CYCLOTRON MODELING PHASE-RESOLVED INFRARED SPECTROSCOPY OF POLARS. II. 
EQ CETI, AN URSMAJORIS, AND VV PUPPISS

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ABSTRACT

We present phase-resolved low-resolution infrared spectra of the polars EQ Cet, AN UMa, and VV Pup obtained with SPEX on the IRTF. In addition, we supplement our IRTF observations for VV Pup with optical data sets. The infrared spectra cover the wavelength range 0.8 μm ≤ λ ≤ 2.4 μm and show cyclotron emission at all orbital phases for the three objects. We use a constant-lambda prescription to attempt to model the changing cyclotron features seen in the spectra. We model the EQ Cet data using two different approaches, yielding final parameters of B ≈ 34.0 MG, kT ≈ 3.5 keV, and log Λ ≈ 4.1. For AN UMa we find orbitally averaged models of B = 32.1 MG, kT = 5.0 keV, and log Λ ≈ 4.3. We modeled phase-resolved spectra for VV Pup at four different epochs. We find the following range in parameters: 30.0 MG ≤ B ≤ 31.9 MG, 4.0 keV ≤ kT ≤ 15.0 keV, and 3.7 ≤ log Λ ≤ 6.5. Finally, we find that in B-kT space, the four epochs are well separated based on the visual brightness of the system at the time of observation.

Subject heading: novae, cataclysmic variables

1. INTRODUCTION

Polars, or AM Herculis stars, are interacting binary systems containing highly magnetized white dwarf (WD) primaries and low-mass main-sequence secondary stars. In contrast to nonmagnetic cataclysmic variables (CVs), the extreme field strengths displayed by the WDs in these systems (up to 240 MG) disrupt the formation of accretion disks; instead, the free-falling material is transported along the magnetic field lines to the accretion regions of the primary star. As the material is transported to the accretion region, the plasma is ionized by particle collisions in the stream and by X-ray heating from the accretion region itself. For large mass accretion rates, a standing hydrodynamic shock is formed near the white dwarf photosphere, with shock heights usually several percent of its radius. Downstream from the shock, the electrons gyrating around the magnetic field emit cyclotron radiation. EQ Cet was discovered as part of the Röntgensatellit (ROSAT) Bright Survey on the basis of its variable soft X-ray flux. In Schwope et al. (1999), the authors presented its low-state discovery spectrum, as well as I-band photometry. The discovery spectrum showed a blue continuum with strong absorption lines, as well as a broad hump at 0.8 μm, which was identified as a single cyclotron harmonic (n = 4). Curiously, no higher cyclotron harmonics were seen in the discovery spectrum, an unexpected result which can easily be explained only by a low plasma temperature and, by extension, a low m. On this basis, EQ Cet became the prototypical low accretion rate polar (LARP). LARPs are defined as polars in which m ≤ 1 g s⁻¹ cm⁻² over the accretion spot. In such systems the timescale required to effectively cool the particle stream from its free-fall energy is less than a mean free path through the stellar atmosphere. This disrupts the formation of the hydrodynamic shock and causes radiation to be emitted at much lower temperatures than would otherwise be expected. EQ Cet’s short, 90 minute period and intermittent forays to bright states differentiate it from the prepolars, a newly defined class of objects that includes MQ Dra (Szkody et al. 2003) and HS 0922+1333 (Reimers & Hagen 2000). Prepolars (cf. Schmidt et al. 2005) are objects that do not yet fill their Roche lobes and are believed to accrete via magnetic siphoning. Because siphoning intrinsically yields low-m systems, high states such as those seen in EQ Cet are unexpected. High-state photometry and polarimetry of EQ Cet were obtained by Schwope et al. (2002, hereafter S02), with the South African Astronomical Observatory (SAAO) 1.9 m telescope. Morphologically, the light curve shows a pronounced photometric minimum near ϕ = 0.9. The polarization curves are much smoother, showing a sinusoidal curve with −10% ≤ V/I ≤ −30%, with the maximum polarization occurring at photometric minimum. The MIDAS analysis-of-variation (AOV) algorithm⁴ was applied to the polarization curves and indicated 92.815 minutes as the orbital period.

AN UMa was discovered by Krzeminski & Serkowski (1977) and identified as the second known polar due to its high polarization. It is a short-period system with P_orb = 1.91 hr and likely contains a low-mass white dwarf of 0.4 M_☉ ≤ M_WD ≤ 0.6 M_☉ at a temperature of ≈20,000 K (Bonnet-Bidaud et al. 1996).

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4 Available at http://www.eso.org/sci/data-processing/software/esomidas.
Although AN UMa seems to have strong high/low states in the past, with $14.5 \leq V \leq 19.0$ (Garnavitch & Szkody 1988), for the last $\sim 15$ yr, AN UMa has been remarkably stable. Kafka & Honeycutt (2005) have published V-band light curves taken from 1990 to 2004 with Roboscope, during which $V = 16.4 \pm 0.4$. The system twice dropped to brief low states of $V \sim 18$. In X-ray light curves, it is clear that AN UMa displays two discrete dips (Ramsay et al. 2004) due to occultation of the emission region by the accretion stream. In the visual, however, the situation is less clear, with reports of a single dip (Szkody et al. 1981) and two dips (Ramsayer et al. 1993).

