Infrared observations of cataclysmic variables

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Abstract. We review infrared (1–2.5 μm) observations of cataclysmic variables, a relatively unexplored part of the spectrum in which the dominant sources of emission are the secondary star, the outer regions of the accretion disc and the accretion column in magnetic systems. We describe the advances that have been made in our understanding of cataclysmic variables based on infrared photometry and, more recently, infrared spectroscopy and present spectra of each class of cataclysmic variable – the dwarf novae, novalikes, polars and intermediate polars.

1. Introduction

The infrared (IR) extends from a wavelength of 1 μm, close to the limit of optical CCDs, through the near-infrared (1–5 μm), the mid-infrared (5–25 μm) and the far-infrared (25–350 μm). In contrast to the optical, the molecules of H_2O and CO_2 in the earth's atmosphere absorb very strongly at some IR wavelengths, resulting in relatively transparent regions which define the IR photometric bands: J (1.1–1.4 μm), H (1.5–1.8 μm), K (2.0–2.4 μm), L (3.0–4.2 μm), M (4.5–5.2 μm), N (8–13 μm) and Q (17–22 μm). At wavelengths longer than Q, the IR is only accessible from space. The vast majority of IR observations of cataclysmic variables (CVs) have been performed in the so-called non-thermal part of the near-infrared (1–2.5 μm), and for good reason. This is the only IR region where CVs can be readily detected against the background, as thermal emission due to the observing environment (such as the telescope structure and optics) and from optically thick telluric absorption lines rises very rapidly at wavelengths longward of 2.5 μm, to such an extent that at 10 μm the background is approximately equal in brightness to the brightest astronomical source known. The 1–2.5 μm wavelength range also happens to be where the spectrum of the G–M-dwarf secondary star in CVs is expected to peak[1] and where low-harmonic, cyclotron emission from the weaker-field magnetic CVs and emission from the cool, outer regions of the accretion disc in non-magnetic CVs would be expected to fall. For the above reasons, it is clear that observations of CVs in the 1–2.5 μm region are highly desirable and this review will concentrate exclusively on this wavelength range – for a description of the very few observations of

[1] The wavelength, λ_{max}, of the peak flux, f_ν, for a star of effective temperature T_{eff} can be approximated by: $\lambda_{max} = 5100/T_{eff}$ μm. With T_{eff} ranging from $\sim$6000–2000 K on the G–M-dwarf secondary stars in CVs, λ_{max} ranges from $\sim$1–2.5 μm.

CVs at longer IR wavelengths, which are mainly sensitive to emission from dust grains in CVs, see Berriman, Szkody & Capps (1985), Jameson et al. (1987), Harrison & Gehrz (1992) and Howell, Herzog & Robson (1996).

Observing in the 1–2.5 μm region is not easy. There are two main reasons for this. First, even though this is the non-thermal region of the IR, the background is still high compared to the optical part of the spectrum. This is due to atmospheric emission from molecules (primarily OH^- and O_2) excited by solar radiation during the day. The resulting airglow is both temporally and spatially variable and results in a sky which can be up to 1000 times brighter in K than it is in V. Second, IR detector arrays have only recently come of age and still have higher readout noise, higher dark current and are of a smaller size than their optical counterparts. It is for these reasons that the astronomical literature on IR observations of CVs is relatively sparse when compared with optical, ultraviolet and X-ray studies (with the exception of novae, which are reviewed by Gehrz elsewhere in this volume and will not be discussed further). In fact, one might regard the present status of IR observations of CVs as akin to the status of optical observations of CVs nearly 40 years ago, when Kraft and co-workers were performing the first spectroscopic surveys and time-resolved studies of CVs in the optical.

2. Infrared photometry of cataclysmic variables

The first IR observations of CVs were performed by Szkody (1977), who obtained J, H, K and L-band photometry of a number of CVs, and Sherrington et al. (1980), who obtained the first IR light curves of CVs (EX Hya and VW Hyi in the J and K-bands). There followed a burst of observational activity, culminating in the work of Berriman, Szkody & Capps (1985), who reviewed the origin of the IR light from CVs. They found that the dominant contributors are the (optically thick) atmosphere of the secondary star and both the optically thin and the (cool) optically thick outer regions of the accretion disc, the optically thin emission arising from the same gas that gives rise to the optical and ultraviolet emission lines. By plotting IR two-colour diagrams, Berriman, Szkody and Capps (1985) found that the proportion of light supplied by each component varies widely from system to system due to the complex nature of the disc. This makes it impossible to disentangle the secondary star and accretion disc components by IR photometry alone, as an earlier-type secondary and an optically thin disc can account for the IR colours of a CV just as well as a later-type secondary and an opaque disc. As a consequence, IR photometry can only give an upper limit to the proportion of light contributed by the secondary star.

IR photometry of CVs has proved of most use in the determination of two fundamental parameters: the inclination of the orbital plane and the distances to CVs. In a binary of moderate to high inclination, the asymmetric Roche lobe causes the flux from the secondary to be modulated twice per orbital period, with maximum brightness when the lobe is seen sideways on. Apart from directly confirming the highly distorted shape of the secondary, this so-called ellipsoidal modulation can aid in determining the inclination of the binary (e.g. Berriman et al. 1983; Somers, Mukai & Naylor 1996). Any contribution to the

IR light from the accretion disc, however, results in an observed modulation which is smaller than the actual ellipsoidal modulation. As the amplitude of the ellipsoidal modulation is correlated with the orbital inclination (large amplitudes imply a high inclination), this means that modelling the observed IR light curves will underestimate the binary inclination. The only way of obtaining accurate inclinations in this way is to determine the contribution of the accretion disc to the IR light by detecting absorption lines from the secondary star with IR spectroscopy (e.g. Shahbaz et al. 1996).

