

## HERSCHEL OBSERVATIONS OF CATAclySMIC VARIABLES\*

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### ABSTRACT

We have used the PACS instrument on the *Herschel Space Observatory* to observe eight cataclysmic variables at 70 and 160  $\mu\text{m}$ . Of these eight objects, only AM Her was detected. We have combined the *Herschel* results with ground-based, *Spitzer*, and *WISE* observations to construct spectral energy distributions for all of the targets. For the two dwarf novae in the sample, SS Cyg and U Gem, we find that their infrared luminosities are completely dominated by their secondary stars. For the two highly magnetic “polars” in our survey, AM Her and EF Eri, we find that their mid-infrared excesses, previously attributed to circumbinary dust emission, can be fully explained by cyclotron emission. The *WISE* light curves for both sources show large, orbitally modulated variations that are identically phased to their near-IR light curves. We propose that significant emission from the lowest cyclotron harmonics ( $n \leq 3$ ) is present in EF Eri and AM Her. Previously, such emission would have been presumed to be optically thick, and not provide significant orbitally modulated flux. This suggests that the accretion onto polars is more complicated than assumed in the simple models developed for these two sources. We develop a model for the near-/mid-IR light curves for WZ Sge with an L2 donor star that shows that the ellipsoidal variations from its secondary star are detected. We conclude that none of the targets surveyed have dusty circumbinary disks.

**Key words:** infrared: stars – novae, cataclysmic variables – stars: individual (V592 Cassiopeiae, SS Cygni, EF Eridani, U Geminorum, AM Herculis, EX Hydrae, WZ Sagittae, V1223 Sagittarii)

*Online-only material:* color figures

### 1. INTRODUCTION

Cataclysmic variables (CVs) consist of a white dwarf accreting from a cool companion star that fills its Roche lobe and transfers matter to the primary. There are two genera of CVs, magnetic and non-magnetic. In non-magnetic CVs, an accretion disk is formed and a limit cycle instability in this disk (see Cannizzo et al. 2010 and references therein) is the source of large-scale outbursts ( $\Delta m \geq 3$  mag). However, the CV family is diverse, and not all species of non-magnetic CVs show large-scale outbursts (see Warner 1995 for a taxonomy). In magnetic CVs, the enormous field strength of the primary ( $B \sim \text{MG}$ ) alters the accretion process. In polars, the accretion stream from the secondary star is captured near the secondary star and forced to follow the field lines to the photosphere of the white dwarf. There, a shock is formed, which emits copious quantities of X-rays. The other flavor of magnetic CV are the intermediate polars (IPs). IPs are believed to have white dwarfs with lower field strengths than polars, and in the majority of such systems, accretion disks are formed that are believed to have truncated inner radii due to the rapidly spinning magnetospheres of their primaries.

The orbital periods of typical CVs with non-degenerate mass donors range from about 9 hr to  $\sim 81$  minutes. It is believed that all CVs evolve from longer to shorter periods. Since the secondary star in a CV system is losing mass, the

binary would evolve to longer periods if there was not a mechanism to shed angular momentum. The commonly invoked method is “magnetic braking,” in which the stellar wind of the synchronously rotating secondary star carries material (and angular momentum) out of the system (Verbunt & Zwaan 1981). Observations of the low-mass, isolated counterparts to CV secondary stars found in open clusters, however, show that the commonly invoked magnetic braking rate (e.g., Skumanich 1972) underestimates their angular velocities (Andronov et al. 2003). Andronov et al. conclude that either additional sources of angular momentum loss are necessary to explain CV evolution or the secondary stars in CVs above the period gap are evolved.

One possible source for additional angular momentum loss is the torque provided by a circumbinary (CB) disk (Taam & Spruit 2001). Such a structure could have formed either from material ejected during the common envelope phase of the pre-CV or from classical novae eruptions. Alternatively, many CVs with luminous accretion disks have spectra that reveal strong P-Cygni profiles (cf. Vitello & Shlosman 1993) that indicate velocities sufficient to escape the system. Such a wind might be able to populate a CB disk with a significant quantity of gas.

While there have been scattered reports of evidence for CB material in CVs, a UV spectroscopic survey of six bright, highly inclined CVs by Belle et al. (2004) found no evidence for gaseous material around these systems. Dubus et al. (2004) conducted a mid-infrared survey for dusty CB disks in eight CV systems. While they reported detections for SS Cyg and AE Aqr, they found that the origin of the emission in those systems was highly variable and inconsistent with the expected behavior of CB disks. They concluded that if CB disks exist, they are either dust free or emit at far-IR wavelengths.

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**Table 1**  
Herschel Observation Log

Name	Observation Start (UT)	70 $\mu\text{m}$ Flux/ $1\sigma$ limit (mJy)	160 $\mu\text{m}$ Flux/ $1\sigma$ limit (mJy)
SS Cyg	2011 Jun 12 01:43:23	$\leq 0.7$	$\leq 8.1$
U Gem	2011 Oct 2 16:18:32	$\leq 0.8$	$\leq 3.6$
V1223 Sgr	2012 Mar 14 22:28:14	$\leq 0.6$	$\leq 0.7$
AM Her	2011 May 27 15:21:29	$1.3 \pm 0.4$	$2.5 \pm 0.9$
V592 Cas	2012 Jan 5 18:53:10	$\leq 1.1$	$\leq 4.5$
EX Hya	2011 Dec 15 22:11:58	$\leq 2.0$	$\leq 1.7$
EF Eri	2012 Feb 9 11:20:46	$\leq 0.7$	$\leq 1.0$
WZ Sge	2012 Apr 6 23:24:55	$\leq 1.3$	$\leq 3.9$

With the launch of *Spitzer*, the ability to look for cool, dusty material around CVs was markedly improved. Brinkworth et al. (2007) reported Infrared Array Camera (IRAC) (3.6–8  $\mu\text{m}$ ) observations of six polars and found five that had significant IR excesses which they proposed were possibly due to CB dust. They went on to show, however, that the amount of material implied by the putative dusty CB disks was insufficient to affect the angular momentum evolution of the observed CV systems.

If the sole source for the heating of circumbinary dust was due to irradiation by the luminosity of the typical CV system ( $L_{\text{CV}} \approx 10^{33} \text{ erg s}^{-1}$ ), at the innermost stable radius of a CB disk ( $1.7a$ , where  $a$  is the binary star separation; Dubus et al. 2004), the dust temperature would be very cool:  $T_{\text{eff}} \leq 900 \text{ K}$ . This would suggest that if dusty CB disks were present around CVs, the existing *Spitzer* observations might not have been at long enough wavelengths to properly characterize such emission. Thus, the existence of very cool dusty CB disks has not yet been fully investigated.

We have used the *Herschel Space Observatory* to conduct a survey of eight well-known CV systems where excess IR emission has been reported to explore the case for cool dust or other emission processes. We combine the results of this survey with data from both *Spitzer* and *WISE*, along with ground-based observations, to fully explore their spectral energy distributions (SEDs). In the next section we discuss the observations and data sets used. In Section 3 we describe the results for each system, and in Section 4 we discuss our conclusions.

## 2. OBSERVATIONS

We observed the eight CV systems using the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) on the *Herschel Space Observatory* (Pilbratt et al. 2010). PACS obtains photometric observations in two bands simultaneously, one blue (60–85  $\mu\text{m}$  or 85–125  $\mu\text{m}$ ) and one red (125–210  $\mu\text{m}$ ). For all of our observations we selected the bluest bandpass ( $\lambda_{\text{eff}} = 70 \mu\text{m}$ ), along with the default red bandpass ( $\lambda_{\text{eff}} = 160 \mu\text{m}$ ). The preferred observing mode with PACS is the “mini-scan map” mode,<sup>6</sup> where repeated scans of the bolometer array across the field of view are amassed to reduce the dominant  $1/f$  noise. Details can be found in the PACS Data Reduction Guide.<sup>7</sup> All of our observations were identical, with scans that spanned 2.5 arcmin, at two different orientations on the sky (at the recommended 70° and 100° position angles). The total duration of the observations for each source was 0.9 hr, and typically reached  $1\sigma$  point source flux density limits of  $\sim 1$  and 3 mJy in the blue and red bandpasses, respectively.

<sup>6</sup> [http://herschel.esac.esa.int/Docs/PACS/html/pacs\\_om.html](http://herschel.esac.esa.int/Docs/PACS/html/pacs_om.html)

<sup>7</sup> [http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/PDRG\\_Dec2011.pdf](http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/PDRG_Dec2011.pdf)

The PACS data were reduced using the Herschel Interactive Processing Environment (HIPE<sup>8</sup>). Reduction of mini-scan mode data is performed using the python-based data reduction template contained within HIPE. Since the PACS data reduction pipeline does not properly propagate errors, we have followed the recommended procedure (Popesso 2012) for estimating the error bars on point source fluxes (or  $1\sigma$  flux density limits) by performing aperture photometry on numerous regions in the final processed images, and calculating the standard deviations for the resulting sets of flux densities. Of the eight CVs, only AM Her was detected; we list the observation log along with the  $1\sigma$  point source flux densities/limits achieved with these observations in Table 1. The 70  $\mu\text{m}$  image for AM Her is displayed as Figure 1.

### 2.1. *Spitzer* and *WISE* Observations

To attempt to use the *Herschel* observations to constrain the SEDs of the program CVs, we have downloaded and reduced the *Spitzer* and *WISE* observations of these objects. Most of the *Spitzer* observations consist of IRAC 3.5 to 8  $\mu\text{m}$  photometry (Fazio et al. 2004) and have been published elsewhere. To achieve mean flux densities for the IRAC, Infrared Spectrograph (IRS) peak-up array, and MIPS 24  $\mu\text{m}$  observations, we have used MOPEX (Makovoz et al. 2006). To generate light curves, however, we have used IRAF to perform aperture photometry, and used the mean flux densities derived using MOPEX to flux calibrate these light curves to the IRAC magnitude system.<sup>9</sup>

