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HYDRODYNAMIC MODELS OF LINE-DRIVEN ACCRETION DISK WINDS IN CATACLYSMIC VARIABLES

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RESUMEN

Desarrollamos modelos de discos-α para vientos por líneas en variables cataclísmicas. Utilizando modelos analíticos 1-D exploramos las condiciones necesarias para la existencia de un viento, y la dependencia de su velocidad y pérdida de masa con el radio. Con el modelo isotérmico 2-D exploramos los efectos de fuerzas centrífugas, mostrando que causan la colisión de líneas de flujo produciendo una región de alta densidad en el viento. Sin estos efectos, la pérdida de masa obtenida produciría densidades ópticas demasiado bajas para explicar los perfiles P-Cygni observados, mostrando la necesidad de modelos 2-D. Con el modelo 2-D adiabático calculamos pérdida de masa, velocidades terminales, y perfiles de la línea de C IV para varios ángulos. Para un disco de luminosidad $L_\odot$ alrededor de una enana blanca de 0.6 $M_\odot$ y 0.01 $R_\odot$, obtenemos $\dot{M}_{wind} = 8 \times 10^{-12} M_\odot \mathrm{yr}^{-1}$, y una velocidad terminal $\sim 3000\,\mathrm{km\,s^{-1}}$. Los perfiles obtenidos son consistentes con las observaciones y, en particular, con la absorción de la componente azul, con las velocidades implicadas por las componentes de absorción, con el ancho de las componentes de emisión, y con la fuerte dependencia con la inclinación.

ABSTRACT

We developed several α-disk models for line-driven winds from cataclysmic variables. Using 1-D analytic models we explore the conditions necessary for the existence of a wind, and the dependence of speed and mass-loss with radius. Using a 2-D isothermal model we explore the effects of centrifugal forces, showing that they cause stream lines to collide producing enhanced density regions in the wind. Without these effects, the mass-loss rates obtained would be too low to produce the optical depths required to explain P-Cygni profiles, showing the necessity of 2-D models. Using a 2-D adiabatic model we calculate mass-losses, terminal velocities, and C IV line profiles for various angles. For a disk with $L_\odot$ around a white dwarf of 0.6 $M_\odot$ and 0.01 $R_\odot$, we obtain $\dot{M}_{wind} = 8 \times 10^{-12} M_\odot \mathrm{yr}^{-1}$, and a terminal velocity $\sim 3000\,\mathrm{km\,s^{-1}}$. The profiles obtained are consistent with observations, in particular with the absorption of the blue-shifted component, the velocities implied by absorption components, the width of emission components, and the strong dependence with inclination.

Key Words: **ACCRETION: ACCRETION DISKS — NOVAE: CATACLYSMIC VARIABLES — STARS: MASS-LOSS**

1. INTRODUCTION

Cataclysmic variables (CVs) are binary systems composed of a white dwarf, a main sequence star, and a disk rotating about the white dwarf. The disk or "accretion" disk is formed by mass accreting from the main sequence star onto the white dwarf. Some of these systems present periodic "outbursts", that is an increase in luminosity with respect to their usual state when they are said to be in "quiescence". The luminosity of the cataclysmic variables is dominated by the radiation emitted by the accretion disk which is typically in the order of the solar luminosity $L_\odot$ (Patterson 1984). The luminosity of the disk is generated through the conversion of the gravitational energy lost as the accreting mass spirals into the white dwarf.

The first evidence for winds from CVs came from the discovery of P-Cygni profiles in the UV resonance lines of SS Cyg by Heap et al. (1978). The dependence of the observability of CV winds with inclination angle and the apparent similarity between CV line profiles and those of OB stars led to the early suggestion by Córdova & Mason (1982) that the winds in CVs originate from the disk and that the line radiation pressure is responsible for the wind in the CV case.

More recently, P-Cygni profiles have been detected from virtually all non-magnetic CVs (e.g., Greenstein & Oke 1982; Córdova & Mason 1982; Prinja & Rosen 1995; Friedjung, Selvelli, & Cassatella 1997; Knigge et al. 1997). The absorption component is most apparent in low inclination systems (line of sight parallel to the disk rotation axis), and is not detected in high inclination or eclipsing systems (disk seen "edge on") (Krautter et al. 1981; Córdova & Mason 1985; Mason et al. 1995). Furthermore, P-Cygni profiles are weak or absent in systems with low inferred mass accretion rates, such as dwarf novae in quiescence.

