Do Magnetically Torqued disks (MTDs) Exist Around Early Type Stars?

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**Abstract.** The main problems posed by the existence of dense quasi-Keplerian disks around hot (especially Be) stars are summarised. Then the way in which the Magnetically Torqued Disk or MTD model of Cassinelli et al. (2002) may help solve them, and some of the issues requiring further work, are discussed. Specific issues addressed include: the minimum stellar rotation, wind momentum flux and surface magnetic field required to torque and contain detectable disks; compatibility of the MTD model velocity distribution with observed line profiles and with long term variations (including V/R); the effect of gravity darkening in very fast rotators.

1. **The MTD Model**

Besides the many challenging issues of spatial structure and variability posed by extensive observational data sets (e.g. Smith et al. 2000), the mere presence of dense disks around some hot stars is a demanding problem. In particular Be star disks demand three model ingredients (cf. Cassinelli et al. 2002—hereafter CBMMT): (a) delivery of material from the star to near the equatorial plane at distances of several stellar radii; (b) compression of material to high density; (c) delivery of angular momentum to the disk material to enable it to remain in (quasi-)Keplerian orbit with minimal inflow/outflow.

The wind-compressed disk (WCD) model of Bjorkman and Cassinelli (1993) proposed answers to (a) and (b) in terms of equatorial collision of north- and south-bound orbiting wind streams from a fast rotating star. However the resulting disk has insufficient angular momentum to stay in orbit and the flow is predominantly radial in/out, contrary to line profile data (Hanuschik 2000) which point to a close to Keplerian structure with little radial flow. In addition (Owocki et al. 1994) found that gravity darkening and non-radial line-driving
forces in fact tend to make the outflow predominantly polar, which does not produce a WCD at the equator.

Using an analytic parametric model, CBMMT propose that the problems of the WCD model can be overcome by the presence of an aligned dipole-like stellar magnetic field of sufficient strength to contain and torque inner stellar wind flow from regions remote from the poles. This redirects the wind flows towards the equator, where a shock compressed disk again forms, and torques the flow beyond some inner radius up to and beyond local Keplerian $v_\phi$ this time with a high specific angular momentum (compared with WCD). The spectral-type dependent ram pressure of the wind governs the stream and disk density and hence the disk detectability and the field required to contain and torque the flow to create the disk. Weak fields do not contain and torque the wind flow to large enough radii to achieve orbital speed. Very large fields steer and torque the disk to very large radii and produce $v_\phi$ higher than observed. There exists an intermediate field regime, for a given stellar wind and rotation rate, which is sufficient to steer and torque the wind flow out to several stellar radii and hence create a dense disk of around Keplerian velocities. ud-Doula & Owocki (2002), Owocki (2003) and ud-Doula (2002, 2003) have explored similar scenarios using an MHD code and obtained somewhat similar results. Their code is, however, run-time restricted to fairly low field strengths sufficient to steer and torque the tenuous wind but allowing breakout or fallback of the denser disk material, which stronger fields can prevent.

Key issues to be addressed in the MTD scenario are the range of parameters (wind, rotation and field) over which it is physically viable and compatible with data, including line emissivity and profiles, scattering polarization, and variability. We summarise below preliminary results and discussion points for these issues.

2. Field Requirements and Disk Detectability

For parameters appropriate to Be stars, CBMMT find that a surface field $B \approx 10$ G (and stellar rotation speeds above about 0.5 of critical) is sufficient to steer and torque the wind flow out to several stellar radii and hence create a dense disk with approximately Keplerian velocities. Fields $B \approx 100$ G as discovered by de Jong et al. (2001) are enough to contain and torque the disk itself and would steer and torque the wind flow out to radii with substantially super-Keplerian speeds. For stars progressively hotter than B2 the higher wind density and speed demand a steeply increasing and implausibly high field (10 000 G for hot O stars). For stars much cooler than B2 a very weak field is enough to create an MTD from the slow low density wind, but of such small density that the disk polarization and emission line strength would be undetectable. The narrow range of Spectral Type around B2 for which the model works to the range in which most Be stars lie, lends support to the MTD model, the apparent fine-tuning of parameters involved perhaps explaining the rarity of Be stars.
3. MTD Velocity Field, Line Profiles, and Variability

