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On the source of viscosity in cool binary accretion disks

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Abstract. We suggest that the low viscosity in close binary accretion disks during quiescence is due to magnetic fields from the companion star. In very late evolutionary phase the companion stars become brown dwarfs and have cooled down to such low a temperature that this process cannot work anymore. The extremely low viscosity in WZ Sge stars supports this connection between companion stars and viscosity. We further suggest that magnetic activity in such very cool stars is cut off by their poor electric conductivity.

Key words: accretion disks – cataclysmic variables – Stars: low-mass, brown dwarfs – Stars: magnetic fields – stars: individual: WZ Sge

1. Introduction

Gammie & Menou (1998) have suggested that the low magnetic Reynolds numbers in the cool state of dwarf novae (DN) accretion disks do not allow any dynamo action and that this might explain the difference between high α values in the hot (outburst) state and low α value in the cool (quiescent) state, (viscosity parametrization according to Shakura & Sunyaev 1973). This result leaves open the question where the friction in the cool state comes from. Our investigation complements the work of Gammie & Menou (1998). Based on the analysis of the very long recurrence times (decades) and very high outburst amplitudes of WZ Sge systems as compared to regular DN systems of similar orbital period we argue that the cause for the friction in low state cannot lie in the accretion disks or the primaries of these systems as they are basically the same, but must be sought in the nature of the secondary stars. We suggest that the standard low α friction in cool accretion disks is due to magnetospheric fields from the secondary. Such fields may be akin to apparent dynamo action of the sun visible as "magnetic carpet" (Schrijver et al. 1998). During the secular evolution the companion star loses mass and cools down. We argue that one can understand the very low value of the α parameter derived from simulations of outburst cycles for WZ Sge stars (1/10 of the standard cool disk values for DN) as due to poor conductivity for the very low temperatures of the late type secondary stars.

This picture supports the long supposed magnetic nature of friction in cataclyscmic variable (CV) accretion disks. It does support Gammie & Menou's explanation of the difference between outburst and quiescent α values. It further shows that quiescent disks without companion stars would need some other source of magnetic field entrainment or need a non-molecular cause of friction.

In the following Sects. 2 and 3 we discuss the low-mass companion stars and their magnetic activity. The consequences for the accretion disks are discussed in Sect. 4. In Sect. 5 we discuss the cut off of chromospheric and coronal activity by low conductivity. The observations for systems in the late evolutionary state support our suggestion (Sect. 6).

2. Evolutionary models for low-mass stars

The evolution of low-mass stars has been studied extensively by D'Antona & Mazzitelli (1982) including the effect of mass loss (occurring during the secular evolution of dwarf novae, Warner 1995). These computations already showed that the stars become very cool late in their evolution. New evolutionary models of low-mass stars are based on the most recent interior physics and the latest generation of non-grey atmosphere models (Baraffe et al. 1998). The electron degeneracy in the interior causes a drop of effective temperature for stars of mass below about $0.2\,M_\odot$. The coolest temperatures of main sequence stars ($0.075 M_\odot$) are only around 2000 K. Though mass loss is not included the effective temperature is hardly affected as confirmed by recent work of Kolb & Baraffe (1998). Figure 1 shows the effective temperature reached at the

Send offprint requests to: Emmi Meyer-Hofmeister final state of evolution as a function of the stellar mass (Baraffe et al. 1998 and Allard et al. 1996).

Companion stars of very low mass belong to the brown dwarf regime. They have probably spent a long time (Gyrs) to arrive at their present CV period. These might be transitional objects of $M \geq 0.06 M_\odot$ or lithium brown dwarfs $M \leq 0.06 M_\odot$ or evolved brown dwarfs that have now exhausted their nuclear fuel and cooled below the coolest main sequence stars (Allard et al. 1997).