Past efforts in the development of disk wind models focused on one-dimensional models (Vitello & Shlosman 1988; Kallman 1988), and on kinematical modeling (Shlosman & Vitello 1993; Knigge, Woods, & Drew 1995), which succeeded in showing consistency between the assumed polar geometry of a disk wind and observed profiles. However, there remain important unresolved issues concerning the dynamics. Among these is the angular dependence of density and velocity of the disk wind inferred from observations; the mass loss rate in the winds and the associated driving mechanism; the origin for the characteristic shapes of the UV resonance line profiles; and the apparent association between outburst state and the wind existence. In particular, the role of rotation has not been included in any previous dynamical treatment, nor has a self consistent two- or more-dimensional calculation been performed. Icke (1980) developed a two-dimensional disk wind model but did not take into account the radiation pressure due to line scattering. We believe that, as in the case of early type stars, line scattering plays an important role as a mechanism to drive the disk wind.

Thus, in spite of previous studies of CV disk winds, a self consistent two-dimensional hydrodynamic model which includes line radiation pressure had not been developed. In an earlier paper (Pereyra, Kallman, & Blondin 1997) we presented in detail our isothermal models, which to our knowledge our the first two-dimensional hydrodynamic models of line-driven accretion disk winds. Recently, Proga, Stone, & Drew (1998) also developed two-dimensional models for these systems, albeit they obtained unstable results with large amplitude fluctuations in velocity and density.

2. ISOTHERMAL DISK WIND MODELS

We approached the development of our models in a systematic manner. As our first step, we developed a one-dimensional isothermal stationary non-spherical analytic model. Results from the one-dimensional analytic model suggest, in analogy with line-driven winds from OB stars, that the terminal velocities are approximately independent of the luminosity of the disk, although luminosity does affect the mass-loss rate. Through our one-dimensional analytic model we have also shown that a minimum optical depth is necessary for a disk wind to exist. This fact is mathematically expressed through the condition that the line radiation pressure parameter α must be greater than 0.5. This could explain the absence of P-Cygni profiles with low inferred mass accretion rates, such as dwarf novae in quiescence, since the parameter α decreases as temperature decreases. Another possible explanation for the absence of P-Cygni profiles in such systems could also be due to the fact that, as we show through our one-dimensional analytic model, the wind mass-loss rate decreases as luminosity decreases, so that although a wind may exist, the density may be too low to produce observable absorption line profiles.

We then developed a one-dimensional isothermal time-dependent non-spherical numerical model based on the PPM (Piecewise Parabolic Method) scheme. The motivation for developing this model was two-fold:

it would serve as a consistency check for the analytic model results since it would be developed under an independent numerical scheme and it could be extended to a two-dimensional model, which was the goal of this work. The one-dimensional numerical model was initiated with arbitrary density and velocity spatial functions and once it achieved stationary state, we found virtually the same results as in our one-dimensional analytic model.

We then developed an isothermal two-dimensional numerical model based upon the PPM numerical scheme which solves a complete set of isothermal three-dimensional hydrodynamic partial differential equations, under azimuthal symmetry. This model allowed us to study the effects of centrifugal forces, which could not be implemented in our previous one-dimensional models due to the two-dimensional nature of disk winds, and served as a stepping stone in our systematic approach towards a more complete (and complex) adiabatic alpha disk model. Through our two-dimensional isothermal model we show that rotational forces are important in the study of winds from accretion disks. They cause the velocity stream lines to collide which results in an enhanced density region. In this region the wind speed is reduced and its density is increased (the same effect is observed in our two-dimensional adiabatic alpha disk model [Figure 1]). The increase in density caused by the collision of stream lines is important because it permits the appearance of blue-shifted absorption lines as observed in P-Cygni profiles of low-inclination CVs.

3. ADIABATIC ALPHA DISK WIND MODELS

We then developed the two-dimensional adiabatic alpha disk model. In this model we introduced the hydrodynamic energy equations and implemented radial temperature and radiation emission distributions along the surface of the disk. These distributions were implemented as an alpha disk distribution, that is we take into account that the spiraling of the accretion disk mass towards the white dwarf is due to the outward transport of angular momentum caused by shear stresses, and assume that the loss of gravitational energy is converted locally into blackbody radiation. The two-dimensional adiabatic alpha disk model presented in this work solves a complete set of adiabatic three-dimensional hydrodynamic partial differential equations, under azimuthal symmetry, using the PPM numerical scheme. Through our two-dimensional adiabatic alpha disk model we calculate the wind mass-loss rate and terminal wind speeds, obtaining values of $\dot{M}_{wind} = 8 \times 10^{-12} M_{\odot}$ yr^{-1} and $v_{\infty} \sim 3000$ km s^{-1} for typical values of CV parameters ($M_{wd} = 0.6\ M_{\odot}$, $R_{wd} = 0.01\ R_{\odot}$, and $L_{disk} = L_{\odot}$). The values we obtain for wind mass loss rates and terminal speeds are consistent with observations.

