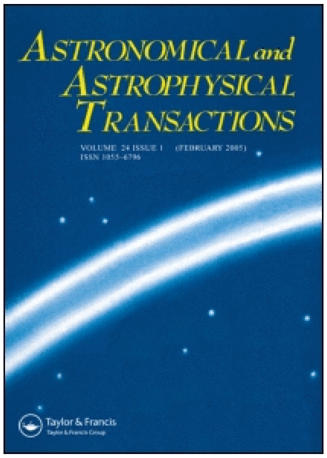

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ON THE POLARIZATIONAL PROPERTIES OF THE ACCRETION COLUMNS IN MAGNETIC CATACLYSMIC VARIABLES

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(7 January, 1991)

The effects of the non-uniformity of the density distribution through the cross-section of the accretion columns are discussed. The resulting spectra in two polarizational modes differ significantly from that computed for the "homogeneous plasma slab" model. The polarization remains significant even if the optical thickness is large in both ordinary and extraordinary polarization modes. The Doppler effect does not change the degree of the polarization, contrary to the spectral energy distribution. The polarizational observations of polars show the orientation changes of the accretion column in respect to the binary system, which were suspected earlier from the photometric data. However, now one may not distinguish between the models of "swinging" and "idling" dipole.

KEY WORDS Polars, accretion, polarization, stars: cataclysmic binaries.

INTRODUCTION

The polars, or AM Her-type stars, or magnetic cataclysmic variables, are the binary systems consisting of the filling its Roche lobe star, and of the magnetic white dwarf, onto which the accretion occurs via an accretion column (AC), but not via disc (see e.g. Lamb, 1985; Liebert and Stockman, 1985; Cropper, 1987, Voykhanskaÿa, 1990 for the recent reviews). The column is believed to be more high than thick, despite the models for some systems that argue for a "polar cap" rather than AC.

In this Paper we discuss some results obtained for the isothermal accretion columns with non-uniform density distribution. We point out that the columns underwent changes, and not only at short time-scales. The possible instabilities and mechanisms of the variability are briefly discussed.

THE ISOTHERMAL TWO-DIMENSIONAL ACCRETION COLUMN

To compute the fluxes in two independent polarizational modes, we used the analytic approximation for the absorption coefficients derived by Pavlov *et al.* (1980). The inhomogeneity of the AC, causes the significant dependence of the "effective" AC radius on the optical depth, τ even if $\tau \gg 1$. The electron number density of the AC follows the approximating expression:

$$n(x, y, z) = n_0 \exp(-(x^2 + y^2)/(2s^2(z))) \tag{1}$$

where $n_0 = n(0, 0, z)$ is the electron number density at the AC's axis, and $s(z)$—the characteristic AC's width, then the flux in the spectral region from ω to $\omega + \Delta\omega$ from the part of the AC of the height Δz may be written as:

$$L_j = B_{wB}(T) s(z) \Delta z \Delta\omega I_{wj} \tag{2}$$

where

$$I_{wj} = \frac{B_w(T)}{B_{wB}(T)} \sin\alpha\, Z_0(\tau_{0j}),$$

$\tau_{0j} = \tau_j(0)$—is the optical depth along the line of sight crossing the column's axis, the index $j(=1,2)$ corresponds to the extraordinary and ordinary polarizational modes, α is the angle between the line of sight and the magnetic field, $B_w(T)$—the Planck function at $\omega = 2\pi c/\lambda$ for the temperature T, $B_{wB}(T)$—the value corresponding to the cyclotron frequency $\omega = eB/mc$, where e and m are

