THE EFFECTS OF MAGNETIC FIELDS ON PERIOD CHANGES, MASS TRANSFER AND EVOLUTION OF ALGOL BINARIES

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ABSTRACT. Variations in the magnetic pressure and flux blocking by starspots during the magnetic cycle of the cool semidetached component of an Algol binary may cause cyclic changes in the quadrupole moment and moment of inertia of the star which can cause alternate period changes. Since several different processes and timescales are involved, the orbital period changes may not correlate strongly with the indicators of magnetic activity. The structural changes in the semidetached component can also modulate the mass transfer rate. Sub-Keplerian velocities, supersonic turbulence, and high temperature regions in circumstellar material around the accreting star may all be a consequence of magnetic fields embedded in the flow. Models for the evolution of Algols which include the effects of angular momentum loss (AML) through a magnetized wind may have underestimated the AML rate by basing it on results from main sequence stars. Evolved stars appear to have higher AML rates, and there may be additional AML in a wind from the accretion disk.

1. INTRODUCTION

Over the past 15 years, it has become clear that large numbers of late-type stars emit radio and x-ray emission like that seen from the solar corona and have emission lines in their UV and optical spectra of the sort observed from the solar chromosphere and transition region. In each case, the emission luminosities that we detect from these stars are orders of magnitude greater than that from the Sun. The data indicate that the x-ray, radio, and emission line luminosities are directly correlated with the angular rotation rates of the stars so that the more rapidly rotating stars have greater luminosities.

The evidence that radio and x-ray emission from late-type stars is due to chromospheric and coronal activity produced by dynamo-generated magnetic fields has been summarized by Dulk (1985) and Rosner et al. (1985). Algols are not discussed as a separate class of stars in these papers because too few of them had been detected in either the radio or

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x-ray region, but many of the original papers on the RS CVn stars treat Algol and HR 5110 (=HD 118216=BH CVn), a non-eclipsing semidetached system (Little-Marenin *et al.* 1986), as members of the RS CVn class of stars. For example, Mutel *et al.* (1987) have compared the properties of the radio emission from Algol and HR 5110 with those of some RS CVn binaries.

In his talk at this meeting, Hall (1988) compared a number of the properties of Algols with those of various other classes of stars that are known to have chromospheres and coronae. The strong similarities between the Algols and these stars and the relationship between chromospheres and coronae and magnetic fields leaves little room to doubt that the components of Algols which are cooler than about 6000 K have magnetic fields. Estimates of the coronal magnetic field strengths obtained from radio observations of Algol and HR 5110 (Lestrade *et al.* 1986) range from a few to several hundred gauss. The photospheric fields are undoubtedly stronger.

Given these similarities, it is natural to suppose that the magnetic components of Algols have magnetic cycles like other solar-type stars (Baliunas and Vaughan 1985). I'm not aware of any observational evidence for this, but this may be due more to the lack of suitable observations than the absence of magnetic cycles. The various direct indicators of magnetic activity, such as chromospheric emission lines, starspot waves in light curves, variable x-ray and radio emission, are more difficult to detect in the typical Algol because it is farther away than most of the stars in which these phenomena have been detected and the light from the late-type component is usually overwhelmed by the light from the much brighter early-type component. The late-type components of Algols are in a different evolutionary state than other stars that are known to have magnetic dynamos, so the properties of their dynamos may also differ. Thus it would be very useful to look for evidence of magnetic cycles in some selected Algols. This will not be easy because the time scales for the cycles may be several decades (Hall 1988).

The best technique may be to monitor the radio emission on a regular basis, if a suitable instrument can be found. Alternatively, one might look for evidence of starspot waves in infrared light curves and then monitor the changes in these once they are found. The major problem in carrying out these observations, aside from the long-term nature of the program, will be to find an observational window that is at sufficiently long wavelengths that the cooler star is a major contributor to the total light from the system but is still shortward of the region where free-free emission from circumstellar material is important. This probably means that the window will have to be between 1 and 2.5 μm, and it may also mean that the search will have to be restricted to systems with relatively low mass transfer rates.

