IUE OBSERVATIONS OF HL CMa AND THE WINDS OF CATACLYSMIC VARIABLES

C. W. MAUCHE and J. C. RAYMOND
Harvard-Smithsonian Center for Astrophysics,
Cambridge, MA, U.S.A.

ABSTRACT. As evidenced by the P Cygni profiles of their ultraviolet resonance lines, cataclysmic variables—like early-type stars—are known to have extensive, high velocity winds. Assisted by AAVSO visual data and *IUE* ultraviolet spectra, we present an observational and theoretical study of the P Cygni profiles of the dwarf nova HL CMa. As these profiles are dependent upon the ionization structure of the wind, we describe a model of a radiatively-driven shocked wind for cataclysmic variables, and present results for the temperature and ionization structure of the outflowing gas.

1. *IUE* OBSERVATIONS OF HL CMa

The dwarf nova HL CMa (1E 0643.0-1648) was discovered serendipitously by the ***Einstein Observatory*** in March of 1979 (Chlebowski, Halpern, and Steiner 1981). As shown by subsequent AAVSO coverage, its light curve varies between ~ 11 mag and ~ 14.5 mag with an average recurrence time of ~ 17 days. Because of this short recurrence time, an intensive program of *IUE* observations was undertaken to study the eruptive behavior of this system throughout its outburst cycle. Of particular interest was the formation and evolution of the P Cygni profiles of the ultraviolet resonance lines during outburst. Figure 1 shows the evolution of the ultraviolet spectrum of HL CMa during the late stages of a burst lasting ~ 15 days. Strong spectral features are apparent at $\log \lambda \simeq 3.095$ and 3.190 corresponding to N V (1240Å) and C IV (1550Å). Weaker absorption features due to C III, Si III / O I, C II, and N IV are present at $\log \lambda \simeq 3.070$, 3.115, 3.125, and 3.235, respectively. As the N V profile is strongly affected by the Lyα profile in these low-resolution spectra, the C IV profile is left as the only straight-forward spectral diagnostic of the structure of the wind of this system during outburst.

A detail of the C IV profile from five *IUE* epochs is shown in Figure 2*b*. Apparent in that figure are the shortward-displaced absorption and symmetric emission characteristic of the P Cygni profiles of cataclysmic variables during outburst. The blue wing of the absorption feature extends to ~ 1500Å or ~ −9700 km sec^{-1}, while the emission component has a full width of ~ 15Å or ~ 2900 km sec^{-1} at the base of the feature. The origin of the feature at ~ 1520Å or ~ −5800 km sec^{-1} in some of the profiles is unknown and remains to be explained.

Paper presented at the IAU Colloquium No. 93 on 'Cataclysmic Variables. Recent Multi-Frequency Observations and Theoretical Developments', held at Dr. Remeis-Sternwarte Bamberg, F.R.G., 16–19 June, 1986.

Astrophysics and Space Science **130** (1987) 269–274.

2. P CYGNI PROFILES

As for early-type stars, the P Cygni profiles manifested by cataclysmic variables , and HL CMa in particular, are thought to be formed by resonant scattering in an expanding wind driven by the radiation pressure of line photons. In contrast to the situation for early-type stars, however, the source of the resonant photons in cataclysmic variables is to be found in the accretion disk, and not in the star itself. Because of this fact, and because of the inclination-dependent shadowing produced by the accretion disk, the P Cygni profiles calculated for early-type stars cannot be applied to cataclysmic variables. This point is made forcibly by Figure 2*a*, which shows the effect on a P Cygni profile as the inclination of the disk is changed from edge-on to nearly face-on: simply by rotation, the feature changes from pure emission to essentially pure absorption. This dependence on the viewing angle introduces an added degree of complexity to the P Cygni profiles of cataclysmic variables absent in the profiles of early-type stars, and accounts, to large measure, for the great diversity of the profiles manifest by cataclysmic variables as a class.