Observed values of white dwarf mass (Leibert 1980) vary between $0.40 M_{\odot} \lesssim M_{wd} \lesssim 0.90\ M_{\odot}$ (in our models $M_{wd} = 0.60\ M_{\odot}$). Within this range we do not expect significant changes in our results. Observed values of white dwarf radii (Leibert 1980) vary between $0.008 R_{\odot} \lesssim R_{wd} \lesssim 0.012\ R_{\odot}$ (in our models $R_{wd} = 0.01\ R_{\odot}$). Within this range we do not expect significant changes in our results. Observed values of CV disk luminosity (Patterson 1984) vary between $0.001\ L_{\odot} \lesssim L_{disk} \lesssim 10\ L_{\odot}$. Through our models we found that the wind velocity is approximately independent of luminosity, thus we do not expect significant changes in wind velocities within this range. However we do find that disk luminosity does affect wind mass loss rate. Within the above luminosity range we expect that wind mass loss rate to increase ($L_{disk} > L_{\odot}$) or decrease ($L_{disk} < L_{\odot}$) by up to approximately an order of magnitude.

Values for the the line radiation pressure parameters applied in our models (Castor, Abbott, & Klein 1975; Abbott 1982) vary within the ranges of $0.02 \lesssim k \lesssim 0.94$ (in our adiabatic alpha disk model $k = 1/3 \approx 0.33$) and $0.44 \lesssim \alpha \lesssim 0.81$ (in our models $\alpha = 0.7$). For the line radiation pressure the variations of the parameter k have, mathematically, the same effect as variations in luminosity. Thus, within the above range for the k parameter, we expect equivalent changes as those described above for variations in disk luminosity. For values of the parameter α within the range $0.60 \lesssim \alpha \lesssim 0.81$ we do not expect significant changes in our results. However our models indicate that, due to the decrease in optical depth, a line-driven disk wind would not be possible if $\alpha \leq 0.5$. Therefore we expect to observe considerable decreases in both wind velocity and wind mass loss rate for values of α close to but above 0.5 . For values of α such that $\alpha \leq 0.5$ a disk wind would not be possible. We note here that the α parameter decreases as temperature decreases (Castor, Abbott, & Klein 1975 and Abbott 1982). Thus, as we have indicated earlier, this could explain why winds have not been detected in CVs with low inferred mass accretion rates.

