MAGNETIC CATACLYSMIC VARIABLES: 25 YEARS OF EXCITING PERFOMANCE

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ABSTRACT. Exactly 25 years ago, Santiago Tapia has detected circular and linear polarization of AM Her varying with the same period as the photometric and spectral characteristics. This had lead to a discovery of unprecedentedly exotic binary systems, in which the strength of the magnetic field is large enough to keep the white dwarf in a synchronism, dominating the accretion torque. Nowadays, about 70 representatives of this class of polars have been registered.

We review the history of study of polars, starting with a "standard model", according to which, the red dwarf fills its Roche lobe and the flow is captured and channelized by a magnetic field of the white dwarf in the vicinities of the inner Lagrangian point. The models of the "propeller", "idling", "magnetic valve", "swinging dipole", "boiling asymmetric rainbow column" are reviewed, with a special attention to the unsolved problems of this study - contradiction between the observed synchronism of spin and orbital periods of the white dwarf with a possible presence of the partially ballistic trajectory of the accretion flow and possibly important contributions of the dipole and multipole components of the magnetic fields; presence of few mechanisms of luminosity variations; various types and mechanisms of variability at different time scales from seconds to decades.

The monitoring of AM Her (and later on other objects) has started in Odessa in 1978 and was regularly continued in the Crimean Astrophysical observatory since 1989. The results will be published in the "Atlas and catalogue of the polarimetric and photometric characteristics" by N.M.Shakhovskoy, I.L.Andronov and S.V.Kolesnikov. Other papers absent in the ADS are available via *http://il-a.pochtamt.ru* or *www.paco.odessa.ua/~il-a*.

Despite 25 years have passed, these stars still exhibit new observational surprizes challenging theoretical models.

Key words: Stars: variable: cataclysmic: AM Her

1. Introduction

AM Her - type stars are the class of systems, which are intensely observed and modeled theoretically since the discovery of linear and circular polarization of their emission superimposed onto synchronous variability of the X-ray, optical and infrared flux and characteristics of the emission lines. Thus these objects are often called "polars".

Despite the photometric variability of this system was detected in 1924, the real progress in understanding has begun in 1976, when the observations obtained by various groups have lead to the development of so-called "standard model" (Chanmugam and Wagner, 1977).

According to it, these objects are highly magnetic cataclysmic variables containing a red dwarf filling it's Roche lobe, and of a white dwarf, the magnetic field of which is sufficient to prevent formation of the accretion disk. The orbital periods lie within intervals 80-120 minutes, with another group of "long-period" polars from another side of the "2-3 - hour period gap".

However, AM Her itself, as well as other objects of this class discovered later, exhibit variability in a very wide range from seconds to decades. Thus it became obvious, that an intensive monitoring is needed to check variations of the characteristics of the phase curves. Nowadays, about 70 representatives of this class of polars have been registered, but only few are observed more or less regularly.

The evolution of these objects is determined by the angular momentum loss due to gravitational radiation and magnetic stellar wind (see recent monographs by Warner (1995) and Hellier (2001)).

A long-term photometric monitoring was initiated by Professor V.P.Tsessevich (1907-1983) and started in the Astronomical observatories of the Odessa (I.L.Andronov, S.V.Vasilieva, V.P.Tsessevich 1980, 1984; Andronov et al., 1983) and Kishinev (V.P.Smykov, L.I.Shakun, 1985) Universities. In 1985-1987, it continued in the Abastumani astrophysical observatory. Since 1978, the polarimetric observations of AM Her and other polars have started in the Crimean Astrophysical Observatory using 2.6m and 1.25m telescopes (Yu.S.Efimov and N.M.Shakhovskoy, 1981, 1982; V.Piirola et al., 1985). Since 1989, the monitoring has moved to CrAO completely. Altogether about 300 nights of observations have been obtained.

In this paper, we present a brief review of the properties of polars with an accent to AM Her. Currently, in the ADS are listed 605 papers corresponding to the "object search" option "AM Her", thus it is not possible to refer to all of them. We also present a self-review of the observational and theoretic results obtained by our research group.