In this paper, I shall explore the possible ways in which dynamo generated magnetic fields and magnetic cycles may affect the periods, mass transfer, and evolution of Algol systems. For this purpose, I shall assume that Algol secondaries that are cool enough to have convective envelopes have a magnetic field generated by dynamo action. I shall also assume that these stars have magnetic cycles like those seen in other late-type stars (Baliunas and Vaughan 1985). Since the effects I am considering are too complicated to attempt realistic models and we lack observations to constrain the models, I shall confine my discussion to qualitative and semiquantitative arguments. I admit that some of my suggestions are highly speculative, but I hope they will stimulate attempts to both look for and model some of possible effect of magnetic fields in Algol binaries.

2. MAGNETIC CYCLES, ALTERNATING PERIOD CHANGES, AND VARIABLE MASS TRANSFER

The existence of both semidetached and detached binary systems which have shown multiple period changes that alternate in sign has been recognized for years (e.g. Hall 1975, Hall and Kreiner 1980). According to Hall (1988), these types of period changes are confined to binary systems which have at least one component that is cool enough to have a convective envelope. Attempts to explain these period changes by mass transfer between the stars (Biermann and Hall 1973, Hall 1975) encounter problems when the period is conserved over long periods of time (Matese and Whitmire 1983) or the stars in the system are detached from the Roche lobe.

Matese and Whitmire (1983) suggested that the alternate period changes are caused by short-term changes in the structure of the convective star which are caused by variations in magnetic pressure in the stellar envelope during a magnetic cycle. Subsequently, and apparently independently, Applegate and Patterson (1987) suggested a similar model to explain the period changes in V471 Tauri. If the magnetic field contributes to the total pressure in the envelope, then variations in the field strength during a magnetic cycle will alter the structure of the star. Depending on the details of the magnetic field structure, the pressure variations may alter either the radius of the star, the mass distribution in the envelope, or both. These structural changes alter the quadrupole component of the gravitational potential and thereby produce an immediate change in the orbital period.

Both groups argue that an increase the magnetic field strength, hence in the magnetic pressure, increases the quadrupolar moment of the star, which causes the orbital period to decrease. Both groups also offer (somewhat different) semiquantitative arguments to support the plausibility of this model. The changes in the quadrupole moment required by the model to explain the period changes are large compared to the quadrupole moment of the Sun, but rapidly rotating, tidally distorted stars have much larger quadrupole moments, and their magnetic activity is also much more intense. Furthermore, models of the Sun which include secular perturbations of the pressure deep in the envelope like those that might be produced by magnetic fields (Endal *et al.* 1985) show that the right kind of perturbation can alter the interior structure in the way required to explain the period changes. Thus this model provides a plausible explanation for the alternate period changes, but the existence of the perturbations that are required must be confirmed by detailed calculations of the behavior of realistic magnetic dynamos.

However, there are reasons to think that this model is either incorrect or seriously incomplete. It predicts that the magnetic star will be largest when the magnetic field is strongest. An increase in the size of the semidetached component of a binary system should lead to a large increase in the rate of mass transfer between the stars, and the model predicts that mass loss bursts should coincide with peaks in various indices of magnetic activity. There are almost no data which can be used to check this, but these correlations are not clearly present in Olson's (1985) observations of U Cephei and U Sagittae. Furthermore, it is not clear that the solar radius variations that have been observed over the past 270 years are correlated with magnetic activity (Gilliland 1981, Endal and Twigg 1982). The available evidence suggests that there is a *negative* correlation between sunspot number and solar radius.

