Some Consequences of Magnetic Fields in High Energy Sources

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Abstract. Magnetic fields likely play a fundamental intermediary role between gravity and radiation in many astrophysical rotators. They can, among other things, 1) induce and be amplified by turbulence, 2) energize coronae, 3) launch and collimate outflows in “spring” or “fling” mechanisms. The first is widely recognized to be important for angular momentum transport, but can also produce intrinsic variability and vorticity growth. The second leads to the production of high energy flares, and also facilitates a test of general relativity from AGN observations. The third can operate from rotators with a large scale fields, though the origin of the requisite large scale fields is somewhat unresolved. I discuss these three points in more detail below, emphasizing some open questions.

1. TURBULENCE, VARIABILITY & VORTICITY IN ACCRETION DISKS

Accretion disks are a widely accepted paradigm to explain a variety of spectral features in sources such as active galactic nuclei (AGN), X-ray binaries, cataclysmic variables (CVs), dwarf novae and protostellar [1,2,3]. As gas orbits a central massive source, internal dissipation drains the orbital energy, allowing material to move in and angular momentum out. Some fraction of the dissipated energy accounts for the observed luminosity. Micro-physical viscosities are often too inefficient so an enhanced transport mechanism, likely involving turbulence, essential. The observational evidence for an enhanced/turbulent viscosity is least direct in the case of AGN disks, though it is natural to expect that the latter would be subject to the same turbulent viscosity generating mechanisms: As astrophysical disks are likely seeded with a magnetic field, the “Balbus-Hawley” or magneto-rotational instability (MRI) [3,4] ensues. This produces self-sustaining turbulence for flows with a radially decreasing angular speed that transports angular momentum in rotationally supported disks. Turbulence driven by the MRI transports angular momentum
outward, unlike convection [3,5,6]. Rossby wave vortices may also transport angular momentum outward [7].

For low enough accretion rates, the dissipated energy may be primarily advected by hot protons in advection dominated accretion flows (ADAFs) rather than radiated, possibly explaining why some sources have engines that are surprisingly quiescent [9,10,11]. For optically thin, geometrically thick ADAFs, the disks may be physically similar to the coronae above the thin disks of Seyferts [12]. The thin disk+corona is something like a hamburger sandwich with the optically thin (geometrically thick) corona being the bun and the optically thick (geometrically thin) disk is the meat. The ADAF is a sandwich with no “meat.”

Alternatives to simple ADAFs suggest that quiescent luminosities might instead result from reducing the accretion rates into the inner regions [13,14,15]. Such models include advection dominated inflow outflow solutions (ADIOS) [13] and convection dominated accretion flows (CDAFs) ([14]; Narayan, these proc). These require a less than maximal viscosity [16].

### Mean Field Disk Theory and Variability

In general, the ubiquity of turbulence in disks has important implications for what the accretion disk equations mean. Analytic disk equations are mean field equations. While non-linear instabilities in thin disks have been extensively simulated locally [17,18] a traditionally useful approach to disk models has been to swipe the details of the stress tensor into a turbulent viscosity of the form [19]

$$\nu_{tb} = \alpha c_s H \approx v_{tb} l_{tb},$$  \hspace{1cm} (1)

where $H$ is the disk height, $c_s$ is the sound speed, $l_{tb}$ is the dominant turbulent scale, $v_{tb}$ is the eddy speed at that scale, and $\alpha_{ss} < 1$ is a constant. Use of this formalism requires a mean field theory, not a replacement of the molecular viscosity with the turbulent viscosity. Assumptions of azimuthal symmetry and steady radial inflow [1,11] require turbulent motions to be averaged over the time and/or spatial scales on which mean quantities vary.

The required mean field approach is complementary to that employed in mean field magnetic dynamo theory, where the field is split into mean and fluctuating components, $B = \bar{B} + B'$, and the induction equation is averaged and solved. For the accretion disk case, the momentum equation must be similarly split, and the evolution equation for the mean velocity field derived. The result is that $\nu_{tb}$ represents a correlation of turbulent fluctuations, that is $\nu_{tb} = \langle \mathbf{v}'(t) \cdot \int \mathbf{v}'(t') dt' \rangle$ [20,21,22].