2. Long-term variability

The long-term variations have been found by Hudec and Meinunger (1976) on the Sonneberg Sky Patrol plates with switches between high and low luminosity states. Feigelson et al. (1978) have measured the Harvard plates and noted the brightness variations by $\approx 3^m$ at the $\approx 100^d$ time scale and more rapid ($0^d.1$) variations by 1^m. The latter ones are caused by orbital variability, whereas the long–term luminosity variations may be a consequence of variable mass transfer. Since 1976, the patrol brightness estimates of the star are being made by various observers, the longest data set obtained by M.Verdenet (AFOEV).

These variations have been recently analyzed by Andronov et al. (1997). The switches between the high and low luminosity states are sometimes very rapid, lasting down to $\sim 3^d$. However, such variability is superimposed onto year-scale variations. Detailed study of photometric and polarimeric curves is in preparation by Shakhovskoy et al. (2001).

3. Orbital variability

The orbital variability and flickering was discovered by Berg and Duthie (1976), who first determined the orbital period of 186 minutes. The compilation of curves of phase variations of different physical characteristics was published by Priedhorsky et al. (1978b).

An excellent estimate of the period made Szkody and Brownlee (1977), who proposed an ephemeris

$$Min.HJD = 2443014.71266 + 0.128927(2) \cdot E \quad (1)$$

The initial epoch for the pulse of the linear polarization, which coincides with the zero crossing by the circular polarization is $T_{pol} = 2443014.7647(5)$ (Tapia, 1977).

The recent ephemeris for the photometric V or R minima obtained using 267 timings (1976-1999) corresponds to

$$Min.HJD = 2446637.0510(6) + 0^d.12892711(3) \cdot E', \quad (2)$$

where $E' = E - 28096$ (Andronov et al., 2002).

From 19 times of the minimum of the circular polarization in the R band, Shakhovskoy et al (2001) derived the ephemeris

$$Min.circ.pol.HJD = 2450304.83378(43) + \\ +0^d.128927088(66)(E - 56545). \quad (3)$$

The phase of the polarizational minima, according to the photometric ephemeris, is 0.500(3), i.e. are accurately in the opposite phase.

They also note the presence of phase shifts with a typical cycle of $\approx 1100 - 1200^d$, which were explaned by the "swinging dipole" model (Andronov 1987a).

Despite these variations, the value of the photometric period is in an excellent agreement with the spectral ephemeris presented by Schwarz et al. (2002) for the superior conjunction:

$$T_{sp}HJD = 2446603.40308(35) + 0^d.128927103(6) \cdot E \quad (4)$$

Andronov, Vasilieva and Tsessevich (1980) have detected drastic changes of the phase curves, with an extreme case, when during two subsequent cycles, the amplitude jumped from $0^m.96$ to $0^m.16$. The tables of observations obtained in 1988-1989 and the atlas of light curves was published by Andronov, Vasilieva and Tsessevich (1984). Based on these data, Andronov (1985) obtained statistical dependence of the phase curve on luminosity in the active and intermediate luminosity state. This dependence was continued to minor amplitude variations at the low state based on the observations obtained in Abastumani in 1985-1987.

Phenomenological classification of the characteristic types of the light curves was presented by Shakhovskoy et al. (1994). The atlas of the polarizational and UBVRI light curves is being prepared by Shakhovskoy et al. (2001).

4. Fast variability ("red noise")

Individual light curves of AM Her exhibit strong flickering, as was first detected by Berg and Duthie (1976). Bailey et al. (1977) made an autocorrelation analysis and have shown, that the autocorrelation function is characterized by an exponential decay with a characteristic time $\tau = 90$ sec both in V and R, despite the cycle-to-cycle values are within the range from 30 to 200 sec. Kornilov and Moskalenko (1979) confirmed this result and estimated a mean flare rate of 0.5 ± 0.3 sec, their mean duration of 20-25 sec and the degree of emitted energy is 0.3 ± 0.2. Stockman and Sargent (1979) found a large difference between the times in V and I: $\tau_V = 28$ sec and $\tau_I = 60$ sec. Subsequent observational study of the fast variability was made by Priedhorsky et al. (1978a), Szkody and Margon (1980) et al. Panek (1980) argued for transformation of initial plasma blobs into long (tidal interaction) and thin (distance between the magnetic field lines decreases when approaching the white dwarf) plasma "spaghetti".

