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“Magnetospheric gate” in polars

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Abstract. The mass-exchange process in polars is discussed. We point out that the strong magnetic field of a white dwarf in these systems can under certain conditions prevent the material from flowing through the L1 point operating as a “magnetospheric gate”. We show that the condition under which the “magnetospheric gate” is closed is satisfied in the majority of polars known to date. This finding opens the question about a possibility to realize an alternative mechanism of mass exchange in these systems. We briefly discuss application of this mechanism to the best studied polars.

Keywords: stars: cataclysmic variables, polars, magnetic fields; accretion; individual: AM Her, QQ Vul, AR UMa

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1 Introduction

Polars are a subclass of magnetic cataclysmic variables. They are close binaries consisting of a magnetic White Dwarf (WD) and a Red Dwarf (RD) which fills its Roche lobe. The rotation of stars in most of these systems is synchronized with the orbital rotation. The radiation of the systems is contributed by a RD, a WD and a source associated with the matter transfer between the system components. The latter manifests itself in X-rays and/or the polarized optical emission and/or the emission lines (Cropper 1990).

The mass transfer in polars is realized according to a so-called channeled accretion scenario. This implies that the matter is streaming from the surface of the RD to the magnetic pole regions of the WD without forming a disk. The factor which prevents disk formation is the magnetic field of the WD. The magnetosphere of a WD under the conditions of interest can be extended up to the surface of a RD making a channel in which the matter flows between the system components (Schneider & Young 2021). Alternatively, if the pressure of the matter at the L1 point is dominating over the magnetic pressure due to the dipole magnetic field of the WD, a stream of matter through the L1 point can be realized (Mukai 1988). This possibility is explored in our paper. We find this condition not to be satisfied in the majority of polars. We suggest that the mass transfer is realized through a magnetic channel made by the process of coupling of the magnetic field of a RD and a WD.

2 Magnetospheric gate at the L1 point

We consider a binary system consisting of a WD and a RD which fills its Roche lobe. The question is under which conditions the matter can flow through the L1 point into the Roche lobe of a WD. A necessary condition reads

$$p_m(r_{\rm L1}) < p_0, \tag{1}$$

where $p_m(r_{\rm L1}) = \mu^2/(2\pi r_{\rm L1}^6)$ is the magnetic pressure (μ is the dipole magnetic moment of the WD) and p_0 is the pressure of the matter at the L1 point which is contributed mainly by the gas pressure $p_{g0} = \rho_0 c_{s0}^2$ (since the free-fall velocity at the L1 point is equal to zero by definition). Here ρ_0 and c_{s0} are the density and the sound speed in the gas at the L1 point.

The distance from the center of the WD to the L1 point can be estimated as (Plavec & Kratochvil 1964) $r_{\rm L1} \simeq a\big[0.5 - 0.227 \log q\big]$, where

$$a \simeq 3.53 \times 10^{10}\ {\rm cm}\ \big[M(1) \times (1+q) P_{\rm orb}^2(h)\big]^{1/3}$$

Table 1. Polars: main parameters and the critical period P_0 at which the "magnetospheric gate" at the L1 point is closed (for details see Ikhsanov et al. 2023 and references therein).

Object	Dist	$M_{\rm opt}$	$M_{\rm wd}$	$B_{\rm wd}$	$\dot{M}_{\rm acc}$	$P_{\rm obs}$	P_0
	pc	$M_\odot$	$M_\odot$	MG	$M_\odot$/yr	hr	hr
AM Her	88	0.26	0.78	14	$\leq 10^{-10}$	3.1	4.5
QQ Vul	215	0.35	0.58	20	$\leq 10^{-11}$	3.7	6.5
AR UMa	85	1.4	0.70	235	$\leq 10^{-12}$	1.9	45.5

is the system separation and $q = M(2)/M(1)$ is the mass ratio. Here $M(1)$ and $M(2)$ are the masses of a WD and a RD, respectively, in solar masses, and $P_{\rm orb}(h)$ is the orbital period in hours.