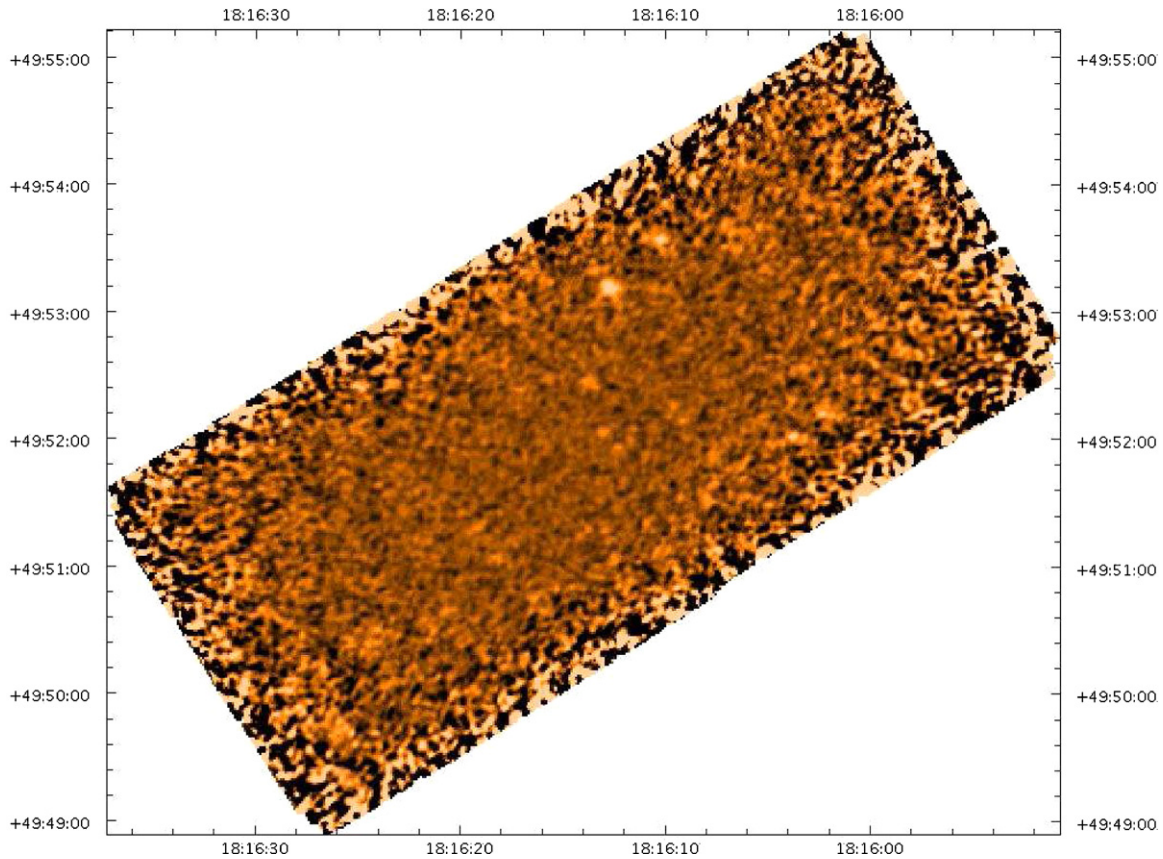
The *WISE* mission (Wright et al. 2010) surveyed the entire sky in four wavelength bands: 3.4, 4.6, 12, and 22  $\mu\text{m}$ . The two short bandpasses (hereafter referred to as W1 and W2) are quite similar to the two short IRAC bandpasses (“S1” and “S2”). The 12  $\mu\text{m}$  channel (“W3”;  $\lambda_{\text{eff}} = 11.56 \mu\text{m}$ ) is similar to that of the *IRAS* 12  $\mu\text{m}$  bandpass, while the 22  $\mu\text{m}$  (“W4”;  $\lambda_{\text{eff}} = 22.09 \mu\text{m}$ ) bandpass closely resembles the *Spitzer* MIPS 24  $\mu\text{m}$  channel (Jarrett et al. 2011). Due to the scanning nature of its orbit, every object was observed by *WISE* on at least 12 separate occasions. Thus, it is possible to generate light curves for our program CVs using the “single exposure” observations from the *WISE* mission. We have extracted these data from the IRSA Web site (<http://irsa.ipac.caltech.edu/>) with the caveat that transient effects (e.g., cosmic rays) make a small number of the single-exposure measurements unusable.

### 2.2. Near-infrared Observations of WZ Sge

For most of the targets in our sample, we have used published optical and near-IR data to construct their SEDs. In the case

<sup>8</sup> [http://herschel.esac.esa.int/HIPE\\_download.shtml](http://herschel.esac.esa.int/HIPE_download.shtml)

<sup>9</sup> <http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/17/>



**Figure 1.** PACS  $70\ \mu\text{m}$  image of the field of AM Her. AM Her is clearly detected at the center of the image (the brighter, more northerly object of the faint pair at the center of this image).

(A color version of this figure is available in the online journal.)

of WZ Sge, however, we obtained near-IR data for nearly two orbital cycles of WZ Sge using SQUIID<sup>10</sup> on the KPNO 2.1 m telescope. SQUIID obtains data in four near-IR channels simultaneously. The observations of WZ Sge occurred on 2003 April 12. We used IRAF to perform aperture photometry on WZ Sge and four field stars, and used the Two-Micron All-Sky Survey (2MASS) data for these field stars to calibrate the *JHK* light curves of WZ Sge.

### 3. RESULTS

The eight objects in our program were selected due to the fact they are among the brightest and closest CVs, and they have been reported as having significant infrared excesses. In addition, however, the eight CVs in our program span the main subclasses of CV systems: prototypical dwarf novae (SS Cyg and U Gem), a short-period disk-dominated system (V592 Cas), an ultra-short-period infrequently outbursting system (WZ Sge), and four magnetic systems (the polars AM Her and EF Eri, and the IPs EX Hya and V1223 Sgr). Due to the small number of systems and their diversity, we order the following discussion based on decreasing orbital period. Note that in the process of constructing the broadband SEDs of our program objects, we will be merging *non-simultaneous* data. It can be dangerous to make such constructions for such highly variable objects as CVs, but they allow us to ascertain the dominant emission processes, especially any constraints imposed by the *Herschel* observations.

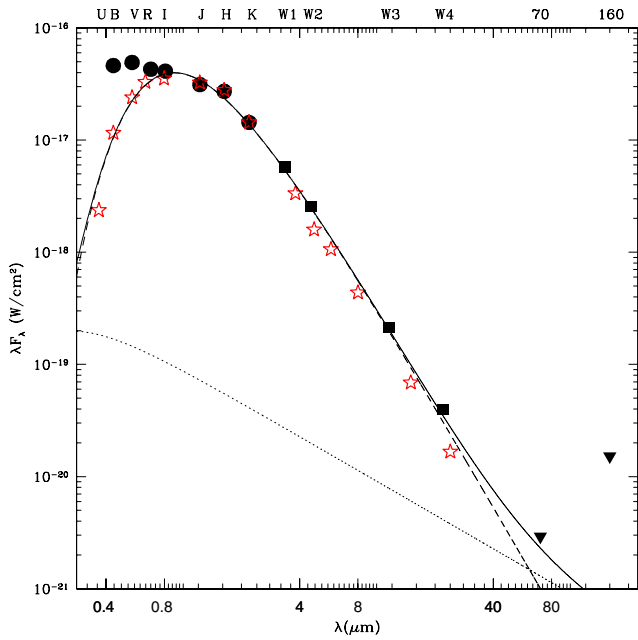
#### 3.1. SS Cygni

SS Cyg ( $P_{\text{orb}} = 6.603\ \text{hr}$ ) is the prototype for long-period dwarf novae. In quiescence it has  $V = 12.2$ , and during outburst it reaches  $V = 8.5$  (see Harrison et al. 2004, and references therein). Harrison et al. (2010) have collected the mid-IR observations of SS Cyg and discuss its outburst SED, including the association of the *IRAS* detections of this source (Jameson et al. 1987) with the synchrotron jet emission inferred from radio observations (Körding et al. 2008). We plot the quiescent SED of SS Cyg in Figure 2. The secondary star of SS Cyg has been classified as a K5IV, which we plot as red stars in this figure. SS Cyg was detected in all four *WISE* bands. The flux from the secondary accounts for nearly all of the observed near/mid-IR flux from SS Cyg. To fully model the observed SED, however, we have summed free-free and blackbody spectral components and achieve an excellent fit to the data. This fit shows that the *Herschel* observations were almost deep enough to detect SS Cyg in quiescence. The  $70\ \mu\text{m}$  limit imposes a strong constraint either on the lack of CB dust emission or on the presence of quiescent synchrotron emission.

It is worthwhile to investigate the origin of the free-free component used to model the SED of SS Cyg, especially since we will encounter similar power-law spectra for several sources, below. In outburst, observations suggest that SS Cyg appears to have a sizeable wind:  $4 \times 10^{-11}\ M_{\odot}\ \text{yr}^{-1}$  (Froning et al. 2002). Such a wind could be a significant bremsstrahlung source for hot, “high-state” disks. However, the observations of SS Cyg presented in Figure 2 correspond to quiescence, where any such wind is expected to be very weak. The more likely source of the

<sup>10</sup> <http://www.noao.edu/kpno/squid/>





**Figure 2.** Quiescent SED of SS Cyg. The *UBVRJIHK* data (solid circles) are from Harrison et al. (2007). The *WISE* data are plotted as solid squares, while the *Herschel* PACS flux density limits are denoted by inverted solid triangles. The SED of a K5 star normalized to the observed *K*-band magnitude is plotted as red stars. The solid line represents a model comprised of the sum of blackbody (dashed line) and bremsstrahlung (dotted line) spectra.

(A color version of this figure is available in the online journal.)

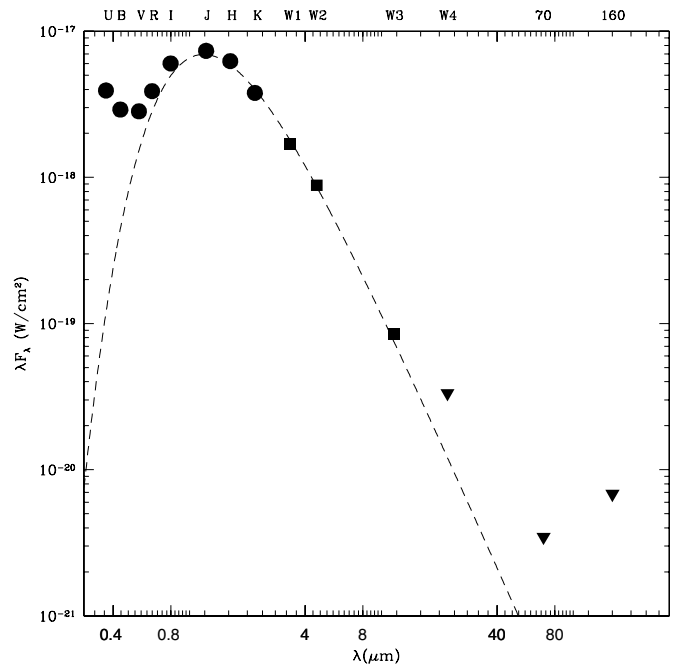
observed free-free emission is the inner regions of the accretion disk. As shown by Smak (1984), the surface density in the accretion disks of dwarf novae is on the order of  $200 \text{ gm cm}^{-2}$  (see Schreiber & Gänsicke 2002 for a specific discussion of the disk of SS Cyg). For the geometrically thin disks expected in CVs (e.g.,  $h/r_{\text{disk}} \sim 0.01$ ; Hirose & Osaki 1991), the mid-plane densities are high:  $\geq 10^{16} \text{ cm}^{-3}$ . Since free-free emission is proportional to  $N_e^2$ , only the innermost regions of the accretion disk are needed to supply the flux necessary to explain the observations of SS Cyg.