The distances to CVs can be measured from K-band photometry using a method first proposed by Bailey (1981) and later refined by Berriman (1987) and Ramseyer (1994). The distance modulus can be rewritten in terms of the K-band surface brightness of a star as $S_k = K + 5 - 5\log d + 5\log(R/R_\odot)$, where K is the apparent K magnitude, d is the distance in parsecs and R is the radius of the star. For a star of one solar radius, S_k is equivalent to the absolute K magnitude. Since the radius of the secondary star is equal to the radius of the Roche lobe, the orbital period and mass of the secondary are sufficient to estimate its radius (there is also a weak dependence on mass ratio). Given the K magnitude, all of which is assumed to be due to the secondary, and the value of S_k, which can be obtained if one knows the V–K colour (or spectral type) of the secondary using the empirical calibrations derived from field dwarfs by Ramseyer (1994), it is possible to estimate the distance using the above equation. This technique has been put to good use by a number of authors, such as Warner (1987), who used the distances to determine the absolute magnitudes of the discs of CVs, and Sproats, Howell & Mason (1996), who used the distances to determine that most faint CVs at high galactic latitude are not in the galactic halo but are nearby and intrinsically faint. It was argued above, however, that IR photometry can only ever give an upper limit to the proportion of light contributed by the secondary star and hence the distances determined by this method are only ever lower limits. The only way of obtaining accurate distances is to determine the contribution of the accretion disc to the K-band light by detecting absorption lines from the secondary star with IR spectroscopy.

3. Infrared spectroscopy of cataclysmic variables

It has only recently become possible to perform IR spectroscopy of CVs at useful spectral resolutions ($\lambda/\Delta\lambda \gtrsim 10^2$–$10^3$): the first published IR spectra of CVs were of the intermediate polar EX Hya (Bailey 1985; see also the very low resolution spectrum of Frank et al. 1981) and the polar AM Her (Bailey, Ferrario & Wickramasinghe 1991). The first spectral surveys in the IR were published by Ramseyer et al. (1993), at a low spectral resolution, and Dhillon & Marsh (1993, 1995), at an intermediate spectral resolution. To date, there have been no published time-resolved studies or high spectral-resolution studies of CVs in the IR. To further illustrate how rarely these objects have been studied in the IR it should be noted that, with the exception of the work mentioned above and the work on polars by Ferrario, Bailey & Wickramasinghe (1993, 1996), every IR spectrum of a CV that has ever been published (to the best of the author's knowledge) is presented in Figures 1–5 and is described below, grouped by class of CV.

3.1. Dwarf novae above the period gap

In Figure 1 we present IR spectra of dwarf novae which lie above the ~2–3 hr period gap (RU Peg, SS Cyg, RX And and IP Peg; Dhillon & Marsh 1995). The IR spectra of the dwarf novae are dominated by strong emission lines of He I and the Paschen and Brackett series of H I. The large velocity widths of these lines (typically 1000–2000 km s^{-1} FWHM, depending on the inclination of the binary) and the fact that they are so strongly in emission (typical equivalent widths of ~10 Å) imply an accretion disc origin. The IR spectra of the dwarf novae also show a number of absorption features which, on comparison with the IR spectra of the M4.5V and K3V field-stars in Figure 1, can be identified with neutral metal lines of Al I, Na I, Ca I, Mg I and ^{12}CO molecular-bands from the secondary star. The M4.5V field-star also exhibits a distinctive water absorption band longward of ~2.3 μm, which is not present in the K3V field-star. This feature is an excellent indicator of spectral type in CVs as it is so prominent. As one might expect, the longer period CVs in Figure 1 (RU Peg, SS Cyg, RX And) do not show this water band, implying their secondary is a K-star, whereas the shortest period CV in Figure 1 (IP Peg) does show the water band, implying its secondary is an M-star.

Once absorption features have been detected, there are two ways in which the contribution of the secondary star to the IR light can be determined from IR spectra. The first is by an optimal subtraction technique (Dhillon & Marsh 1993), where a constant times a spectrum of a field-dwarf template is subtracted from the CV spectrum, the constant being chosen to minimize the residual scatter in regions containing secondary star features (the scatter is measured by carrying out the subtraction and then computing the χ^2 between the resulting spectrum and a smoothed version of itself). The spectral type of the template which gives the lowest value of χ^2 is the spectral type of the secondary star. Note that if the above optimal subtraction is performed on normalized spectra, the constant is then equal to the fractional contribution of the secondary star to the IR light and the resulting spectrum is that of the fractional contribution of the accretion disc. The second technique relies on plotting flux-deficit ratios (Wade & Horne 1988; Dhillon & Marsh 1995). The equivalent widths of individual absorption features cannot be used to determine the contribution of the secondary star to the IR light, since they are affected by the continuum from the accretion disc. The accretion disc is too hot to contribute to the cool stellar absorption features, however, and hence the ratios of absorption-line flux deficits can be used. In the K-band, Dhillon & Marsh (1995) found the optimum results were obtained using the ratio of the strength of the water band longward of ~2.3 μm to Na I at 2.21 μm plotted against the ratio of the same water band to the predicted continuum level above the water band. On such a plot, the spectral-type of a CV can be determined from its position relative to field-dwarf templates on the water/Na I axis and the contribution of the disc to the IR light is given by the distance of the CV from the field-dwarf templates along the water/continuum axis. From the spectra presented in Figure 1, Dhillon & Marsh (1995) concluded that the spectral types of the secondary stars determined from IR spectra are in agreement with optical estimates, which indicate that all but the longest period CVs generally contain secondary stars which are indistinguishable from main-sequence stars (Smith & Dhillon 1997).