We have observed AM Her and a group of cataclysmic variables with a time resolution from 12 sec (1.25m, UBVRI) to 1-4 sec (2.6m, R) (Shakhovskoy et al., 1994, 2001). The periodograms show a presence of the strong "red noise", i.e. a systematic decrease of the test function with trial frequency. This could be explained within the physical model of accreting "spaghetties" (or "shot noise"), or in a frame of mathematical model of first-order auto-regressive processes. Andronov (1994) has derived precise formulae for autocorrelation analysis, taking into account the length of the run and removal of the long-periodic trend. This method allowed to interpret minute-scale variability as the "shot noise" without quasi-periodic oscillations (as one could suggest using the formulae for infinite undetrended runs), and to detect variations of the model characteristics of the with luminosity. The values of τ ranged from 99 ± 19 sec for high state to 38 ± 6 sec in the low state.

Beardmore and Osborne (1997b) explained the hard X-ray variability from the Ginga observations by shot noise, with a time-scale of 70s, and a correlation between the hard X-ray and optical red variability. They derived a blob length-scale of $\sim 10^{10}$ cm, a blob radius of $6 \cdot 10^5 - 4 \cdot 10^6$ cm, and a mass of $\sim 10^{16}$g.

Using the "corrected ACF analysis" (Andronov, 1994), Halevin et al. (2000) have studied phase-dependent flickering activity in magnetic cataclysmic variables BY Cam and QQ Vul and estimated the characteristic length of "spaghetties".

The scalegram analysis of the optical data has shown a power law character of the dependence of unbiased estimate of the r.m.s. deviation of the data from the fit on the filter half-width Δt, which is valid for a remarkably wide interval from 3 seconds to 10 years (7.5 orders of magnitude). This argues for a presence of variations at all time scales and a joint component acting both in fast and slow variability (Andronov et al., 1997).

The wavelet analysis (Andronov, 1998, 1999) of AM Her confirms, that irregular variability dominates over possible periodic or quasi-periodic oscillations, except at the orbital frequency and its first harmonic, as the phase curve exhibits a double-peaked behaviour.

Some methods for mathematical modelling of the "red noise" have been elaborated and originally applied to AM Her, i.e. the periodogram-, scalegram-, wavelet-, autocorrelation-, principal component- analysis, as well as the determination of the characteristics of the multicolor correlated and uncorrelated variability. They are briefly reviewed by Andronov (1999) and comparatively described by Andronov (2001).

5. Fast quasi-periodic oscillations (QPO)

Langer et al. (1992) have theoretically shown the possibility of excitation of the QPOs and thus second-scale variability of the structure of the accretion column. According to their computations, the period of QPOs is inversely proportional to the accretion rate per unit area. Imamura (1985) theoretically studied the stability properties of white dwarf radiative shocks and determined conditions needed to the excitation of quasi-periodic oscillations.

Larsson et al. (1990) discussed the possibility of mapping the accretion frow using the QPO studies during eclipse of the column by the white dwarf. Wu et al. (1992) reviewed QPOs in magnetic cataclysmic variables.

Beardmore and Osborne (1997a) failed to detect 1-3s quasi-periodic oscillations in AM Her, EF Eri and V834 Cen in the GINGA hard X-ray observations, giving upper limits of 4, 5 and 18 per cent, respectively. However, such QPOs are possible within these limits, as, for EF Eri and V834 Cen the amplitude of QPOs in the optical bands is 1–3%.

It should be noted, that the density of the accretion column, even if to neglect blobby structure, is not constant through the cross-section. Thus one may assume oscillations of individual blobs at different frequencies, what will significantly decrease the effect. There may be additional types 3-d variations of the structure, which have been discussed by Andronov (1987b).

6. X-ray, UV, optical and IR emission

6.1. Observations

AM Her was detected as an X-ray source by Hearn et al. (1976), and since then is one of the often observed objects. X-ray properties of AM Herculis binaries have been described e.g. by Beuermann (1998).

Silber et al. (1996) made a fit for the IUE and our optical data. The temperature of the white dwarf during phases of low brightness is estimated to be of 20 000 K, whereas at phases of brighter flux, a second component is present, which may be explained as a bright spot with a temperature of 35 000±5 000 K, which covers $\leq 8\%$ of the surface.