### 3.2. U Geminorum

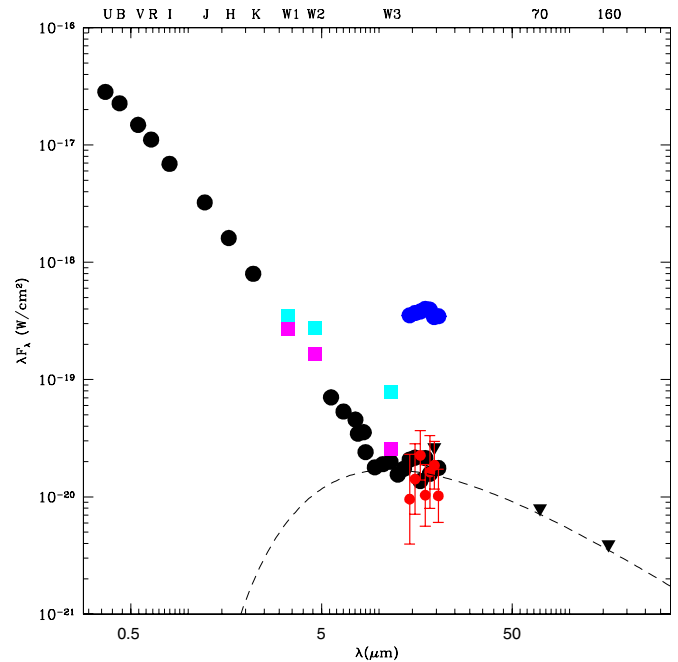
U Gem has an orbital period of 4.425 hr and is a typical dwarf nova. Harrison & Gehrz (1992) reported a strong  $60 \mu\text{m}$  *IRAS* detection for U Gem. In quiescence it has  $V = 14.6$ , though it is an eclipsing system that dims to  $V = 15.1$ . The secondary star of U Gem has a spectral type of M4V (Harrison et al. 2005). U Gem was detected by *WISE* in the three shorter wavelength bands. The SED of U Gem is shown in Figure 3, and is dominated by the cool secondary star. The limits imposed by the *Herschel* observations are not as tight as those for SS Cyg, but still imply that any cool dust emission must have less than 1% the luminosity of the secondary star.

### 3.3. V1223 Sagittarii

V1223 Sgr is an IP with an orbital period of 3.37 hr. Harrison et al. (2007) described *Spitzer* IRS spectroscopic observations of V1223 Sgr that suggested it is a persistent source of synchrotron emission, like its cousin AE Aqr. Further IRS observations of V1223 Sgr by Harrison et al. (2010) caught a large mid-IR flare from this source that they suggested must be due to a compact synchrotron source. We plot the SED of V1223 Sgr in Figure 4, with data from Harrison et al. (2010). The *WISE*

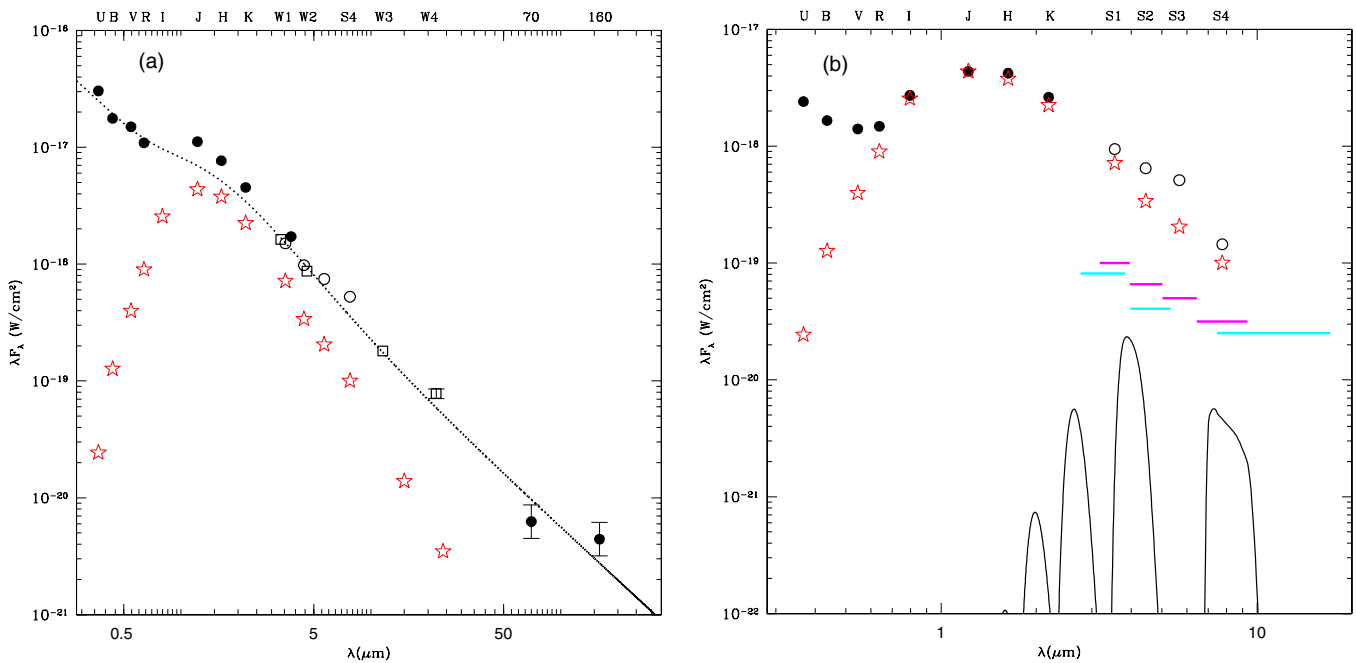


**Figure 3.** SED of U Gem with the *UBVRJIHK* data from Harrison et al. (2000, symbols as in Figure 1). The dashed line is a 3100 K blackbody fitted to the IR SED.



**Figure 4.** SED of V1223 Sgr, adapted from Harrison et al. (2010). The blue points are the binned IRS fluxes for the flaring event observed in 2008 November, while the red points are for when it had returned to quiescence. The black data are from Harrison et al. (2007). The *WISE* light curves of V1223 Sgr showed a flare that lasted for about 6 hr. We have plotted those data as cyan squares. These are to be compared to the “quiescent” *WISE* fluxes of V1223 Sgr plotted in magenta. The thin dashed line is a representative synchrotron spectrum (see <http://www.jca.umbc.edu/~markos/cs/comptontoy/Comptontoy.html>) normalized so that it is consistent with the quiescent fluxes of this source (in generating this spectrum we have assumed an index of 0.75 on the electron energy distribution power law, and left the other parameters at their default values).

(A color version of this figure is available in the online journal.)



**Figure 5.** (a) High-state SED of AM Her. The means of the *UBVR* data from Kjurkchieva et al. (1999) and the means of the *JHK* data from Szkody et al. (1982) are plotted as solid circles. The *WISE* data are plotted as open squares, while the *Spitzer* IRAC data are plotted as open circles. The SED of an M4V at the distance of AM Her (79 pc) is indicated by red stars. A fit to the data comprised of the sum of a power law ( $f_\nu \propto \nu^{0.5}$ ) and the secondary star spectrum is plotted as a dotted line. (b) The low-state SED of AM Her. The *UBVRJHK* data are from Campbell et al. (2008a). Also plotted is a model cyclotron spectrum with  $B = 13.8$  MG, a shock temperature of 5 keV, a viewing angle of  $\Theta = 60^\circ$ , and a plasma optical depth of  $\Lambda = 1.0$  (see Campbell et al. 2008a for details on modeling the cyclotron emission from AM Her). The IRAC (magenta) and *WISE* (cyan) bandpasses are plotted as horizontal line segments.

(A color version of this figure is available in the online journal.)

observations confirm the flaring nature of this source. We plot both the quiescent W1–W3 observations (which confirm the quiescent IR excess seen in the IRS data) and the data for a flare from this source. The *WISE* light curve for V1223 Sgr suggests that this flaring event lasted for about 6 hr. Unfortunately, the *Herschel* observations were not quite deep enough to detect V1223 Sgr, but do allow a quiescent synchrotron source that fits both the *WISE* and IRS data sets. The extrapolation of this spectrum to 8 GHz suggests that, in quiescence, V1223 Sgr has a flux density approaching 1 mJy, and should be easily detected with the EVLA. The radio flaring nature of AE Aqr has long been unique among CV systems, but it is clear that there is one other IP system that appears to behave in a nearly identical fashion, at least at mid-IR wavelengths.

### 3.4. AM Herculis

AM Her is the prototypical polar. It has an orbital period of 3.09 hr and a secondary star with a spectral type of M4V (Harrison et al. 2005). Campbell et al. (2008a) modeled phase-resolved IR spectra with cyclotron emission from accretion in a 13.8 MG field. Like all polars, AM Her transitions back and forth between a “low state” and a “high state.” The exact cause of these state changes in polars has not been explained. In their low states, polars can exhibit strong cyclotron emission from optically thin harmonics. In high states, the mass accretion rate in polars is believed to be a factor of 10–100 times higher than that in the low state. In a high state, the cyclotron emission should become optically thick, and discrete cyclotron harmonics should not be prominent in their spectra.

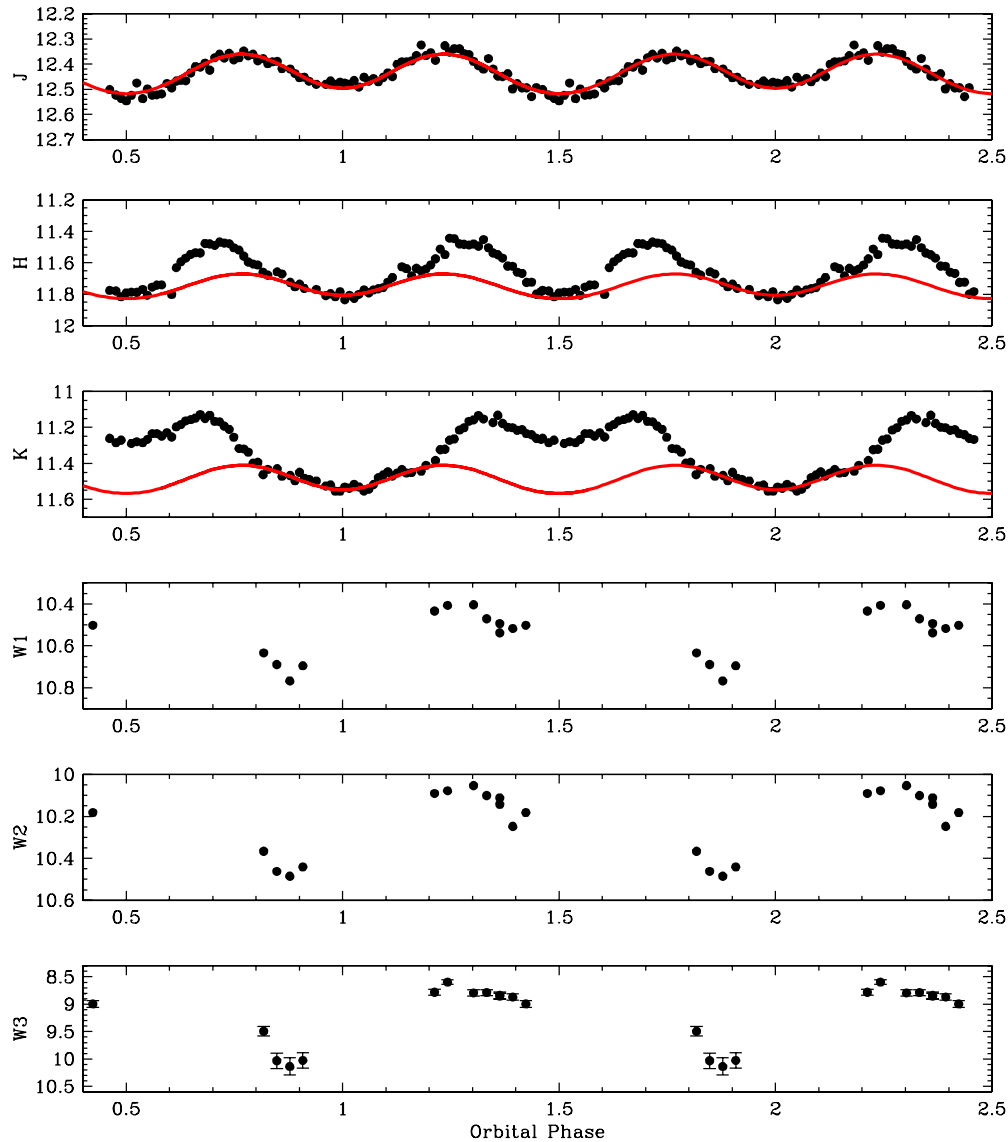
AM Her was in a high state when observed with *Herschel* and was subsequently the only CV detected in our survey. *Spitzer* IRAC observations were obtained during both high and low