In order to better understand the formation of these profiles, we have carried out computer calculations of the scattering of resonant-line photons in a spherical, radially expanding wind, with a velocity profile of the form $V(r) = V_0 + [(V_\infty - V_0) \times (1 - r/R)^\beta]$, where V_∞ is the terminal velocity, taken to be 5000 km sec^{-1}; R is a scale length, taken

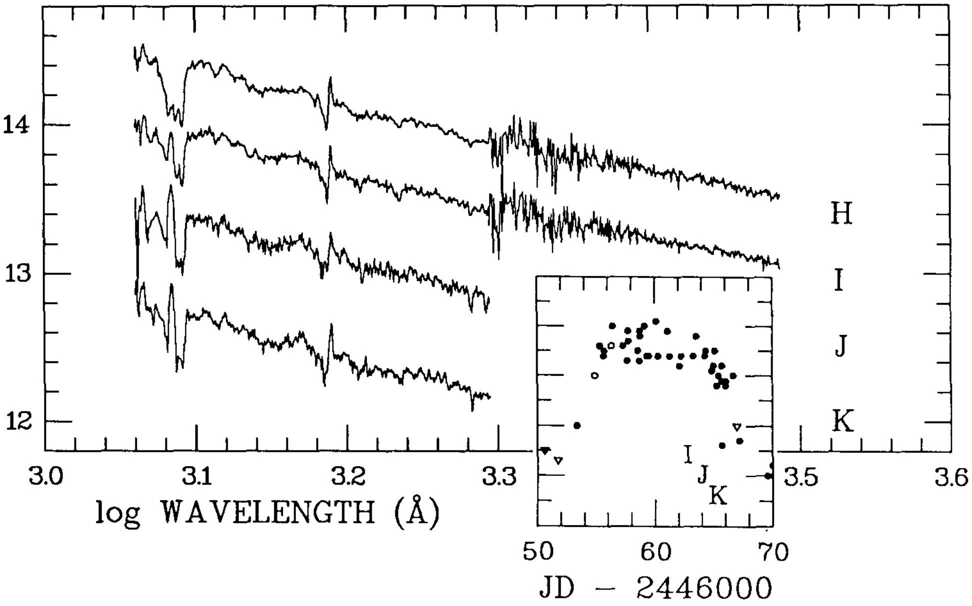

Fig. 1.—*IUE* spectra of HL CMa at epochs H–K. The ordinate scale [log flux (ergs cm^{-2}sec^{-1}Å^{-1})] refers to epoch H; subsequent spectra are offset downward by 0.5(I), 1.0(J), and 1.5(K) decades relative to H. The inset plots the AAVSO visual data for the outburst containing epochs I, J, and K; the ordinate scale is visual magnitudes [$15 \leq m_V \leq 10$ mag].

to be approximately equal to the radius of the white dwarf; and β is a parameter we vary between 2 and 6. The calculation itself is a single-scattering approximation to the radiation transfer in an expanding medium, where the fraction of scattered photons varies as $\exp[-\tau(r)]$, and the optical depth $\tau(r) \propto [V(r)\, r^2\, dv(r)/dl]^{-1}$, where $dv(r)/dl$ is the local apparent velocity gradient along the ray $\mathbf{l}$, whose origin lies in the accretion disk. The radial brightness profile of the disk is determined by the Shakura and Sunyaev (1973) temperature profile $T(x) = 106{,}000\,[\dot{M}_{-9}\,(1 - x^{-1/2})x^{-3}]^{1/4}$ K, where $\dot{M}_{-9}$ is the mass accretion rate in units of $10^{-9}\ M_\odot$ year^{-1} and x is the radial distance scaled by the radius of the white dwarf. The radiation transfer in these calculations is less sophisticated than the models of Drew (1985;1986) for the winds of cataclysmic variables, though we obtain similar results.

The results of our calculations for a given viewing geometry for various values of the exponent in the velocity law and rates of mass loss in the wind are shown in Figure 2*c*.