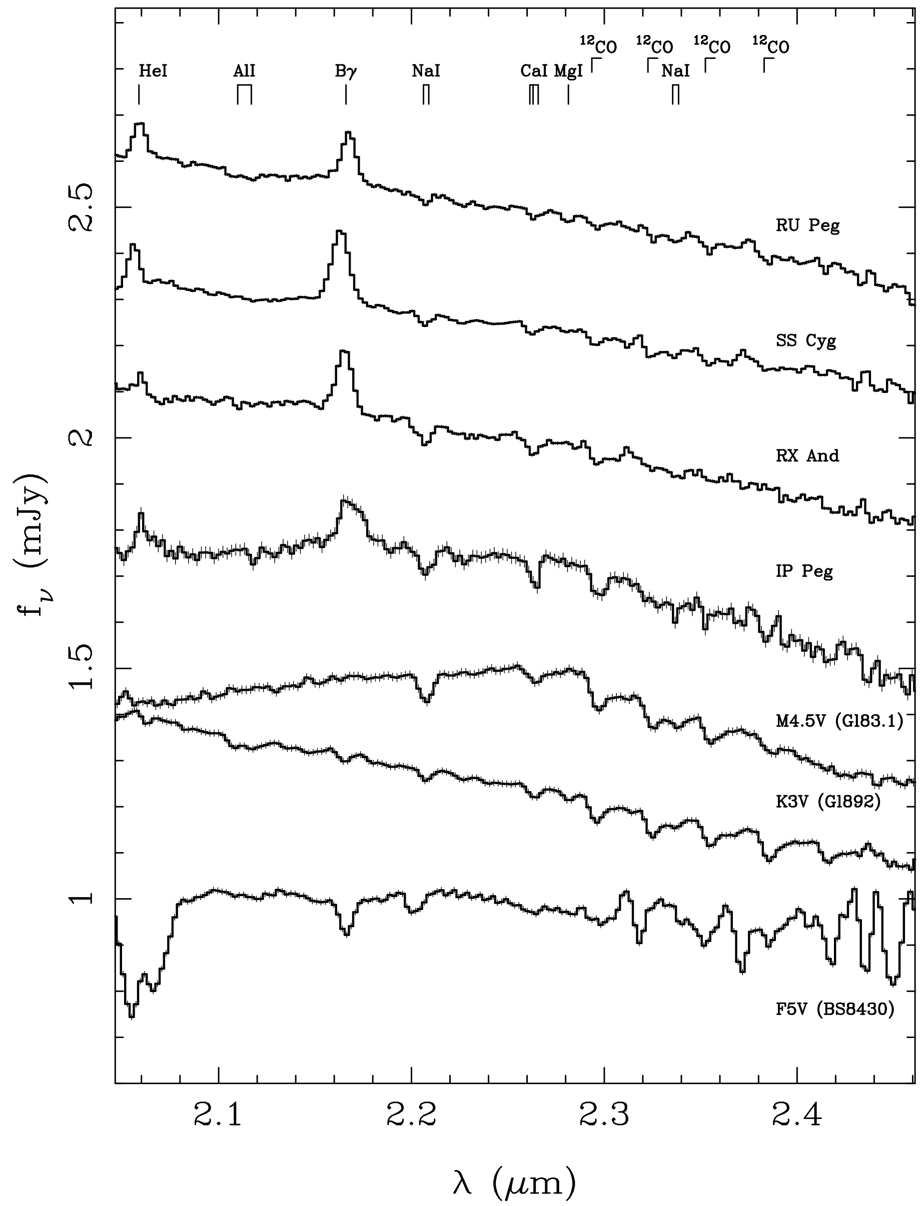

Figure 1. Infrared spectra of the dwarf novae RU Peg, SS Cyg, RX And and IP Peg, which all lie above the period gap. Also shown are the spectra of M4.5 and K3 dwarf stars. The spectra have been normalized by dividing by the flux at 2.24 μm and then offset by adding a multiple of 0.25 to each spectrum. The lowermost spectrum is of an F5V star, normalized by dividing by a spline fit to its continuum, which indicates the location of telluric absorption features.

3.2. Dwarf novae below the period gap

In Figure 2 we present IR spectra of dwarf novae which lie below the period gap (YZ Cnc, LY Hya, BK Lyn, T Leo, SW UMa and WZ Sge; Dhillon et al. 1997b). As in Figure 1, the spectra are dominated by strong emission lines of H I and He I. The higher resolution of this data (compared to the data presented in Figure 1) has resolved the double-peaked emission lines of the high-inclination dwarf novae LY Hya and WZ Sge, thereby confirming that the emission lines originate in the accretion disc. Unlike the IR spectra of the dwarf novae above the period gap, however, there are no clear detections of absorption features from the secondary star in the IR spectra of the dwarf novae below the period gap. The only possible exception is WZ Sge, which appears to display the red continuum indicative of a late-type secondary star (c.f. the spectrum of the M7V star at the foot of Figure 2). If the continuum in WZ Sge were largely due to the secondary star, however, one would also expect to see a change in slope redward of $\sim$2.3 μm due to the strong water absorption band displayed by M-dwarfs. Such a change in continuum slope is not observed in WZ Sge, although it is conceivable that blended emission lines near the H I Pfund-limit act to fill in the absorption band.

Most of the dwarf novae presented in Figure 2 have also been studied in the optical for evidence of absorption features from the secondary star – in every case the secondary remained undetected (Friend et al. 1988; Still et al. 1994; Smith et al. 1997). In fact, the results of these optical surveys reveal that virtually all of the secondary stars in dwarf novae below the period gap remain undetected (HT Cas (Marsh 1990) and Z Cha (Wade & Horne 1988) are two of the rare exceptions to this rule). The secondary stars in CVs below the period gap are expected to be of spectral type $\sim$M5 or later,[2] indicating that their spectra should peak in the K-band. Hence it is perhaps not surprising that optical surveys have struggled to find the small, cool secondary stars in dwarf novae below the period gap. The fact that even our K-band survey presented in Figure 2 has not detected them implies that the secondary stars in dwarf novae below the gap generally contribute a smaller fraction (typically $<$25%) of the total IR light than the secondary stars in dwarf novae above the period gap (which usually contribute $>$75%).