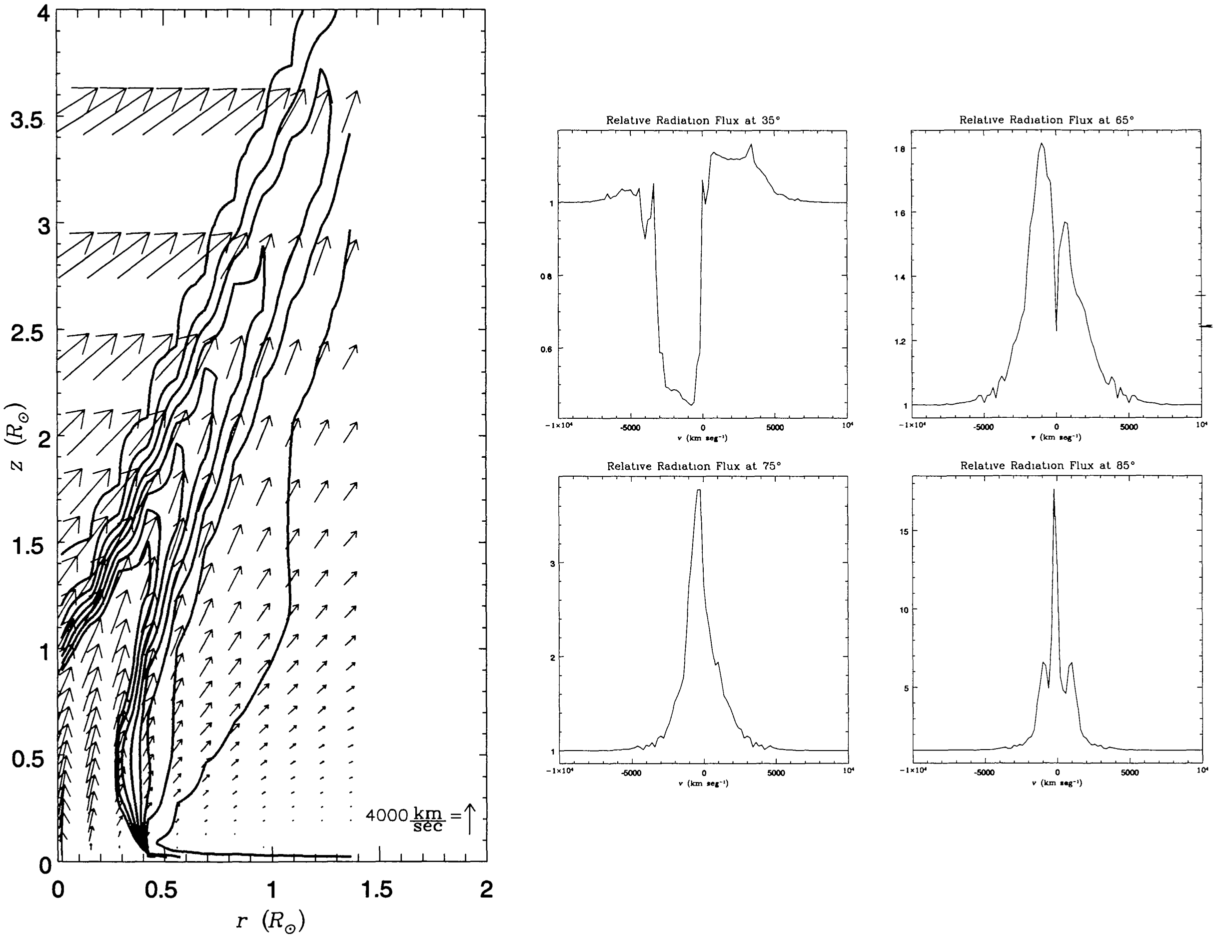

Fig. 1. (*left*) Vector field graph of wind velocity superimposed with a contour graph of wind density for the two-dimensional adiabatic alpha disk model. The primary star is at the origin of the graph, and the disk is over the horizontal axis. The contour levels vary uniformly from a value of 3.6×10^{-16} g cm^{-3} down to a value of 0.1×10^{-16} g cm^{-3}. (*right*) C IV 1550 Å line profiles obtained by the two-dimensional adiabatic alpha disk model for several angles (*upper left*: 35°, *upper right*: 65°, *lower left*: 75°, *lower right*: 85°). In the calculation of these line profiles we have assumed single scattering and a relative abundance of carbon with respect to hydrogen of $n_{\rm C\ IV}/n_{\rm H} = 10^{-3}$ throughout the wind. The physical parameters here used are $M_{wd} = 0.6\ M_\odot$, $R_{wd} = 0.01\ R_\odot$, and $L_{disk} = L_\odot$.

4. C IV 1550 Å LINE PROFILES

To further study CV winds we calculated line profiles for C IV (1550 Å) from our adiabatic alpha disk wind model (Figure 1). The line profiles obtained in this work were calculated through our adiabatic alpha disk wind model assuming single scattering and a relative abundance of carbon with respect to hydrogen of $n_{C\ IV}/n_H = 10^{-3}$ throughout the wind. At low inclination angles ($0° \leq i \lesssim 55°$) we obtain P-Cygni profiles (blue-shifted absorption line superimposed with an emission line) finding maximum absorption at roughly half the terminal velocity for the blue-shifted component and magnitudes of the wind velocities implied by the absorption components of ≈ 3000 km s^{-1}. For high-intermediate inclination angles ($55° \lesssim i \lesssim 70°$) we obtain double peaked emission lines with FWHM in the order of ≈ 2500 km s^{-1}. For high-high inclination angles ($70° \lesssim i \lesssim 85°$) we obtain single peaked emission lines with FWHM in the order of ≈ 2500 km s^{-1}. For high-orthogonal inclination angles ($85° \lesssim i \leq 90°$) we obtain double peaked emission lines with FWHM in the order of ≈ 1500 km s^{-1}.

The line profiles obtained through our adiabatic alpha disk wind model are consistent with observations in their general form, in the maximum absorption at roughly half the terminal velocity for the blue-shifted component, in the magnitudes of the wind velocities implied by the absorption components, in the FWHM of the emission components, and in the strong dependence in inclination angle. Thus, through our two-dimensional adiabatic alpha disk wind model we are able to predict the general observed wind properties of CVs.