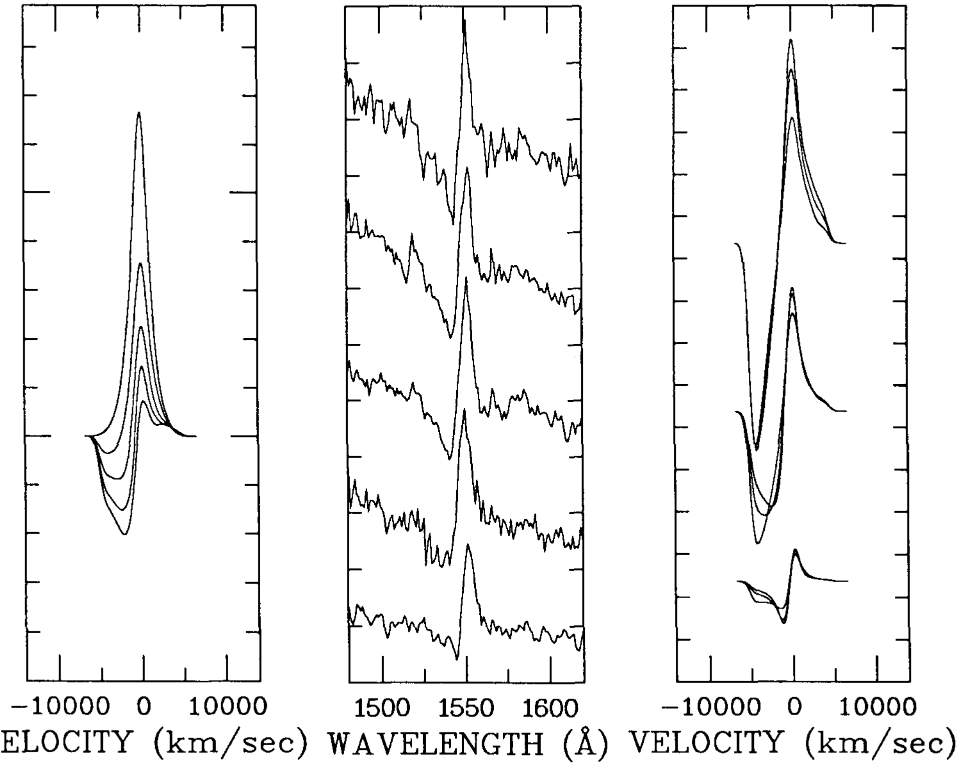

Fig. 2.—(*a*) Theoretical P Cygni profiles as a function of the inclination of the accretion disk for $i = 90°, 75°, 60°, 45°$, and $30°$ for $\dot{M}_{\rm wind} = 10^{-11}\ M_\odot$ year^{-1}, $V_\infty = 5000$ km sec^{-1}, and $\beta = 6$. (*b*) Five *IUE* measurements of the C IV profile of HL CMa. (*c*) Three sets of theoretical P Cygni profiles for $\dot{M}_{\rm wind} = 10^{-10}, 10^{-11}$, and $10^{-12}\ M_\odot$ year^{-1} (top to bottom) for $V_\infty = 5000$ km sec^{-1} and $i = 50°$ for three values of the exponent in the velocity law: $\beta = 2, 4$, and 6. The ordinate scale for each figure is relative flux.

Top to bottom, they correspond to a mass loss rate of $\dot{M}_{\rm wind} = 10^{-10}$, 10^{-11}, and 10^{-12} $M_\odot$ year^{-1} for an assumed ion fraction of unity. For each mass loss rate, the exponent in the velocity law was taken to be $\beta = 2$, 4, and 6. The slowest velocity law produces, for each mass loss rate, the most prominent emission component, and, for the unsaturated profiles, the largest amount of absorption near zero velocity. This last feature, given the shapes of the profiles of in Figure 2*b*, suggests that the winds of cataclysmic variables are accelerated very slowly. This is realized either by a large value of β in the velocity law, or by a much larger scale length for the acceleration of the wind. This fact argues against the model of the wind proposed by Torbett (1986), wherein bipolar flows are accelerated to high velocities within a very short distance of the white dwarf.