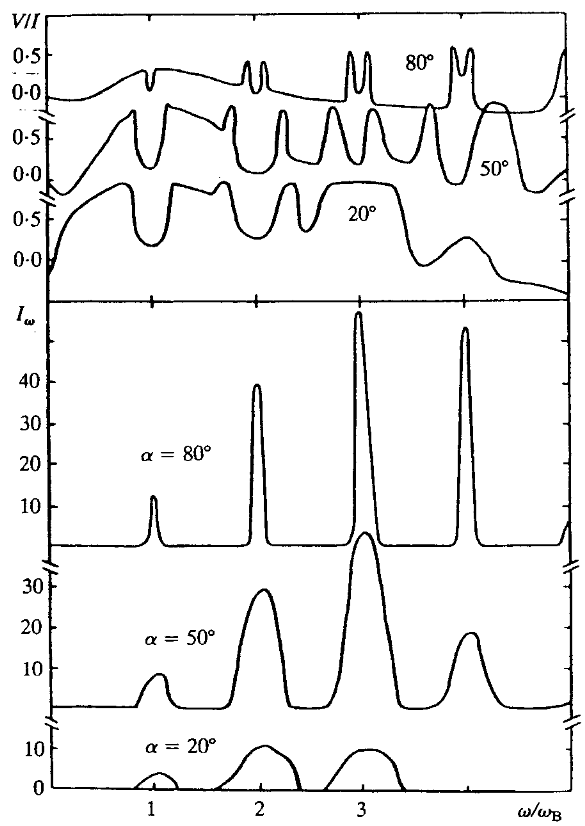

Figure 1 The dependence of the circular polarization (V/I) and the intensity (I) in dimensionless units, on the frequency, for three values of the angle α between the line of sight and the column's axis, for $s = 10^8$ cm, $n_0 = 10^{14}$ cm^{-3}, $T = 10^8$ K, $B = 10^7$ Gs in the case of small optical thickness between the cyclotron lines.

the charge and mass of the electron, c is the light velocity, B—the magnetic field (in Gaussian units). The function $Z_0(\tau)$ depends on the law of the electron number density distribution, and for the expression (1) is equal to:

$$Z_0(\tau) = \frac{\pi}{2} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}\tau^n}{n!\sqrt{n}}. \tag{3}$$

This sum converges formally for all values of τ, but practically for $\tau \geq 3$ one may use the approximation (Andronov, 1990):

$$Z_0(\tau) = t + 0.591t^{-1} - 0.169t^{-2} - 0.409t^{-3}, \tag{4}$$

where $t = (2 \log \tau)^{1/2}$. The maximal deviation from the true value for $7 < \tau < 10^{10}$ is only 0.02.

The illustrative curves for the total intensity $I_w = I_{w1} + I_{w2}$ and the degree of the circular polarization V/I are shown in Figure 1 and Figure 2. To obtain the total flux in the cyclotron line, one has to integrate the expression (2) over the frequency ω. The corresponding analytical approximations were also derived by Andronov (1990), and thus will not be repeated here. The illustrative curve for the intensity and the polarization is shown in Figure 3.

The results, briefly discussed above, were obtained for the electron number density distribution (1). This approximation is intermediate between the two

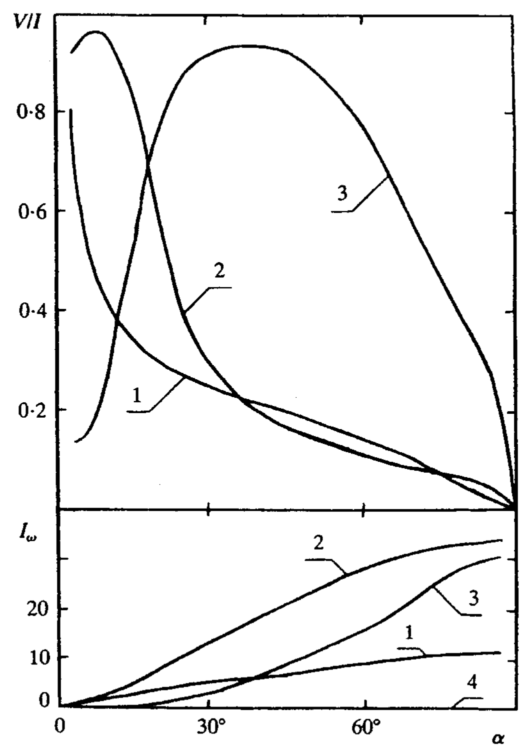

Figure 2 The dependence of the circular polarization (V/I) and the intensity (I) on the angle α for the different cyclotron harmonics, for $s = 10^8$ cm, $n_0 = 10^{14}$ cm^{-3}, $T = 10^6$ K, $B = 10^8$ Gs. The data correspond to the centers of harmonics (that is frequency $w = mw_B$, lines marked by numbers m).