There is a strong motivation to detect the secondary stars in CVs below the period gap. The models of Kolb (1993) predict that 99% of the present-day intrinsic population of CVs should be below the period gap and approximately 70% of these systems will have already reached the orbital period minimum (at $\sim$80 min) and should be evolving back towards longer periods. The secondary stars in these post-period-minimum CVs have been modelled by Howell, Rappaport & Politano (1997), who find them to be degenerate, brown dwarf-like objects with masses between 0.02–0.06 $M_\odot$ and radii near 0.1 $R_\odot$. Howell, Rappaport & Politano (1997) further speculate that the so-called tremendous outburst amplitude dwarf novae, or TOADs, are these post-period-minimum CVs. If this is true, then one test of their hypothesis would be to obtain IR

[2]The spectral type of the secondary star in a CV can be determined from its orbital period, P, using the relationships $27.1 - 0.9P$ (for $P < 4$ hr) and $33.7 - 2.7P$ (for $P > 4$ hr), where G0=0, K0=10 and M0=20 (Smith & Dhillon 1997).

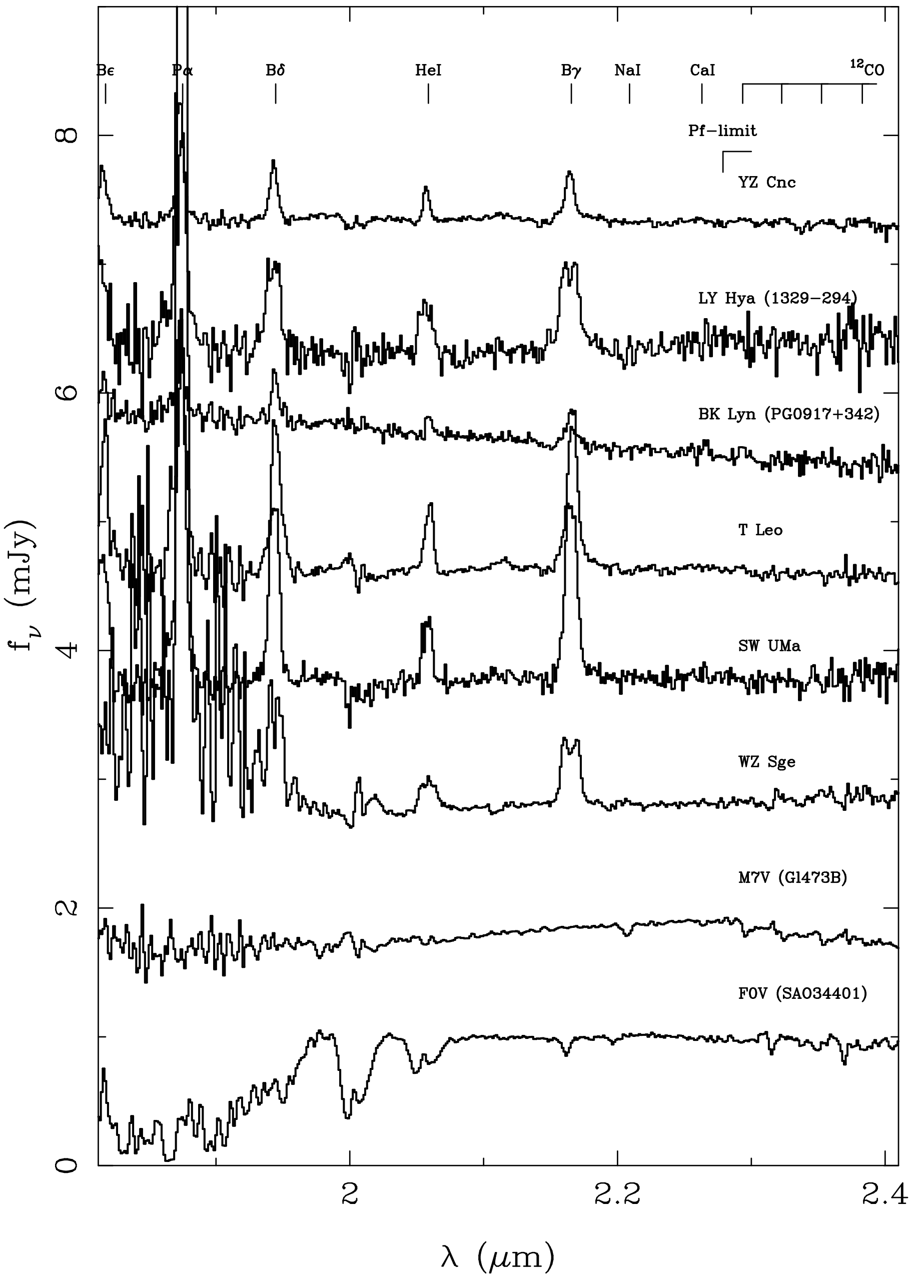

Figure 2. Infrared spectra of the dwarf novae YZ Cnc, LY Hya, BK Lyn, T Leo, SW UMa and WZ Sge, which all lie below the period gap. Also shown is the spectrum of an M7 dwarf star. The spectra have been normalized by dividing by the flux at 2.24 μm and then offset by adding a multiple of 0.9 to each spectrum. The lowermost spectrum is of an F0V star, normalized by dividing by a spline fit to its continuum, which indicates the location of telluric absorption features.

spectra of TOADs with orbital periods near 2 hr (the longest period attainable by a post-period-minimum CV given current estimates for the age of the galaxy) and determine the spectral types of their secondary stars. If the TOADs are pre-period-minimum CVs, a system with an orbital period of 2 hr should contain a main-sequence secondary of spectral type ∼M5,[2] whereas if the TOADs are post-period-minimum CVs, a 2 hr system would have a brown dwarf-like secondary, with a spectrum similar to that of a very late-type M-dwarf (cooler than M9; Jones et al. 1994). Assuming the secondary star can be detected, it is a simple matter to differentiate between an M5 and an M9 dwarf with IR spectra, thanks to the strong water absorption bands around 1.7 and 2.3 μm, which show a dramatic increase in strength towards later-type M-dwarfs (Jones et al. 1994). The problem with this approach, of course, is that it is not easy to detect the secondary stars in CVs below the period gap, as evidenced by the IR spectra of the TOADs WZ Sge, T Leo and SW UMa displayed in Figure 2. Even if we had detected the secondary star in WZ Sge, T Leo or SW UMa, however, these TOADs all have periods close to the orbital-period minimum and are hence not very sensitive to the test outlined above.