Mean field theory has a limited precision, and thus predicts variability. Let the mean represent a global average over azimuth and half thickness, without averaging over the radius. Since all mean velocities are scalings of the Keplerian velocity, each radius is in principle “labelled” by its Keplerian speed. However, the averages over fluctuations produce an uncertainty in this labelling. Since the luminosity at a
given frequency depends on the radius of emission for accretion disk models, we can relate the uncertainty in the observed luminosity to the uncertainty in the radius. That is,

$$\frac{\Delta L_\nu}{L_\nu} \simeq |R \partial_R \ln L_\nu| \Delta R/R = \Psi \Delta R/R$$  \hspace{1cm} (2)

where $\Psi$ can depend on temperature but $\sim 1$ for a range of frequencies for thin and thick disk models [23]. Let us estimate $\Delta R/R$. The “error” associated with a single turbulent fluctuation of scale $l_{tb}$ is reduced by $N^{1/2}$ for each averaged dimension, where $N$ is the number of eddy spatial scales averaged over in that dimension. As observational data are taken in a time averaged sense, there is also a reduction that depends on observation time, $t_{obs}$. The result is $\Delta R \simeq l_{tb}/[N_{\phi}N_z(1 + t_{obs}/t_{tb})]^{1/2}$, where $N_{\phi}$ and $N_z$ are the number of dominant eddy scales in the $\phi$ and $z$ directions, and $t_{tb}$ is the dominant correlation time.

To make further progress, note that for fully developed MHD turbulence, near equipartition between kinetic and magnetic energy is generically reached, and is $v_A \sim 2^{1/2}v_{tb}$ [3,17,18] in the case of accretion disks. The factor of $\sqrt{2}$ comes from shear that adds a bit more amplification to the field. The MRI instability onset time scale is of order the dominant eddy turnover or cascade time and is $t_{tb} \sim l_{tb}/v_{tb} \sim \Omega^{-1}$, where $\Omega$ is the rotation speed. Using these and (1) we have

$$v_A^2/2\Omega = \alpha_{ss} c_s H.$$  \hspace{1cm} (3)

Using $\Omega H \sim c_s$ for vertical pressure support, we then have

$$\alpha_{ss} \simeq v_A^2/2c_s^2 \simeq (l_{tb}/H)^2.$$  \hspace{1cm} (4)

The next step is to note that $N_\phi = 2\pi R/(2l_{tb}) = (\pi R/H\alpha_{ss}^{1/2})$, where the extra 2 on the bottom comes from eddy elongation in the $\phi$ direction from shear, and $N_z = H/2l_{tb} = \alpha_{ss}^{-1/2}$, where the 2 is from the 1/2 thickness.

Collecting all of the above into (2) gives

$$\frac{\Delta L_\nu}{L_\nu} \simeq \Psi \alpha_{ss} (H/R)^{3/2}(1 + \Omega t_{obs})^{-1/2}.$$  \hspace{1cm} (5)

For thick disk ADAF models, $H/R \sim 1$ and $\alpha_{ss} \sim 1$ [8], large variability around the predicted luminosities can be expected unless $t_{obs} >> \Omega^{-1}$. When variability is not seen, or a systematic deviation from the theory is seen in a sample of observations at widely separated times or in different objects, the simplest ADAF type model may not be capturing the physics. Such systematic deviations seem to be evident in some of the large ellipticals [24] Other such quiescent accretor variations such as CDAFs (Narayan these proc.) or ADIOS type models [13] which involve outflows may be more appropriate there.
Vorticity

There are other effects of mean field theory in addition to the variability. If one considers the vertical disk averaging to be taken only over one hemisphere, then in addition to the scalar Shakura-Sunyaev turbulent viscosity transport term used in simple analytic accretion disk modeling, a pseudoscalar transport term also arises [22]. This term is analogous to that which appears in magnetic dynamo theory, and can lead to vorticity growth [21,25].