For strong fields the resulting MTD is itself contained and torqued to near corotation and, since it extends over several stellar radii $R$, can have substantially super-Keplerian $v_\phi(r) \propto r$ at outer radii $r$. For excessively high fields this would produce emission line profiles much wider than observed (e.g. Hanuschik 1996). For moderate fields $v_\phi(r)$ is super-Keplerian but below corotation and results in emission line profiles not easily distinguishable from those of a Keplerian disk of similar extent—see Telfer et al. (2003). For lower fields, only the wind and not the disk is contained and torqued. Consequently the field lines only serve as a conduit 'dropping' torqued-up wind streams onto the equatorial disk whose high density will then dominate the field and wind it up. Such material dropped on the disk and free from the field would have its orbit viscously circularised, resulting in an essentially Keplerian disk. This would be fully compatible with observed line profiles, especially optically thin Fe II emission lines (Hanuschik 1987, 1996). Such a quasi-Keplerian disk could also host precessing spiral density wave instabilities believed to produce long term V/R variations (Papaloizou et al. 1992, Hanuschik et al. 1995) which poses problems for the strong field MTD case (CBMMT).

In the outer regions of an MTD disk the field is too weak to contain the wind flow from high stellar latitudes and so is blown open, the outflow pattern being more akin to that in the WCD (Bjorkman & Cassinelli 1993), Ignace et al. (1996, 1998) regimes. Dense disk outflows in Be stars are strictly precluded by absorption line profiles (Hanuschik 1996, 2000), but a preliminary estimate of the outer MTD model outflow region parameters suggests that the density and inverse velocity gradients are too small to be detectable in absorption lines.

Other important observational constraints are the short and long term variability of the Be star phenomenon. In the MTD model the disk is the result of radiative wind driving, stellar rotation, and a magnetic field. The first two of these are expected to be very stable and unlikely to create short term (hours–days) variability which one must then attribute to changes or MHD instabilities in the magnetic field or to additional wind driving effects such as stellar pulsations. For the latter to work either they would have to be of very large amplitude (to affect the highly supersonic wind flow) or the star would have to be very close to critical rotation so as almost to cancel equatorial gravity. In the light of our discussion of the latter in Section 4 below, our view is that local or global field changes of some kind are at least one likely source of short term disk fluctuations. Long term variations (years to decades), including disk disappearance and re-formation may also be associated with field changes, either in the stellar magnetic field itself or induced by the long term loop-filling build up disk mass which CBMMT found to have about the right timescale in the MTD model.

4. Effects of Gravity Darkening

In modelling the dependence of MTD model disk structure on stellar rotation rate $S_o = v_{EQ}/(GM/R)^{0.5}$, CBMMT found that higher $S_o$ produces disks of greater radial extent and for lower threshold magnetic field. Expressing doubts about the MTD model based on instability in his (low field) MHD simulations,
Owocki (2003) even suggests that very fast rotation (rendered undetectable in \(v_{\text{EQ}}\) by gravity darkening) might in fact be the primary factor in ejecting material from the star into a disk. However, both of these analyses ignore the effect on the wind outflow of rapid rotational gravity darkening. This is to shift the mass flux towards the poles—this was indeed one of Owocki et al. (1994) reasons for rejecting the WCD model. In the MTD scenario, the latitudinal redistribution of stellar mass loss flux by rotational gravity darkening sends the field-steered wind mass flux towards larger equatorial radii. This reduces the mean wind ram pressure towards the equatorial plane, reducing the shock compressed disk density and moving the peak density further from the star. As \(S_\alpha\) is increased, more and more of the flow falls outside the equatorial radii at which the field is strong enough to steer it and the total mass of the shock-compressed MTD is reduced. This reduces the associated emission measure and makes the disk less detectable by scattering polarization or emission strength. Quantitative analysis is under way, but preliminary estimates suggest that \(S_\alpha\) values around 0.5–0.75 are optimal in terms of disk detectability. In Owocki's rotation dominated model the idea is for pulsational or magnetic stellar surface perturbations to help 'throw' near-isotropic matter off a surface rotating at almost critical speed, the prograde moving matter attaining orbit and the retrograde falling back—as in the original proposal of Kroll & Hanuschik (1997). Apart from issues of whether this is a more likely way to raise and torque matter from the stellar surface than radiation pressure and a magnetic torquing, it is not clear that rapid rotation really helps in defeating gravity since the centrifugal effect is offset by the gravity darkening reduction in radiation force.