VV Pup is another well-studied object, which is perhaps best known as the archetypal two-pole polar (Wickramasinghe et al. 1989). The magnetic field structure is well represented by a 40 MG dipole, offset from the center of the WD by $\sim 0.1 R_{\text{WD}}$. VV Pup has a 1.67 hr period, $M_{\text{WD}} = 0.73 \pm 0.05 M_{\odot}$, and a secondary star mass of $0.10 \pm 0.02 M_{\odot}$, with a spectral type of M6 or M7 (Howell et al. 2006). Araujo-Betancor et al. (2005) deduced $T_{\text{WD}} = 12300 \pm 700$ K, which implies a distance of 144 pc. In addition, VV Pup has been detected over a large range of brightnesses, $14.5 \leq V \leq 19.5$, but seems to spend most of its time at $V \leq 16.0$ (Mason et al. 2007, hereafter M07). However, stochastic monitoring of this object reported in Howell et al. (2006) seems to indicate that recently (from late 2002 to late 2005), VV Pup has frequently been in low states. Prior light curves exist in the IR (Szkody et al. 1983), in the optical and UV (Hoard et al. 2002), and in X-ray (Pandel & Cordova 2005). The light curves show that VV Pup has two brightness phases per orbit: in X-ray and also in the UV/optical/IR, one sees a strong increase in brightness centered near $\phi = 0.00$. This bright phase lasts for roughly 30% of an orbit, from $\phi = 0.80$ to 1.10, correlating well with the peak in the polarization curve found by Liebert et al. (1978). The geometrical interpretation of this has been that the WD has two active sites of accretion, a primary pole at high southern colatitude and a secondary pole near the northern rotation axis.

Below we present and model new phase-resolved infrared spectra of EQ Cet, AN UMa, and VV Pup. In each case, we show that variable cyclotron emission over the orbit is responsible for the spectroscopic morphology. In § 2, we describe the observations of each object. We fit these data with cyclotron models in § 3, discuss our results in § 4, and draw our conclusions in § 5.

2. OBSERVATIONS

EQ Cet, AN UMa, and VV Pup were each observed using SPECT on the Infrared Telescope Facility (IRTF) on the nights of 2005 September 2, 2006 February 6, and 2006 February 2–3, respectively. SPECT was used in low-resolution prism mode with a 0.3\" $\times$ 15\" slit. To remove background, each object was nodded along the slit. In its low-resolution mode SPECT produces $R \sim 250$ spectra, with exposure times short enough to obtain phase-resolved spectra of polars with $K \leq 16.0$. For both EQ Cet and VV Pup, we used 240 s exposure times, while AN UMa required slightly longer integrations of 360 s. Each of these spectra were then median-combined with two or three other spectra to allow for cosmic-ray removal and to improve the signal-to-noise ratio (S/N). The spectra were reduced using the SPECTOOL package (Vacca et al. 2003). A telluric correction was applied using an A0 V star of air mass similar to our program objects.

Because of the narrow slit size on IRTF/SPECT (0.3\"), infrared photometry is required to calibrate the fluxes. $JHK$ photometry for both EQ Cet and VV Pup were obtained with OI from the Kitt Peak National Observatory (KPNO) 2.1 m telescope. EQ Cet was observed on 2004 October 12, while the VV Pup $JHK$ photometry was obtained on 2003 April 9.

For VV Pup, we augment our IRTF spectra with three additional data sets to allow for direct comparison of the phase-resolved spectra at four epochs. The earliest two are from 2004 March 16 and 22 (M07). These spectra were obtained using VLT + FORS1, covering wavelengths from 0.48 to 0.72 $\mu$m, with an average phase resolution of $\Delta \phi = 0.17$ over two full orbits. In addition, we include phase-resolved spectra obtained with the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope on 2006 December 10. Those data were obtained with the RCSPEC spectrograph using a 1\" slit, together with the KPGL1 filter. The dispersion was 1 A pixel$^{-1}$ with wavelength coverage from 0.35 to 0.59 $\mu$m. The spectra had integration times of 600 s and were phased with the Walker (1965) ephemeris, producing a phase resolution of $\Delta \phi = 0.11$.

3. MODELING

To produce our cyclotron models, we use a constant-$\Lambda$ (CL) cyclotron code first developed by Schwope (1990). In Campbell et al. (2008, hereafter Paper I), we presented a theoretical synopsis of CL modeling. In summary, CL codes use four parameters to produce models of the cyclotron emission from polars. These are $B$, the magnetic field strength; $kT$, the plasma temperature; $\Theta$, the viewing angle to the magnetic pole; and $\Lambda$, the size parameter, which is closely tied to the column density along the line of sight through the accretion region. CL codes imagine the accretion column in polars as a unitary entity with single values for each of the four parameters.

In Paper I, we modeled phase-resolved near-IR spectra of EF Eri with our CL code over an entire orbit, finding that cyclotron emission was the dominant cause of the photometric variations seen in the near-IR. The spectra used in that effort were heavily contaminated by the primary star. Constraining this component was relatively straightforward, as priors for both the WD temperature (Harrison et al. 2004; Beuermann et al. 2000; Schwope et al. 2007) and the WD flux (Schwope et al. 2007) were available. This WD was then co-added with a spectrum generated by our cyclotron code, producing a series of models. Below we use this WD addition technique to model the three program objects, finding that a second stream-emission subtraction technique, described below, often produces tighter fits to the observed data.

3.1. EQ Ceti

EQ Ceti lacks the well-constrained WD temperatures or fluxes by which to confidently estimate the contribution of the WD, which was vital to our modeling of EF Eri. Because of this impediment, we consider two separate approaches for modeling EQ Ceti. First, we replicate the procedure adopted in Paper I and co-add a WD approximating the primary to our cyclotron models. Second, we adopt the method used in S02. In that work, it was shown that in the low state, EQ Cet has no definitive cyclotron features at photometric minimum. The remaining, fiducial spectrum at that phase was termed the stream-emission (SE) component, which was assumed to represent all the contaminating sources, and therefore subtracted from the remaining phase-resolved spectra. In this section we model EQ Cet with both WD addition and SE subtraction and compare the resulting models.