In the same way that the mean field magnetic dynamo characterizes an inverse cascade of magnetic helicity [26], the vorticity dynamo highlights some growth of vorticity on larger scales than the input turbulence. Enstrophy exhibits an inverse cascade in 2-D turbulence [27]. The growth of vorticity in primarily 2-D rotating fluids has been seen in nature (e.g. Jupiter [28]) as well as in simulation [29] and experiment [30]. Statistical mechanics approaches have modeled this [31]. Vorticity growth in sheared thin accretion disks has been studied less than the associated vortex evolution [32,33,34].

For an accretion disk in which mean quantities depend only on radius, Ref. [22] showed that

\[ d_t \omega = \nabla \times \alpha_0 \omega - \nabla \times (\nu_{tb} \nabla \times \omega) \]  

in the frame comoving with the cartesian velocity tangent to the mean rotation, where the coefficients are

\[ \alpha_0 = \left( \tau_c / 3 \right) \langle \omega'(0) \cdot \mathbf{v}'(0) \rangle \]

\[ \nu_{tb} = \left( \tau_c / 3 \right) \langle \mathbf{v}'(0) \cdot \mathbf{v}'(0) + \mathbf{b}'(0) \cdot \mathbf{b}'(0) \rangle \]

and \( \mathbf{b}'(0) \equiv \mathbf{B}'(0) / 4\pi \bar{\rho} \), with \( \bar{\rho} \) as the mean density. (This equation presumes that 1st order cross correlation terms vanish, that is \( \langle \mathbf{b}'(0) \cdot \mathbf{v}'(0) \rangle = \langle \omega'(0) \cdot \mathbf{b}'(0) \rangle = \langle \omega'(0) \cdot \nabla \times \mathbf{b}'(0) \rangle = 0 \).) Note that \( \nu_{tb} \) is not the only transport term. There is also the pseudoscalar \( \alpha_0 \) term as in the magnetic field case. It is this pseudoscalar term which can lead to vorticity growth. Interestingly, the pseudoscalar for the vorticity, unlike for that of the mean magnetic field, has a kinetic helicity term without a current helicity term [22]. The \( \alpha_0 \) can be parameterized as \( \alpha_0 = q\alpha_{ss}c_s \). One necessary condition for growth turns out to be \( q > H/R \).

The simplest growth solutions [22] show a dominant growth scale \( \sim H \), leading to intermediate scale vortices that should survive at least a vertical diffusion time, that is, \( \sim \text{few} \times 1 / \alpha_{ss} \) orbits. For \( \alpha_{ss} \sim 0.01 \), the resulting anti-cyclonic vortices may allow dust trapping, catalyzing planet formation when applied to star+planet system forming disks [31,33,35].

Note that this simplified model of intermediate scale vorticity growth cannot tell how many vortices grow, or where in height or azimuth these vortices are, only that they are growing solutions. This is because here the variables are averaged to depend only on radius. Note also that if the vertical averaging is taken over
the full scale height, then the $\alpha_0$ coefficient should vanish because the pseudoscalar reverses sign across the mid-plane. Then vorticity growth could not be identified in this over simplified formalism.