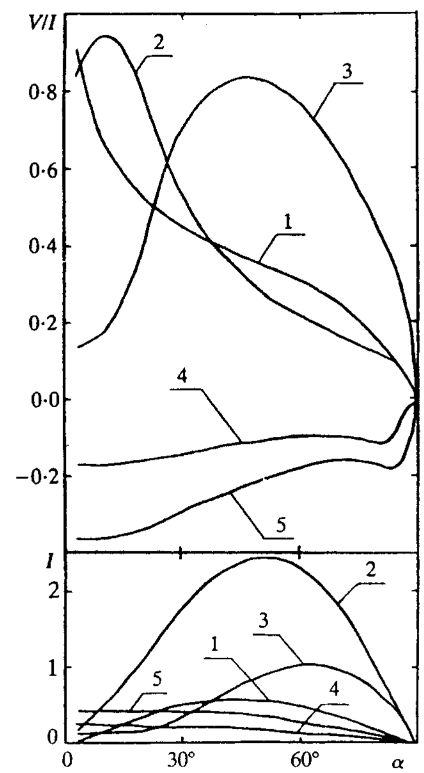

Figure 3 The dependence of the circular polarization (V/I) and the intensity (I) on the angle α for the different cyclotron harmonics, for $s = 10^8$ cm, $n_0 = 10^{14}$ cm^{-3}, $T = 10^6$ K, $B = 10^8$ Gs. The data correspond to the values integrated over the shape of the m-th cyclotron harmonic (numbers near lines).

limiting cases, which will be studied in brief. For the first of them, the homogeneous cylindrical column of radius $s(z)$ (that is $n(x, y, z) = n_0$, while $x^2 + y^2 < s^2$, else 0), one may obtain the expressions:

$$Z_0(\tau) = \tau(\pi/4 - \tau/3 + \tau^2/32 - \ldots) \tag{5}$$

for $\tau \ll 1$, and

$$Z_0(\tau) = 1 - \tau^{-2} - 6\tau^{-4} + \ldots \tag{6}$$

For the 'Lorentz shape':

$$n(x, y, z) = n_0/(1 + (x^2 + y^2)/s^2) \tag{7}$$

(e.g. Wang and Frank, 1981; Stockman and Lubenow, 1987), we obtained:

$$\tau(y) = \tau(0)/(1 + y^2/s^2)^{1/2} \tag{8}$$

For this expression, the integral:

$$Z_0(\tau) = \int_0^\infty (1 - \exp(-\tau(y)) \frac{dy}{s} \tag{9}$$

is infinite for all values of $\tau_0 = \tau(0) \neq 0$. Compared with (4), one may choose the value r (corresponding to $\tau(y) = 1$) as the "characteristic radius of the column." For the expression (7), $r \approx \tau_0$. However, the parts of the AC with $\tau < 1$ will formally add the infinite contribution to the integral (9).

Assuming that the velocity of plasma depends only on z, one may determine the accretion rate as:

$$\dot{M} = n_0(z)v(z)s^2(z)F_m(z) \tag{10}$$

where

$$F_m(z) = \int_0^\infty \int_0^\infty n(x, y, z)/n_0(z) \frac{dx}{s}\frac{dy}{s}. \tag{11}$$

For the homogeneous cylinder $F_m = \pi$, for the "normal" distribution (1), $F_m = 2\pi$; for the "Lorentz shape" (8), $F_m = \pi \log(1 + r^2)$ (if we replace infinity by r in the integral (9)). This expression has infinite values for $r \to \infty$. In this sense, the "Lorenzian shape" is the "limiting" one, corresponding to the "infinitely wide column."