**Table 2**  
*Spitzer* IRAC Flux Densities for AM Her

State	Date	3.6 $\mu$ m (mJy)	4.5 $\mu$ m (mJy)	5.8 $\mu$ m (mJy)	8 $\mu$ m (mJy)
Low	2006 Aug 10	$11.18 \pm 0.04$	$9.61 \pm 0.04$	$9.68 \pm 0.04$	$3.74 \pm 0.02$
High	2007 Aug 16	$17.80 \pm 0.11$	$14.53 \pm 0.13$	$14.14 \pm 0.08$	$13.60 \pm 0.05$

states, while the *WISE* observations occurred during a high state (2010 March). We list the flux densities for both sets of IRAC data in Table 2. The high-state SED of AM Her is shown in Figure 5(a). To construct this SED we use the means of the *UBVR* photometry from Kjurkchieva et al. (1999) and the means of the *JHK* data from Szkody et al. (1982). The flux from the secondary star has been well calibrated (Campbell et al. 2008a) and thus can be fully accounted for in fitting the observed SED. We find that a single power-law spectrum (with  $f_\nu \propto \nu^{0.5}$ ) added to the known secondary star SED explains the observations at both ends of the spectrum, from the optical to the *Herschel* detections, but fails in the near/mid-IR. A power law with this slope can be easily explained as a combination of the sum of a hot blackbody spectrum ( $f_\nu \propto \nu^2$ ) with a strong free-free source ( $f_\nu \propto \nu^0$ ). As shown by Lamb & Masters (1979), these two spectral components are very strong in high-state polars. Their relative contributions, however, depend on the magnetic field strength, the mass of the white dwarf, and the accretion rate (for a more recent treatment, see Fischer & Beuermann 2001).

In Figure 5(b), we present the optical/IR SED of AM Her in its low state (*UBVRJHK* data from Campbell et al. 2008a). There is an excess in the low-state SED that is strongest in the S2 and S3 bandpasses that is also present in the high-state SED. Obviously, it is possible to fit this feature in either spectrum with



**Figure 6.** Light curves of AM Her phased using the ephemeris of Kafka et al. (2005). The *JHK* data are low-state photometry from Campbell et al. (2008a). The red line overplotted is their light curve model for  $i = 50^\circ$ . The *WISE* data are from a high state and show large amplitude variations identically phased to those seen in the near-IR. In the W1 bandpass, the secondary star of AM Her would have a magnitude of  $W1 \approx 11.3$ , and be below the magnitude limits of the panel for that bandpass. (A color version of this figure is available in the online journal.)

a cool blackbody ( $T_{\text{eff}} \approx 700$  K), consistent with CB dust. A clue to understanding what is going on at this wavelength, however, comes from the *WISE* light curves of AM Her. In Figure 6, we present those light curves along with the *low-state JHK* light curves from Campbell et al. (2008a), including the secondary star ellipsoidal variation models they derived for the near-IR bandpasses. The excess flux above the light curve models in the *H* and *K* bandpasses is due to cyclotron emission from the  $n = 4, 5,$  and  $6$  harmonics detected (and modeled) in their phase-resolved *JHK* spectra. Due to the cooler plasma temperatures of the shock in the low state ( $\sim 4$  keV), emission from the higher harmonics is not expected, and thus the *J*-band light curve is uncontaminated by such emission, and the ellipsoidal variations due to the secondary star are clearly seen.

Surprisingly, the high-state *WISE* light curves, though sparse, have morphologies identical to the *H* and *K* low-state light curves! Obviously, orbitally modulated cyclotron emission must be present to account for the 0.4–0.5 mag amplitude variations seen at the same orbital phases in the *H*, *K*, *W1*, and *W2* bands.

The amplitude of the modulations is even larger,  $\Delta m = 1.6$  mag, in the *W3* bandpass. As shown in Figure 5, the  $n = 2$  and  $3$  harmonics for the low-state conditions in AM Her could be quite prominent, and being centered near  $2.6$  and  $3.9 \mu\text{m}$ , would contribute flux in the *W1* and *W2* bands. The  $n = 1$  harmonic would be centered near  $7.2 \mu\text{m}$  and supply orbitally modulated flux in the *W3* band.

The highly unusual aspect of these light curves is that in the high state, it is expected that the lower number cyclotron harmonics *should be* completely optically thick, and thus should not contribute significant orbitally modulated flux. This is demonstrated in Harrison et al. (2007, their Figure 10): as the optical depth of the cyclotron emitting region increases, the discrete cyclotron hump spectrum transitions to a blackbody-like SED, with the peak emission shifting to shorter and shorter wavelengths as the optical depth increases. To get significant emission in the  $n = 1$  harmonic requires *low* optical depths. We conclude that while the central regions of the accretion column might become optically thick in polar high states, there must be

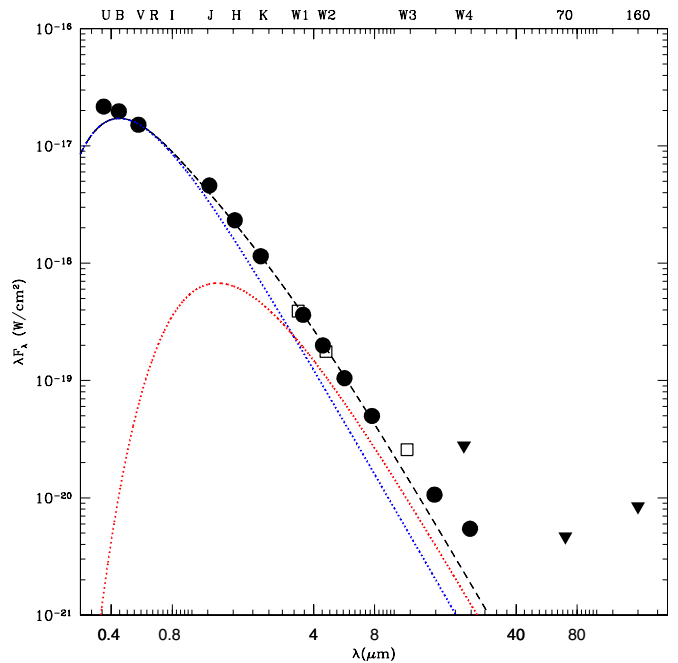
considerable amounts of optically thin material accreting along the “halo” of that column.

As shown in Figure 5(b), the cyclotron model for a  $B = 13.8$  MG field does not have a harmonic centered near the S3 bandpass. It is important to note that the series of cyclotron models evolved by Campbell et al. (2008a) to explain their phase-resolved spectra had a varying magnetic field strength ( $13.2 \text{ MG} \leq B \leq 14.1 \text{ MG}$ ). The issue with the “constant- $\Lambda$ ” cyclotron model they used to construct the synthetic spectra is that it assumes a constant optical depth and field strength for the entire accretion column. Such an assumption is unrealistic, though such models at least allow for the derivation of useful constraints on the plasma conditions in such columns. To better align the  $n = 2$  harmonic with the S3 bandpass requires the magnetic field to have a strength of  $B \leq 13$  MG (see the cyclotron model used for EF Eri, below). This suggests that either the simplistic constant- $\Lambda$  model prescription has slightly overestimated the magnetic field strength or the lower harmonic emission occurs slightly further from the magnetic pole (where the effective field strength is lower) than the higher harmonic emission Campbell et al. (2008a) modeled for AM Her.

### 3.5. V592 Cassiopeiae

V592 Cas is an interesting, disk-dominated, non-magnetic CV with an orbital period of  $P_{\text{orb}} = 2.47$  hr. This period puts it in the middle of the infamous CV “period gap,” a region of period space extending from two to three hours where very few non-magnetic CVs are found (see Kolb et al. 1998 and references therein). There have been a number of attempts to explain the dearth of CVs with these periods, usually focusing on the cessation of the magnetic breaking as the secondary star becomes fully convective (e.g., Howell et al. 2001). Hamilton et al. (2011) have examined some of the issues with this scenario, and we refer the reader to that discussion (but also see Davis et al. 2008; Willems et al. 2007). Hoard et al. (2009) have summarized the properties and behavior of V592 Cas, including their inference of a dusty CB disk in this system. We downloaded and reduced the *Spitzer* IRAC, IRS peak-up array, and MIPS-24 data for V592 Cas and arrived at nearly identical fluxes as those reported by Hoard et al. (2009).