The gas density at the L1 point can be estimated as $\rho_{\rm L1} = \dot{M}/Ac_s$, where $\dot{M}$ is the mass transfer rate, $A = \pi\sigma^2$ and σ is the effective radius of the accretion flow streaming through the L1 point. Combining the above expressions and solving the inequality with respect to $P_{\rm orb}$ one finds $P_{\rm orb} \geq P_0$, where

$$P_0 \simeq 2.2\,{\rm hr} \times \mu_{34}^{1/2}\,\sigma_9^{1/2}\dot{M}_{15}^{-1/4}\,c_6^{-1/4} \times \left[\frac{1}{[0.5 - 0.227\log q][(1+q)M(1)]^{1/3}}\right]^{3/2}. \quad (2)$$

Here $\mu_{34} = \mu \times 10^{-34}\,{\rm G\,cm^3}$, $\sigma_9 = \sigma \times 10^{-9}\,{\rm cm}$, $\dot{M}_{15} = \dot{M} \times 10^{-15}\,{\rm g/s}$ and $c_6 = c_s \times 10^{-6}\,{\rm cm/s}$.

Substituting the values $q = 0.35$, $M(1) = 0.8\,M_\odot$, corresponding to the parameters of the most fully studied polar AM Hercules, into the expression eq. (2), we find

$$P_0(q = 0.35, M(1) = 0.8\,M_\odot) \simeq 4.5\,{\rm hr} \times \mu_{34}^{1/2}\,\sigma_9^{1/2}\dot{M}_{15}^{-1/4}\,c_6^{-1/4}. \quad (3)$$

3 Discussion

The orbital periods of the systems identified with polars are clustered mainly in a range between 1 hour to 5 hours (Norton et al. 2004). In light of this, our result indicates that "magnetospheric gate" at the L1 point is closed in the majority of polars (see Table 1 and Fig. 1).

In the systems where "magnetospheric gate" at the L1 point is closed, mass exchange between the system components can occur through a magnetic channel formed by reconnection between the magnetic fields of a WD and a RD. If the condition of eq. (2) is not met, the magnetic channel will be strong enough to withstand the gas flow from the surface of the RD at a rate observed in the polars characterized by the highest luminosity. At the same time, the characteristic time of stability

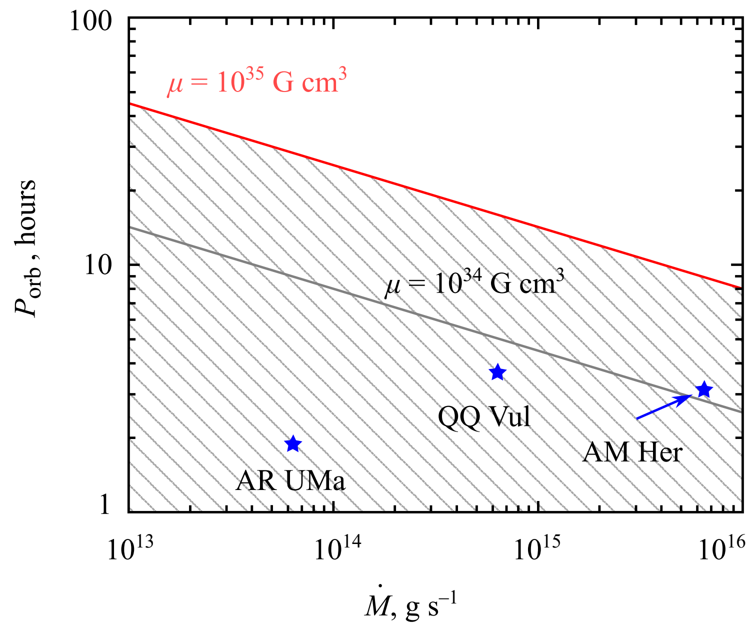

Fig. 1. Critical value of the orbital period, P_0, versus the mass accretion rate, calculated for two values of the WD dipole magnetic moment, $\mu = 10^{34}$ G cm^3 (black) and $\mu = 10^{35}$ G cm^3 (red). The shading shows the range of $P_{\rm orb}$ for which the "magnetospheric gate" at the L1 point is closed.

of such a channel will be determined by the time of reconnection of the field lines, which implies a possibility of a fairly strong variability in the rate of mass exchange between the components. Finally, the mass exchange scenario in which the matter flows along the filed lines, connecting the surfaces of a WD and a RD, allows us to avoid a very complicated question about the mode by which the stream of matter enters the WD magnetosphere (for a discussion see e.g. Ikhsanov & Pustil'nik 1996, and references therein). This question remains open in the scenario of mass-transfer through the L1 point.

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