The SQIID $JHK$ light curves of EQ Ceti are presented in Figure 1. Morphologically, the $J$ and $H$ bands show significant variability, while the $K$ band is relatively constant. Thus, we normalize each of our spectra for EQ Ceti in the $K$ band to this flux, using the period determined by S02 to ensure that the relative phases of the photometry and spectroscopy are consistent. We find that the accumulated $1 \sigma$ uncertainty in phase over the interval
between data sets was significant ($\Delta \phi = 0.15$), but due to the lack of a more accurate ephemeris, we will use it to phase the EQ Cet data set.

To help constrain the model cyclotron parameters, we used priors from the literature. In S02, phase-resolved spectra of EQ Cet were presented and modeled over the entire orbit. No harmonics past the $n = 4$ ($0.8 \mu m$) feature were observed, which was most easily explained by assuming that EQ Cet had a very low plasma temperature of $kT = 1-2$ keV and a correspondingly low value of $\log \Lambda$. However, the $n = 4$ harmonic was broader than could be accounted for; thus, a series of low $kT$, low $\log \Lambda$ models with variable magnetic field strengths were co-added to produce the final EQ Cet spectrum. For the $0.8 \mu m$ feature, the best-fit parameters were $kT = 2$ keV, $32.0 \leq B \leq 35.5$, and $\log \Lambda = 1$. The high value of circular polarization seen in the S02 polarization curves near photometric maximum, coupled with the fact that the circular polarization is nonvanishing, indicates a system geometry with $i \approx \beta \approx 40^\circ$, where $i$ is the inclination of the system and $\beta$ is the colatitude of the accreting spot.

3.1.1. Cyclotron + WD Models

First, we co-add a blackbody to the cyclotron models. To this end, we needed values for both the temperature and flux of the WD primary, as both of these are relatively unconstrained. Schwope et al. (1999) note that the slope and flux level of the blue continuum in their optical spectra of EQ Cet are consistent with a WD of $T = 10,000$ K and $M_1 = 0.6 M_\odot$ at 130 pc, although higher temperatures also fit their data. To produce a reliable estimate of the WD temperature, we fit a range of blackbody (BB) models with temperatures between 8000 and 20,000 K to the underlying continuum at $\phi = 0.95$, the IR photometric minimum. We found that a WD temperature of 16,000 K, which produces all the flux at 2.19 $\mu m$, is a reasonable approximation of this component. The resulting BB spectrum was added to the cyclotron model at each phase.

The second step of this procedure was to determine the CL parameters. To this aim, we populated a grid of likely cyclotron models based on the values of these parameters determined in S02, further constraining $\Theta$ by using a geometry similar to S02 ($i = 35^\circ$ and a magnetic colatitude to the accretion spot of $\beta = 30^\circ$) to generate the value of $\Theta$ at each phase. Our grid of models had the following range in parameters: $50$ MG $\leq B \leq 36.0$ MG, $2.0$ keV $\leq kT \leq 5.0$ keV, $\Theta > 30^\circ$, and $1.0 \leq \log \Lambda \leq 5.0$. The resulting grid was compared to our actual SPEX data, and the fit was assessed based both on the $\chi^2$ and visual appearance of the model.

Figure 2 shows our stacked series of spectra covering $0.09 \leq \phi \leq 0.95$. The best-fit cyclotron model has also been plotted at each phase. Table 1 logs the changing CL parameters over the orbit, which in general agree with those found by S02, $B \geq 34.0 \pm 1.0$ MG, $kT = 4.0 \pm 1.5$ keV, $42.0^\circ \pm 5^\circ \leq \Theta \leq 72.0^\circ \pm 5^\circ$, and $3.8 \pm 0.5 \leq \log \Lambda \leq 4.4 \pm 0.5$, with the most dramatic evolution occurring at $\phi = 0.90$, the spectrum nearest to photometric minimum. The errors on the model parameters listed here and in all subsequent sections were estimated through visual inspection of the resulting models. The models provide decent fits to the data with $(\chi^2_N) = 1.31$.
3.1.2. Subtracting the Stream Emission

Here we use the SE subtraction method used previously by S02. In that work, the authors assumed that the low-state spectrum at photometric minimum represented SE, which we define to be all the emission not due to cyclotron radiation. We use the spectrum at photometric minimum as our SE component. As noted above, the polarimetry and photometry presented in S02 indicate that the photometric minimum occurs near $\phi = 0.90$. We used our spectrum at $\phi = 0.95$ to represent the SE spectrum. This component was then subtracted from each of the other phases. We then fit cyclotron models from the existing grid computed in § 3.1.1. Figure 3 shows the stacked series of SE-subtracted spectra for EQ Cet. Morphologically, these spectra show three cyclotron harmonics ($n = 2$, $3$, and $4$), which occur at $\sim 1.59$, $1.07$, and $0.81 \mu m$, respectively. After subtraction, hydrogen emission lines corresponding to both the Brackett and Paschen series are still apparent. The top spectrum ($\phi = 0.80$) is almost pure continuum emission, with only a very small feature near $0.80 \mu m$. Unfortunately, disentangling the relative contribution of the $(n = 4)$ cyclotron harmonic from the Paschen continuum is difficult.