The SED for V592 Cas is shown in Figure 7 and includes the optical/IR data from Hoard et al. (2009) along with the *WISE* photometry and the  $1\sigma$  limits of the PACS non-detections for this source. Hoard et al. constructed a complex model to explain the SED of this object that includes a hot white dwarf ( $T_{\text{eff}} = 45,000$  K), a cool secondary star (M5V), an accretion disk model with eight parameters, and a CB disk with nine parameters. We have fitted the observed SED with the sum of two blackbodies having the primary and secondary star temperatures used by Hoard et al. ( $T_{\text{eff}} = 45,000$  and 3030 K). While our simple model may be considered unrealistic, it only has three parameters (the two blackbody temperatures plus their relative normalization) and fits the SED quite well. Note that the hot blackbody modeled here is the sum of all hot, optically thick components in the system (white dwarf, boundary layer/inner accretion disk, and accretion disk hot spot). The infrared observations are on the Rayleigh–Jeans tail of these sources; thus, they simply sum together as a single power-law spectrum in this wavelength regime. Assuming a main-sequence object, the secondary star blackbody component plotted in Figure 7 would suggest a distance of 186 pc. This is slightly lower than previous distance estimates (see Hoard et al.), but well within the errors of the technique used to make those



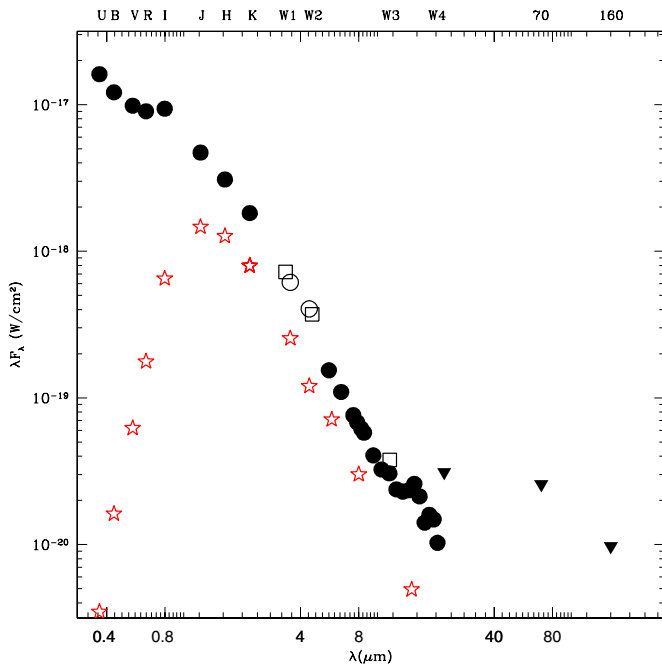
**Figure 7.** SED of V592 Cas. The data plotted as solid circles are from Hoard et al. (2009). The *WISE* detections are plotted as open squares. We have fitted the SED of V592 Cas using the sum of two blackbodies:  $T_{\text{eff}} = 45,000$  K (blue dotted line) and 3030 K (red dotted line). In the *K* band, the cool blackbody supplies 40% of the total flux, suggesting that this secondary star should be detectable with moderate resolution IR spectroscopy.

(A color version of this figure is available in the online journal.)

estimates (the  $M_V - P_{\text{orb}}$  calibration of Warner 1995 or Harrison et al. 2004).

The W3, IRS peak-up array ( $\lambda_{\text{eff}} = 15.8 \mu\text{m}$ ) and MIPS 24  $\mu\text{m}$  photometry indicate an excess above the simple two blackbody model and may be due to dust. It also appears that the W3 photometric point is a little higher than expected when compared to the nearby data points. This deviation is probably due to the combination of the large point spread function of the *WISE* images at this wavelength ( $\text{FWHM} \approx 6''.5$ ), and the fact that V592 Cas has a very bright neighbor located  $13''$  to the east (2MASS J00205373+5542192,  $K = 9.9$ ,  $J - K = 0.82$ ) that dominates the W3 image (note that *WISE* individual scan data are not tabulated for V592 Cas due to the necessity of point spread function fitting to properly extract its fluxes). In the IRS peak-up and MIPS 24  $\mu\text{m}$  images, the contaminating source is better separated from V592 Cas, suggesting that the long-wavelength excess is real. At these longer wavelengths, the field of V592 Cas becomes more complex, with large regions of diffuse dust emission, with V592 Cas being located within one of these. Our MOPEX reduction of the IRS peak-up data resulted in a flux that was 10% lower than that reported by Hoard et al. (the only significantly different data point), but still supports the small excess above the two blackbody model at this wavelength.

We are unable to rule out a small amount of cool CB dust emission from this source, and the *Herschel* observations are not deep enough to constrain such a low-luminosity feature. It is very easy, however, to add a small bremsstrahlung component to the primary + secondary star SEDs to reproduce the observations. Such a component might arise in the strong accretion disk wind observed for this source (see Prinja et al. 2004 and references therein) but, as described above, it is much more likely that this component would have its origin in the accretion disk.



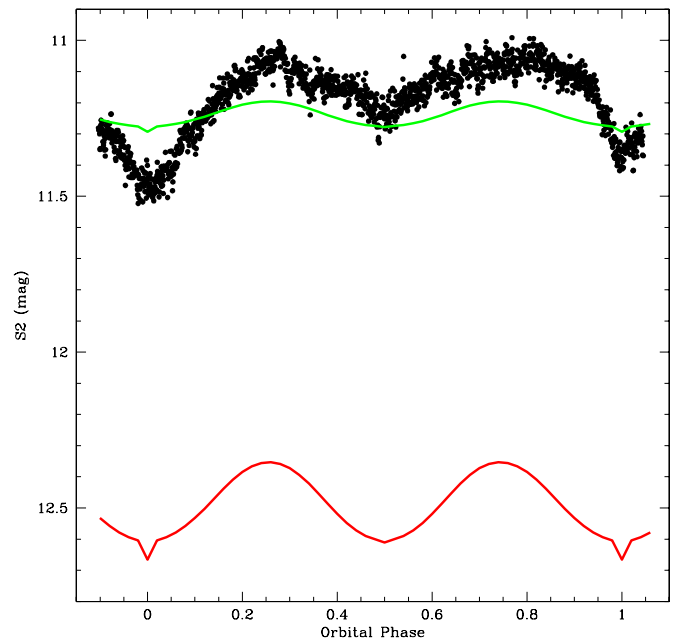
**Figure 8.** SED of EX Hya from Harrison et al. (2007). As in previous figures, the *WISE* detections are plotted as open squares and the IRAC data as open circles. The SED of an M5V with 44% of the *K*-band flux (see Hamilton et al. 2011) is plotted as red stars.

(A color version of this figure is available in the online journal.)

### 3.6. EX Hydrae

EX Hya is a short-period ( $P_{\text{orb}} = 1.64$  hr) IP with an M5V secondary star that supplies 44% of the *K*-band flux (Hamilton et al. 2011). Harrison et al. (2007) reported *Spitzer* IRS spectra of EX Hya in which they found evidence for a small, long-wavelength excess that they attributed to synchrotron emission. Follow-up IRS spectra, however, did not confirm this excess (Harrison et al. 2010). The SED of EX Hya, with data from Harrison et al. (2007), and including the *WISE*, *Spitzer*, and *Herschel* observations, is shown in Figure 8. As discussed in Harrison et al. (2007), this SED is completely consistent with a single power law ( $f_{\nu} \propto \nu^{-1}$ ) when combined with the known secondary star SED. There is no evidence for cool blackbody emission in this spectrum.

A light curve of EX Hya was obtained with IRAC Channel 2 (GO60107, PI: Belle), and we have reduced those data using IRAF. The AAVSO database indicates that EX Hya was quiescent at the time of this observation (2009 August 18). We present this light curve in Figure 9. When this light curve is phased to the ephemeris of Hellier & Sproats (1992), the primary minimum occurs at  $\phi \sim 0.95$ , and not exactly at phase 0.0 as would be expected for an eclipsing binary. A similar offset was observed in the first *XMM* (X-ray) light curve presented by Pekön & Balman (2011). Belle et al. (2002) found two sharp dips that were centered at  $\phi = 0.97$  and 1.04. They suggested that the primary optical minimum may be due to the eclipse of an accretion structure and that the *Extreme-Ultraviolet Explorer* eclipse at  $\phi \sim 0.97$  might actually be that of the white dwarf. Or, perhaps, the two sharp dips they observed were due to the eclipses of accretion structures located near the magnetic poles of the white dwarf. Other than the offset in the phasing of the minima, the morphology of the S2 light curve does not closely resemble any of the published optical or high-energy light curves of EX Hya.



**Figure 9.** IRAC Channel 2 ( $4.5 \mu\text{m}$ ) light curve of EX Hya (black circles). A light curve model, assuming that only the two stellar components contribute any flux, is shown in red. A light curve model with a significant third light component (69% of the total flux at  $\phi = 0.125$ ) is plotted in green.

(A color version of this figure is available in the online journal.)

**Table 3**

System Parameters for Light Curve Modeling of EX Hya and WZ Sge<sup>a</sup>

Parameter	EX Hya	WZ Sge
$M_1$	$0.49 \pm 0.13 M_{\odot}^b$	$0.85 \pm 0.04 M_{\odot}^d$
$M_2$	$0.078 \pm 0.014 M_{\odot}^b$	$0.078 \pm 0.06 M_{\odot}^d$
$T_{\text{eff}1}$	15,000 K <sup>c</sup>	14,500 K <sup>c</sup>
$T_{\text{eff}2}$	3000 K <sup>c</sup>	1800 K <sup>d</sup>
$P_{\text{orb}}$	98.3 min <sup>c</sup>	81.6 min <sup>f</sup>
$i$	$77.8 \pm 0.4^c$	$77.0 \pm 2.0^d$
$l_{3K}$	N/A	33%
$l_{3S2}$	69%	42%
$l_{3S4}$	N/A	51%

**Notes.**

<sup>a</sup> The bandpass-specific third light (“ $l_3$ ”) contributions are at the normalization phase of  $\phi = 0.125$ .

<sup>b</sup> Hoogerwerf et al. (2004).

<sup>c</sup> Beuermann & Reinsch (2008).

<sup>d</sup> Steeghs et al. (2007).

<sup>e</sup> Cheng et al. (1997).

<sup>f</sup> Patterson et al. (1998).

With the precise specification of the system components (see Beuermann & Reinsch 2008; Hoogerwerf et al. 2004), we can construct a realistic light curve model for EX Hya. Beuermann & Reinsch (2008) quote  $K = 12.89$  for the secondary star in EX Hya. Using the tabulations of IRAC photometry of late-type stars and brown dwarfs by Patten et al. (2006), this corresponds to  $S2 = 12.49$  for an M5V. We used the derived values for the masses and radii of the components in EX Hya, and then used the most recent release of the Wilson–Divinney (Wilson & Divinney 1971) code (WD2010<sup>11</sup>) to calculate a model light curve for the S2 bandpass (see Table 3). WD2010 does not have the IRAC bandpasses incorporated, so the actual bandpass used

<sup>11</sup> <ftp://ftp.astro.ufl.edu/pub/wilson/lcdc2010/>



in our modeling is the Johnson  $M$  band. While the Johnson  $M$  band ( $\lambda_{\text{eff}} = 4.75 \mu\text{m}$ ) is not an exact match for the S2 bandpass ( $\lambda_{\text{eff}} = 4.44 \mu\text{m}$ ), these observations are on the Rayleigh–Jeans tail of the spectra for the two stellar sources, and we expect the WD2010 models to reproduce reasonably realistic light curve amplitudes and morphologies (note that WD2010 considers both stellar components in EX Hya to have blackbody spectra). Unfortunately, limb-darkening coefficients have not yet been calculated for the  $M$  band. We decided to use the square-root,  $K$ -band limb-darkening coefficients tabulated by Claret (1998) for a 3000 K main-sequence star in generating these models.

