'SWINGING DIPOLES' IN MAGNETIC CLOSE BINARY STARS

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ABSTRACT. The recently discovered phenomena in polars - Magnetic Close Binary Stars (MCBS), are discussed. Asynchronous MCBS are on the 'propeller stage' (which is analogous to the investigated one for neutron stars), and are synchronizing during $t_s \lesssim 10^3$ yr, being during this stage rapidly evolving, mass ejecting systems. The accretion rate is largest when the angle θ between the magnetic axis and the line of centers is near zero. If $\theta \approx 90°$, then the magnetic field prevents the plasma flow, and the 'magnetic valve' becomes closed. Near this position the oscillations of the orientation of the white dwarf's magnetic axis may be excited. This model of a 'swinging dipole' has such observational properties: (a) the system's luminosity changes with characteristical times of some years; (b) the phase curves of light, polarization and radial velocities must be cyclically changing with a few year cycle; (c) one would observe the correlation between the phase shift of these curves, and the system's luminosity. The observational data on polars are briefly discussed. All these phenomena are observed in AM Herculis and some other polars, but subsequent studies are needed to investigate the orientation changes of the magnetic axis, and so the structure and evolution of this exotic class of our Galaxy population.

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INTRODUCTION

Ten years have passed since Tapia (1976) discovered an exotic class of Cataclysmic Variables (CV) - the AM Herculis-type stars. These objects were intensively investigated in a wide spectral band from X-ray to radio. This allowed to suggest the main postulates of the 'standard model' of polars (so these objects are often called because of their highly polarized emission), which were discussed in detail in the reviews of Kruszewski (1978), Chiapetti et al. (1980), and in recent papers of Lamb (1985) and Liebert and Stockman (1985). In this paper we shall briefly discuss the 'standard model' itself, but the main attention will be drawn to the recently discovered phenomena, which essentially contribute to our knowledge about polars.

THE 'STANDARD MODEL'

The group of polars differs from other CV's due to some properties:

(a) the optical and IR emission is highly polarized; the polarization changes with the same period, like the flux and radial velocities do;

(b) strong emission lines of hydrogen, helium and other elements are present in their spectra; the 'base' and 'peak' characteristics may not change in phase;

(c) X-ray and UV emission is observed; the spectral energy distribution usually has local maxima in hard and soft X-ray regions, and in optical or near-IR regions as well.

The second and third properties are also characteristic for other CV's. The polarization itself is not the evidence that the object is a polar: the synchronous (but not phase-locked) changes are necessary for this conclusion. To explain such observational properties some authors proposed the 'standard model'.

The ultra-short period binary has components, one of which is a filling its Roche lobe secondary, and the other is a white dwarf (with synchronous orbital and rotational motions) with a strong (10^{7-8} Gauss) magnetic field. Magnetosphere's dimensions r_a exceed the orbital separation a, and the plasma 'evaporating' through the vicinities of the inner Lagrangian point moves along the magnetic field lines.

One may call such an object a 'Magnetic Close Binary System' (MCBS), to distinguish it from objects with $r_a \lesssim a$.

It is suitable to distinguish the main zones of plasma motion, which are shown in Figure 1. Let us consider some main processes taking place in these zones.

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ZONE B: 'PROPELLER' OR 'PENDULUM'?

We begin our review with the second zone, namely the trajectory of the moving plasma. This zone is the largest one, and mainly here the moment of plasma impulse is transferring to the white dwarf (WD), determining its rotational evolution. The most prominent peculiarity of polars is the synchronism between the orbital and rotational motions of WD, in contrast to many other CV's with rapidly rotating WD's or neutron stars (NS).

Explaining this phenomenon, Joss et al. (1979) proposed a mechanism of WD's deceleration connected with the dissipation of the induced currents (generated in the secondary's atmosphere by the rapidly rotating magnetic field). The derived estimates of the characteristical time $t_s \approx 10^{8-10}$ yr are too large to explain the existence of polars. Other mechanisms were more effective, and the values of $t_s \approx 10^4$ yr (Chanmugam and Dulk, 1983, unipolar induction), $t_s \approx 10^{2-7}$ yr (Campbell, 1983, turbulence in the secondary's atmosphere), $t_s \approx 10^{3-5}$ yr (Lamb et al., 1983, MHD-waves) were derived.

Model calculations of the Equations of motion along field lines (Andronov, 1982b, 1983c) show that asynchronous MCBS are on the 'propeller' stage (which is analogous to the investigated one for NS by Illarionov and Sunyaev (1975)), and are synchronizing during $t_s \lesssim 10^3$ yr, being rapidly evolving, mass ejecting systems during this stage.