The parameters derived by this method were similar to those derived via WD addition, except that they have lower temperatures (see Table 1). Approximate phase-averaged values were $B = 34.2 \pm 1.0$ MG, $kT = 3.0 \pm 1.5$ keV, $38.0^\circ \pm 5^\circ \leq \Theta \leq 68.0^\circ \pm 5^\circ$, and $4.0 \pm 0.5 \leq \log \Lambda \leq 4.4 \pm 0.5$. The fits were much tighter than those produced using WD addition, with $(\chi^2_{\nu}) = 1.05$.

3.2. AN Ursa Majoris

In AN UMa, the H I emission lines are even more prominent than in EQ Cet. To subtract these features because of the lack of strong constraints on the WD, we were forced to repeat the SE subtraction method shown in § 3.1. Because of the narrow slit on SPEX, phase-resolved photometry obtained simultaneously with our spectra or at a similar brightness state is required to flux-calibrate our spectra. However, because no near-IR light curves exist for AN UMa, a different approach is necessary. Because, like EQ Cet, there are no obvious cyclotron harmonics in the $K$ band, we assume that the variability in this bandpass is negligible. Thus, to relatively calibrate our data, we normalize each spectrum to a constant value in the $K$ band. We then used the spectrum at $\phi = 0.23$ as our SE spectrum and subtracted it from the rest of the data set. Figure 4 shows our SE-subtracted SPEX data for AN UMa, along with the cyclotron models, which is discussed below. The cyclotron features are at wavelengths similar to EQ Cet’s, with the $n = 2$, $3$, and $4$ harmonics visible at $1.5$, $1.06$, and $0.8 \mu m$, respectively, indicating a field strength similar to that object.

To help constrain the parameters used in our modeling, we use published values from the literature. AN UMa’s $n = 4$ harmonic was modeled by Cropper et al. (1989) for the nonrelativistic case, finding a magnetic field of $35.8 \pm 1.0$ MG and $kT \sin^2 \Theta = 6.9 \pm 1.8$ keV, where $\theta$ is the viewing angle. In addition, prior work places some constraints on the nature of the accretion region in this polar. Sirk & Howell (1998) used the Extreme Ultraviolet Explorer (EUVE) to produce UV light curves for 10 polars. For AN UMa, the resulting light curve was consistent with a system displaying an inclination of $i = 50^\circ$ and a magnetic colatitude of $\beta = 17^\circ$. Thus, $30^\circ \leq \Theta \leq 70^\circ$. This geometry seems to agree well with other estimates: $i \approx 40^\circ$–$60^\circ$ (Bonnet-Bidaud et al. 1996) and $i \approx 65^\circ$–$5^\circ$ and $\beta = 20^\circ$–$5^\circ$ (Cropper et al. 1989). Unfortunately, no prior estimates exist for $\log \Lambda$; thus, we used our previous modeling experience to hone in on a likely value for this parameter.

The final models are shown in Figure 4, along with the SPEX data for each phase. In addition, the cyclotron parameters for each model are logged in Table 2. In general, the values of each

![Fig. 3.—IRTF SE-subtracted phase-resolved spectra of EQ Cet, shown as a stacked series, as in Fig. 2. At each phase (red numbers), we have subtracted the spectrum nearest to photometric minimum ($\phi = 0.95$) from the original data to yield the SE-subtracted spectra shown. The cyclotron models are plotted in green.](image)
parameter are consistent with previously published results. The fits to the data were reasonable except at the earliest phases, where residual features in the SE spectrum result in some oversubtraction.

3.3. \textit{VV Puppis}

\textit{VV Pup} was observed in four separate epochs, spanning 2.5 yr. Here we define three states for \textit{VV Pup}, based on the $V$-band magnitude at the time of observation. \textit{VV Pup} is considered to be in a high state when $V < 16.0$, a midstate when $16.0 \leq V \leq 18.0$, and a low state when $V > 18.0$. Using this definition, \textit{VV Pup} was seen in all three states, a low state during the 2004 March 16 Very Large Telescope (VLT) observations, midstates for the 2004 March 22 VLT and 2006 December CTIO observations, and a high state for the 2006 February IRTF observations.

To compare the relative brightnesses of each epoch, we have generated synthetic light curves by convolving a square bandpass covering wavelengths from 0.49 to 0.58 $\mu$m with the spectra in our CTIO and VLT data sets using the IRAF routine SBANDS. The data are phased to the Walker (1965) ephemeris. The light curves show \textit{VV Pup} in a low state (VLT Mar 16) and a high state (CTIO). In addition, it shows \textit{VV Pup} in transition between these two extremes (VLT Mar 22).

![Graph showing light curves for VV Pup](image)

**Fig. 4.**—Comparative artificial light curve for \textit{VV Pup} generated by convolving a square bandpass covering wavelengths from 0.49 to 0.58 $\mu$m with the spectra in our CTIO and VLT data sets using the IRAF routine SBANDS. The data are phased to the Walker (1965) ephemeris. The light curves show \textit{VV Pup} in a low state (VLT Mar 16) and a high state (CTIO). In addition, it shows \textit{VV Pup} in transition between these two extremes (VLT Mar 22).

![Graph showing VV Pup spectra](image)

**Fig. 5.**—Comparative artificial light curve for \textit{VV Pup} generated by convolving a square bandpass covering wavelengths from 0.49 to 0.58 $\mu$m with the spectra in our CTIO and VLT data sets using the IRAF routine SBANDS. The data are phased to the Walker (1965) ephemeris. The light curves show \textit{VV Pup} in a low state (VLT Mar 16) and a high state (CTIO). In addition, it shows \textit{VV Pup} in transition between these two extremes (VLT Mar 22).