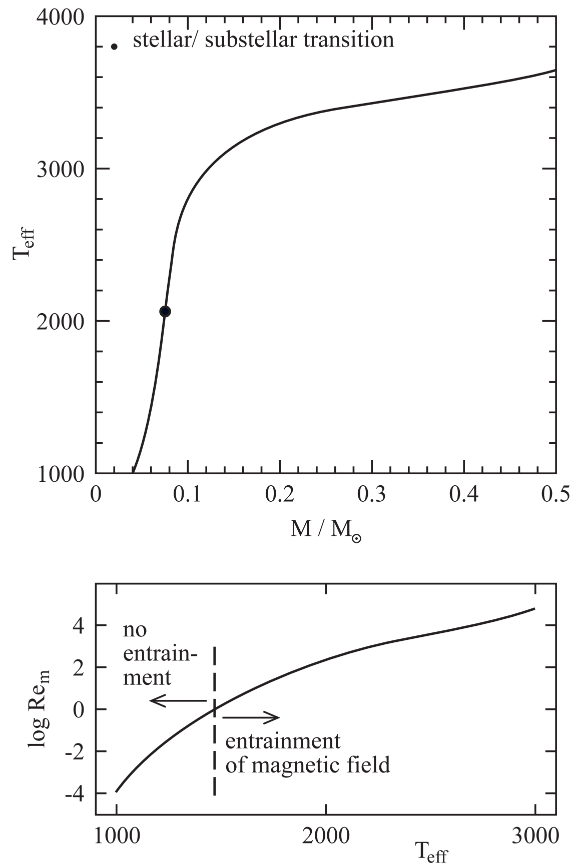

Fig. 1. Upper panel: Effective temperature of low-mass stars reached during evolution, from Baraffe et al. (1998) and BD models, taken at an age of 2 Gyrs from Allard et al. (1996). Lower panel: Magnetic Reynolds number of the accretion stream at L_1 from a low-mass secondary star.

3. Magnetic activity of low-mass stars

The solar cycle dynamo is located at the interface between radiative interior and convective envelope. Similar cycles on low-mass companion stars in CVs have been thought to be responsible for orbital period variations of such systems (Applegate 1992).The magnetic fields generated by such a dynamo and pulled out with a wind from the secondary star are thought to be responsible for the braking of the orbital motion of systems above the period gap. The disappearance of this dynamo when stars become fully convective, is commonly accepted as the cause for the occurrence of the period gap (Spruit & Ritter 1983, Rappaport et al. 1983). But also stars of smaller mass, $M \leq 0.3 M_\odot$, show chromospheric and coronal activity, indicating magnetic activity. In the quiet sun such activity is seen in the network of supergranular cells covering the surface like a "magnetic carpet" (Schrijver et al. 1998).

The steady and impulsive heating of chromosphere and corona is attributed to release of magnetic stresses brought into the field by twisting and shearing subsurface motion. This activity thus requires deviations from current-free potential field configurations. For very low effective temperatures the gas becomes neutral and the electrical conductivity of the few remaining metal electrons is exponentially reduced. Thus for very low temperatures one expects that a near-surface dynamo will stop working and no magnetic fields are present. Alternatively a dynamo operating in the bulk of the convection zone will continue to work beneath the surface. However it is unable to transport magnetic energy through the non-conductive current-free surface layers. In both cases observable activity ceases (see evaluation Sect. 5). This seems to be supported by observations (for a review of stellar activity in low-mass stars and brown dwarfs see Allard et al. 1997).

4. Magnetic flux entrained in the accretion disk

The situation described in the preceding section has consequences for the accretion stream. As long as the secondary star's magnetic field is present and conductivity is sufficient the magnetic flux pervading the gas will be brought over to the disk. As soon as the field disappears or the conductivity has become so poor that the field can diffuse out of the gas this process ends and the accretion disk is fed by non-magnetic gas. Thus one expects a significant change of the magnetic properties of the accreting gas when the secondary stars become too cool for magnetic activity.

In order to determine whether the gas passing through the L_1-point entrains the magnetic field we have determined a magnetic Reynolds number $\mathrm{Re}_m = H \cdot V_s/\eta$, where H is the length scale, V_s the isothermal sound speed, and η the magnetic diffusivity, all values calculated at the L_1-point. We take the length as the square root of the cross section Q