A model light curve calculated assuming that the only source of light in the system is the two stellar components is plotted in Figure 9. As demonstrated by the brief eclipses, the primary white dwarf contributes very little to the total flux at this wavelength. Obviously, there is a significant “third light” component. We have added a third light contribution to the base model so as to match the flux in the S2 light curve at phase 0.125. This model, shown in green, has 69% of the flux coming from the third light component at this phase.

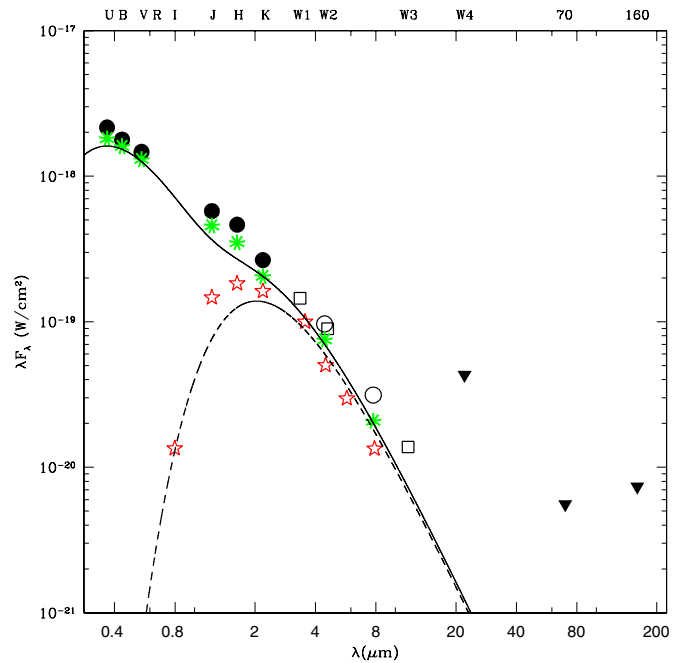
The resulting light curve shows that the ellipsoidal variations of the secondary star in this system can only explain about one-third of the observed modulations away from “primary eclipse.” We also find that we need to change the phasing of the S2 light curve by  $\Delta\phi = +0.05$  to best match the maxima and minima of this model light curve to the data. This may confirm the suggestion by Belle et al. (2002) that the timing of the optical minima in EX Hya does not correspond exactly to binary phase 0. The source of the main modulations (away from the eclipse) in the S2 light curve must be dominated by other emission components in the system.

The *WISE* light curves for EX Hya each consist of 10 data points obtained over a 22 hr period (13 orbits). The amplitudes of the variations in the W1, W2, and W3 bands are about 0.5 mag over this interval. This is approximately the same size as the variations seen in the IRAC S2 light curve. The *WISE* data are too sparse for useful conclusions, but suggest that the same processes shape all of the mid-IR light curves. Such large amplitude variations on such short time scales suggest that a dusty CB disk cannot explain their origin.

### 3.7. WZ Sagittae

WZ Sge is an ultra-short-period ( $P_{\text{orb}} = 81.6$  min) dwarf nova. WZ Sge is the prototype for a small family of dwarf novae that have infrequent, but very large and long-lasting outbursts (see Howell et al. 1995). The last “superoutburst” of WZ Sge occurred in 2001 July, where extensive photometric (e.g., Patterson et al. 2002) and spectroscopic (e.g., Nogami & Iijima 2004) data sets were obtained. WZ Sge is also the closest CV, with  $d = 43.5$  pc (Thorstensen 2003; Harrison et al. 2004). Steeghs et al. (2007) have presented a radial velocity study of WZ Sge, and derive a relatively high mass for its primary ( $0.85 M_{\odot}$ ) and a low mass for the donor star ( $0.08 M_{\odot}$ ). They propose that the secondary star mass they derive is consistent with an L2 dwarf. WZ Sge is the only CV where molecular line emission (from both  $\text{H}_2$  and CO) has been observed (Howell et al. 2004). This suggests that there are cooler ( $T_{\text{eff}} \leq 4000$  K), high density regions in the disk of WZ Sge.

Howell et al. (2008) present *Spitzer* observations of WZ Sge where they propose that a dust disk of material exists just outside the accretion disk of WZ Sge. We plot the optical, near-IR, *Herschel*, *WISE*, and *Spitzer* data in Figure 10. The IR light curves of WZ Sge (e.g., Skidmore et al. 2002) show a brief, sharp

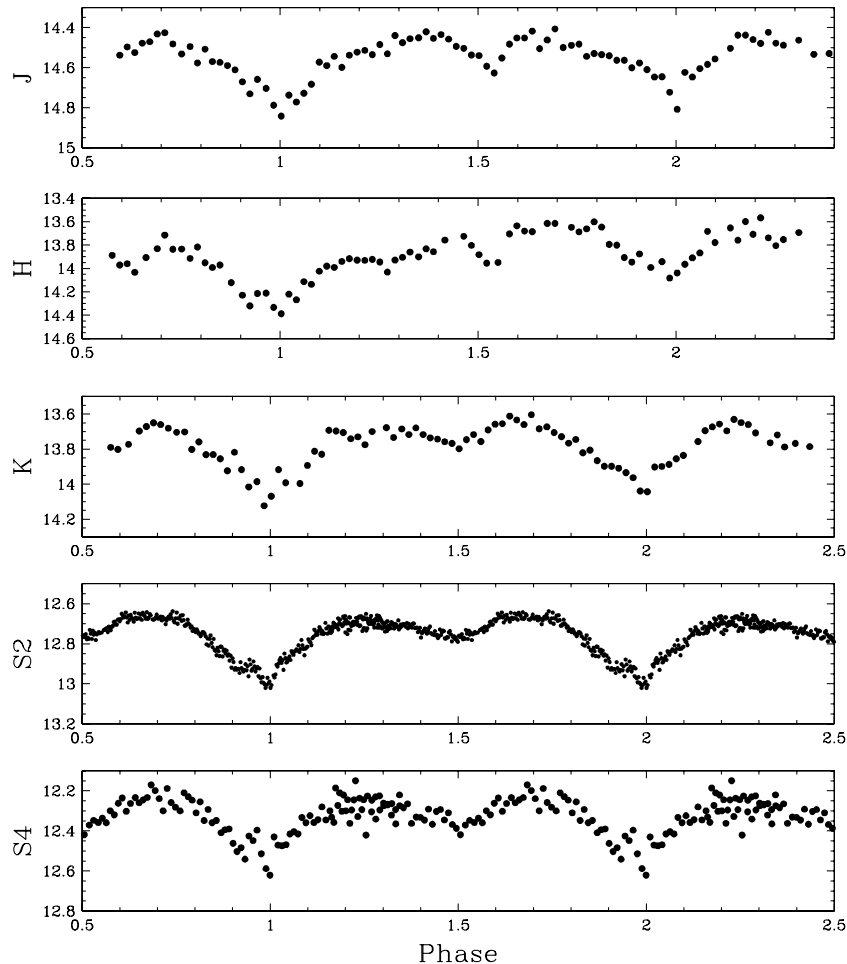


**Figure 10.** SED of WZ Sge. The *UBV* data points are from Krzemiński & Smak (1971). The solid/open circles and squares represent the mean fluxes for this highly variable source. The green asterisks represent the minimum light fluxes at those wavelengths where there are light curve data. The SED of an L2 dwarf at the distance of WZ Sge is plotted as red stars. The solid line is the sum of a 10,000 K blackbody and an 1800 K blackbody (dashed line). The *WISE* and *Herschel* upper limits are plotted as filled triangles.

(A color version of this figure is available in the online journal.)

minimum. In Figure 10, we have plotted both the mean flux SED and that at minimum light. Given the inference of an L2 dwarf secondary star in WZ Sge, we have fitted the minimum light SED with a two-blackbody model:  $T_{\text{hot}} = 14,500$  K +  $T_{\text{cool}} = 1800$  K. As for the previous objects, the hot blackbody is a combination of the white dwarf plus the accretion disk and its hot spot. The simple two-blackbody model does a remarkable job of fitting the observations. The main deviation from the model SED occurs in the near-IR, but as shown in Figure 10, the spectrum of an L2 dwarf has excess emission in the near-IR when compared to a simple 1800 K blackbody. Thus, the result is that the entire minimum light SED can be reasonably well explained with just a hot blackbody and an L2 dwarf. While the *Herschel* observations are not very constraining, there does not appear to be a reason to add a cool dust source given the existing observations.

One of the reasons Howell et al. (2008) proposed an extended dust disk appears to be the broad minima of the IRAC light curves. In Figure 11, we plot the *JHK* photometry obtained with SQIID, along with the IRAC S2 and S4 light curves, phased to the eclipse ephemeris of Patterson et al. (1998). Howell et al. (2008) find that the longer duration of the minima in the S2 light curve, when compared to the optical light curve, requires an extended source of IR emission. We have measured the width of the minima in the five light curves presented in Figure 11 and find that they are essentially identical: the first *JHK* minima are broader than seen in S2 and S4 bands, but the second minima are narrower than seen in the S2 and S4 bands. Unfortunately, the temporal resolution and the photometric quality of our *JHK* data set is inadequate to compare directly to the IRAC light curves. However, Skidmore et al. (2002) present a much higher quality *K*-band light curve and the primary minimum in that



**Figure 11.** *JHK* light curves of WZ Sge obtained with SQIID in 2003, along with the S2 and S4 IRAC light curves. The S4 data have been re-binned by a factor of four to reduce the noise present in those data.