5. Conclusions

The aligned field Magnetically Torqued disk model of Cassinelli et al. (2002) seems to provide a natural solution of some of the key physics problems posed by Be star disks, while broadly consistent with many of their observed properties. Important open issues to be addressed about the model include:

1. reconciling the analytic/parametric MTD findings of CBMMT with the unstable disks found in the low field MHD simulations of Owocki & ud-Doula—in particular to see whether higher fields reduce these instabilities and to compare quantitatively the parametric and numerical predictions of disk density, radial extent etc. as functions of the key model parameters—the ratios of magnetic to wind flow and wind rotational kinetic energy densities;

2. to what extent the quantitative MTD model may be relevant to other systems; the centrifugal aspect of MTD is lacking in current magnetic models of systems such as those with slower rotation, stronger fields etc. and especially with oblique rotation—e.g. Smith and Groote (2001), Babel & Montmerle (1997) and by Donati et al. (2001). In the case of orthogonal magnetic and rotational axes for example, wind flow will still tend to create a compressed layer in the magnetic equator. However, this layer will have little or no centrifugal support near the points where the rotational axis crosses and maximum centrifugal support near the points at right angles to
these, and we expect two dense clumps or ‘ear’ like structures rather than an azimuthally uniform disk as in the aligned case. Any obliquely rotating disk should show a variable polarization in electron scattering and any non-uniformity of density around the disk would create a different polarimetric signature which might help test the validity of an extended MTD model.

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References

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Discussion

*Ignace:* Your models predict gaps between the disk and the photosphere. Could you comment on how the gap size, in tandem with the disk density and extent, will affect the electron scattering polarization?

*Brown:* CBMMT found that the MTD model gave polarization of order typical data. Nett polarization of light scattered at \( r \approx R \) is small because of the range of scattering vectors and hence polarization directions. So the polarization is not very sensitive to that inner gap width unless it is at quite large \( \approx R \)—slow rotation—when the polarization would fall. For fast rotation the gap is smaller, but the gravity darkening pushes the disk peak density outward which would reduce the polarization. So there should be some optimum spin rate.

*Baade:* The overall shape of emission lines is not too sensitive to disk dynamics (Telfer et al., these proceedings). More stringent constraints come from the V/R variations (attributed to slow oscillations in a Keplerian disk) and the central quasi-emission features present in shell absorption lines (attributed to negligible radial motions of a Keplerian disk). Rivinius et al. (2003) find that among two dozen Be shell stars, both phenomena occur equally often but never together in the same star at one time. This would reinforce the need for the disks to be very close to Keplerian in any acceptable model.

*Brown:* I did try to touch on these problems briefly but to reiterate:-

- I agree that these observations strongly indicate close to Keplerian \( v_\phi(r) \) and \( v_r \ll v_\phi \) in the dense disk. The outer outflow region in the MTD model is relatively tenuous and accelerating so the issue is whether its Sobolev optical depth is small enough to be undetected as yet. On the other hand if the convincing spiral density wave interpretation of V/R variations is correct then the disk indeed cannot deviate much from Keplerian. This would favour the scenario of a field strong enough to torque the wind and steer it to the equator but not strong enough to greatly influence \( v_\phi(r) \) in the disk material itself, which would ‘Keplerise’ viscously. How the long term V/R producing density waves survive the rapid disk variability sometimes seen is another puzzle to me.