According to Campbell (1984), after this stage subsequent variants are possible: (a) if the accretion began after synchronization, and does not exceed some critical value, the magnetic axis may reach some equilibrium position; (b) in the opposite case the white dwarf is rotating not exactly in synchronism, and makes one more rotation relative to the observer during a few years. Such situation must lead to the cyclical switching of poles at which the accretion occurs.

The observational consequence of this process is the sharp half-period shift of the phase curves of emission characteristics, which is more pronounced in the radial velocity curves. Unfortunately, such observations near the middle of the 'inactive state of polars' do not exist. Though the accretion simultaneously onto two poles is sometimes observed (Liebert and Stockman, 1980), the fact of switching has not yet been registered, so such observations are very necessary. Presently there is no evidence to doubt Case (a).

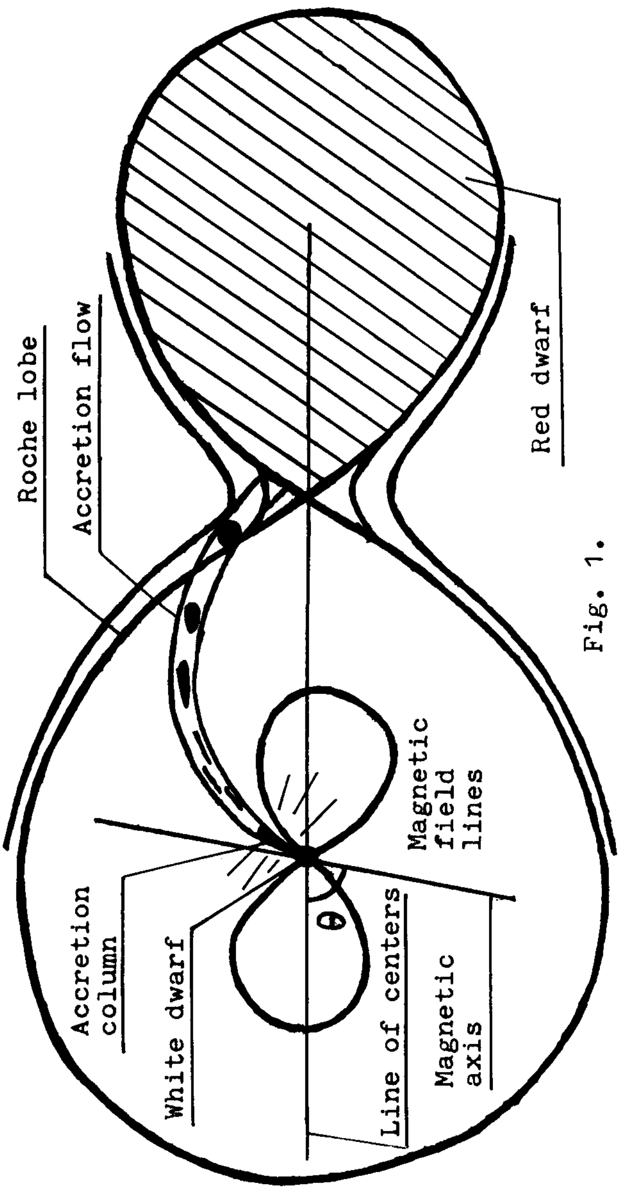
Roche lobe
Accretion flow
Red dwarf
Magnetic field lines
Accretion column
White dwarf
Line of centers
Magnetic axis

Fig. 1.

Figure 1. The scheme of the Magnetic Close Binary System.

ZONE A: THE 'MAGNETIC VALVE'

The mass penetration through the vicinities of the inner Lagrangian point was discussed in detail by Lubow and Shu (1975). The presence of a magnetic field affects also the structure of the transition zone between the Roche lobes of the compenents. Model calculations show (Andronov 1982a, 1984), that for practically exact synchronism, the accretion rate is largest when the angle θ between the magnetic axis and the line of centers is near zero (this position is slightly shifted when the secondary is not synchronized). If $\theta \approx 90°$, then the magnetic field prevents the plasma flow, and the 'magnetic valve' becomes closed. But just this position is the position of the stable equilibrium (Joss et al., 1979; Andronov, 1982c, 1983a,c), near which the oscillations of WD's orientation may be excited. In this case the oscillations are needed to realize the accretion rate with the value, which is determined by the evolutionary stage of the system (Tutukov and Yungelson, 1979). According to Campbell (1984), the equilibrium position is shifted, and is approximately equal to $\theta \approx 75°$. In this case the accretion is possible even with the constant orientation of the magnetic axis, but the oscillations may increase the 'capacity' of the 'magnetic valve'. The equilibrium position may be affected also even by the secondary's small asynchronism.