$$Q = \frac{2 \frac{\mathcal{R}}{\mu} T a^3}{GM} \frac{1}{6.056} \tag{1}$$

where $\mathcal{R}$ is the gas constant, μ the molecular weight,T the temperature, a the distance between the stellar centers, G the gravitational constant, and M the total mass of the binary. The numerical factor results for the assumed mass ratio $q = M_2/M_1 = 1/10$, characteristic for $0.7 M_\odot$ primaries and Roche lobe filling late main sequence brown dwarf secondaries. For the orbital period $P_{orb} = 2\pi(a^3/GM)^{1/2}$ we take 80 min. The density ρ in the flow is obtained from $\dot{M} = QV_s\rho$, where we assume a value for the mass transfer rate $\dot{M}$ of $10^{-11}M_\odot/yr$, characteristic for such systems (Kolb 1993). In $V_s = (\frac{\mathcal{R}}{\mu}T)^{1/2}$ we use $\mu = 2.4$ for a mixture of molecular hydrogen and 10% helium. Values of ρ are then of order 10^{-6} g/cm^3, dependent on the temperature. The value of the magnetic diffusivity η is determined from the electron density and electron-molecule collision frequency (for cross sections see Ramanan and Freeman, 1991). See also Gammie and Menou (1998) for the same procedure for an accretion disk situation. This yields

$$\eta = 10^{3.99}T_3^{1/2}n_n/n_e \tag{2}$$

where T_3 is temperature in units of 1000K and n_n and n_e are number densities of neutrals and electrons, respectively. The ratio of number densities can be derived from ionization equilibrium (Allen 1973) of the electron providing alkali metals. For low temperatures the contribution of K dominates. We obtain

$$\log\frac{\mathrm{n_e}}{\mathrm{n_n}} = 6.48 - \frac{10.94}{\mathrm{T_3}} + \frac{3}{4}\log\mathrm{T_3} - \frac{1}{2}\log\mathrm{n_n}. \tag{3}$$

The number density of neutrals is obtained from the density by division with the mean particle mass. Putting everything together we obtain

$$\log\mathrm{Re_m} = 7.13 + 2\log\mathrm{T_3} - \frac{10.94}{\mathrm{T_3}} \tag{4}$$

This function is plotted in Fig. 1. It mirrors the strong temperature dependence of electron number density at temperatures below the ionization temperature. At temperatures below 1470K the Reynolds number becomes smaller than 1, indicating that the accretion stream can no longer entrain any magnetic field of the secondary.

It is remarkable that this temperature divides the very late main sequence stars from old brown dwarfs that have cooled for 10^9 to $10^{9.5}$ yrs. Our interpretation suggests that the typical secondaries of WZ Sge type stars with their long outburst intervals and small α-values are old brown dwarfs consistent with the upper bound of $T_{\rm eff}$ from Ciardi et al. (1998).

5. Suppression of chromospheric and coronal activity for low temperatures of secondaries

At the same low temperatures the photospheres of the secondary stars become extremely poor electrical conductors. This must quench any magnetic dynamo that operates in surface near layers. It also drains energy from a dynamo that operating in the depth of the convection zone and might bring its dynamo number below the critical value. The magnetic field then would disappear.

We illustrate this poor conductivity by calculating a critical length scale $l_{\rm crit}$ at the surface of the secondaries. For motions on scales smaller than $l_{\rm crit}$ the magnetic flux is no longer carried along by the convective motions. We use data for photospheric temperature and density kindly provided by I. Baraffe and F. Allard Assuming a convective velocity v_c=1 km/s we obtain the following values.

(a) For a low-mass star, $M = 0.08M_\odot$, $\mathrm{T_{eff}}$=2300K, $\log\rho$=-4.5: $l_{\rm crit}$= 50 km. (b) For a brown dwarf, cooled to $\mathrm{T_{eff}}$=1000K, $\log\rho$=-4: $l_{\rm crit}$= $1.6\,10^8$ km, much larger than the stellar radius. (c) For a young brown dwarf with $\mathrm{T_{eff}}$=2700K, as observed in X-rays by Neuhäuser & Comerón (1998) and assumed $\log\rho$=-4.7: $l_{\rm crit}$=6 km. The values depend sensitively on the temperature.

Thus stars and brown dwarfs with $\mathrm{T_{eff}}$ above about 1600K would be expected to show activity as long as they rotate sufficiently fast (c.f. Delfosse et al. 1998), while cooler brown dwarfs might still have magnetic fields from a subsurface dynamo but could not have magnetically produced activity in their atmospheres and coronae.