If one were to find post-period-minimum CVs, this would have a number of very interesting consequences. First, it would allow one to study brown dwarf-like secondary stars, and by invoking the Roche-lobe filling criterion, investigate the mass-radius relation. Second, the orbital periods of CVs with brown dwarf secondary stars can be used in conjunction with the models of Howell, Rappaport & Politano (1997) to place a lower limit on the present-day age of the Galaxy, t_G, and therefore an upper limit to the Hubble constant, H_0.

3.3. Novalikes

In Figure 3 we present IR spectra of the novalike variables GP Com, DW UMa, V1315 Aql, RW Tri, VY Scl and UU Aqr (Dhillon & Marsh 1997). Note that the anti-dwarf novae DW UMa and VY Scl were both in their high state when the spectra in Figure 3 were obtained. With the exception of the double-degenerate system GP Com, which will be discussed in more detail below, the spectra in Figure 3 are dominated by strong, single-peaked emission lines of H I (Bγ and Bδ) and He I (2.06 μm). This is in stark contrast to what one might expect from standard accretion disc theory, which predicts that emission lines from high inclination discs, such as those in the eclipsing systems DW UMa, V1315 Aql, RW Tri and UU Aqr, should appear double peaked. The absence of double-peaked profiles in high-inclination novalikes is also observed in the optical (e.g. Dhillon 1996) and is one of the defining characteristics of the so-called SW Sex stars, of which DW UMa and V1315 Aql are members.

RW Tri is the only novalike presented in Figure 3 which shows absorption features from the secondary star – one can clearly make out the profiles of Na I, Ca I and ^{12}CO in the spectrum. The distinctive water absorption band at ∼2.3 μm, so prominent in the spectrum of the M5V star at the foot of Figure 3, is absent in RW Tri, indicating that its secondary is most likely a late K-dwarf. This is confirmed both by the orbital period of RW Tri (5.6 hr), for which one would expect a secondary of spectral type ∼K7–M0 [2] and by the skew mapping experiments of Smith, Cameron & Tucknott (1993). There is no evidence for the secondary star in any of the other novalikes in Figure 3. This implies that