As slow rotation of the WD's magnetic dipole axis relative to the secondary (Lamb et al., 1983), with the 'pendulum swinging' (Andronov, 1983c), may explain the generation of the radio emission of AM Herculis, which was discovered by Chanmugam and Dulk (1982). Such 'swinging' may also be dumped and would decrease the magnitude of luminosity changes and the mean luminosity itself. Because such phenomena may be apparent in the observations of AM Herculis taken by Götz (1986 and refs. therein), the detailed study of such mechanism is also needed.

Let us consider the observational consequences of the model of a 'swinging dipole':

(a) The system's luminosity changes with characteristical time of some years. Such changes were discovered in AM Herculis by Hudec and Meinunger (1976), who distinguished the 'active' and 'inactive' states, and were later observed practically in all polars. Detailed investigations allowed to discover also 'intermediate' states, during which the instability of light curves increases. The descending branch of the luminosity curve is 1.5 times shorter than the ascending branch (Andronov et al., 1983). Because of the instability of characteristics of the secondary's atmosphere, one would not expect the 'dipole's swinging' to be exactly periodical

(Wentzel and Fuhrman, 1983): the energy source of such 'self-oscillations' is accretion. It is interesting to provide the complex observations of the polar candidate IO Andromedae, where a 5-yr periodicity was suspected in brightness variations (Andronov, 1983b).

One may note, however, that luminosity changes may also be observed, even if the dipole's orientation is constant; and may be explained by the instability of the secondary's atmosphere, connected with the WD's hard emission (Basko and Sunyaev, 1973; King and Lasota, 1984).

(b) The phase curves of light, polarization and radial velocities must be cyclically changing with a few year period. This phenomenon was discovered first in AM Herculis (Andronov et al., 1982), for which more than a hundred minima were observed. Their residuals from the ephemeris (O-C) were changing with a 1100^d-cycle and were explained by Andronov (1982c, 1983a,c) as the observational evidence of the dipole's self-oscillations with a 17° amplitude. Similar changes may be observed in BL Hyi=H 0139-68 (Pickles and Visvanathan, 1983; Thorstensen et al., 1983), V 834 Cen=E 1405-451 (Tuohy et al., 1985), and in other polars. However, the number of observations is too small to draw more certain conclusions. The difficulty of the determination of this phenomenon is also connected with the light curve instability and accompanying dispersion of phases of minima (what is most prominent in the polar candidate HV And (Andronov and Banny, 1985)). Long sequences of homogeneous observations are needed, but this is connected with large expenditures of observational time.

(c) See Figure 1 again. With increasing values of θ, the residuals (O-C) are decreasing. But in this case the accretion rate is increasing (if $-90° \leq \theta \leq 0°$), or decreasing (if $0° \leq \theta \leq 90°$), but in both cases one would observe the correlation (positive or negative, respectively) between (O-C) and m. Such correlation was again first discovered in AM Herculis by Smykov and Shakun (1985). They found that with increasing luminosity, the values of (O-C) also systematically increase, what is consistent with the model of a 'swinging dipole', or 'stellar pendulum', so with the theoretical prediction about the equilibrium value of θ between 0° and 90°. A similar correlation between the phase of minimum and the luminosity one may see from the observations of AN UMa (Aslanov and Shugarov, 1981) and some other polars.

Obviously, these observational tests need an independent confirmation using not only photometric data, but also polarimetric and spectroscopic data. Unfortunately, although the changes of dipole's orientation were suspected on the base of polarimetric observations of AN UMa by Efimov and Shakhovkoj (1981), and also in AM Her by Bailey and Axon (1981), one needs the subsequent investigations to obtain more significant conclusions.

ZONE C: THE ACCRETION COLUMN

Near the magnetic pole of the WD, the plasma (moving with velocities of a few thousand km/sec) collides with the decelerated matter, and a shock wave appears. The accretion column between its front and the WD's surface is the main source of the system's emission from X-ray to near-IR bands. So the emission of the accretion column is the main source of the disposed information.

