# ABSORPTION BY CYCLOTRON HARMONICS IN THE OPTICAL SPECTRUM OF VV PUPPIS

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## I. INTRODUCTION

Most theoretical models of the AM Her variables (AM Her, AN UMa, VV Pup and 2A0311-22) rely on strong cyclotron emission at the fundamental cyclotron frequency and higher harmonics to produce the observed, strongly-polarized optical continuum (e.g. Lamb and Masters 1979). The cyclotron lines, which presumably originate in the hot, isothermal accretion shock at the surface of the white dwarf ($kT \gtrsim 10$ keV, $h/R_* \lesssim 0.1$), should be blurred into a continuous spectrum by both optical depth effects and electron Doppler broadening. Thus the lack of even weak cyclotron features in the optical spectra of these objects is still compatible with a cyclotron origin.

Recently Visvanathan and Wickramasinghe (1979) and Wickramasinghe and Visvanathan (1979, WV) reported and discussed spectra of VV Puppis obtained on 1979 February 2, which showed deep absorption troughs near 5750, 5000 and 4400Å. These were interpreted as the sixth, seventh and eighth cyclotron harmonics, corresponding to a magnetic field strength of $2.9 \times 10^7$ gauss. While offering little explanation for the sudden appearance of these features, WV constructed a series of parameterized emission regions which could produce the observed spectrum. A novel feature of their emission region models is that the radiation transport is assumed to be strictly perpendicular to the magnetic field. In this case thermal Doppler broadening vanishes, and narrow absorption features can be formed in a reasonably hot ($kT_e \sim 4$ keV) atmosphere.

We have obtained spectra confirming the broad absorption features in VV Pup and providing additional information. These data strongly support the WV cyclotron interpretation. We argue, however, for quite a different physical description of the absorbing gas.

## II. OBSERVATIONS

Image tube spectrophotometry was obtained some 10 months before and also 1 month after the WV observations. In Figure 1 Bond's 1978 April 13 (U.T.) spectrum is shown; it was obtained with the Kitt Peak 2.1-m reflector and intensified image dissector scanner. The summed spectrum included all scans obtained over slightly more than a 100-minute period. The scan labelled "VV Pup 12" covers the maximum part of the bright phase. Photometry obtained by Bond 6 nights earlier showed the object ranging from blue magnitude 15 at maximum to about 16 at minimum. At no time during the bright phase was there any evidence for absorption features at 4400, 5000Å or anywhere else. The emission lines included very strong He II λ4686 and the λ4640 blend, while the Balmer decrement appeared somewhat Planckian, as previously noted for AM Her in an active state (e.g. Stockman et al. 1977).

Finally, it should be noted that the strong emission lines were not completely eclipsed during any of the 8-minute individual scans, though the measured fluxes were lower during the bright phase than during the faint phase.

Spectrophotometry was obtained by Liebert and Stockman on 1979 February 26 and 27, using the Steward 2.3-m reflector and intensified Reticon system. The second night's observations covered an entire period and Bond was able to obtain simultaneous photometry covering most of that period. On 27 February the blue magnitude ranged from around 16.9 just before eclipse to 17.8 at minimum light. On both nights, VV Pup was clearly much fainter than during the 1978 observations--see also Liebert and Stockman (1979)--though not as faint as previously noted in 1977 when the emission lines may have disappeared completely.

The 26, 27 February spectra are displayed in Figures 2 and 3. Figure 2 shows consecutive 8-minute scans on 27 February. Figure 3 consists of composites of the 27 February bright phase scans (numbers 6-8 in Figure 2), the remaining 27 February faint phase scans, and the 26 February bright phase. These observations (1) confirm the WV absorption features during the bright phases, and (2) show weaker line emission which is mostly eclipsed during the bright phases.