Van Buren and Young (1985) have suggested that magnetically induced structural variations during the magnetic cycle of a component of a close binary together with tidal spin-orbit coupling can cause alternating period changes. Stars in close binary systems are usually rotating synchronously with the orbital period so that the equilibrium tide is aligned with the line joining the stars. If one of the stars has a magnetic cycle, variations in the magnetic pressure in the convective envelope of the star during the cycle may alter the star's moment of inertia by changing the radius of the star or the mass distribution in the envelope. An increase in the magnetic pressure will increase the moment of inertia and cause a decrease in the rotation rate. This will cause the tidal bulge to lag the substellar point. They argue that the tidal torque acts on this bulge to transfer angular momentum from the the star's rotation to the orbit, so that the orbital period increases, on a time scale of a few years. Angular momentum is transferred in the opposite direction when the field decays, thereby accounting for the alternating period changes.

Van Buren and Young's paper has been strongly criticized by Hall (1987) and Applegate and Patterson (1987) because the sense of the angular momentum transfer is wrong (an increase of the moment of inertia will lead to a transfer of angular momentum from the orbit to the star's rotation and a period decrease) and the time scale of tidal spin-orbit coupling has been underestimated by 6 dex. The first of these problems is not fundamental, but the second is. However, Hall (1987) noted that this model might still be relevant if the efficiency of tidal spin-orbit coupling is increased by effects (he suggests magnetic fields) that are not included in the traditional model of tidal friction (Zahn 1977).

Recently, Tassoul (1987) has described a hydrodynamical process which acts to synchronize axial rotation and orbital motion in double stars and is much more efficient in many situations than tidal friction. The spin-down time t_{sd} for this process is

$$t_{sd} = 535\mathrm{x}10^{-N/4}\left(\frac{1+q}{q}\right)L^{-0.25}M^{-1.25}R^{-3}P^{2.75} \tag{1}$$

where L, M, and R are the luminosity, mass, and radius of the asynchronously rotating star in solar units, P is the orbital period in days, $q = M'/M$ is the mass ratio and 10^N is the ratio of the vertical component of the eddy viscosity to the radiative viscosity. It is difficult to estimate N theoretically for convective stars, but Tassoul (1988) has used the observed time scales for circularizing orbits of late-type stars to obtain N=10. When this value of N is used in equation (1), the parameters of typical short-period Algol systems yield estimated spin-down times of a few months, or if we follow Tassoul and adopt $t_{synch}=10t_{sd}$, synchronization times of a few years. This is comparable to, or shorter than, the expected lengths of the magnetic cycles, so this process can contribute to the alternating period changes.

Photometric observations of two active binaries, λ Andromedae (Dorren and Guinan 1984) and V711 Tauri (Dorren *et al.* 1986), have shown that the V-band luminosities of these stars are anticorrelated with starspot area. This suggests that large starspots either trap radiation in the envelope of the spotted star or cause the radiation to be redistributed from the V-band to other regions of the spectrum. Unfortunately, there are insufficient observations of these stars in other bandpasses to distinguish between these possibilities. If starspots trap energy in the envelope, the star will expand (Dearborn and Blake 1982). Expansion and contraction of the star during a starspot cycle will produce changes in the quadrupole moment and moment of inertia of the star that are at least approximately in phase with those produced by variations of the magnetic pressure. In close binary stars, these structural changes will produce period changes through the actions of the same processes discussed above.

Finally, I have already noted (see also Hall 1987) that the expansion of the semidetached component of a binary system will produce an increase in the mass transfer rate. If the mass transfer takes place conservatively, the period of the system will probably increase, because a semidetached component that is cool enough to have a convective envelope and a magnetic dynamo will usually be the less massive component of the binary system. This is *opposite* to the sense of the period changes produced by the other effects we have described.

Since the changes in the quadrupole moment and the moment of inertia are caused by the same processes, it seems likely that if either process is important, the other is also important. Orbital period changes are anticorrelated with changes in both the quadrupole moment and the moment of inertia, but the period changes due to the former are instantaneous, while those due to the latter will lag behind changes in the moment of inertia, hence the magnetic cycle, by a few years. If variations of the flux blocking are in phase with the magnetic cycle, the structural changes that result will lag the magnetic cycle by the thermal time scale t_{th} of the layer of the envelope where the energy is stored. The observations (Dorren and Guinan 1984, Dorren *et al.* 1986) and the models (Dearborn and Blake 1982) suggest that this time scale is similar to t_{sd} (*i.e.* a few months to a few years). This is the time scale for the structural changes to develop, and it is in addition to the time scales for the period changes to occur, though the time scales may not add arithmetically.