For the AC with finite radius rs, the expression (8) may be rewritten as:

$$\tau(y) = (2/\pi)\tau_0 s(s^2 + y^2)^{-1/2} \operatorname{atan}\left(\frac{r^2s^2 - y^2}{s^2 + y^2}\right)^2. \tag{12}$$

The integral (9) may be thus approximated as:

$$Z_0(\tau_0) = \begin{cases} \tau_0 + \log(r/\tau_0) & \text{while} \quad r > \tau_0 \gg 1 \\ r & \text{while} \quad \tau_0 > r \gg 1 \\ \tau_0 \operatorname{atan} r & \text{while} \quad \tau_0 \ll 1, \; r \gg 1. \end{cases} \tag{13}$$

These expressions correspond to (3–6). For all of them, $Z_0(\tau)$ is proportional to τ while $\tau \ll 1$. For $\tau \gg 1$, the function $Z_0(\tau)$ strongly depends on the shape of the function $n(x, y, z)$. For the homogeneous plasma slab, or homogeneous cylinder, for large τ values $Z_0(\tau) \approx 1$; for the "normal distribution", $Z_0(\tau) \approx (2 \log \tau)^{1/2}$; Z_0 is the most far from unit for the "Lorentz shape", where $Z_0(\tau) \approx \tau$ while $\tau \ll r$. In the opposite case $\tau \gg r$ the function $Z_0(\tau) \approx r$ and almost independent on τ.

In other words, the spectral flux distribution changes significantly as compared with that obtained in the "homogeneous cylinder" (Canalle and Opher, 1986) or "plane-parallel plasma slab" models (for which $Z_0(\tau) = 1 - \exp(-\tau)$). The fluxes from the real accretion columns are believed to depend on τ in the intermediate manner, as compared with the limiting cases discussed above. Obviously, the models may be significantly complicated, and other effects may be taken into account. However, we did not compute the two-layer model, like that proposed recently by Wu and Chanmugam (1988). The main polarizational effects are discussed in the monograph of Dolginov, Gnedin and Silantjev (1979).

THE ASYMMETRY OF THE COLUMNS

The above discussed approximations correspond to the case of the axi-symmetrical columns. However, in the real objects, the deviations from the symmetrical case may be sufficiently large, and may significantly affect the polarization and the fluxes. For the stationary AC, the most important cases are: a) the inclination of the column; b) its ellipse-like shape.

The geometrical effects of the column's inclination were discussed earlier (Andronov, 1986). One may note that this effect is reduced with the increase in the column's height.

Here we will discuss the elliptical approximation. The electron number density distribution may be rewritten in the form:

$$n(x, y, z) = n_0 f(r). \tag{14}$$

In the previous cases, we defined r from the equation $r^2 = (x^2 + y^2)/s^2$. Now we will replace this expression, taking into account that s is dependent on the position angle φ: $r^2 = x^2/a^2 + y^2/b^2$, where $a = s(90°)$ and $b = s(0°)$. Thus the ratio of the fluxes for the same angle α, between the line of sight and the column's axis:

$$A = \frac{L_j(0°)}{L_j(90°)} = \frac{bZ_0(\tau_{aj})}{aZ_0(\tau_{bj})} \tag{15}$$

For the elliptical cross-section, the optical depth along the line of sight crossing the column's axis, is:

$$\begin{aligned} \tau_{aj} &= 2\,(\sin\alpha)^{-1}\chi_j n_0 a \int_0^\infty f(r)\,dr = Ba, \\ \tau_{bj} &= 2\,(\sin\alpha)^{-1}\chi_j n_0 b \int_0^\infty f(r)\,dr = Bb. \end{aligned} \tag{16}$$

As one may see, the value of B is independent on φ. For the above written approximations, one may obtain $A = 1$ for $\tau \ll 1$ for all three approximations for $f(r)$. For $\tau \gg 1$, $A = b/a$ for the homogeneous elliptical cylinder; $A = (b(\log B + \log a))/(a(\log B + \log b))$ for the "normal" distribution; $A = 1$ for the "Lorentz shape" and $\tau \ll r$, and $A = b/a$ for $\tau \gg r$. Thus the parameter A is characterizing the ratio of the fluxes if $\alpha = \text{const}$. The ellipse-like deviation from the axi-symmetric case is more significant for the columns with finite width, as compared with the models, where the function $f(r)$ reaches zero value only at the infinity.