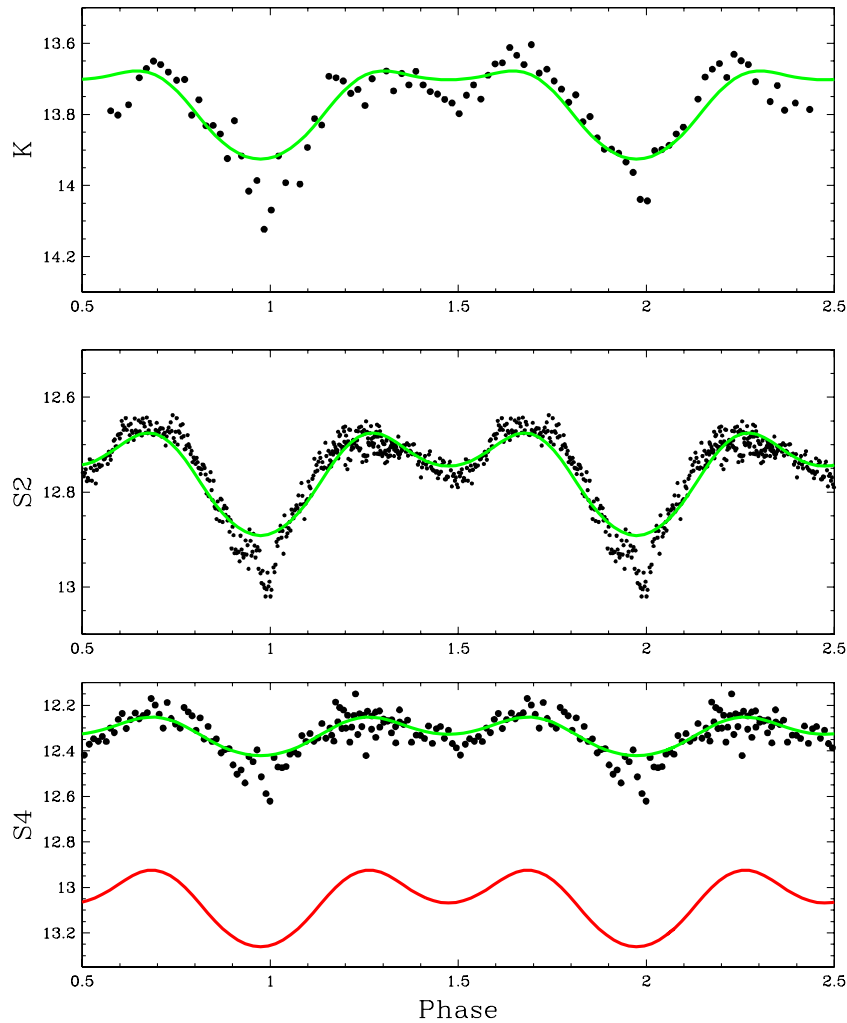
light curve is identical to that observed in the S2 band. Both light curves have a “knee” near  $\phi = 0.9$ , followed by a sharp decline to minimum light. The total amplitudes (maximum light to eclipse minimum) of the *K*-band and S2 light curves are identical. Skidmore et al. (2002) propose that the knee is due to an eclipse of the accretion disk in WZ Sge, while the deeper eclipse is due to the eclipse of the hot spot (where the accretion stream from the secondary impacts the outer edge of the disk). They proposed that binary phase 0 is at the center of the disk eclipse:  $\phi = 0.954$ .

The S4 light curve for WZ Sge is quite a bit noisier, and we have re-binned the data plotted in Figure 11 by a factor of four. The resulting light curve has an identical morphology to those seen at the shorter wavelengths. We conclude that both the SED and light curves of WZ Sge do not require any type of dusty structure to be explained. If there was a cool dust disk surrounding this source, we would expect the S4 light curve to show some evidence for its presence, at least when compared to that of the *J* band.

Given the reasonably well-known binary system parameters for WZ Sge, we can construct models to gain insight on the morphology of the observed light curves. Like the model calculated for EX Hya, we again use the *M* band to model the S2 data. To model the S4 ( $\lambda_{\text{eff}} = 7.76 \mu\text{m}$ ) light curve, we use an average of the light curves in the *M* band with those in the Johnson *N* band ( $\lambda_{\text{eff}} = 10.0 \mu\text{m}$ ) to simulate the S4 bandpass. While obviously not ideal, we again emphasize that these longer

wavelength bandpasses are on the Rayleigh–Jeans tails of the stellar SEDs, and *Spitzer* IRS spectroscopy of L dwarfs (Cushing et al. 2006) shows that there are no significant spectral features present at these wavelengths (WD2010 uses blackbody spectra for both components in the WZ Sge system). We use the solar metallicity *K*-band, square-root limb-darkening relations from Claret (1998) for the coolest star ( $T_{\text{eff}} = 2000 \text{ K}$ ,  $\log g = 5.0$ ) in her tabulation for *all* three modeled bandpasses. As noted earlier, limb-darkening coefficients have not yet been calculated for the *M* or *N* bands, but their values in the *JHK* bandpasses are all quite similar and change very slowly with increasing wavelength.

The details of the WZ Sge system are listed in Table 3, along with the final light curve quantities. We assume that the secondary star is a normal L2 dwarf ( $M_K = 11.1$ ) at a distance of 43.5 pc. We have then added a bandpass-dependent third light component until a good match to the observed light curves is attained. We again use  $\phi = 0.125$  as the normalization phase. The resulting data and models for the *K*, S2, and S4 bands are shown in Figure 12. If we believe that the secondary star is an L2 dwarf and the orbital inclination is  $77^\circ$ , then the majority of the light curve variation in these three bands is due to the (irradiated) ellipsoidal variations of the secondary star. Note that to produce the best fit of the models to the data, we adjusted the minima of our models to occur at  $\phi = 0.974$ , closer to the center of the primary eclipse than the binary phase 0 suggested by Skidmore et al. (2002). The light curve models suggest that



**Figure 12.** *K*-band, S2, and S4 light curves of WZ Sge along with light curve models that assume an L2 secondary star. In the bottom panel, we plot both the pure white dwarf + secondary star model (red) and the light curve that includes the addition of a third light component (green). Only the models with third light are plotted in the *K*-band and S2 panels.

(A color version of this figure is available in the online journal.)

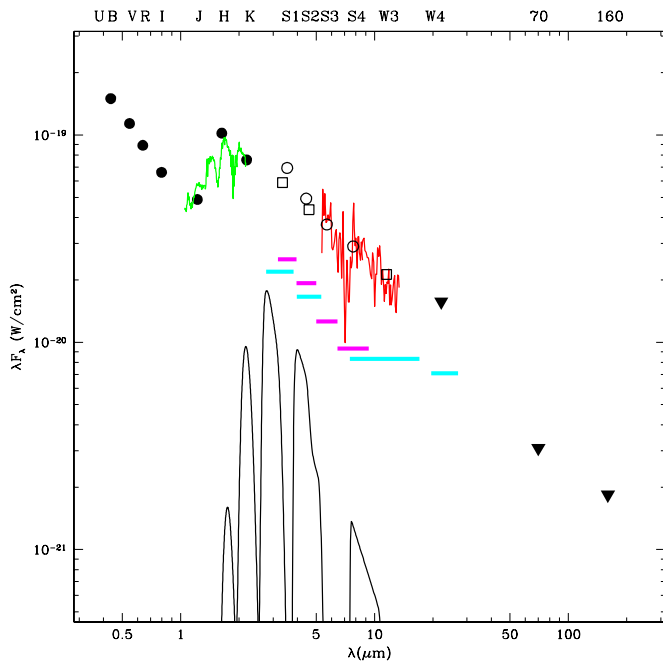
the “knee” seen in the light curves might actually be due to the minimum in the ellipsoidal variations of the secondary star. The amount of third light we had to add to the models ( $\sim 40\%$  of the total flux; see Table 3) is consistent with that required to achieve the fit to the SED.

Given this result, why have we not yet conclusively detected the secondary star in WZ Sge? As can be seen in Figure 12, during the *K*-band minima, such an object would supply nearly 80% of the total luminosity! A *K*-band eclipse spectrum is presented by Howell et al. (2004, their Figure 4), but shows no signs of the strong CO absorption features expected from a normal L2 dwarf. The presence of CO accretion disk emission features, and the conclusion by Cheng et al. (1997) that the white dwarf has an enhanced carbon abundance, suggest that unlike other non-magnetic CVs (see Hamilton et al. 2011), the secondary star in WZ Sge is not carbon deficient. Thus, the CO features should have been visible. Perhaps the observed CO emission is sufficient to fill in these features near  $\phi = 0$ , creating the relatively flat continuum at  $\lambda \gtrsim 2.29 \mu\text{m}$  seen in the eclipse spectrum. Photospheric absorption features from the secondary star in WZ Sge remain strangely elusive, casting some doubt on the validity of our model for this system.

### 3.8. EF Eridani

The final object in our survey is EF Eri, a very short period ( $P_{\text{orb}} = 81.0 \text{ min}$ ) polar that has been stuck in a prolonged low state for more than a decade (see Szkody et al. 2010 and references therein). Campbell et al. (2008b) modeled phase-resolved near-IR spectra of EF Eri and found that cyclotron emission from accretion onto a 12.6 MG field dominated the luminosity of the system at those wavelengths. Howell et al. (2006) presented a radial velocity study that suggested the secondary star in EF Eri has a mass that is close to the stellar/substellar boundary. Schwöpe & Christensen (2010) present a similar analysis and suggest that the secondary star may be a “post period-minimum” object. Phase-resolved *H*- and *K*-band spectroscopy of EF Eri using the Gemini telescope (Harrison et al. 2004) failed to detect the secondary star. Hoard et al. (2007) and Brinkworth et al. (2007) presented *Spitzer* observations of EF Eri, and proposed that a CB dust disk is present in this system and that this dust disk supplies the majority of the system’s mid-IR luminosity.

The SED of EF Eri is presented in Figure 13. Where possible, the data in this figure are the means of the observed light



**Figure 13.** SED of EF Eri. The optical and near-IR photometric data are means of the light curves presented in Harrison et al. (2003). The green spectrum is the average of the *JHK* spectra presented in Campbell et al. (2008b). As in previous figures, the *WISE* data are presented as open squares, while the *Spitzer* data are indicated by open circles. For the W1, W2, W3, and the S2 and S4 bands, mean flux values of their light curves are plotted. Only single snapshot observations of EF Eri in the S1 and S3 bands were obtained. The noisy red spectrum is the means of the *Spitzer* IRS data for this source. Upper limits are indicated by filled triangles. The *Spitzer* bandpasses are plotted as solid magenta line segments, and the *WISE* bandpasses are indicated by cyan line segments. The solid black line is an optically thin [ $\log(\Lambda) = 3.0$ ] cyclotron spectrum for a 12.6 MG field, with a shock temperature of 5 keV, and a viewing angle of  $\Theta = 60^\circ$  (see Campbell et al. 2008b for a full description of modeling the cyclotron emission of EF Eri).

(A color version of this figure is available in the online journal.)

curves—EF Eri exhibits large variations at all wavelengths, from the *GALEX* NUV (see Szkody et al. 2010) to the near-IR. As shown in Figure 14, this variability continues into the mid-IR: the *WISE* W1 and W2 (not shown) and the *Spitzer* S2 light curves all show large amplitude variations of the same scale as that seen in the *H*- and *K*-band light curves. The morphology of the W1, W2, and S2 light curves is *also* very similar to that seen in the *H* and *K* bands. As shown in Campbell et al. (2008b), accretion onto a 12.6 MG field explains the phase-resolved *JHK* spectra of EF Eri. This leads us to conclude that the W1, W2, and S2 light curves are also dominated by cyclotron emission. As shown in Figure 13, a 12.6 MG field has its  $n = 1, 2,$  and  $3$  harmonics centered near  $8.0, 4.2,$  and  $2.8 \mu\text{m}$ , respectively. As such, cyclotron emission can easily explain the light curves in the W1, W2, and S2 bandpasses. Like AM Her, significant emission in these lowest harmonics is not expected to be optically thin for the accretion conditions in EF Eri derived by Campbell et al., but there is little alternative to a cyclotron interpretation for explaining the large amplitude modulations observed in these bandpasses.