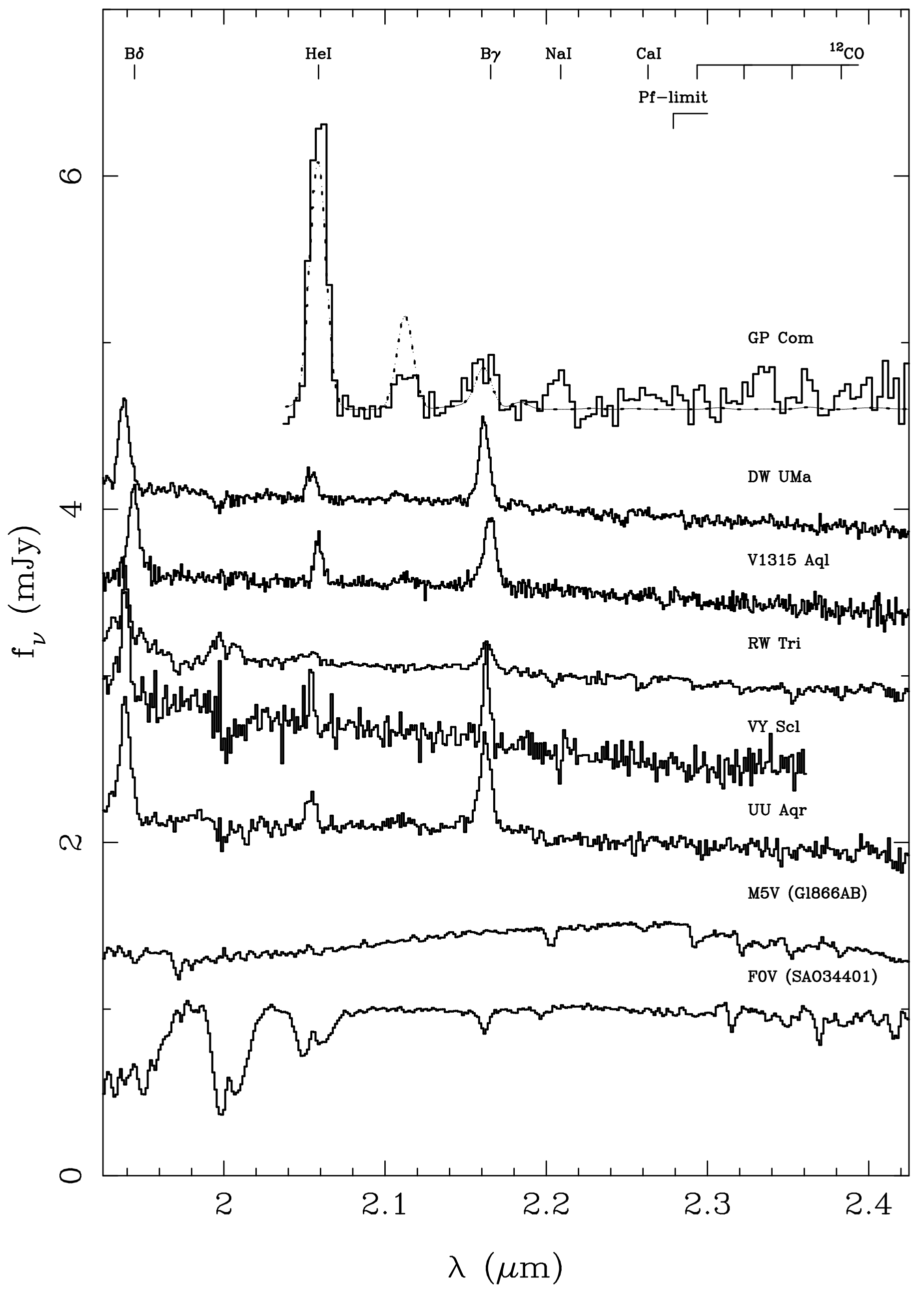

Figure 3. Infrared spectra of the novalike variables GP Com, DW UMa, V1315 Aql, RW Tri, VY Scl, UU Aqr and an M5V star. The spectra have been normalized by dividing by the flux at 2.24 μm and then offset by adding a multiple of 0.5 to each spectrum. Also shown is the spectrum of an F0V star, normalized by dividing by a spline fit to its continuum, which indicates the location of telluric absorption features. The dashed line under the spectrum of GP Com is a model spectrum from gas in LTE (see text for details).

the discs in these novalike variables (which are all just above the period gap) contribute a much larger fraction of the IR light than the discs of dwarf novae just above the period gap (e.g. IP Peg, Figure 1). In fact, it is possible to place an upper limit on the amount of light contributed by the secondary star, even when absorption features from the secondary are not visible. This can be done by normalizing all spectra and then subtracting a constant times a spectral-type template from the CV spectrum and inspecting the residuals for any (reversed) secondary star features. The value of the constant at which these reversed features become apparent in the residual spectrum then represents an upper limit to the fractional contribution of the secondary star to the total light. Applying this technique to the novalikes in Figure 3, we find that the secondary star generally contributes $\lesssim 25\%$ to the K-band light. A similar upper limit to the secondary star contribution was deduced from I-band observations of the novalike DW UMa in a low state by Marsh & Dhillon (1997). This is remarkable, as the low state was some 3 to 4 magnitudes fainter than the normal state of DW UMa, and yet there was still no sign of the secondary star. This implies that the secondary star in DW UMa has an apparent magnitude of I>19.5 and hence a distance of at least $\sim$850 pc if the secondary star has spectral type M4.[2] If this lower-limit to the distance is typical of most novalikes (or specifically, SW Sex stars), then it means that the mass transfer rates derived from techniques such as eclipse mapping (Rutten, van Paradijs & Tinbergen 1992) are underestimating the true values.

GP Com consists of a CO white dwarf and a helium degenerate star in an orbit of 46 min period. Neither star is directly visible – the optical light from the system is dominated by the accretion disc, which has a spectrum composed almost entirely of helium and nitrogen emission lines reflecting the products of hydrogen burning and CNO processing in the helium degenerate donor. A very simple model, based upon LTE emission from an $\sim 11\,000$ K optically thin (in the continuum) slab, provides a surprisingly good fit to the optical spectrum of GP Com (Marsh, Horne & Rosen 1991). In Figure 3, the same model has been applied to the IR spectrum of GP Com, with equally good results. The model predicts the existence of three strong emission lines in the K-band, all of He I, which are all present in the actual spectrum. Note that there is also some evidence for a fourth emission line in the spectrum at 2.2 μm that we have been unable to identify.

3.4. Polars

Polars were the first class of CV to be studied in detail with IR spectroscopy (Bailey, Ferrario & Wickramasinghe 1991). The motivation behind these and subsequent observations (Ferrario, Bailey & Wickramasinghe 1993, 1996) was a desire to determine the magnetic field strength of the white dwarf by observing cyclotron humps in their spectra. Cyclotron radiation in polars is produced by electrons gyrating along magnetic field lines in the accretion shock at the base of the accretion column and occurs at discrete harmonics of the fundamental frequency. In the high-energy environment of the accretion region, the harmonics are broadened and merge, causing humps in the emitted spectrum. The shape of these cyclotron humps provide invaluable measurements of the magnetic field strength, density, temperature and optical depth in the emission region.