THE DOPPLER EFFECT

Recently Shakura and Postnov (1987) pointed out that the Doppler effect may be observable, not only during the investigation of the line spectrum, but during the investigation of the continuum, in some cases as well. To investigate the possible effect of the relative motion of the emission source in respect to the observer, we used the Lorentz transformation for the electromagnetic waves (for example, Landau and Lifshitz, 1962).

If the source is moving parallel to the X-axis (the observer is suggested to be at the beginning of the co-ordinates x, y, z) with the velocity $v = \beta c$ (where c is the light velocity), one may write:

$$\begin{aligned}
&\sin\theta = (1-\beta^2)^{1/2} s'/(1+\beta c'),\\
&\cos\theta = (c'+\beta)/(1+\beta c'),\\
&E_x = E'_x, \qquad H_x = H'_x,\\
&E_y = (E'_y + \beta H'_z)\gamma, \qquad H_y = (H'_y - \beta E'_z)\gamma,\\
&E_z = (E'_z - \beta H'_y)\gamma, \qquad H_z = (H'_z + \beta E'_y)\gamma,
\end{aligned} \tag{17}$$

where $s' = \sin\theta'$, $c' = \cos\theta'$, and $\gamma = (1-\beta^2)^{-1/2}$. Let us assume that the electric field vector $\mathbf{E}$ is located at the angle φ in respect to the xy-plane. In this case:

$$\begin{aligned}
&E'_x = -E's'\cos\varphi, \qquad H'_x = H's'\sin\varphi,\\
&E'_y = E'c'\cos\varphi', \qquad H'_y = -H'c'\sin\varphi.\\
&E'_z = E'\sin\varphi', \qquad H'_z = H'\cos\varphi'.
\end{aligned} \tag{18}$$

Combining the formulae (17) and (18), one may obtain:

$$\begin{aligned}
&E_x = -E's'\cos\varphi', \qquad H_x = H's'\sin\varphi',\\
&E_y = (E'c' + \beta H')\gamma\cos\varphi', \qquad H_y = -(H'c' + \beta E')\gamma\sin\varphi',\\
&E_z = (E' + \beta c'H)\gamma\sin\varphi, \qquad H_z = (H' + \beta c'E')\gamma\cos\varphi.
\end{aligned} \tag{19}$$

Taking into account that $E' = H'$, these expressions may be rewritten as:

$$\begin{aligned}
&E_x = -E's'\cos\varphi', \qquad H_x = E's'\sin\varphi',\\
&E_y = E'(c'+\beta)\gamma\cos\varphi', \qquad H_y = -E'(c'+\beta)\gamma\sin\varphi',\\
&E_z = E'(1+\beta c')\gamma\sin\varphi', \qquad H_z = E'(1+\beta c')\gamma\cos\varphi'.
\end{aligned} \tag{20}$$

The Poynting vector

$$\begin{aligned}
\mathbf{S} &= \frac{\bar{c}}{4\pi}[\mathbf{EH}] = \frac{\bar{c}}{4\pi}(E'\gamma(1+\beta c'))^2(\mathbf{i}\cos\theta + \mathbf{j}\sin\theta)\\
&= \frac{c}{4\pi}E^2(\mathbf{i}\cos\theta + \mathbf{j}\sin\theta).
\end{aligned} \tag{21}$$

Here we took into account that $E = E'\gamma'(1+\beta c')$. Introducing the angle φ, one may obtain $E_x = -E\sin\theta\cos\varphi$, $E_y = E\cos\theta\cos\varphi$, $E_z = E\sin\varphi$, $H_x = H\sin\theta\sin\varphi$, $H_y = -H\cos\theta\sin\varphi$, $H_z = H\cos\varphi$. Thus $\cos\varphi = \cos\varphi'$, $\sin\varphi = \sin\varphi'$, and $\varphi = \varphi'$. In other words, the angle between the vector $\mathbf{E}$ and the xy-plane is independent on the relative velocity v, contrary to the direction and the flux. The ratio of the fluxes in two polarization modes (that is the degree of the polarization) is independent on v as well. Thus the Doppler effect may not be observed from the polarizational measurements.