2. BUOYANCY, CORONAE & AGN IRON LINE PROFILES

Coronae

MHD turbulence likely involves spatial intermittency of the magnetic field [36], even in accretion disks. While the dynamics of intermittency is not fully understood, the random component of the field would be preferentially amplified at regions of strongest shear. Since small scale shear varies spatially and spectrally in a turbulent medium, the field strength would also be expected to vary in correlation. The strongest magnetic field regions might form a kind of dynamic sponge, intermixed with “void” regions that have much weaker fields. The extreme situation, in which the magnetic field occupies a distinct volume from the thermal material, could maintain dynamical equilibrium when the ratio of the the average particle to magnetic pressure in the disk ($\equiv \beta_p$) is large. To see this, consider the field to reside in magnetically dominated flux tubes. The pressure inside balances the external particle pressure. However, if $\beta_p >> 1$, the tubes would occupy only a small volume filling fraction ($\sim 1/\beta_p$) [37]. Since the distance between tubes would be large, intersections with other tubes would be too infrequent to significantly load particles into the tubes. In contrast, if the magnetic volume filling fraction were large, frequent reconnection events over a large fraction of the tubes’ longitudinal cross section would more easily mass load the tubes and lead to one phase medium. The amount of intermittency remains to be understood. Understanding this intermittency is important because extremely evacuated tubes rise at speeds of order their internal Alfvén speeds and form coronae. Coronal magnetic dissipation is as important a problem for disks [38] as it is for the Sun [39].

While coronae have been long thought to form above disks [38, 40] analytic work often does not incorporate the turbulence and/or the origin of the initial large field. The usually invoked Parker instability favors wave modes which can be shredded by the Balbus-Hawley instability on time scales approximately equal to rise times. Simulations of turbulent disks show that coronae do form in turbulent disks [41] but the dominant mechanism, and its relationship to the process of formation in the solar corona is not fully sorted out.

If the disk were not subject to MRIs and turbulence, the induction equation tells us that the disk field would grow linearly from shear. It would saturate at a value that is higher than the saturation value of the MRI. This is because the shear can amplify the field over a much longer time in a laminar disk; the field remains coherent longer. Field strengths of order the thermal pressure could incur before buoyancy (in this case by the Parker instability) drained the field into the
corona. For MRI driven disks, the shear only operates on a single magnetic field filament for a correlation time (one rotation) after which that filament loses its identity. The field energy saturates by a factor of $\alpha_{ss}$ lower for the turbulent case. Also for the the laminar case, the corona would be more intermittent. This is because the buoyancy and the dissipation would likely get rid of the field faster than it builds up. For a laminar disk, the field growth would be linear in time whereas for the MRI disk, the growth is exponential. A laminar disk + corona should thus exhibit longer variability periods than a turbulent disk, but with larger amplitudes. The observational evidence in the case of AGN disks/corona seems to suggest a turbulent disk. While X-ray variabilities of factors of several are observed [42], factors of orders of magnitudes are not, suggesting a steady background level of coronal dissipation.

**AGN Iron Lines and Engine Geometries**

Seyfert galaxy X-ray spectra, are best modeled as a combination of direct emission from a hot corona and reprocessed emission from a cold, optically thick accretion disk [43]. The direct component results from inverse Compton scattering of thermal disk UV photons. The reprocessed component incurs as photons are scattered back onto the disk.

If it weren’t for the active coronae, we would lose a probe of strong gravity [44]. The reprocessed coronal emission includes the broad iron Kα fluorescence line of rest energy 6.4 keV, which carries information about the geometry and dynamics of the reprocessing material near the black hole [44]. ASCA has observed iron lines in $\sim 18$ Seyfert Is [45]. The best studied iron line is that of MCG-6-30-15 [46,47]. In addition to the geometry, the iron line profiles are sensitive to the disk illumination law, the disk inclination, and the inner and outer radii [44]. Most work on reprocessing in AGN has invoked thin flat disks with axially symmetric illumination laws representing a “point” X-ray source.

Some AGN line profiles like MCG-6-30-15 are consistent with flat disks [46,47] but the current data may be not precise enough to rule in or out non-axisymmetric engines in other cases. Such engines are also worth considering in order to provide robust comparisons to flat disk models. Ref [48] considered finite disk thicknesses and Ref [49] considered concave disks. Warped disks have also been considered around Schwarzschild black holes [50]. There are plausible theoretical reasons for disk warping including radiation driven warping [51] and tidal warping [52]. On the observational side, water maser emission of NGC 4258 at 0.1pc from the central engine (on larger scales than the inner accretion disk) traces a disk warp [53]. There may also be indirect evidence on these larger scales from observations of Seyfert Is which suggest that the broad line regions are not coplanar with the inner disk [54]. Dusty tori of Seyfert unification paradigms might also involve warped disks [55].