It is obvious from Figure 14 that the morphology of the large-scale variations slowly changes with increasing wavelength. The broad symmetric hump centered near  $\phi = 1.05$  seen in the *H* and *K* bands has evolved to a double-humped structure in the S2 band. By the S4 band, the light curve shows slightly smaller amplitude ( $\Delta m \sim 0.4$  mag) modulations, but with a significantly

different morphology. The strongest minimum, which occurred near  $\phi = 0.6$  in the *H*- and *K*-band light curves, now occurs near  $\phi = 1.06$  in the S4 data. The onset of this feature can be first seen in the W1 light curve, getting more prominent in the S2 data, and is strongest in S4. Given the complexities inherent to cyclotron emission processes, there are a number of ways to reproduce these light curves such as a multi-polar field structure (see Beuermann et al. 2007), a changing value of the magnetic field strength as one moves away from the magnetic pole, or a changing pitch angle of the magnetic field with increasing distance above the photosphere (cf. Szkody et al. 2008). These effects can change the relative fluxes seen in the various harmonics, the dominant wavelength at which this emission occurs and/or the phasing of maximum emission.

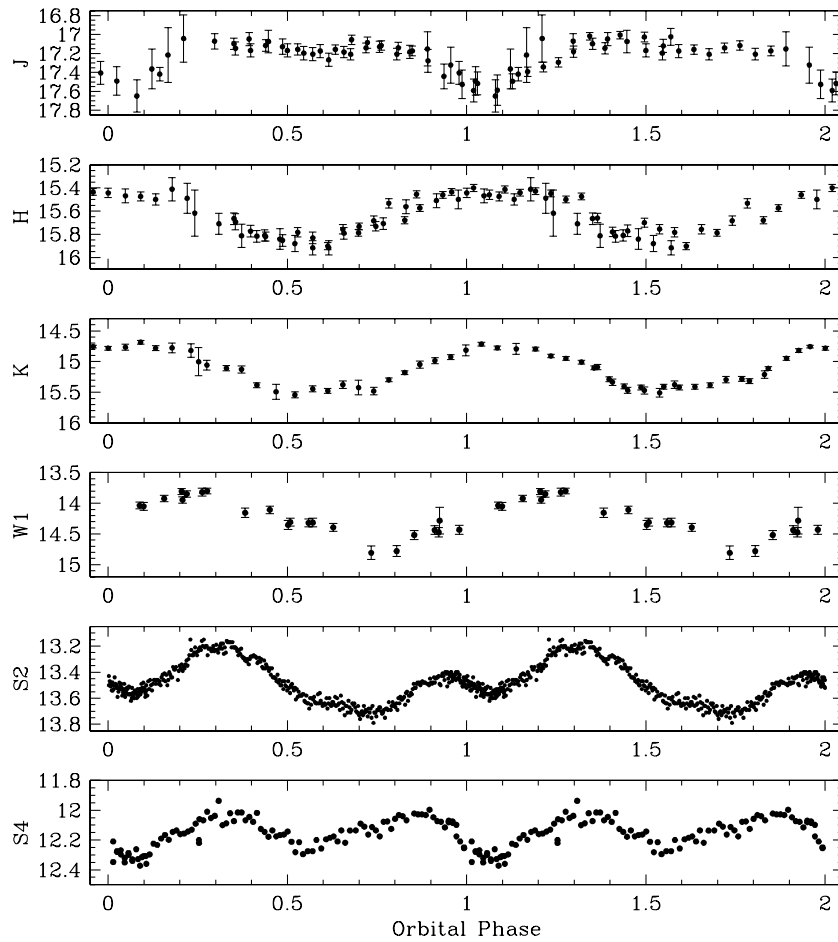
With the proposition that the W1, S2, and S4 bandpasses are dominated by emission from the  $n = 3, 2,$  and  $1$  cyclotron harmonics, respectively, one of the simplest interpretations for the changing light curve morphology is an increasing optical depth. As noted above, as cyclotron harmonics become optically thick, their spectra transition from discrete humps to a blackbody-like continuum. This change leads to a dramatic decrease in the orbitally modulated flux due to the fact that the optically thin cyclotron emission is preferentially emitted in directions perpendicular to the magnetic field lines. As the accretion column becomes optically thick for a particular harmonic, the emission from that harmonic is radiated isotropically. Thus, at those phases where we had the maximum amount of cyclotron emission in the higher harmonics, we now have reduced emission, as the lowest harmonics are partially/mostly optically thick at this phase. It is interesting to note that the *J*-band and S4 light curves are remarkably similar. As discussed in Campbell et al. (2008b), the cyclotron harmonics in the *J* band for EF Eri are  $n = 7, 8,$  and  $9$ . For the conditions of the shock in EF Eri, these harmonics are weak and indistinct, forming a pseudo-continuum. The light curves for EF Eri provide a revealing insight into the low-state behavior of polars, but a fuller understanding will require new cyclotron modeling efforts.

We conclude that the SED of EF Eri in the near- and mid-IR is dominated by cyclotron emission. Any model for the mid-infrared spectrum of this source must incorporate the fact that there are large amplitude variations at these wavelengths that are identically phased to the cyclotron emission seen in the near-IR. We find that the (mean) infrared spectrum can be fitted with a single power-law spectrum that extends from  $1.5$  to  $12 \mu\text{m}$ . Since the majority of the luminosity in these bands is generated by cyclotron emission, we conclude that nearly the entire infrared luminosity of EF Eri is due to accretion onto its magnetic white dwarf primary.

#### 4. DISCUSSION

We have used the PACS instrument on the *Herschel Space Observatory* to conduct a deep survey of eight cataclysmic variables at far-IR wavelengths. The only source detected was the polar AM Her, which was in a “high state” at the time. By combining the limits derived from the *Herschel* observations with data at shorter wavelengths, we have been able to put constraints on the presence of cool dust around these objects. In every case, the derived limits suggest that any dust disks/shells around the program CVs have less than 0.1% of the quiescent luminosities of these systems. This result strengthens the conclusions of Dubus et al. (2004), Brinkworth et al. (2007), and Hoard et al. (2009): if CB disks exist, they are either of





**Figure 14.** Infrared light curves of EF Eri phased to the ephemeris of Schwöpe & Christensen (2010). The *JHK* data are from Harrison et al. (2003).

insufficient mass to affect the angular momentum evolution of CV systems or they are dust free.

With the *Herschel* observations in hand, we took the opportunity to extract archived *Spitzer*, and the recently released *WISE* data, to construct SEDs that spanned the optical/far-IR region. The results for several of the CVs were surprising. In the case of the two polars that were observed, the mid-IR fluxes are dominated by orbitally modulated cyclotron emission. While this might be expected for EF Eri, since it was in a low state, this should not be the case for AM Her. In both objects, the cyclotron models that were developed to explain their phase-resolved *JHK* spectra would not have predicted that the lowest harmonics in these two objects would be optically thin. That the  $n = 1$  harmonic is strong and optically thin during the high state of AM Her suggests that there is significant material accreting onto the white dwarf in regions that have conditions different to those responsible for causing the bulk of the near-IR cyclotron emission. As far as we can tell, the phasing between the cyclotron emission features in the near- and mid-IR is the same, suggesting that emission from the cyclotron fundamental must be located relatively close to the magnetic pole that is the source of the higher harmonic emission. Thus, the scenario of a well-defined accretion column with relatively uniform conditions cannot be used to correctly model the cyclotron emission from polars. The vision of the accretion region in polars as patchy oval arcs, resembling Earth’s auroral zone (Beuermann 1987), is probably a more realistic picture. Such a structure can simultaneously present a variety of viewing angles to the accreting “column,”

gradients in the magnetic field strength, and a wide range of optical depths.

In modeling AM Her and EF Eri, we have shown that their mid-IR fluxes can be completely explained with cyclotron emission. This suggests that the reports of excess mid-IR emission from the other polars observed by *Spitzer* might be explained in a similar fashion. Of the five polars with suggested mid-IR excesses in the survey by Brinkworth et al. (2007), the two best cases for having CB disks were EF Eri and V347 Pav. Like EF Eri, V347 Pav has a low magnetic field strength ( $B \sim 15$  MG) and thus emission from the lowest cyclotron harmonics could explain its mid-IR excess. This is confirmed by the *WISE* single-scan light curves: the W1 and W2 photometry shows  $>1$  mag variations over an orbit! Of the other detected polars in their sample, the *WISE* data show large amplitude variations for VV Pup and V834 Cen, while the light curves for MR Ser were relatively constant (GG Leo was not detected). Light curve data from Kafka & Honeycutt (2005) suggest that the 2MASS observations of MR Ser occurred during a high state, while the AAVSO database shows that MR Ser was probably in a low state in early 2005 when the *Spitzer* data were obtained. Such circumstances might result in an unusual SED for this object. Given these results we conclude that CB dust is not necessary to explain the *Spitzer* observations of polars.

WZ Sge has also been proposed as the host of a CB dust disk. However, the light curves from the *J* band to S4 are essentially identical, suggesting that the mechanism responsible for creating these light curves changes very little over this large

wavelength range. It is difficult to envision a scenario where a dusty disk could be capable of producing such a result. To attempt to explore the morphology of the light curves of WZ Sge, we constructed a model that assumed an L2 secondary star around the previously characterized white dwarf. Much to our surprise, we found that the ellipsoidal variations from such an object can explain most of the observed light curve morphology in the *K*, *S2*, and *S4* bandpasses. While this result is pleasing, the lack of the detection of the secondary star in WZ Sge remains a conundrum. Our SED deconvolution suggests, however, that a dedicated campaign of *K*-band spectroscopy during the primary eclipse might eventually reveal this elusive object.

Unlike WZ Sge, we could not explain the *S2* light curve of EX Hya as resulting from ellipsoidal variations, even with its well-constrained system parameters. It would be a useful exercise to obtain *JHK* light curves of this object to explore the wavelength dependence of these variations. We do not believe, however, that there is a need to invoke dust emission to explain this light curve, as the SED can be fitted with a simple power law.

Both SS Cyg and V1223 Sgr have been shown to be sources of synchrotron emission. The *Herschel* observations of SS Cyg strongly constrain any quiescent synchrotron emission, and thus this object probably only generates such emission during outburst. Unfortunately, the *Herschel* observations were not deep enough to confirm the quiescent synchrotron emission implied by the *Spitzer* observations of V1223 Sgr. The *WISE* light curves, however, show that V1223 Sgr is highly variable at long wavelengths. The extrapolation of a synchrotron spectrum fit to the existing data set suggests that radio observations should easily detect V1223 Sgr in quiescence.

Of all of the objects in our survey, the only one for which a case might be made for CB dust emission is V592 Cas. The observed excess above the simple two-blackbody model is stronger than that seen in SS Cyg. As noted above, however, V592 Cas is known to have a very strong accretion disk wind, and it is likely that bremsstrahlung emission from this wind, or from its accretion disk, can fully explain the detected excess. As noted by Hoard et al. (2009), even if you consign the entire mid-infrared excess to CB dust emission, the amount of material found there would be insufficient to affect the long-term evolution of this object. We conclude that dusty CB disks are probably not the missing source of extra angular momentum loss that some propose is required to explain the orbital evolution of CVs.

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