### Table 2

| Phase     | $B$ (MG) | $T$ (keV) | $\Theta$ | logA | $\chi^2$ |
|-----------|----------|-----------|----------|------|----------|
| 0.04      | 32.5     | 5.0       | 40.0     | 4.3  | 1.27     |
| 0.12      | 32.9     | 5.0       | 48.0     | 4.0  | 1.19     |
| 0.23      | .........| ......... | .........| ....  | .........|
| 0.36      | .........| ......... | .........| ....  | .........|
| 0.48      | 31.9     | 5.0       | 58.0     | 4.5  | 1.22     |
| 0.56      | 31.9     | 5.0       | 60.0     | 4.5  | 1.22     |
| 0.68      | 31.9     | 5.0       | 58.0     | 4.1  | 1.17     |
| 0.79      | 31.9     | 5.0       | 56.0     | 4.0  | 1.11     |
| 0.90      | 31.9     | 5.0       | 54.0     | 4.4  | 1.22     |

\textit{VV Pup} shows a photometric bright phase when cyclotron emission from the primary pole dominates the spectrum and a dim phase when this region is self-eclipsed. For \textit{EQ Cet}, we used the spectrum at minimum light as our SE subtraction spectrum because the cyclotron flux at this phase is small. In \textit{VV Pup}, however, the photometric minimum occurs during the dim phase, when there is significant emission from the secondary pole. Thus, a straight-up SE subtraction is risky. To mimic the SE subtraction process, without subtracting the component from the secondary pole, a third-order continuum was fit to the spectrum at minimum light (near $\phi = 0.50$) and subsequently subtracted from the raw spectra at each phase. By subtracting just the continuum, we preserve both sets of cyclotron harmonics. For the IRTF data, however, the secondary pole was not visible near the photometric minimum. Because of heavy secondary contamination at these wavelengths, we do a normal SE subtraction on only the IRTF data for \textit{VV Pup}.
Schwope & Beuermann (1997) determined the following system parameters for VV Pup. The primary pole was found to be at high southern colatitude, \( \beta_1 = 145^\circ - 155^\circ \), whereas the secondary pole is near the north pole, \( \beta_2 = 10^\circ \), with a significant separation in azimuth between the two accretion regions, \( \Delta \phi \approx 165^\circ \). Because of the high inclination of the system, \( i = 75^\circ \), the primary pole is eclipsed for nearly 60% of the orbit. There are also preexisting constraints, the plasma temperature and \( \log \Lambda \), which are useful to our modeling efforts. The plasma temperature is highly variable in VV Pup and depends on the particular accretion state at the time of observation. M07 measured \( kT = 5.0 \) keV for low-state observations of VV Pup and \( kT = 7.0 \) keV when VV Pup was in the midstate described above. Meanwhile, Ferrario & Wickramasinghe (1990), found a much hotter temperature of 10 keV, presumably indicating a high state. Values for the size parameter have been found to be \( \log \Lambda \approx 5.5 \) for the primary pole (M07). All data sets were phased with the Walker (1965) ephemeris, despite the existence of a new spectroscopically defined ephemeris in Howell et al. (2006), for which the orbital \( T_0 \) is corrected by about 0.03 in phase from the Walker (1965) ephemeris. Keeping in mind the Walker phasing allows us to make a more direct comparison with published results. In Table 3, we fit models to the phase-resolved spectra for each epoch and compare the resulting parameters, with the goal of analyzing how they change between states.

### 3.3.1. The VLT Low State

VV Pup was observed in a rare, very faint state on 2006 March 16 with \( \langle V \rangle = 19.3 \), which is among the lowest of recorded observations for this object. The stacked series of spectra shown in Figure 6 covers the phase interval \( 0.83 \leq \phi \leq 2.04 \). In the first three spectra, the \( n = 5, 6, \) and 7 harmonics of the primary (32 MG) pole are visible at 0.72, 0.61, and 0.53 \( \mu \)m, respectively. In addition, cyclotron emission from the secondary (56 MG) pole is seen with \( n = 3 \) and 4 at 0.69 and 0.53 \( \mu \)m, respectively. After \( \phi = 1.08 \), the primary pole is self-eclipsed. Thus, from \( \phi = 1.20 \) to 1.80, only the secondary pole is visible. The primary pole then returns for the last two spectra in the series. This meshes well with the Schwopa & Beuermann (1997) geometry, which predicts that the primary pole would be visible from \( 0.83 \leq \phi \leq 0.17 \).

For this low state, M07 combined the spectra between 0.80 and 0.20 into a single bright orbital phase spectrum, while they combined those between 0.80 and 0.20 into a faint orbital phase spectrum. By modeling those phase-averaged spectra with a cyclotron code based on Wickramasinghe & Meggitt (1985), M07 found \( B_1 = 31.5 \), \( kT_1 = 5 \) keV, \( \log \Lambda_1 = 5.5 \), and \( \Theta_1 = 85^\circ \) and \( B_2 = 54.6 \), \( kT_2 = 5 \) keV, \( \log \Lambda_2 = 3.0 \), and \( \Theta_2 = 75^\circ \), where the subscripts refer to the primary and secondary poles, respectively. In addition, we use constraints on \( \Theta \) from Schwopa & Beuermann (1997) to explain the observed harmonic motion.