Recently, de Martino et al. (1998) detected a deep X-ray low state of AM Herculis with a flux decrease by a factor of 7 during 40 min. Usually, coronal emission from the secondary may contribute significantly during the inactive phase. The new BeppoSAX observations of AM Her (Matt et al., 2000) show that during an intermediate state, the source was in its "normal" one-pole accretion mode. In the high state it switched an atypical "two-pole" accretion mode, with significant soft and hard X-ray emission from both poles. However, the emission from the second pole is much softer than that from the primary pole, suggesting the blobs penetrating deeply in the photosphere.

Thus, the complete emission contains at least 5 components, partially separated in wavelengths:

1. Cyclotron emission from the accretion column, increasing from visual to near-IR bands;
2. Hard X-ray bremsstrahlung emission from the shock;
3. Hard UV and soft X-ray nearly blackbody

emission from irradiating the cyclotron and bremsstrahlung emisson by the white dwarf and possibly from the local thermonuclear reactions;

4. Secondary emission of the accreting stream above the shock and of the irradiated atmosphere of the secondary;

5. Emission of the secondary filling its Roche lobe.

6.2. The polar cap model

Having no possibility to describe numerous models of X-ray emission, we point out two of them. The model of surface polar cap (Andronov, 1986b) used constant and variable distribution of brightness and assuming absorption in the accretion column. It was shown on the base of the X-ray curve published by Hearn and Richardson (1977), that the accretion column is optically thick. Moreover, the source of the emission is extended in height and is assymmetric owed to the inclination of the column.

Silber et al. (1996) modeled the UV spectrum within the frame of two-component model, and estimated temperatures of the white dwarf and of the heated spot.

The observed soft X-ray excess is owed to the blob - type accretion instead of the homogeneous column (Andronov, 1987b; Wu et al., 1995) Most recent models of the ionization structure of the accretion region are presented by Wu et al. (2001).

7. Polarization and magnetic field of the white dwarf

Polarization of the emission was discovered by Tapia (1977), who noted a spike of linear polarization with a few minute duration, and continuous variations of the circular polarization. He suggested a mechanism of cyclotron emission of plasma in the strong magnetic field. Polarization decreases with wavelength, disappearing at $\lambda = 4000\mathring{A}$. This allows to estimate an upper value of the magnetic field of 270 MGs (Kruszewski, 1978) assuming that the emission occurs at the cyclotron frequency $\omega_B = eB/mc$, estimated it as 230 MGs.

The penetration and polarization of emission in the cosmic medium was studied by Dolginov et al. (1979).

Assuming that the emission occurs at the cyclotron frequency, which is dependent on the height above the surface of the white dwarf, Priedhorsky et al. (1978b) have studied dependence on the wavelength of the polarization minimum. Their conclusion was that the field strength varies with height more slowly than according to the dipole $\sim r^{-3}$ law.

However, direct measurements of the magnetic field from the Zeeman absorptions in the spectrum of the white dwarf during inactive state had lead to the conclusion, that the magnetic field in AM Her itself is really much smaller, i.e. only ~ 14 MGs (Schmidt et al., 1981).

8. Accretion column

The accretion column is the main source of emission, which exceeds the emission of stellar components by a factor of few dozens. To interpret the corresponding variations, the relalistic models of the column are needed. A brief review of the models was presented by Andronov (1990), who studied the influence of the inhomogeneity of accretion column onto polarization and spectrum of its emission. In stationery symmetric models, one should assume the temperature and density structure. The observational spectra in both polarizational modes are strongly dependent on these assumptions. E.g., for a finite-width column, the emission is not dependent on optical thickness τ, if $\tau \gg 1$. Geometrical effects of the inclination of the columns were studied by Andronov (1986a).

For the columns with gradually decreasing density, the effective radius of the column is dependent on the density distribution, wavelength, polarization mode and the angle between the column and line of sight.

Elliptic columns will produce an additional dependence on the second angle between the major axis and the projection of the line of sight onto the cross-section.

The dependence of the spectrum on the magnetic field, as well as the vertical structure of the column may cause an effect of the "rainbow" column, if the spectrum contains strong cyclotron lines. This method of determination of the magnetic field strength in the emission region was proposed by Mitrofanov (1980) and then widely used in the case of cyclotron emission at few harmonics (cf. Cropper, 1990).