The issue of bipolar wind geometries is itself a topic addressed by these models. The original motivation for bipolar winds in cataclysmic variables was based on the inability (e.g. Greenstein and Oke 1982) to fit the shapes of the profiles of cataclysmic variables, particularly the relative strengths of the absorption and emission components, with the theoretical P Cygni profiles for early-type stars (e.g. Castor and Lamers 1979). Little agreement between these profiles and the profiles of cataclysmic variables is expected, however, given the drastic changes in the relative strengths of the emission and absorption components of a profile as the inclination is varied (cf. Fig. 2*a*). Indeed, although the C IV profile for RW Sex presented by Greenstein and Oke (1982) bears no resemblance to any of the profiles in Castor and Lamers (1979), it does look very similar to the profile in Figure 2*a* for a system at an inclination of ~ 30°, the inclination appropriate to this source. Furthermore, the observation by Córdova and Mason (1982) that the absorption component of the P Cygni profiles of cataclysmic variables is more pronounced than the emission component for systems at low inclination is a natural consequence of a spherical wind illuminated by an accretion disk, and cannot be taken as evidence of a conical wind geometry. We have argued elsewhere (Mauche and Raymond 1985) that conical winds are in conflict with the necessity of producing sufficient amounts of absorption for intermediately inclined systems, and so fail to explain the general observational situation for cataclysmic variables.

3. THE WINDS OF CVs

As these results are dependent upon our assumption about the radial ionization profile of the wind, we turn to consider the temperature and ionization structure of the wind of a cataclysmic variable in the face of the intense EUV/soft X-radiation emitted by the boundary layer. The basic problem regarding the ionization state of the wind is the fact the boundary layer radiation is predicted to be intense enough, if the wind is smooth and represents a mass loss rate which is a fraction of the mass accretion rate, to ionize the wind beyond the observed ionization stages of C IV, Si IV, and N V. Kallman and Jensen (1985) have suggested that the resolution of this problem is to be found in the existence of a wind of sufficient density to photoelectrically absorb the EUV/soft X-radiation emitted by the boundary layer—thereby explaining the discrepancy between the predictions of the flux of the soft X-ray component of the boundary layer and the many nondetections by *HEAO-1* and the *Einstein Observatory* of cataclysmic variables—and for collisional recombination to win out over photoionization—thereby explaining the low ionization state of the wind. Unfortunately, the requirements of this wind are met only by one which produces a mass loss rate in excess of the mass accretion rate. Drew and Verbunt (1985) have found that a relatively slow velocity law, as well as variations in the temperature and luminosity of the boundary layer, help to increase the ionization fractions of C IV, Si IV, and N V, but not by an amount sufficient to explain the intensity of the P Cygni profiles of cataclysmic variables.

Rather than smooth winds, we advocate a model for the winds of cataclysmic variables analogous to the models of the winds of early-type stars. Such winds, being driven by the radiation pressure on optically thick lines, are predicted to be unstable to the formation of compressive waves which steepen into shocks which travel through the wind with velocities of hundreds of kilometers per second. The presence of these shocks explains not only the observed X-ray emission from early-type stars and the discrepancy between the profiles of the ultraviolet resonance lines and the classical predictions for the shapes of the profiles, it also is capable of producing the requisite compression for a fraction of the outflowing gas to cool to the degree that reasonably large ion fractions of moderately ionized C, N, and O are realized (cf. Lucy and White 1980; Lucy 1982a,b; Krolik and Raymond 1985).

We have computed a few models of the temperature and ionization structure of a radiatively-driven shocked wind similar to the models of Krolik and Raymond (1985) for the winds of O stars containing time-steady shocks. For the admittedly simplified assumptions of a constant shock velocity of 100 km sec^{-1}, a constant shock thickness of ~ 30 km sec^{-1} to control the number of shocks per unit length, and the velocity law given in the previous section, we have computed, as a function of radius, the heating and cooling of the outflowing gas in the presence of the radiation field generated by the accretion disk (Shakura and Sunyaev 1973) and the ~ 200,000 K (Patterson and Raymond 1985) blackbody boundary layer. The resulting temperature profile of the wind is shown in Figure 3 for a model with $\dot{M}_{\rm accr} = 10^{-8}\ M_\odot\ {\rm year}^{-1}$ and $\dot{M}_{\rm wind} = 10^{-9}\ M_\odot\ {\rm year}^{-1}$ for $\beta = 4$. While the X-ray and ultraviolet emission from the shocks in this wind are negligible, the factor of ~ 100 compression they produce is sufficient to realize (cf. Fig. 3) reasonably large ion fractions of C IV, N V, and O VI.