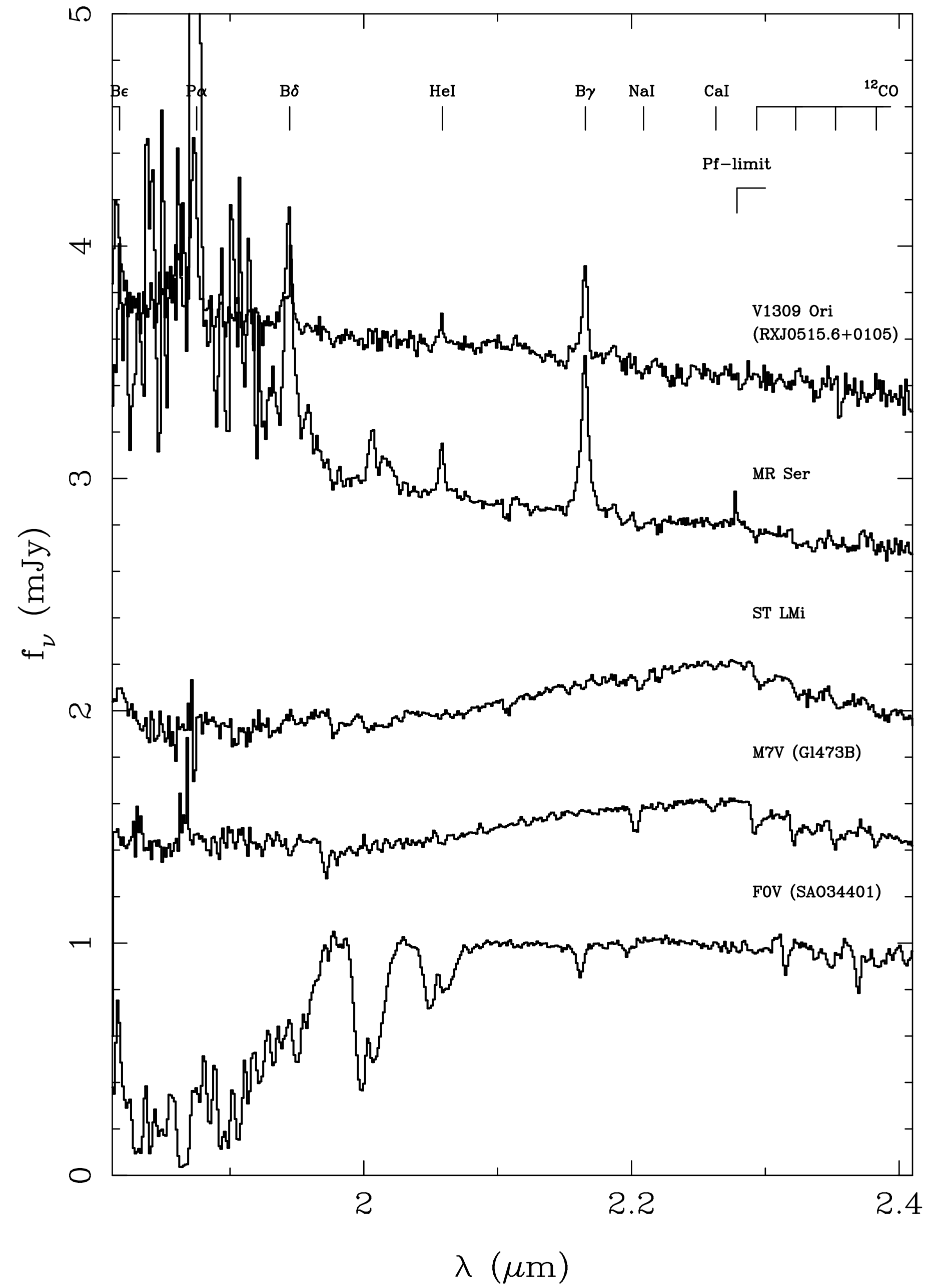

Figure 4. Infrared spectra of the polars V1309 Ori, MR Ser, ST LMi and an M7 dwarf star. The spectra have been normalized by dividing by the flux at 2.24 μm and then offset by adding a multiple of 0.6 to each spectrum. Also shown is the spectrum of an F0V star, normalized by dividing by a spline fit to its continuum, which indicates the location of telluric absorption features.

With fields in the range $B \sim$10–70 MG, the fundamental cyclotron frequencies in polars are in the IR from approximately 10 to 1 μm, respectively. The cyclotron humps extend bluewards from the fundamental, the higher order harmonics generally appearing in the optical and the lower order harmonics in the IR. It is not easy to detect high-order harmonics as they are often smeared by field spread and variations in temperature and density across an extended emission region. Low-order harmonics, however, are more easily resolvable, which led Bailey, Ferrario and Wickramasinghe to obtain IR spectra of the polars AM Her, ST LMi, EF Eri and BL Hyi and successfully detect cyclotron humps in these relatively weak-field systems for the first time.

In Figure 4 we present IR spectra of V1309 Ori (RXJ0515.6+0105; Harrop-Allin et al. 1997a), MR Ser and ST LMi (Dhillon et al. 1997b). V1309 Ori has a 7.98-h orbital period, the longest of any polar yet identified. The spectrum in Figure 4 was obtained around orbital phase 0.5 and reveals strong Paschen, Brackett and He I emission lines from the accretion column. No obvious spectral features from the secondary star are detected; the K-band emission is dominated instead by cyclotron radiation from the accretion region. By modelling the cyclotron emission in V1309 Ori, Harrop-Allin et al. (1997a) concluded that the shape of the IR spectrum is consistent with the long-wavelength tail of the cyclotron fundamental from a 60 MG field.

The IR spectrum of MR Ser shows no evidence of cyclotron humps or secondary star features. ST LMi, on the other hand, appears to have an IR spectrum composed entirely of light from the secondary star, as it looks virtually identical to the spectrum of the M7V star plotted directly beneath it. This is close to the spectral type one might expect of the secondary star given the 1.90-hr orbital period of ST LMi.[2] One can see that the rapid rotation of the secondary star in ST LMi has broadened the ^{12}CO absorption bands when compared to the ^{12}CO profiles in the slowly rotating M7 field dwarf. The most likely explanation for the spectrum of ST LMi is that we have observed it during one of its low states when there is no accretion occurring. It is exceptional, however, for the emission lines from the irradiated inner hemisphere of the secondary star to disappear in polars during a low state – the obvious explanation that our spectrum was obtained at an orbital phase when the inner hemisphere was obscured cannot be true as the spectrum in Figure 4 is a whole-orbit average.