6. Indications from observation

WZ Sagittae is the prototype of DN systems in the evolutionary latest phase (Osaki 1996). They show rare and luminous outbursts which can only be understood assuming very low viscosity (for recent modeling see Meyer-Hofmeister et al. 1998). In Fig. 2 we show the recurrence time of superoutbursts as a function of the orbital period. The recurrence time can be used as an indicator of the viscosity.Thus the very low α values are expected for the shortest periods. Note, that systems with regular and with very long recurrence time both populate this region. This suggests different temperatures of the corresponding secondary stars. We note that for extremely low masses in latest evolution the radius of the brown dwarfs increase with the decreasing mass (Hubbard 1994) and therefore brown dwarfs and main sequence stars can have the same mean density (that is similar periods), but different temperature and thus different friction in the disks. We point out that near-infrared broad band photometry has confirmed the low temperature of the secondary star of WZ Sge, $T_{\rm eff}$ less than 1700K (Ciardi et al. 1998).

7. Conclusions

7.1. Hierarchy of viscosity values

Why the viscosity during quiescence is so small in WZ Sge stars has been an open question addressed by several authors (e.g. Smak 1993, Howell et al. 1995, Lasota et al. 1995, Osaki 1995, Warner et al. 1996, Hameury et al. 1997). In their work on TOADs Howell, Szkody and Cannizzo (1995) already raised the question whether the magnetic flux entrained in the mass stream could stop. We suggest the following picture: the companion stars have magnetic activity and their magnetic field passing through

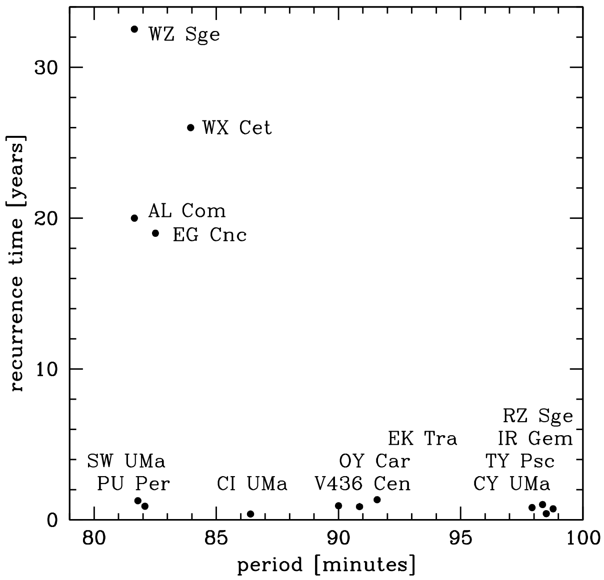

Fig. 2. Recurrence time of superoutburst of SU Uma stars taken from Ritter & Kolb (1998), in addition times for WX Cet (O' Donoghue D. et al. 1991) and EG Cnc (Matsumoto et al. 1998)

the disk or entrained with the mass flow causes a viscosity of a few hundredths (in the α parametrization) as needed for the modeling of quiescent disks, but only if the secondaries are not too cool. The hierarchy of viscosity values can be understood as follows

- In hot accretion disks the small scale dynamo in the disk can produce a viscosity of a few tenths (α parametrization). The companion's star magnetic field is not important.
- In cool disks the fields from the secondaries' magnetosphere penetrating the disk or entrained with the mass stream are the origin of the viscosity.
- If the secondary is very cool (WZ Sge stars), its magnetic activity ceases, no fields exist or can be entrained anymore and no magnetic viscosity is generated in the disk.

The origin of the extremely low viscosity is still unknown, it might be generated by any kind of waves (Narayan et al. 1987, Spruit et al. 1987, Sawada et al. 1987, Spruit 1987). The extremely low viscosity in WZ Sge stars might then be of the same nature as the viscosity in disks around young stars (FU Orionis stars) and in AGN disks. The fact that the outburst of WZ Sge can be modeled with α=0.3 for the hot disk (Osaki 1995) supports the concept that the viscosity in hot disks is caused in the same way in all dwarf novae.

7.2. Cut off of magnetic activity

The observation of chromospheric and coronal activity in low-mass stars suggest a dynamo working in the convective region of the stars. We argue, that magnetic activity in very cool stars is cut off due to their extremely poor electrical conductivity.

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