## III. DISCUSSION

The late February 1979 spectra showed absorption features centered near the positions reported by WV, plus an additional broad feature near 6900Å (aside from atmospheric "B"). The even spacing of the absorption features in frequency, $\Delta\nu \simeq 7.6 \times 10^{13}$ Hz corresponding to a field of $2.7 \times 10^7$ gauss, supports the cyclotron interpretation of WV. Thus, VV Puppis is the first AM Her variable for which the field strength near the surface is accurately known. These observations also indicated that the absorption features were seen throughout the bright phase (to the 8 minute time resolution). The absorption appeared whenever the primary emission region was in view (Chanmugam and Wagner 1978, Liebert et al. 1978). Thus, the absorption at this time must have been effectively isotropic and not perpendicular to the magnetic field as in the WV model. For isotropic absorption, the observed narrow absorption widths place an upper limit on the thermal broadening corresponding to a temperature of only $kT \simeq 0.2$ keV. However, the opacities for the 6th to 8th harmonics at 0.2 keV are extremely anisotropic (beamed perpendicular to the field) and are very low ($\sigma_8 \lesssim 10^{-4}\sigma_T$ and $\kappa_n \propto (kT/mc^2)^n$). In order to reconcile the strong absorption features with the required low temperatures, we have reconsidered current models for the accretion shock and have reached the following conclusions:

(1) The isotropy of the absorption spectrum is due to Compton scattering of the light in the x-ray heated, pre-shock accretion column having $kT_e \lesssim 0.2$ keV.

(2) The required column density for Compton scattering and the upper limit on the column height set by simultaneous photometry ($h/R < 0.04$) yield a pre-shock density in the accretion column of $n_e \gtrsim 3 \times 10^{16} cm^{-3}$. Together with the derived field strength, this indicates that the dominant cooling mechanism in the shock is bremsstrahlung and not cyclotron emission (Masters et al. 1977, Lamb and Masters 1979).

(3) The temperature of the "reversing" layer responsible for the cyclotron absorption is limited to a narrow range, $4keV \gtrsim kT_e \gtrsim 1keV$ by relativistic Doppler broadening (WV) and by the rapid drop in opacity for lower temperatures. Within this range, the required optical depth is approximately $10 > \tau_e > 0.01$. For a white dwarf with $M \gtrsim 0.4M_\odot$, the bremsstrahlung-dominated shock temperature is too high and the pre-shock/post-shock transition region has insufficient optical depth.

(4) Therefore, the absorption probably arises in streams of lower density ($n_e \lesssim 0.3\ \bar{n}_e$), high temperature gas in the accretion column above the shock. Since the cyclotron opacities are much greater than the Compton opacity for $kT_e \gtrsim 2$ keV, these underdense streams need occupy only ~ 1% of the accretion column. Evidence for variable and uneven accretion flows is provided by the strong photometric flickering observed in VV Pup. Note that in the presence of Compton scattering, it is no longer necessary that the absorption be isotropic. In order for the absorption to be seen through most of the bright phase, we require the absorbing layer to lie just above the shock, whose height is less than the cylindrical diameter--i.e. our continuum emission region is a squat "pillbox," rather than the narrow cylinder adopted by WV. This model has the attractive feature that the absorption lines will not be observed if the Compton scattering optical depth falls much below unity.

(5) Our spectra also indicate that the emission lines are absent for part of the bright phase. In addition the flux ratio of $H\beta/H\alpha$ appears more nearly recombinational (lower) than in earlier data. These results, together with coarse radial velocity measurements, indicate that these emission lines arise from x-ray heating of the secondary star. Perhaps they are similar to the narrow emission line

component in AM Her (Greenstein et al. 1977). We may speculate that a turning off of the high-density, broad emission line component may be linked to the accretion characteristics which result in the absorption features: either a narrower accretion column (lower f) or possibly the shielding of the upper part of the accretion column by Compton scattering.