The final model parameters that we derive were similar to those found by M07. The cyclotron fits to these VLT data are shown in Figure 6, and the parameters for each phase are listed in Table 3. For the primary pole, \( B_1 \approx 31.2 \pm 0.3 \) MG, \( kT_1 = 4.0 \pm 0.5 \) keV, with \( 5.5 \pm 0.2 \leq \log \Lambda_1 \leq 6.1 \pm 0.2 \). Meanwhile, the second pole was fit with \( B_2 = 51.2 \pm 0.5 \) MG, and \( kT_2 = 5.0 \pm 1.0 \) keV, and \( \log \Lambda_2 \) ranged from 2.8 to 3.6, with an uncertainty of 0.3. We

![Graph showing the SE-subtracted phase-resolved spectra of VV Pup at a low state.](image)

**Figure 6**—VLT SE-subtracted phase-resolved spectra of VV Pup at a low state, shown as a stacked series. Here we approximate the SE spectrum as a low-order continuum fit to the spectrum nearest to photometric minimum (\( \phi = 1.56 \)) and subtract this fit from the spectra at all other phases. The data are phased to the Walker (1965) ephemeris and stacked with an increment of \( 6 \times 10^{-14} \) ergs s\(^{-1}\) cm\(^{-2}\). The order of each harmonic is also labeled for both the primary pole, \( n_1 \), and the secondary pole, \( n_2 \).
also found that $\theta_{1,2}$ matched well with the orbital variation expected by adopting the Schwope & Beuermann (1997) geometry. The mean reduced $\chi^2$ for the fits was excellent, $\langle \chi^2 \rangle = 1.10$.

### 3.3.2. The VLT Midstate

Six nights later, M07 reobserved VV Pup. The system had brightened by $\sim 1.5$ mag during the intervening interval. Initially, as shown in Figure 7, the spectra appear similar to those of the low state. By the reappearance of the primary pole, at $\phi = 1.78$, the spectral morphology had already changed, with the higher harmonics pumped up. In addition, the H$\alpha$ emission is stronger than observed before, indicating that CL parameters strongly correlate to the visual brightness of VV Pup.

Using the same procedure as for the low-state data, we arrive at the models shown in Figure 7. The final parameters for these fits are listed in Table 4. Our results show large changes in the plasma temperature between the first and second bright phases for the primary pole, which had been stable at 7.7 keV over the first bright phase and is now significantly hotter ($\sim kT = 9.0$ keV), with an uncertainty of 0.5. We also found that $\log \Lambda$ increased from $5.0 \pm 0.2$ to $5.7 \pm 0.2$. The same trends were not apparent for the secondary pole. In general, the fits to the midstate are qualitatively similar to those derived for the low state; however, there is a noteworthy divergence of the cyclotron models from the observed continuum over the wavelength intervals 0.62–0.65 $\mu$m and 0.69–0.72 $\mu$m. These two bandpasses correspond to the same regions where M07 found significant photospheric Zeeman absorption, explaining the observed deviations.

### 3.3.3. The CTIO Midstate

The CTIO data set was obtained on 2006 December 10 and appears to be a state similar to the second bright phase of the VLT midstate. The SE-subtracted data are presented in a stacked series in Figure 8, and the pertinent parameters are listed in Table 5. The CTIO data set is further to the blue than the VLT and thus exhibits higher harmonics (primary pole, up to $n = 10$; secondary pole, up to $n = 6$). The time series covers nearly a full orbit, during which both the bright phase and dim phase are seen. The modeling procedure was identical to that employed for the VLT spectra. For initial estimates, we used the parameters from the second bright phase of the VLT midstate data set. We then generated a grid of models with similar parameters. The phase-averaged parameters were found to represent the data well. Approximately, $B_1 = 31.7 \pm 0.5$ MG, $kT_1 = 9.3 \pm 1.5$ keV, and $\log \Lambda = 6.5 \pm 0.3$. For the secondary pole, $B_2 = 54.6 \pm 1.0$ MG, $kT_2 = 6.1 \pm 1.5$ keV, and $\log \Lambda = 3.6 \pm 0.5$, with $\langle \chi^2 \rangle = 1.01$. These parameters are similar to the second-phase VLT midstate, indicating that CL parameters strongly correlate to the visual brightness of VV Pup.

### 3.3.4. The IRTF High State

Our final data set was obtained on 2006 February 2–3 and is presented as a time series in Figure 9. Because the 55 MG pole is not obvious in the IR and also because of the larger secondary star contamination, we used full SE subtraction. Qualitatively, the spectra appear quite different from the previous data sets because of the low resolution ($R \sim 250$) and strong hydrogen emission.

### Table 4

**Midstate VLT Cyclotron Parameters for VV Pup**

| Phase | $B_1$ (MG) | $kT_1$ (keV) | $\Theta_1$ | $\log \Lambda_1$ | $B_2$ (MG) | $kT_2$ (keV) | $\Theta_2$ | $\log \Lambda_2$ | $F_1$ | $\chi^2_1$ |
|-------|------------|-------------|------------|-----------------|------------|-------------|------------|-----------------|-----|----------|
| 0.81  | 31.4       | 7.7         | 89.9       | 5.0             | 54.3       | 6.0         | 78.0       | 3.0             | 0.70| 1.10    |
| 0.95  | 31.7       | 7.7         | 82.3       | 5.0             | 54.3       | 6.0         | 79.9       | 3.0             | 0.66| 1.03    |
| 1.05  | 31.6       | 7.7         | 81.2       | 5.2             | 54.3       | 6.0         | 79.2       | 3.6             | 0.77| 1.04    |
| 1.17  | 31.5       | 7.7         | 89.9       | 4.9             | 55.0       | 5.3         | 76.2       | 2.7             | 0.45| 1.16    |
| 1.29  | ...        | ...         | ...        | ...             | 55.3       | 5.3         | 72.6       | 2.7             | 0.00| 1.02    |
| 1.41  | ...        | ...         | ...        | ...             | 54.6       | 5.3         | 70.2       | 2.7             | 0.00| 1.09    |
| 1.53  | ...        | ...         | ...        | ...             | 54.4       | 5.3         | 70.5       | 2.5             | 0.00| 1.39    |
| 1.66  | ...        | ...         | ...        | ...             | 54.4       | 5.3         | 73.6       | 2.5             | 0.00| 1.02    |
| 1.78  | 31.3       | 9.0         | 89.9       | 5.5             | 54.6       | 5.5         | 77.2       | 2.5             | 0.83| 1.01    |
| 1.90  | 31.3       | 10.0        | 84.5       | 5.7             | 54.6       | 5.5         | 79.7       | 3.0             | 0.85| 1.28    |
| 2.02  | 31.3       | 8.5         | 80.2       | 5.8             | 54.6       | 5.5         | 79.6       | 3.0             | 0.90| 1.16    |
| 2.14  | 31.5       | 8.0         | 88.5       | 6.0             | 54.6       | 5.0         | 77.1       | 2.5             | 0.90| 1.30    |
lines, which obscure much of the underlying cyclotron continuum. Despite the strong H i features, the $n = 2$–5 humps of the 32 MG pole are visible (Table 6).