The observed lag between the period changes and the magnetic cycle will depend on the relative importance of magnetic pressure and flux blocking in changing the structure of the star, whether the changes in the quadrupolar moment or moment of inertia are more significant, and the importance of variations in the mass transfer rate. The relative significance of the various processes and the lag times for each are likely to vary from system to system. Consequently, we should not expect to find clear correlations between the period changes and various indicators of magnetic activity.

3. PROPERTIES OF MAGNETIZED GAS STREAMS AND ACCRETION DISKS

Estimates of the magnetic field strengths of Algols that have been obtained from radio observations refer to coronal structures (i.e. hot gas trapped on magnetic loops) (Mutel *et al.* 1987) in the system rather than the stream or accretion disk. It is possible that there is some mechanism that excludes the magnetic field from the mass flows near the L1 point, but I think it is reasonable to assume that the magnetic fields are at least as likely to occur there as elsewhere. One might even suppose that magnetic flux tubes are more likely to surface near L1, because the surface gravity is lower, hence the buoyancy of flux tubes is higher, in this region.

If we assume that the gas stream in an Algol system has a circular cross-section, the magnetic field strength B required for equipartition between the magnetic energy and the kinetic energy is

$$B = 50(\dot{M}v)^{1/2}r^{-1} \qquad (2)$$

where B is in gauss, v is the velocity of the flow in km s^{-1}, r is the radius of the cross-section through the stream in units of 10^{10} cm, and $\dot{M}$ is the mass loss rate in units of 10^{-8} solar masses per year. r is of order unity in a typical Algol system (Lubow and Shu 1975, Hadrava 1984), and $\dot{M}$ is also of order unity for a system transferring mass at the thermal rate. Equation (2) shows that the value of the field required for equipartition of energy is comparable to the field strengths derived from radio observations of the coronae of Algol systems. This is especially true in the low velocity region of the stream near the L1 point where the magnetic fields are probably stronger than in the coronal regions sampled by the radio observations. Therefore it seems likely that magnetic fields play an important role in the dynamics of gas streams in Algol systems where the semidetached component is cool enough to have a convective envelope.

The mass transfer rate from the semidetached component could be significantly reduced by a strong bipolar spot group passing through the region of the L1 point, because a magnetic field of several thousand gauss is probably sufficient to stop the flow in the region where the field lines are closed in most Algol systems. Even if the flow is not completely choked off, the outflow velocity near the L1 point will be reduced. If the magnetic field lines are open or the field is not strong enough to stop the flow, the additional pressure in the flow from the magnetic field will cause the stream to be broader than it would be if there were no magnetic field. The spreading field lines can act like a de Laval nozzle and cause the flow to be accelerated to higher velocities than would otherwise be the case. Finally, if the field dominates the flow near the L1 point, the direction of the stream may be determined by the magnetic field geometry. This may be why the streams in U Cephei (Kondo *et al.* 1980) and Algol (Richards et al. 1988) do not follow the paths predicted by the hydrodynamic models.

I think it is likely that in most, if not all, cases the drop in field strength and the increase in the flow velocity with distance from the L1 point will cause the behavior of the stream to shift from the magnetic field dominated regime to the flow dominated regime well before it reaches the accretion disk or the detached component, if the stream strikes the star. The field lines will be bent and stretched in the region near the accreting star as the flow is carried around the star. Since the flow may circle the star many times, the field can be strongly amplified and a great deal of energy can be stored in the form of magnetic stresses. There is likely to be additional amplification of the field by turbulence and convection in the accretion disk (Stepinski and Levy 1988). Under these conditions, it is difficult to see how the magnetized gas can settle onto the accreting star until the magnetic connections with the other star are broken, and this may be why transient disks form in systems where the stream strikes the accreting star.