Because of many difficulties, the authors often calculate the stationary one-dimensional (e.g., King and Lasota, 1978) and two-dimensional (e.g., Wang and Frank, 1980) models. Because the accretion column is situated in the strong (10^{7-8} Gauss) magnetic field, the emission is highly polarized (for the penetration of the emission in such objects see the monography of Dolginov et al., 1978; the papers of Pavlov et al., 1980; Chanmugum and Dulk, 1981, and references therein). The recently obtained models were used for solving the inverse problem - the determination of the characteristics of accretion columns. Particularly, recently such methods have been proposed: determination of the orbital inclination i and the angle δ between the columns axis and the rotational axis, using the changes of the Stokes parameters (Efimov and Shakhovskoj, 1981; Chanmugam and Dulk, 1981; Brainerd and Lamb, 1985); of the relation between i and δ (Stockman et al., 1977; Kruszewski, 1978); of i and δ using the phase curves of the soft X-ray flux (Andronov, 1983c). If the function which is used for the determination of the column's orientation depends only on the angle between the column's axis and the line of sight, so replacing i and δ, one will not affect the theoretical phase curve. To choose true values, one may use the dependence of the rate of the position angle's changes from the angle i (Meggitt and Wickramasinghe, 1982). It may be noted, that the values of i between 51° and 64° and of δ between 30° and 34°, derived from soft X-ray observations, are in good agreement (in limits of the error bars) with the results obtained for AM Her from the polarimetric data ($63° \leq i \leq 76°$, $\delta \approx 34°$). The theoretical phase curves of the soft and hard X-ray fluxes (derived by Imamura, 1984), also are in agreement with the cited values of i and δ.

The asymmetry of the phase curves may be explained by the inclination of the column to the WD's surface, and also by the deviations of the column's structure from the symmetrical one (Andronov, 1983c, 1986). The changes of orientation influence on the structure, that is observed as the effect of statistical dependence of light curve of AM Her on its luminosity (Andronov, 1983c, 1985a).

It may be noted, that the stationary models are usually used for the determination of the column's orientation. However, according to Langer et al. (1981, 1982), the oscillations of the column's height with the characteristic time of a few seconds, may be excited. During these oscillations, the temperature changes in 2 times, the luminosity in 1.5 times. Taking into account the heterogeneity of the accretion flow, one may suppose, that in particular plasma clots ('spaghetti'), i.e. shock waves with independently changing parameters, may be excited. As a result, quasi-periodical light variations with the same characteristical time are excited, lasting some tens of seconds (the time, during which the 'spaghetti' passes the distance equal to its length). This is the idealization, but similar light variations were in fact discovered (Larsson, 1985; Kornilov and Moskalenko, 1979; and references therein). The cycle duration of the oscillations of the particular 'spaghetti' may be changing during its motion.

In the three-dimensional column, 5 types of instability may be present (Andronov, 1985b). In this case the not phase-locked plasma motion along the field lines may lead to the observational effect of the 'convection' and the 'meridional circulation' relative to the column's axis. The 'boiling' of such a column increases the effectivity of energy transfer from the column's base.

THE PROBLEMS

In a brief review one has no possibility to discuss all results obtained for polars during the last ten years. The 'standard model' cited above and its modifications may not explain all the surprizes connected with this exotic group of population of our Galaxy. Extensive investigations are needed, and they are provided by astrophysicists from different countries.

What are the main objectives for the investigation of AM Her-type stars?

First, the modelling of accretion columns. To determine the density, temperature and velocity distribution of the plasma, one must solve the self-consistent three-dimensional non-stationary MHD problem, taking into account the emission transfer. The difficulties are great, and during the next few years, apparently only first approximations will be derived.

Second, the elaboration of methods for the determination of the system's orbital elements (also parameters, which characterize the orientation of the column relative to the WD, and the orientation of the WD's axis relative to the secondary). The self-consistent model must explain phase changes of the flux in all spectral regions, and of the polarization and spectral line profiles. Obtaining systematically parameters of an object, one may investigate their evolution.

Third, regular observations of polars, which would help to determine the characteristics of the rotation of the 'nearly synchronous' WD. Orientation changes are not in doubt, but the details must be studied. Ideally, a model is needed, which explains the column's orientation and structure with processes taking place at the other end of 'accretion canal'.

Fourth, a systematic search for new objects is needed. As Brainerd and Lamb (1985) noted, the number of observable polars is nearly 3 times greater than the number of known and observable objects of this type. Therefore it is interesting to note, that a cataclysmic component was found near 4 Dra - an M 3 III star (Reimers, 1985), since the secondaries of the known CV's are generally red dwarfs and not giants.

Fifth and last is the generalization of the models of different objects, the investigation of the generic relationship between their classes, and the determination of their place in the evolutionary scenario of the Universe.

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