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Figure 1

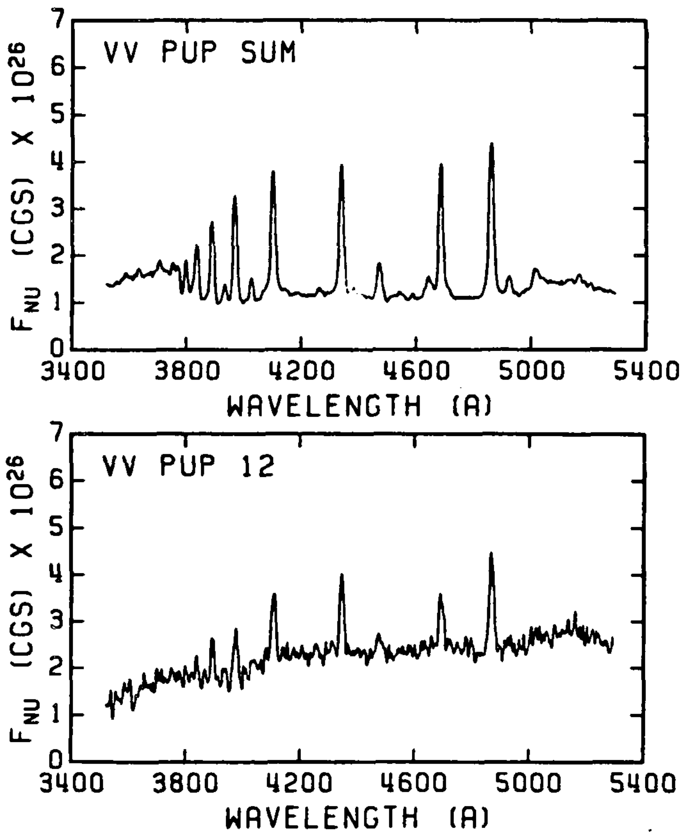




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Figure 2(a)