There are a number of otherwise puzzling observations that may be explained if the circumstellar material around the accreting star is strongly magnetized. The storage of energy from the flow in the magnetic field may contribute to the sub-Keplerian velocities that are often observed in the circumstellar envelopes around the accreting stars (Kaitchuck 1988). The stretching and bending of the field in the flow will eventually lead to magnetic instabilities which will cause the field lines to be disconnected from the mass losing star. The magnetic energy is likely to be released in the form of localized mass motions (surges) that are accelerated by the release of tension in the magnetic field lines.

The magnetic activity is likely to be very intense because the the field lines are severely stretched and distorted by the high velocity and acceleration of the flow around the accreting star. If mass motions produced by magnetic reconnection in the solar atmosphere are any guide, the velocities of these surges will be supersonic. The velocities of these flows will be randomly directed and the scale will be small compared to the size of the disk, so the flows will be observed as nonthermal broadening of spectral lines or "turbulence". The surges may be concentrated in the outer regions of the disk, but I see no reason to expect that they will be localized on one side of the accreting star.

I think this is the most likely explanation for the supersonic turbulence that has been reported in the spectral lines from circumstellar material around a number of stars (Plavec 1983, Peters and Polidan 1984), and it also explains why the supersonic turbulence is not confined to the region near the impact point of the stream, as it would have to be if it were true turbulence (Plavec 1983). The interaction between the surges and the gas in the disk will convert the kinetic energy in the surge to thermal motions of the disk gas. This additional source of energy may be responsible for the high temperature accretion regions that are seen in a number of Algol systems (Peters and Polidan 1984).

Finally, it has been very noticeable at this meeting that where there is information on the thickness of an accretion disks (*e.g.* Peters 1988, Olson 1988, Plavec 1988), the disk always seems to be thicker than predicted by the standard models which do not include magnetic fields. If the disk is magnetized, the contribution of the magnetic stress to the vertical pressure support will cause the disk to be thicker, perhaps considerably thicker, than if the pressure is due only to thermal motions of the gas. The magnetic field can be amplified in the disk until flux tubes become buoyant and float to the surface of the disk (*i.e.* the strength of the field is self-limiting). The buffeting of the field lines in these flux tubes by turbulent motions in the disk will transfer energy to the low density outer layers of the disk through MHD waves, and this is likely to produce hot layers above each face of the disk that are analogous to the solar chromosphere and corona.

4. EVOLUTION WITH ANGULAR MOMENTUM LOSS THROUGH MAGNETIC WINDS

There have been a number of theoretical studies of the effects of AML in magnetic winds on the evolution of detached and contact binaries (Mochnacki 1981) and cataclysmic variables (Spruit and Ritter 1983, Cannizzo and Pudritz 1988), but so far as I'm aware, there are only two investigations that have attempted to calculate the effect of magnetic winds on the evolution of Algol binaries. Mochnacki (1981) included one Algol system, AS Eridani, in his study of the evolution of contact binary stars, and Kraicheva *et al.* (1986, see also Yungel'son 1988) have undertaken a more general investigation of the evolution of Algols with AML in a magnetic wind.

Mochnacki (1981) assumed that the average poloidal magnetic field B_p scales linearly with angular rotation rate. To calculate the time scale for AML t_{AML}, he assumed the wind is spherically symmetric, adopted Belcher and MacGregor's (1976) expression for the terminal wind velocity, and calculated the Alfven radius for the limiting case of rapid rotation. This leads to the result that $t_{AML} \propto B_p^{-4/3} \dot{M}^{-1/3}$, where $\dot{M}$ is the mass loss rate in the wind. For AS Eridani, this yields $t_{AML}=2\mathrm{x}10^9$ years, after a numerical error in the original calculation is corrected. This is the required order of magnitude to explain the AML from the system that must have taken place. t_{AML} would be similar for other Algols.

Tutukov (1984) has obtained an alternate expression for t_{AML} by adopting Skumanich's empirical law for rotational braking of field stars. His expression also yields values of t_{AML} of the order of 10^9 years for typical Algol systems. Kraicheva *et al.* (1986) used Tutukov's formula for AML to calculate evolutionary models for a number of Algol systems with secondary components with convective envelopes. They found that they could reproduce the initial parameters of these systems without contradiction.