Non-stationery "boiling" columns will significantly change the spectrum of the outgoing radiation (Andronov, 1987b).

Another problem arizes, if the accretion column is not single. In this case, the inverse problem of parameter determination becomes much more uncertain, as the inclined asymmetric columns may correspond to magnetic poles of different strength, which are located not exactly at the opposite points of the white dwarf (Kruszewski, 1978; Piirola et al., 1985; Muslimov et al., 1995 et al.).

9. Synchronization

9.1. Dipole - sphere interaction

One of the most striking features of the polars is the synchronism between the rotation of the white dwarf and the orbital motion. This class of binary stars is the only one, where such a synchronism exists, because the angular momentum of the infalling matter should be compensated by some loss mechanism (e.g. Lipunov, 1987).

The fact of synchronization is justified by the coincidence of the period of variations of polarization and X-ray flux (originated near the white dwarf) with the period of radial velocities measured using emission lines (dominating in the high state and originating in the accretion flow and heated part of the red dwarf) and using the narrow Na lines (originating in the atmosphere of the red dwarf and seen at the low luminosity state).

Despite it was obvious, that this synchronism is caused by a sufficient strenght of the magnetic field, the first physical model was proposed by Joss et al. (1979). The accretion was neglected, the orbit was assumed to be circular, and the interaction between the rotating white dwarf with a conducting sphere caused excitation of the Faucot currents, the Ohm dissipation of which caused heating of the atmosphere and thus the decrease of rotation energy. However, the characteristic times for such synchronization are $\sim 10^{11}$ years ($5 \cdot 10^9$ yrs for most optimistic estimates of the magnetic field). This is too long to explain the existence of the synchronism.

Andronov (1983) extended this model to the case of elliptic orbits. This mechanism leads to the circularization of orbits, but is much less effective than the tidal circularization.

9.2. Magnetic field - plasma stream interaction

Andronov (1982, 1987a) has proposed a "propeller" model, assuming that the accretion stream is frozen into magnetic field. An additional centrifugal force ejects the matter causing deceleration of the rotation. The corresponding synchronization time is only 6-260 years, i.e. $\leq 10^3$ years. This stage is similar to the "propeller" stage in the systems (Illarionov and Sunyaev, 1976), but in the polars it differs by an absence of symmetry of the structure of infalling matter. Syncronization with such characteristic time was found in the Nova 1975 Cyg (V 1500 Cyg) (Pavlenko and Pelt, 1991) and BY Cam (an extensive observational campaign of this star was organized by Silber et al., 1997).

Other estimates of the synchronization time were larger $\sim 10^3 - 10^5$ years (Lamb et al., 1983). Recent review of the situation may be found in the monographs by Warner (1995), Campbell (1997) and Hellier (2001).

10. "Swinging dipole" model

10.1. Magnetic interaction with secondary

An important question is the further evolution of the rotation of the synchronizing white dwarf. Will it be "phase-locked", "idling" or "swinging" around some equilibrium state?

According to Joss et al. (1979), the synchronization leads to a phase-locked state. However, there may be damping oscillations of the orientation of the magnetic axis around the stable position with a characteristic period of a dozen of years, i.e. the "swingings".

10.2. "Magnetic valve"

The model of structure of the accretion flow in the vicinities of the inner Lagrangian point in the presence of dominating magnetic field was proposed by Andronov (1982a). The flow is maximal, when the magnetic field near the inner Lagrangian point is oriented along the line of centers, and vanishes, when they are orthogonal. Thus one may call this model "the magnetic valve".

The drag force from the accretion stream is also dependent on the angle ψ between the magnetic axis and the line of centers. The equilibrium positions are $\psi = 0°$ and $\psi = 90°$ (Andronov, 1987a), which coincide with that of the "dipole-sphere" interaction by Joss et al. (1979). A grid of models of orientation oscillations, computed taking into account both these effects in various proportions, has shown, that the period value is dependent on the accretion rate and on the amplitude. However, the equilibrium position at $\psi = 90°$ corresponds to the "magnetic valve" closed. However, the theory of evolution predicts, that the mean accretion rate should be non-zero owed to gravitational radiation and magnetic stellar wind (cf. Tutukov and Yungelson, 1979; Warner, 1995). Thus should be the auto-excited oscillations, during which the portions of plasma are accreted at a mean level corresponding to evolutionary status. The estimated value of the characteristic time P ranged from 1 to 10 years.