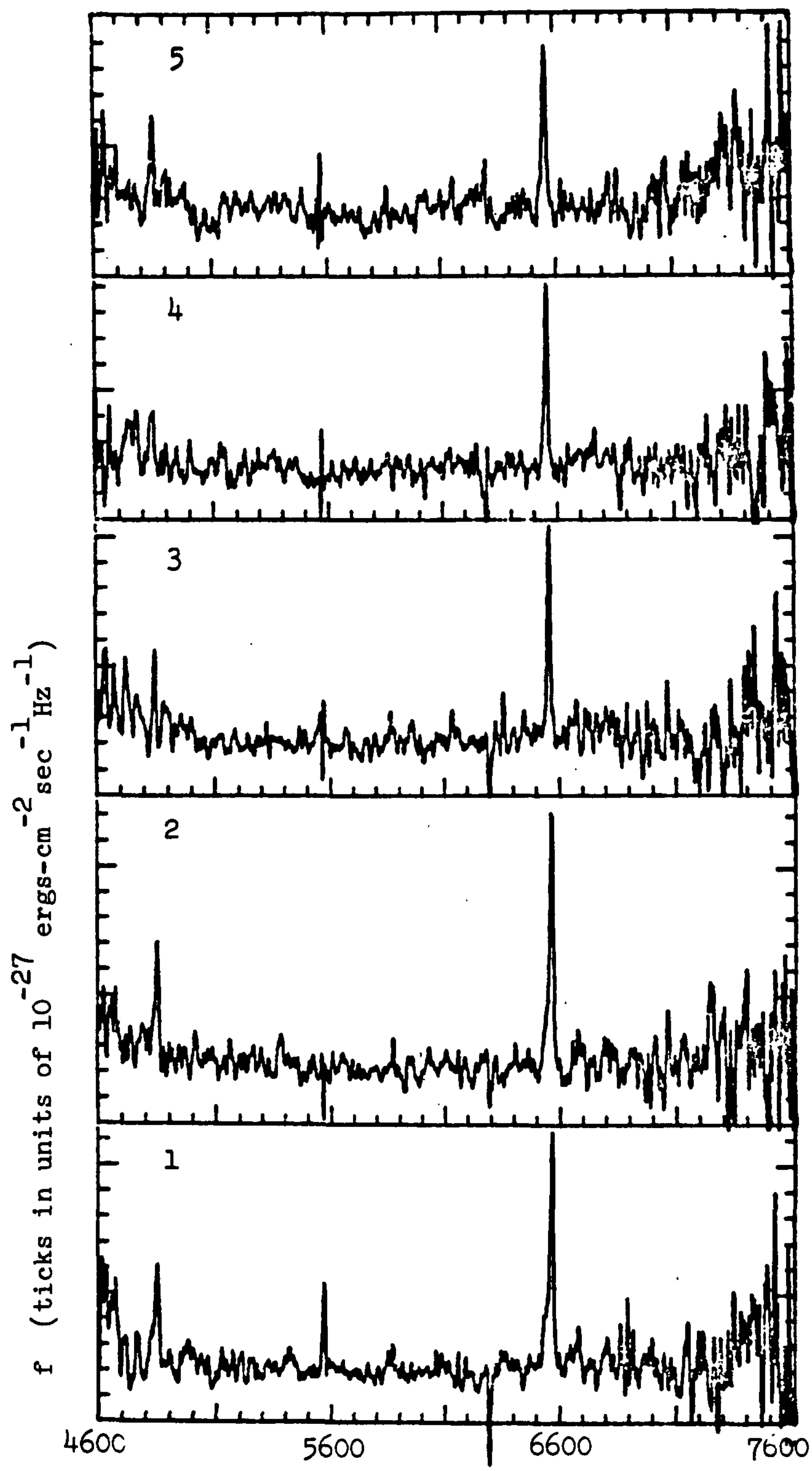




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Figure 2(b)