Warped disk studies reveal line features that are impossible for unobscured flat thin disks. First, shadowing of the source by the disk and shadowing of reprocessed
emission by the disk blocks regions of the disk from contributing to the iron line. Sharper red than blue cutoffs or very soft blue cutoffs can also arise. The latter characteristic is seen in some profiles of Ref [45]. The sharp red cutoffs result for large inclination angles, which is consistent with some Seyfert IIs [56]. Second, non-axisymmetry of the disk means that line profiles can show time variability if the warp precesses around the disk. Third, there can be sharper peaks near the rest frequency compared to a flat disk since concavity can offer more solid angle covering fraction. Fourth, apparent misalignment of central disk plane with the obscuring torus can be accounted for.

For a concave disk, sharper peaks near the rest frequency can be accompanied by a total reprocessed emission fraction that is larger than 1/2 [49], where 1/2 is the maximum limit for a point source above a flat disk. This may play a role in ultra-soft narrow-line Seyferts (Brandt, private communication 1999), though there are other ways to achieve this enhanced reprocessing fraction.

Line profiles from a distribution of dense clouds in an optically thin, geometrically thick disk may apply to ADAFs. Dense clouds formed from thermal instability can survive long enough to produce reprocessing signatures in otherwise optically thin flows [57]. This needs more investigation.

### 3. SPRINGS, FLINGS & LARGE SCALE FIELDS

Many large scale jets and winds in astrophysics including those of young stellar objects, microquasars, gamma-ray bursts, and AGN jets may be magnetically driven. Even supernovae may also involve magnetically driven bipolar outflows (Wheeler, these proc.). How MHD jets work and where the requisite large scale magnetic fields come from are integrated questions, but are usually studied independently.

The large amount of work on MHD jet launching and collimation will not be reviewed here (see [58,59]). However, note that the launching mechanisms could be divided into “spring” [60] and “fling” [61] mechanisms. In the former class, the jet is launched initially by toroidal magnetic field pressure. Imagine for example, a dipole magnetic field anchored in a star which incurs rapid differential rotation (such as the collapse from a white dwarf to a young neutron star as invoked in [62] for gamma-ray bursts) or in a supernova core collapse (Wheeler, Meier personal comm.). As the differential rotation winds up the field, the toroidal field pressure grows quadratically in time. When the pressure reaches some critical value, the field will act something like a coiled spring and can drive a strong torsional Alfvén wave containing directed Poynting flux outward. This could in principle power a jet. Related mechanisms have been discussed for disks [60,63]. In this regard, note that in the case of AGN, it is not clear if the jet emission we see represents dissipation from instabilities at the edge of the jet, re-acceleration inside the jet along the bulk flow, or just emission from a very small number of particles carrying the currents [63] which support the magnetic fields.
In the “fling” launch mechanism [61], the initial launch is driven by centrifugal force. The rigid field lines significantly weaken the effective gravitational potential when sufficiently inclined to the normal, allowing material fling out along poloidal field lines. Subsequently, before reaching the Alfvén surface, the driving does become magnetically driven as in the “spring” mechanism. Since simulation of such launching treats the base of the jet (e.g. its initial launch point in the corona) as a boundary condition, simulators often load the field lines with a little mass flow to get the process started [64]. The initial launching is different for spring and fling, but the ultimate collimation mechanisms could be the same, e.g. hoop stresses. The extent of the collimation appears to be sensitive to the boundary conditions of the outflow however [65].

MHD jet luminosity is fueled by the rotational energy. In systems which have both central compact rotators and disks, outflows could emanate from both e.g. [66]. In black hole systems, the relative contribution to the jet power from regions within and outside of the last stable orbit of the disk has been addressed [67]. Even if a Blandford-Znajek type mechanism is operating from the hole, a jet from the disk may in fact always dominate. However, the black hole spin can still influence the jet, since it determines the inner edge of the disk, and is ultimately important for understanding the magnetospheres [68].