The narrow slit width of SPEX (0.3") demands that we photometrically calibrate our spectra. Thus, we include 2003 KPNO JHK photometry of VV Pup taken during a high state in Figure 10. The light curves show a somewhat similar morphology across each of the IR bands, with a maximum beginning between $\phi = 0.80$ and 0.00, depending on the band, and minima near $\phi = 0.50$. The $J$ band, however, shows additional modulation, which causes a local maximum in the light curve at $\phi = 0.35$. As we show below, this is caused by the onset of the 55 MG pole in VV Pup, which is known to be active in the range $0.30 \lesssim \phi \lesssim 0.70$. In addition, there appears to have been a small transient event near $\phi = 1.00$, where there is a substantial discrepancy in the photometry with that taken one orbit earlier. The effect is large (0.25 mag) in the $H$ band and rather smaller (0.18 and 0.16 mag) in the $J$ and $K$ bands, respectively. The explicit cause of the event is unknown, but it is probably related to a nonsteady accretion rate.

To ensure proper SE subtraction, we had to photometrically correct our SPEX data. American Association of Variable Star Observers (AAVSO) data confirm that the system was in an optical high state ($V = 14.5$) at the time of the KPNO photometry. Serendipitously, M. Bonnardeau\(^5\) reports visual photometry obtained on 2006 February 1 (within 1 day of our IRTF data) that shows the system in the same high state ($v \sim 14.5$) as in our KPNO photometry. Hence, we normalize our phase-resolved spectra to the $K$-band light curve presented in Figure 10. The normalization was small at every phase, yielding final fluxes within \(\pm 20\%\) of their observed values.

\(^5\) See http://mbond.free.fr/VVPup/VVPup.htm.

### Table 5

| Phase | $B_1$ (MG) | $kT_1$ (keV) | $\Theta_1$ | log $\Lambda_1$ | $B_2$ (MG) | $kT_2$ (keV) | $\Theta_2$ | log $\Lambda_2$ | $F_1$ | $\chi^2_\nu$ |
|-------|-----------|-------------|-----------|----------------|-----------|-------------|-----------|----------------|------|-----------|
| 0.00  | 31.6      | 9.3         | 80.0      | 6.5            | 54.4      | 6.0         | 79.8      | 3.5            | 0.55 | 1.01      |
| 0.11  | ...       | ...         | ...       | ...            | 54.8      | 6.5         | 76.5      | 3.8            | 0.00 | 1.00      |
| 0.24  | ...       | ...         | ...       | ...            | 54.8      | 6.5         | 74.0      | 3.8            | 0.00 | 1.00      |
| 0.37  | ...       | ...         | ...       | ...            | 54.8      | 6.5         | 70.1      | 3.8            | 0.00 | 1.00      |
| 0.49  | ...       | ...         | ...       | ...            | 54.4      | 6.5         | 70.1      | 3.8            | 0.00 | 1.00      |
| 0.62  | ...       | ...         | ...       | ...            | 54.4      | 6.5         | 72.4      | 3.8            | 0.00 | 1.00      |
| 0.76  | 31.6      | 9.3         | 89.9      | 6.5            | 54.4      | 6.5         | 76.7      | 3.8            | 0.75 | 1.00      |
| 0.88  | 33.9      | 9.3         | 86.4      | 6.4            | 54.4      | 6.0         | 79.4      | 3.5            | 0.65 | 1.02      |
We encountered two difficulties in modeling these data. First, the spectra show strong H I emission features, which caused uncertainty about the relative contribution of cyclotron emission. Second, we were unable to model the dim-phase spectra, because in the IR the secondary pole produces only the cyclotron fundamental and its first overtone, both of which are optically thick. Because of the low S/N, it is difficult to discern these features in our spectra. Thus, we have produced models only for \( \phi > 0.05 \), 0.14, and 0.91, the phases during which the primary pole is active. The final models (Table 6) had lower primary field strengths than the rest of the optical spectrum, is hotter, with 14.0 \( \pm 3.0 \) keV \( \leq kT' \leq 15.0 \pm 3.0 \) keV. Even with strong H I emission, the models do a fair job of re-creating the data, producing fits with an average \( \chi^2 \) of 1.20.

## 4. DISCUSSION

As demonstrated in Paper I, SPEX is the ideal tool to study objects such as EF Eri, where the global magnetic field strength (13 MG) places the active cyclotron harmonics in the near-infrared. Each of the current objects have magnetic field strengths of \( B > 30 \) MG, which results in coverage of fewer harmonics and consequently increases our dependence on the literature in constraining the parameters used. The consistency of our models with those previously published should therefore come as no surprise. However, some small but significant differences were found.