This work has been supported by NASA contracts NAG-528 and NAG5-87 to the Smithsonian Astrophysical Observatory.

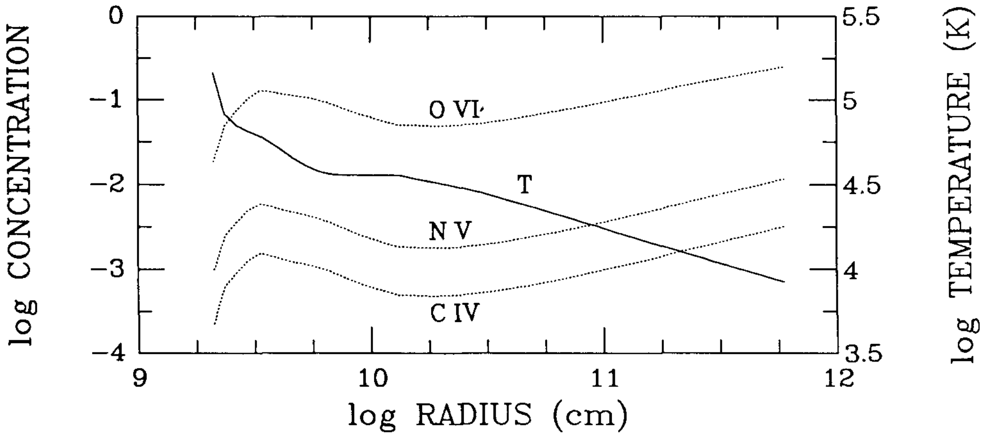

Fig. 3.—Temperature of the gas and ion concentration for C IV, N V, and O VI as a function of radius for a radiatively-driven shocked wind for $\dot{M}_{\rm accr} = 10^{-8}\ M_\odot\ {\rm year}^{-1}$ and $\dot{M}_{\rm wind} = 10^{-9}\ M_\odot\ {\rm year}^{-1}$ for $\beta = 4$. The concentration of Si IV is everywhere $< 10^{-4}$.

4. REFERENCES

Castor, J. I. and Lamers, H. J. G. L. M., 1979, *Ap. J. Suppl.*, **39**, 481.
Chlebowski, T., Halpern, J. P., and Steiner, J. E., 1981, *Ap. J. (Letters)*, **247**, L35.
Córdova, F. A. and Mason, K. O., 1982, *Ap. J.*, **260**, 716.
Drew, J. E., 1985, in *Proceedings of the Ninth North American Workshop on Cataclysmic Variables*, ed. P. Szkody (Seattle: University of Washington), p. 40.
Drew, J. E., 1986, *M. N. R. A. S.*, submitted.
Greenstein, J. L. and Oke, J. B., 1982, *Ap. J.*, **258**, 209.
Kallman, T. R. and Jensen, K. A., 1985, *Ap. J.*, **299**, 277.
Krolik, J. H. and Raymond, J. C., 1985, *Ap. J.*, **298**, 660.
Lucy, L. B. and White, R. L., 1980, *Ap. J.*, **241**, 300.
Lucy, L. B., 1982a, *Ap. J.*, **255**, 278.
Lucy, L. B., 1982b, *Ap. J.*, **255**, 286.
Mauche, C. W. and Raymond, J. C., 1985, in *Proceedings of the Ninth North American Workshop on Cataclysmic Variables*, ed. P. Szkody (Seattle: University of Washington), p. 93.
Patterson, J. and Raymond, J. C., 1985, *Ap. J.*, **292**, 550.
Shakura, N. I. and Sunyaev, R. A., 1973, *Astr. Ap.*, **24**, 337.
Torbett, M. V., 1986, *Can. J. Phys.*, **64**, in press.