This "wave-like" formalism allows us to obtain the same results for the monochromatic flux changes, as that obtained by Postnov and Shakura (1987) and Shakura and Postnov (1987) by using the "corpuscular" formulae.

CHANGES IN THE COLUMN'S ORIENTATION

The orientation of the columns underwent changes, probably of cyclic character. It can be seen from the photometric and polarimetric observations of AM Her, QQ Vul and apparently some other polars (cf. Andronov, 1987a). For example, the duration of the circular polarization sign reversal in V-band varies from 0.14 to 0.31 in AM Herculis. In Figure 4 one may see the "i–β" diagram for the values of $\Delta\varphi = 0.14$, 0.24, 0.27, 0.31 compiled from the literature (Tapia, 1977; Brainerd and Lamb, 1985; Piirola *et al.*, 1976; Chanmugam and Wagner, 1977; our data). Here i is the orbital inclination (the angle between the rotational axis and the line of sight), and β is the angle between the rotational axis and the magnetic axis. The column's axis is supposed to coincide with the magnetic axis. For the inclination $i = 64°$, the corresponding values of β vary from 28° to 41° (see the discussion of the corresponding methods in Aslanov *et al.*, 1989). For $i = 35°$

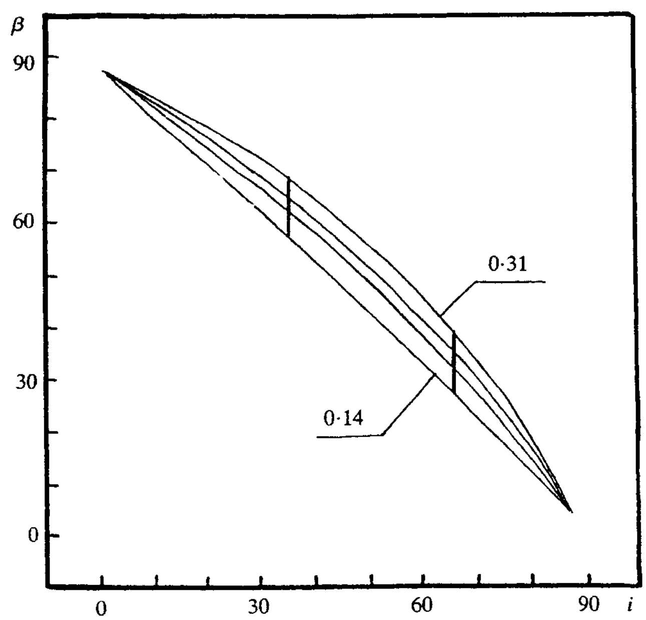

Figure 4 The i–β diagram for the values of the phase of the polarizational sign reversal $\Delta\phi = 0.14$, 0.24, 0.27 and 0.31. The vertical lines correspond to the range of the variations of the angle β for the two fixed values of the orbital inclination, $i = 35°$ and $i = 64°$.

(Brainerd and Lamb, 1985), β varies from 58° to 69°. This discrepancy in i is due to the various approaches of the determination of the position angle. This is, because the angle α, between the line of sight and the column's axis, is independent on the reversal of the values of β and i, because:

$$\cos \alpha = \cos i \cos \beta + \sin i \sin \beta \cos(2\pi(t - t_0)/P_{\text{orb}}) \tag{22}$$

(cf. Aslanov *et al.*, 1989). The variations of the "longitude" ψ in AM Her has double the amplitude ~28° (Andronov, 1987a and refs. therein). However, the number of the available data about the sign reversal is unsufficient to obtain the $\psi(t)$ and $\beta(t)$ curves. However, one of the main tasks for the investigation of polars is to study the rotational evolution of the white dwarf in respect to the binary system, and thus the regular polarizational observations of polars are needed.