10.3. Dipole-dipole interaction

In this model, the potential energy is dependent on orientations of both dipoles. Andronov (1995) has computed a grid of time-dependent models. However, the red dwarf has much larger moment of inertia then the white dwarf, so the cycle of orientation variations is ~ 6 times larger then of the white dwarf. So the "free oscillations" may be described as relatively slow variations of the red dwarf, and faster cycles of the primary around slowly changing position of equilibrium. For non-planar case, both the longitude and latitude chaotically vary, with redistribution of oscillation energy between the two co-ordinates and two dipols. Sometimes even the changing of the pole facing to the larger star occurs for few dozens cycles. A very interesting phenomenon, which should be searched in the observations!

Recent theory of the orientation changes was described by Campbell (1997).

10.4. Observational tests

The "swinging dipole" model may be tested by the presence of the statistical dependence of the orbital light curve on luminosity and characteristic time of its variability. There are some observational facts, which may give evidence on the type of changes of the accretion structure in AM Her:

1 Long-term variations of the luminosity;

2 Long-term variations of the shape of the phase curves of various physical characteristics;

3 Statistical luminosity dependence of the phase curves.

The systematic study of the phase characteristics has begun with the monitoring, what lead to detection of the statistical dependence of the phase curve on luminosity at high and intermediate state (Andronov 1985). The phases underwent 3-yr modulation, just in the middle of theoretically predicted range 1-10 yr (Andronov et al., 1982), what was interpreted as orientation oscillations with an amplitude of $17^\circ \pm 3^\circ$. Smykov and Shakun (1985) confirmed this result, noting an existence of the "phase-luminosity" dependence in the sense that brighter curves are more positive-shifted from the linear ephemeris. Another object showing cyclical variability of phases with variable amplitudes is QQ Vul (Andronov and Fuhrmann, 1987).

However, it is not expected that these "swingings" will be strictly periodic, as varies not only the longitude of the magnetic pole, but the latitude as well (Shakhovskoy et al., 1992). Moreover, the luminosity variations may be also modulated by the irradiation of the secondary by the hard emission from the vicinities of the white dwarf (Basko and Sunyaev, 1973; King and Lasota, 1984). Another unpredictable source of modulation of the accretion rate may be spots on the red dwarf (Hessman et al., 2000). The light curves show a strong flickering displacing the phases of minima. The joint influence of these mechanisms cause very complicated changes both in luminosity and shapes.

The model of "swinging dipole" may be challenged for some polars by a model with a ballistic part of the trajectory and the capture of the stream much closer to the white dwarf then the inner Lagrangian point (cf. Warner, 1995). However, even in this case, the orientation oscillations should exist, thus new realistic models of the emission are needed, as well as determinations of orientation from individual photometric and polarimetric chase curves.

Much more accurate are polarimetric timings, which are less affected by flickering. Detailed discussion of these results is prepared by Shakhovskoy et al. (2001).

11. The red dwarf

11.1. Effective radius of the Roche lobe and the "Period-mass" relation

An usual assumption is that the low-mass red dwarf is unevolved and thus belongs to the main sequence either in magnetic and non-magnetic systems. The classical mass-radius relations obtained for single stars must be revised by introducing an "effective" radius of the Roche lobe. So the problem is splitted into two: dependence of the effective radius of the star filling it's Roche lobe on the mass ratio and the mass-radius relation for real stars. Assuming that the distorted star has the same volume as the spherical one, Warner (1976) obtained $M_2/M_\odot = 2.45(P/1^d)$; Echevarria (1983) proposed a revised approximation, $M_2/M_\odot = 0.0751(P/1^h)^{1.16}$. Recently de Loore and Doom (1992) redetermined the mass-radius relation for low-mass main sequence stars, and thus one may obtain much stronger dependence $M_2 \propto P^{2.5}$.