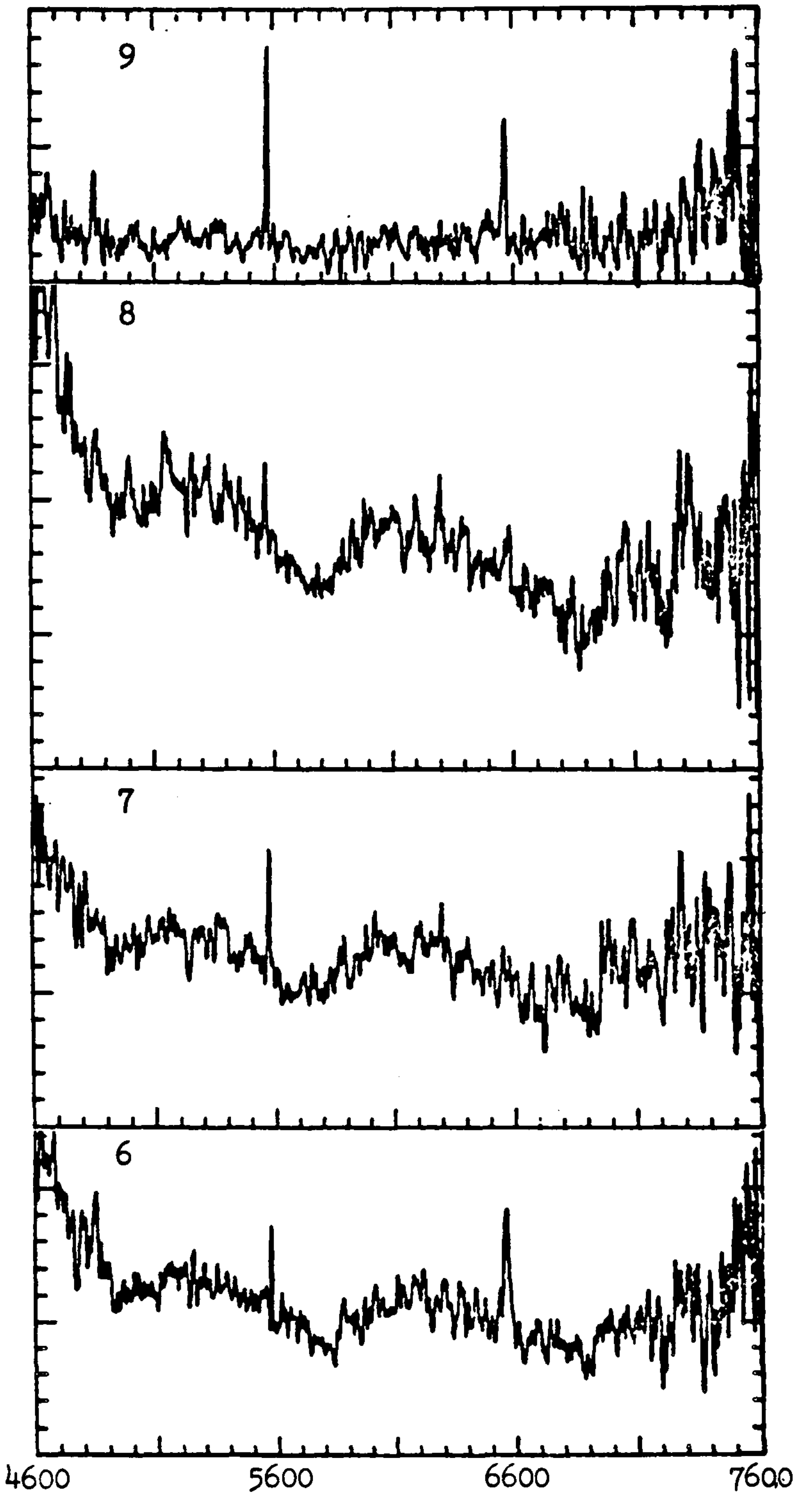




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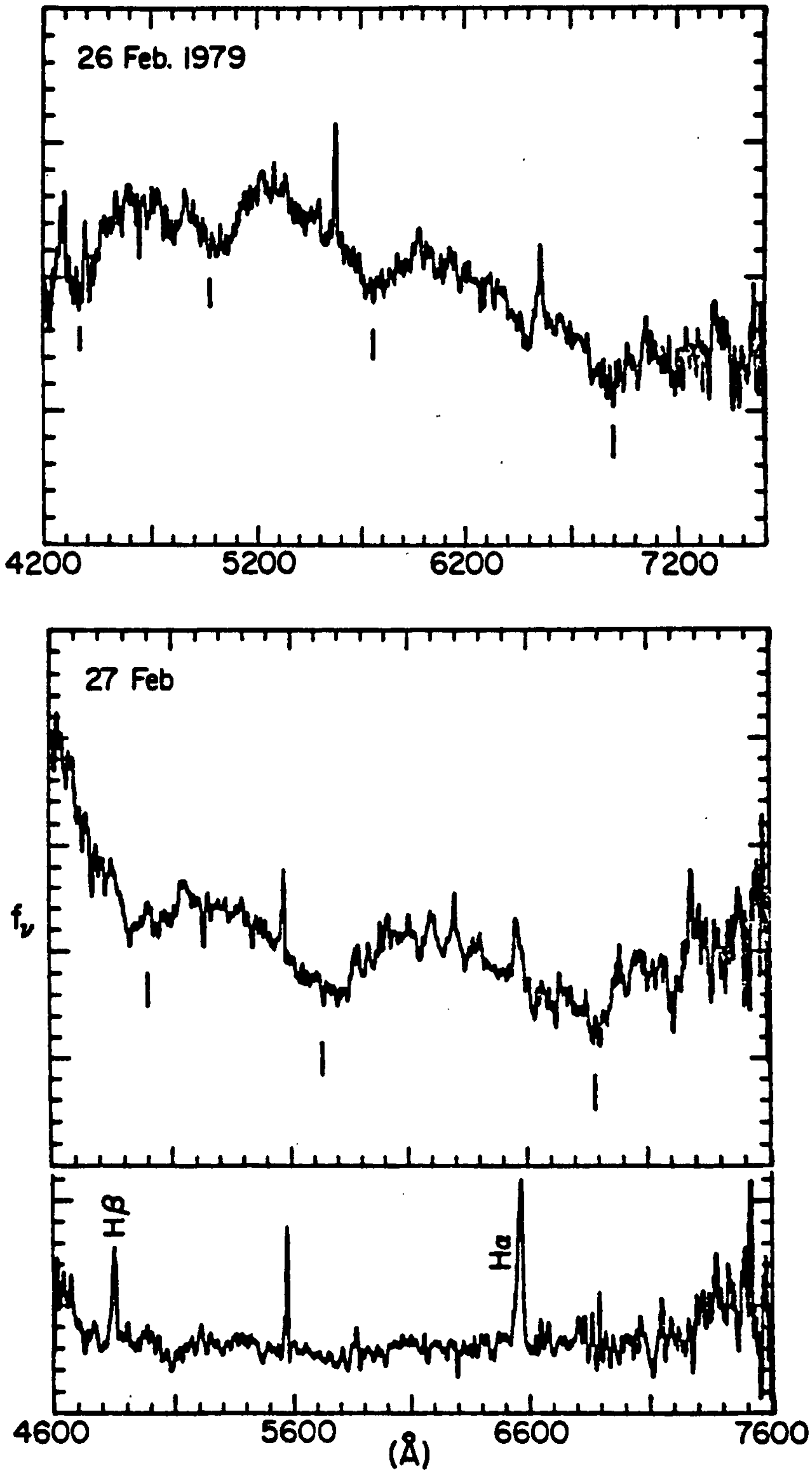
Figure 3



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