Where do the required magnetic fields [58] come from? The first possibility is that they are accreted. But this may not work for a turbulent accretion disk. Consider a turbulent disk threaded by a large scale vertical magnetic field. The field is subject to turbulent diffusion and may incur a net diffusion outward [69] (with some dependence on turbulent Prandtl number.) The role of reconnection may not yet be fully appreciated in this process. Without reconnection, the mean field is indeed subject to turbulent diffusion, but it cannot ultimately separate from the gas which has a systematic inward motion. In the absence of a topology change that can release field lines from the initial material they thread, the field would accrete on the diffusion time scale.

If the fields cannot be accreted then they would have to have been threading the central object before the disk formed, or be generated by a dynamo in the central object (if not a black hole) or disk. A traditional approach to the amplification of fields on scales larger than the scale of the input turbulence is the mean field dynamo [70] mentioned earlier. Only modes which have an initial seed field can be amplified. For an accretion disk dynamo, the limit of field energy density is the turbulent energy density. This limit is $\alpha_{ss}$ times the thermal energy density, which suggests that “spring” mechanisms are less likely from dynamo produced fields than “fling” mechanisms in turbulent disks.

It is important to distinguish between “large” scale and “mean” fields. Standard mean field theory is degenerate with respect to the topology of the field on scales smaller than the scale of the mean. Disconnected loops can have the same mean as a connected winding field line. In the formalism of mean field dynamo theory, reconnection is therefore not strictly required (though it is likely happening anyway). This is not commonly recognized. Said another way, neither the mean field nor the
fluctuating component of the field are the topologically physical field. To generate jets, common wisdom holds that the mean fields actually do have to correspond to the topologically physical field. Perhaps this need not be the case if the Poynting flux driving the jet is an average quantity: \( \langle \mathbf{E} \times \mathbf{B} \rangle = \langle \mathbf{e} \times \mathbf{b} \rangle + \mathbf{E} \times \mathbf{B} \), where the first term on the right, due to only fluctuating quantities, is usually ignored in this context (but see [71] where the collimation is non-magnetic.) If we do ignore fluctuating components, then to magnetically launch and collimate jets by the “fling” mechanism, the mean fields would need to be topologically large scale. One plausible way this could arise in a disk corona is if flux loops make their way to the surface and subsequent reconnection events inverse cascade smaller loops to larger loops [40].

The role of boundary conditions is particularly important for mean field dynamos. First, generating a net flux of the mean field in a quadrupole mode inside an object is accomplished by diffusion of the reverse flux through the boundary. Fast cycles (e.g solar cycle) of a dipole field also require boundary diffusion to change the flux inside. Incompressible simulations which employ periodic boundary conditions over the scale of the mean cannot see mean field growth because the induction equation then constrains the mean field to be time independent.

In addition, ref. [72] showed that conservation of magnetic helicity means that the growth of large scale field with one sign of magnetic helicity inside the system requires helicity of the opposite sign to diffuse out the boundary. Some results showing strong dynamo coefficient \( \alpha \) quenching [73] may therefore highlight just an effect from the assumed boundary conditions rather than dynamical suppression. In general, to properly test large scale field formation in a turbulent disk one must really utilize a global study, with significant scale separation and diffusive boundary conditions.

Closing Comment

There is much to be learned on all of the above subjects by looking at the sun [74], as others would also advocate [58]. Note that dynamos in the Sun may operate differently than in disks. For the Sun, strong shear amplification may take place below the actual turbulent zone, whereas in disks, the turbulent zone and the shear are the same region. However the sun has a large scale wind and with an active corona [74], consistent with MHD outflows along open field lines and x-ray activity resulting from dissipation of closed field lines. We should expect the same for a wide variety of turbulent astrophysical rotators.

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