The first object modeled was EQ Cet. The derived cyclotron parameters found here (\( B = 34 \pm 5.0 \) MG, \( kT' \approx 3.0 \pm 1.5 \) keV, and \( \log \Lambda = 4.0 \pm 0.5 \)) are in slight contrast, especially in \( \log \Lambda \), with those found by S02. In that case, the authors attempted to model the optical spectrum as two spots. For spot(1), the single (\( n = 4 \)) cyclotron feature at 0.8 \( \mu m \) was computed as the sum of a series of low-temperature, multifield models (\( B = 32.0 \)–35.5 MG, \( kT' = 2.0 \) keV, and \( \log \Lambda = 1.0 \)) due to the fact that the \( n = 5 \) harmonic was not seen. Spot(2), which is used to model the 0.8 \( \mu m \) peak, for which the spot(1) models were derived, is visible in our IRTF spectra, the parameters we derive seem to incorporate features from both spots, \( kT' \) from spot(1), but \( \log \Lambda \) from spot(2). The fact that we observe three prominent humps allowed us to find single-field models that fit the data well at all phases, without multi-\( \phi \) solutions. However, much of the differences between the parameters derived here and those found in S02 may simply result from EQ Cet being in a different brightness state at the time of our observations.

In general, our results for AN UMa are similar to those previously published. The Cropper et al. (1989) value of \( kT \sin^2 \Theta = 6.9 \pm 1.8 \) keV implies a most likely temperature of 4.0 keV using the geometry described above. Our modeling, however, suggests a higher, although consistent, temperature of 5.0 \( \pm 2.0 \) keV. We do find a substantially smaller value for the magnetic field strength (\( B = 32.1 \pm 1.0 \) vs. 35.8 \( \pm 1.0 \) MG). Two factors may explain these differences. First, AN UMa was in a significantly brighter state during our IRTF observations (\( V = 15.8 \)) compared to those of Cropper (\( V = 17.3 \)).

### 4.1. The Multiepoch Evolution of VV Pup

The power of multiepoch phase-resolved spectroscopy lies in its ability to track system evolution over time and allows us to study how the accretion regions in polars respond to changes in \( \dot{m} \). The multiepoch data for VV Pup we have presented offer an intriguing glimpse into these possibilities.

We have assembled phase-resolved spectra of VV Pup spanning the interval 2004 March to 2006 December and three discrete brightness states. For direct comparison, we have included
Fig. 11.—(a) Accretion parameters for the main pole accretion region as a function of phase. Top to bottom: Magnetic field $B$, the plasma temperature $kT$, the viewing angle $\theta$, and the size parameter $\log A$. In each panel, the VLT low state (dark blue triangles), VLT mid/high state (green squares), CTIO (cyan pentagons), and IRTF (red hexagons) are plotted. (b) Same as (a), but for the secondary pole.
made a transition to a brighter state. The high state is hotter still, with temperatures of 15 keV. A similar monotonic trend was not apparent in the derived values for log $\Lambda$. Except for the IRTF data, where low values of log $\Lambda$ were seen, the variation in log $\Lambda$ for the mid- and low states was complex. A plot of $\Theta$ versus orbital phase is also included. Figure 11b shows the orbital evolution of the CL parameters for the secondary 55 MG pole. Similar dramatic evolution was not observed for the secondary pole.

Although Figure 11 sheds some light on the evolution of VV Pup over a three-year baseline, it is difficult to couch these changes in physical terms. What is needed is a way of correlating changes of $B$, $kT$, and log $\Lambda$ with changes in $m$. Fischer & Beuermann (2001) show that both $T_{\text{max}}$, the maximum temperature, and $X_0$, the column density, are proportional to $mB^{-2.6}$. In Figure 12 we plot $B$ versus $kT$ for each of our observations. In addition, we graph the function $kT = cB^{-2.6}$, where $c$ is a proxy for $m$ and varies by a factor of 6.0 (in increments of 0.5), increasing from the lower left to the upper right in this diagram. In $B$-$kT$ space, the different states of VV Pup are apparent: the low-state VLT observations are found at the lowest values of $c$, the midstate VLT and CTIO data are at intermediate values of $c$, and the IRTF high-state data have the highest values. These results seem to indicate that $m$ is directly correlated with the system brightness at the time of observation. To better understand this relationship between $m$ and the accretion parameters, additional multipoint optical + IR observations will be needed.

5. CONCLUSION

We have modeled IRTF/SPEX $JIHK$ spectra for three polars, EQ Cet, AN UMa, and VV Pup. EQ Cet was modeled two ways, via the WD addition method used on EF Eri in Paper I and also via SE subtraction. The parameters derived from both theoretical tacks were similar to each other and also to those presented in S02. For AN UMa, the data set was modeled using only the SE subtraction technique, and our results are in agreement with previously published sources. Finally, we compare phase-resolved spectra of VV Pup taken at four different epochs over a span of 2.5 yr and at three different brightness states. Our analysis shows that over time VV Pup exhibits at a large range of accretion parameters, 30.0 MG $\leq B \leq 31.9$ MG, 4.0 keV $\leq kT \leq 15.0$ keV, and $3.7 \leq \log \Lambda \leq 6.5$. Finally, we find that in $B$-$kT$ space the system is naturally partitioned by brightness states potentially offering an exciting way to study the $m$ evolution in polars. Future optical + IR phase-resolved spectroscopy at multiple epochs will shed light on how changes to $m$ are manifested in the shocks of polars.

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