These results are very encouraging, but I think it is likely that both models underestimate the AML in the wind because they are based on results derived from main sequence stars. Gray (1982, 1985) has found that the rotational velocities of luminosity class III giants and subgiants drop very sharply as the stars evolve past spectral types G5 and G0 respectively. This suggests that the AML rates for evolved stars are very high compared to those for main sequence stars. On the other hand, if the interiors of the progenitors of these stars are rotating more slowly than their envelopes, the marked increase in the depth of the envelope during the evolution could account for part of the observed drop in the rotation velocities (Rucinski 1988).

If this is true, there should be a sharp drop in the orbital angular momentum of Algols once the semidetached component becomes cooler than 6000 K (approx.). I thought I had found this effect when I plotted the log of the orbital angular momentum *vs.* secondary temperature using the tabulation of the properties of Algols by Giuricin *et al.* (1983). However, when I examined the data further, I found that there are strong correlations between orbital angular momentum and system mass and system mass and secondary temperature, so the correlation between orbital angular momentum and secondary temperature is not significant. An attempt to remove these first order correlations to look for second order effects was not conclusive, although there were some indications that the systems with cooler secondaries tend to have lower angular momentum.

The picture of the accretion disk that I sketched in the previous section strongly suggests that there is also a hydromagnetic wind driven off the faces of the disk. If so, it is likely that the wind carries away a significant amount of angular momentum (Cannizzo and Pudritz 1988). According to their equation (7), a terminal velocity of 1000 km s^{-1}, which is not much larger than the escape velocity from the system, will yield $t_{AML} \approx 10^9$ years for a typical Algol system if the mass loss rate is approximately 10^{-11} solar masses per year. This is less than 0.1 percent of the the thermal mass transfer rate. Since $t_{AML} \propto \dot{M}^{-1} v_{\infty}^{-2}$, a larger terminal velocity requires lower mass loss rate for the same t_{AML}. Thus we see that if these winds exist they are another efficient mechanism for AML.

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DISCUSSION

Rucinski said that he believed this was the first time someone had suggested that magnetic fields could be shot from one star to another. Although the whole area is very uncertain, he thought that there might be a mechanism preventing this. Observations of the sun and calculations of models of magnetic stars suggest that there are eddies free of fields and other regions where the field is concentrated. Perhaps only field-free regions can be transferred from one star to the other.
Bolton disclaimed any originality for the ideas which, he said, had their origin in 1974 in attempts to model the radio flares on Algol and to explain how the magnetic field is carried into the disk.

Peters believed that Bolton's ideas might explain the behaviour of

AU Mon, about which she had spoken earlier (p.84). There is a time-lag, in this system, between the build-up of circumstellar matter and the formation of the high-temperature accretion region and she believed that a magnetic field might be responsible. Bolton thought it unlikely that magnetic cycles would have periods as short as 411^d, but agreed that it might be worth looking for evidence of magnetic activity in the secondary component.

Tout was not convinced that one could safely conclude that a strong magnetic field would make a star bigger. It was possible that the field would so change the convective structure of the star that the latter would become smaller. Bolton agreed that there is much room for uncertainty, if only because the geometry of the magnetic field is not well-known. Some calculations have been made by R.L. Gilliland and (*Astrophys. J.* **253**, 399, 1982) and the mechanism has been studied in a different context by J.H. Applegate and J. Patterson (*Astrophys. J.* **322**, L99, 1987) but more theoretical work is still needed. Hall commented that the effect of changing magnetic fields in the sun appeared to depend on the initial field strength, where the change took place and how long it took. Depending on these factors, the radius might either increase or decrease. He mentioned his own discussion of these problems in *Publ. Astron. Inst. Csl.*, No. 70, 77, 1987. Hall and Bolton agreed that this was an area in which more observations might help the theoreticians.