For example, the mass estimates for the polar AM Her obtained by using these statistical relationships and different sets of parameters are 0.32, 0.28 and 0.061 solar masses, respectively. The last value significantly differs from that with $n \approx 1$ and does not seem to be realistic. Götz (1991) noted that the mean estimate of the spectral class of the red dwarf in AM Her (M4.5) is in a good agreement with the estimate M5.4 obtained from the "period – spectral class" relation by Echevarria (1983). It corresponds to the mass $M_2 = 0.266 M_\odot$ and radius $R_2 = 0.314 R_\odot$.

A comparative analysis of various models was made by Andronov (1982b) and revised by Andronov (1992b), who tabulated numerous characteristics of the Roche lobe and proposed approximating fits. It is important to note that the values of the "barotropic" radius are systematically larger by 2–4% than that of the "equi-volume" one for the same mass ratio. This leads to a $\sim 10\%$ difference in the theoretically expected volumes, mean densities and thus masses.

11.2. Is the red dwarf a main sequence star?

Current models of the red dwarfs in cataclysmic variables show that they may be slightly evolved stars (Echevarria, 1983; Warner, 1995). Beuermann et al. (1998) showed that in the short-period cataclysmic variables, the red dwarf is close to the main sequence, whereas in the long-period (> 3 hours), the majority of secondaries have later spectral types owed to the nuclear evolution prior to mass transfer and lack of thermal equilibrium due to mass transfer.

11.3. Magnetic activity of the red dwarf

The secondary in magnetic cataclysmic variables is a red dwarf, thus one may assume corresponding physical variability. Solar-type magnetic activity may cause variations of the accretion rate in cataclysmic variables (Bianchini, 1990), as well as the migrating spots (Hessman et al., 2000). The star underwent an unprecedented UV Cet - type flare (Shakhovskoy et al., 1993). Statistical study of the variability of accretion and flare nature was published by Bonnet-Bidaud et al. (2000). An additional mechanism of modulation of the accretion rate may be present, if a third body (massive planet or brown dwarf) causes minor variations of the orbital separation.

12. Conclusion

To make a statistical study of variability with characteristic times from seconds to decades, a long-term monitoring has been carried out since 1978. The phase light curve of sometimes undergoes drastic changes even from one cycle to another. Its shape statistically depends on luminosity, despite of significant physical variability. AM Her exhibits a variety of types of variability, with a cease of the fast variability and polarization in the low state. An unprecedented flare has been detected, which resembles the flares of the UV Cet-type stars, and is within 5 most powerful flares. Much smaller accretion event at a low state was registered spectrally at the 6m telescope. Our low state multicolor observations and the IUE data allowed to propose a two-temperature model for the emitting region. For overlapping flares producing a "red noise" (flickering), we have used statistical methods. The most accurate photometric ephemeris (based on 279 minima timings), was determined. The 3 year variations of the phase shift of the curve have been interpreted as a result of the "swinging dipole" model - two-dimensional variations of the orientation of the white dwarf in respect to the red dwarf both in the latitude and longitude. Because of few processes involved, the variations are not strictly periodic, but show some characteristic cycle a time scale of 1–10 years. Our theoretical models were applied to a "standard model" (Chanmugam and Wagner 1977), according to which, the dependence of the accretion rate on the orientation of the magnetic axis of the white dwarf exists in a case, when the magnetic field is strong enough to capture the flow near the inner Lagrangian point ("magnetic valve"); the synchronization time may not exceed 10^3 years (an excellent example of such a system is BY Cam). Following the model of the dipole-star interaction for synchronization of the white dwarf by Joss et al., (1979), we estimated characteristic times of the orbit circularization. Using a simplified column model, the soft X-ray curves were modelled showing either large optical depth of the column as well as the non-zero height of the emitting "polar cap" region. The accretion column exhibits effects of asymmetry, inclination, instability of few types. This causes changes in the polarization and spectra, as compared with stationary axi-symmetrical models.

Results of 13 recent years of polarimetric monitoring of AM Her are prepared for publication in the monograph "Atlas and catalogue of the polarimetric and photometric characteristics of the magnetic cataclysmic variable star AM Her" by Shakhovskoy, Andronov and Kolesnikov (2001).

Despite an unprecedented database of polarimetric observation already exists, the star needs further multi–wavelength monitoring, which will allow to study details of structure and evolution of these interesting objects.

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