
V1711 Sgr	6999.49	9.17	8.72	8.21	6.74
	7040.39	9.14	8.63	8.10	6.60
AI Sco	7000.40	6.87	6.12	5.42	3.91
	7042.38	7.25	6.52	5.86	4.29
R Sct	6991.45	3.54	2.93	2.66	…
	6991.48	3.11	2.54	2.30	1.90
	6991.53	2.94	2.32	2.04	1.52
	7000.49	3.10	2.49	2.22	1.65
	7040.26	3.11	2.57	2.36	1.91

* Error = ±0.2 mag.

Table 5. CTIO infrared photometry.

Star	JD 2 440 000+	J	H	K	L	M
DS Aqr	6958.91	8.94	9.03	8.94	…	…
R Sge	6953.83	7.44	6.92	6.17	4.50	3.14*
	6958.83	6.67	6.53	5.90	4.55	3.70*
	6958.92	6.66	6.56	5.96	…	3.77*
RY Sgr	6958.84	4.93	5.19	4.57	2.64	1.40
R Sct	6953.76	3.16	2.62	2.25	1.69	1.13
	6958.80	3.03	2.56	2.22	1.71	1.46

* Error = ±0.2 mag.

Table 6. SAAO infrared (*MNQ*) photometry.

Star	JD 2 440 000+	[*H*]	*M*	*N*	*Q*
UY Ara	6994.34	...	...	3.96	...
SX Cen	6992.26	...	4.10	1.99	1.97
RY Sgr	6991.55	...	1.66	0.27	–0.61
	7000.50	...	1.36	–0.46	–0.84
V1711 Sgr	7000.49	8.02	5.19	3.45	...
	7040.39	...	6.51	5.43	...
AI Sco	7000.39	...	2.89	0.97	0.09
	7041.33	5.94	3.24	1.27	–0.18
	7042.39	...	1.89	1.53	0.04
R Sct	6991.45	...	1.15	0.36	0.46
	7040.28	...	1.67	0.93	–0.01