5. CONCLUSIONS

We have developed a one-dimensional isothermal stationary non-spherical analytic model, a one-dimensional isothermal time-dependent non-spherical numerical model, a two-dimensional isothermal time-dependent numerical model, a two-dimensional adiabatic alpha disk time-dependent model, and obtained line profiles from our two-dimensional adiabatic alpha disk model. Results from the one-dimensional models suggest, in analogy with line-driven winds from early type stars, that the terminal velocities are approximately independent of the luminosity of the disk, although luminosity does affect the mass-loss rate. Through our one-dimensional analytic model we have shown that a minimum optical depth is necessary for a disk wind to exist. The two-dimensional isothermal disk wind model developed in this work shows that rotational forces are important in the study of winds from accretion disks. They cause the velocity stream lines to collide which results in enhanced density regions. These enhanced density regions reduce the speed and increase the density of the wind. The increase in density caused by the collision of stream lines is important because it permits the appearance of blue-shifted absorption lines observed in P-Cygni profiles of low-inclination CVs. The two-dimensional adiabatic alpha disk model developed in this work obtains wind mass-loss rates and terminal speeds in CVs consistent with observations. The line profiles obtained through our adiabatic alpha disk wind model are consistent with observations in their general form, in particular in the maximum absorption at roughly half the terminal velocity for the blue-shifted component, in the magnitudes of the wind velocities implied by the absorption components, in the FWHM of the emission components, and in the strong dependence in inclination angle. Thus, through our two-dimensional adiabatic alpha disk wind model we are able to predict the general observed wind properties of CVs. To our knowledge, we have developed the first two-dimensional hydrodynamical models of line-driven accretion disk winds. Recently we have included local ionization equilibrium in our models obtaining similar results.

6. FUTURE STUDIES

In the future we plan to include radiative cooling and heating in our models, which with local ionization equilibrium, would allow a more detailed calculation of line profiles for several atoms at different ion stages.

We also plan to extend our models to the study of the wind dynamics of LMXBs and AGNs where local ionization equilibrium may play an important role in the overall dynamics.

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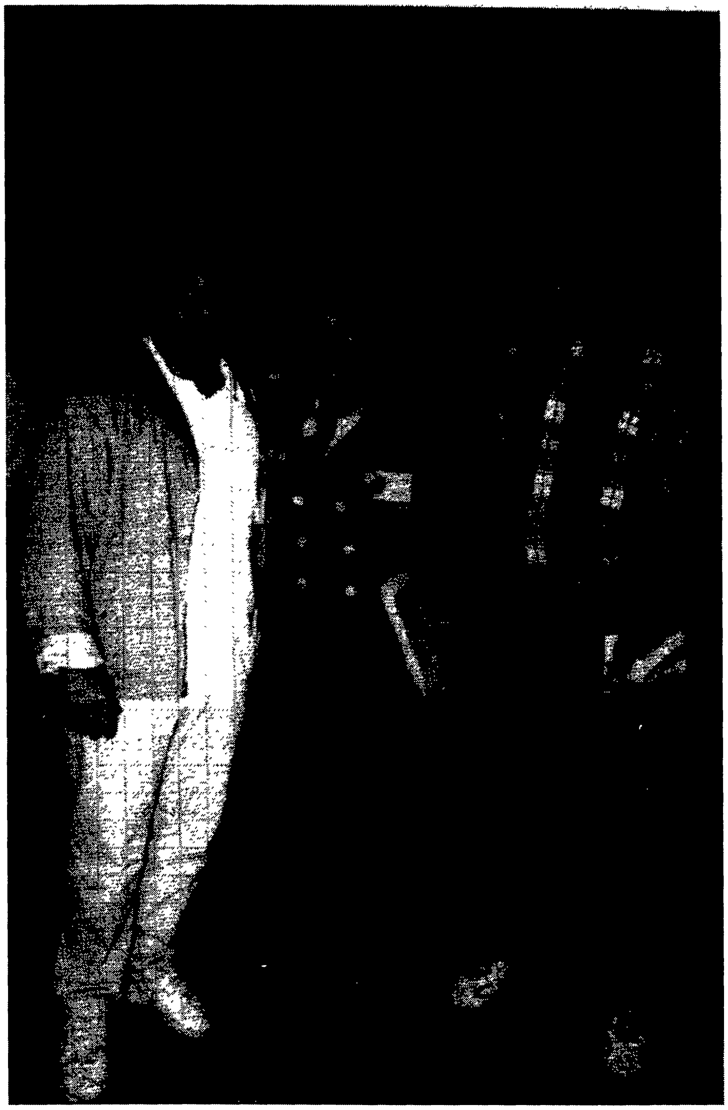

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