One may note that the values of $\Delta\varphi$, depend not only on time, but are also strongly dependent on the wavelength (cf. Piirola *et al.*, 1986). This may mean that the column is extended, and is highly inclined to the magnetic axis, and/or the accretion occurs in the vicinities of both poles. If the last suggestion is correct, it means that the magnetosphere of the white dwarf is smaller compared with the distance to the inner Lagrangian point. This is contrary to the "standard" model. Because the column is inclined to the orbital plane, the magnetic axis will change its location in respect to the binary system not in one plane. One may achieve that these changes in ψ and β are characteristic for the "limit cycle". However, these results will be discussed elsewhere.

The changes of the orientation of the dipole may cause the modulation of the mass transfer rate due to the "Magnetic Valve" mechanism (Andronov, 1984), and/or due to the changes in the hard flux heating the secondary, in the vicinities of the inner Lagrangian point. It may be noted that if the column is located at the "far side" of the white dwarf, the "inactive state' may be seen from the Earth, even if the accretion rate is not reduced. Other mechanisms of the transitions between "active" and "inactive" states can be linked with the solar-type activity of the secondaries (Bianchini 1990 and refs therein) and possible minor changes of the distance between the stars (and the corresponding dimensions of the Roche lobe) due to the presence of the planet-like third body.

DISCUSSION

Despite the substantial simplifications, the models of "homogeneous columns," till now, are widely used for the interpretation of the observations. The main directions are the following: a) the determination of the column's orientation from the curves of the polarization (Brainerd and Lamb, 1985; Efimov and Shakhovskoj, 1982; Meggitt and Wickramasinghe, 1982 *et al.*); b) computations of the column's structure and of the spectral energy distribution (Frank, King and Lasota, 1983, 1988; Imamura, 1984; *et al.*), particularly, for the interpretation of the soft X-Ray excess (Patterson *et al.*, 1984; Lamb, 1985; *et al.*); c) estimation of the magnetic field from the wavelength of the possible cyclotron emission (Gnedin and Sunyaev, 1974; Voykhanskaya and Mitrofanov, 1980 *et al.*) or absorption (Wickramasinghe and Visvanathan, 1979; Canalle and Opher, 1988; *et al.*) lines. It may be noted that the shape of the cyclotron emission spectrum is significantly dependent on the column's density. If it is small, and the optical depth $\tau \ll 1$ in continuum, then the separate cyclotron lines will be achieved at the frequences corresponding to the magnetic field strength. If the column's height is comparable to the radius of the white dwarf, the value of the cyclotron frequency (which is inversely proportional to the third power of the distance from the dipole's center) may differ significantly along the column, and the cyclotron lines from the different parts may overlap, thus making the 'continuum'. Such a case allows us to estimate, not only the column's orientation, but also the height of the emission region as well (for example, Priedhorsky *et al.*, 1978; Bailey and Axon, 1981). This method may not be applied, if $\tau \geq 1$ in continuum, or if the column is extended ("polar cap", see for example Chanmugam and Frank, 1987).

Another difficulty arises due to the instabilities of the column (see Andronov, 1987b for a review). Langer *et al.* (1982) showed, that the structure of the columns may undergo drastic changes with a 1–10 second cycle, even if the column is assumed to be homogeneous. However, the accretion flow is not homogeneous, thus the accretion shock is "bombarded" by the relatively long "plasma strips", which Panek (1980) called "spaghetti". The ultrarapid (2-second) QPO's may arise in the single "spaghetties" and last for dozens of seconds (the characteristic time of the penetration of the single "spaghetti" through the shock). Andronov (1987b) also described such possible exotic types of instability, as the "boiling", "tornado" or "beacon" columns. All these fluctuations are usually smoothed during the observations. However, the polarization and spectra, which are computed by using the "stationary" models, may differ significantly from that computed for the non-stationary columns. This effect may particularly enable us to solve the "soft X-Ray Puzzle' in the spectral energy distribution (Thompson *et al.*, 1986; Frank *et al.*, 1988).

The model calculations are very complicated because the one-dimensional models are not appropriate for describing the observations. The 3-D time-dependent models are to be computed, despite the large number of parameters that have to be determined.

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