3.5. Intermediate polars

The intermediate polars (IPs) are believed to have magnetic field strengths intermediate between polars and dwarf novae. The white dwarf rotation is not synchronized with the orbit in IPs, and the rotating magnetosphere of the primary is able to disrupt the accretion disc out to a radius where the ram pressure of the accretion flow balances the magnetic pressure: sufficiently strong fields are able to prevent the formation of an accretion disc altogether. A knowledge of the magnetic field strength in IPs is thus vitally important in determining the mode of accretion in IPs. Unfortunately, it has proved remarkably difficult to determine the field strength in IPs due to their weak fields. The success of Bailey, Ferrario and Wickramasinghe in measuring cyclotron features in the IR spectra of weak-field polars prompted Dhillon et al. (1997a) to observe intermediate polars (IPs) in the IR, since if the IPs have weaker fields than polars

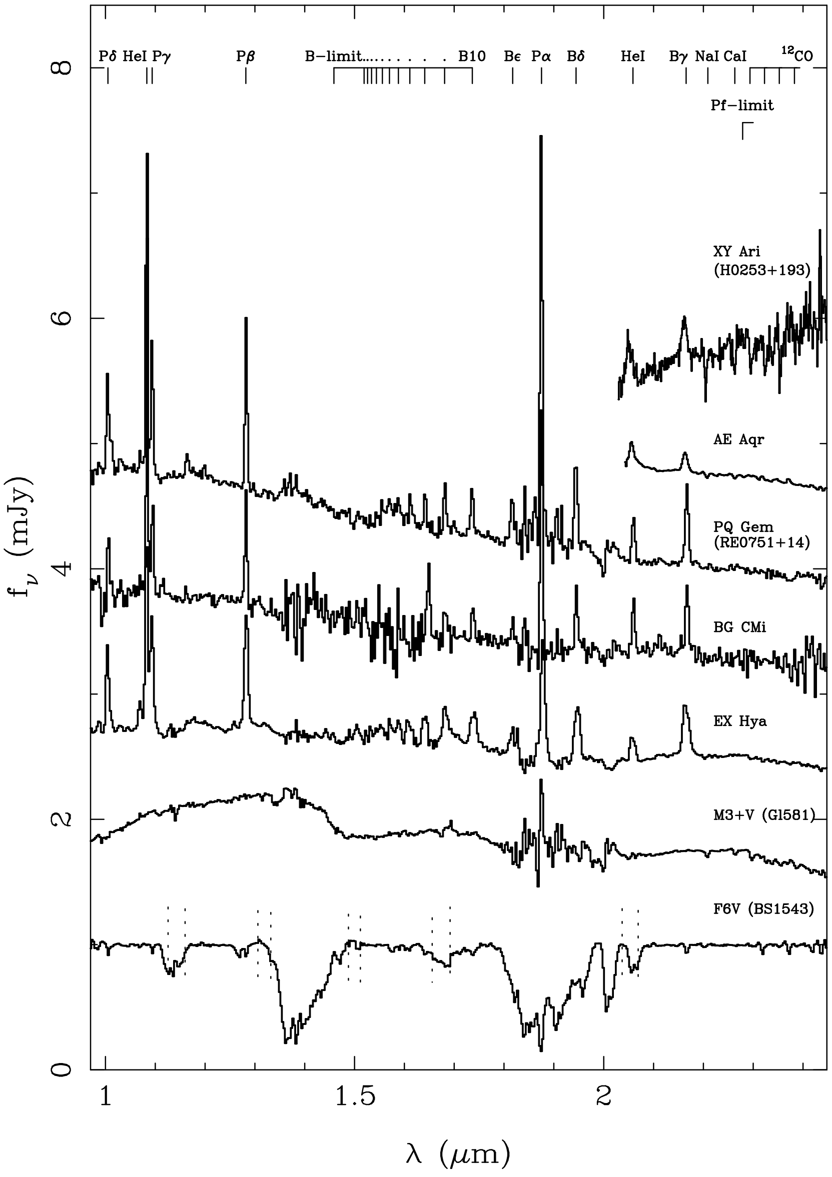

Figure 5. Infrared spectra of the intermediate polars XY Ari, AE Aqr, PQ Gem, BG CMi, EX Hya and an M3+ dwarf star. The spectra have been normalized by dividing by the flux at 2.24 μm and then offset by adding a multiple of 0.75 to each spectrum (with the exception of XY Ari, which has been normalized by dividing by 2 (effectively expanding its y-axis by a factor of 3.7 relative to the other spectra) and then offset by adding 2.1). Also shown is the spectrum of an F6V star, normalized by dividing by a spline fit to its continuum, which indicates the location of telluric absorption features. The spectra of PQ Gem, BG CMi and EX Hya consists of six subspectra which have been merged by matching the flux levels in overlapping regions (illustrated by the vertical dotted lines in the lowermost spectrum).

one would expect their cyclotron humps to be most easily observed in the IR, where the cyclotron humps are closer to their fundamental frequency and therefore more easily resolvable. The results of this study are presented in Figure 5, where we show IR spectra of the intermediate polars XY Ari (Harrop-Allin et al. 1997b), AE Aqr (Dhillon & Marsh 1995), PQ Gem, BG CMi and EX Hya (Dhillon et al. 1997a).

The spectra of the IPs in Figure 5 are all dominated by strong, single-peaked emission lines of H I and He I from the accretion regions. Absorption features of Na I, Ca I and ^{12}CO from the secondary star are clearly observed in XY Ari and AE Aqr. The K4V secondary star in AE Aqr has already been well studied in the optical, but the IR spectrum of XY Ari and the detection of its secondary are unique, owing to its location behind a dense molecular cloud which renders it invisible in the optical (Zuckerman et al. 1992). The strong reddening is evident in the continuum of XY Ari, as is the absence of a change in slope around 2.3 μm, implying that the secondary is most likely a K-star (in agreement with the orbital period of 6.06 hr [2]). The secondary star has also been detected in the IR spectrum of EX Hya, in which the continuum is dominated by water absorption bands around 1.4, 1.7 and 2.3 μm from an $\sim$M3V secondary. In none of the spectra in Figure 5 is there any evidence for cyclotron humps and hence it is impossible to measure the magnetic field strengths of the IPs from these data (Dhillon et al. 1997a). It may be possible to detect cyclotron humps in IPs with higher signal-to-noise IR spectra as long as great care is taken correcting for telluric absorption and the secondary star spectrum (which is also humpy in appearance). A better approach would be to use IR circular spectropolarimetry, which would be sensitive only to cyclotron emission and hence insensitive to the contributions of the secondary star and telluric absorption.

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