Making black holes visible: accretion, radiation, and jets

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With the fundamental stress mechanism of accretion disks identified—correlated MHD turbulence driven by the magneto-rotational instability—it has become possible to make numerical simulations of accretion disk dynamics based on well-understood physics. A sampling of results from both Newtonian 3-d shearing box and general relativistic global disk MHD simulations is reported. Among other things, these simulations have shown that: contrary to long-held assumptions, stress is continuous through the marginally stable and plunging regions around black holes, so that rotating black holes can give substantial amounts of angular momentum electromagnetically to surrounding matter; the upper layers of accretion disks are primarily supported by magnetic pressure, potentially leading to interesting departures from local black-body emitted spectra; and initially local magnetic fields in accretion flows can, in some cases, spontaneously generate large-scale fields that connect rotating black holes to infinity and mediate strong relativistic jets.

1. Prolog: the classical view of accretion disks

It has been understood for decades that accretion through disks can be an extremely powerful source of energy for the generation of both photons and material outflows. When the central object is a black hole, the gravitational potential at the center of the disk is relativistically deep, so that the amount of energy that might be released per unit rest-mass accreted can be a substantial fraction of unity. If the central black hole spins, an additional store of tappable energy resides in its rotation.

At the same time, however, the physical processes by which matter inflow is transmuted into observable outputs has long remained extremely murky. For matter to move inward, it must somehow lose its orbital angular momentum. That there might be some sort of inter-ring friction seems plausible, given the orbital shear, but the way this friction is generally envisaged is in terms of an imaginary “viscosity coefficient” famously parameterized by Shakura & Sunyaev (1973) as $\alpha c_s h$, for local sound speed $c_s$ and vertical scale-height $h$. This ansatz is based entirely on dimensional analysis: the (unknown) local stress is set equal to a dimensionless number $\alpha$ times the local pressure solely because the local pressure has the same units as stress. Although there is no particular reason why the stress, measured in local pressure units, should always have the same value, $\alpha$ is very frequently assumed to be a constant at all places and at all times. Moreover, despite the fact that ordinary molecular viscosity fails miserably to explain the friction, it is often assumed that the stress is some sort of intrinsically dissipative kinetic process whose operation is at least analogous to that of conventional viscosity.

Inter-ring torques do work, moving energy outward. Simultaneously, matter moves inward, carrying its orbital energy. In a steady-state disk, where the mass inflow rate is the same at all radii, these two energy fluxes do not cancel. Instead, there is a net amount of energy that must be deposited in each ring. If one thinks of the torques as due to some sort of kinetic process like viscosity, it is natural to suppose that this energy imbalance is deposited as heat. The radial profile of this heating in a steady-state disk can be easily written down when the disk is in steady state, provided one is able to guess a boundary condition at the inner edge of the disk (we will return to this issue in
greater detail later). Integrating over the radial heating profile then immediately yields the total amount of energy per accreted rest-mass that could, in principle, be used for radiation, i.e., the radiative efficiency. Unfortunately, its value depends strongly on the guessed boundary condition.

When the matter density is large enough (as it often should be), atomic collisional processes can efficiently transform the heat into photons, which can then escape after diffusing vertically through the disk. In conditions of high density and large optical depth, the emergent spectrum should be nearly thermal, an argument that has led many to assume that the spectrum is locally Planckian. Note the use of “it is natural to suppose” and “can” and “should be” and generic terminology such as “collisional processes” here; the specific mechanisms for all these steps are as little understood as the actual torque is when analyzed through the $\alpha$-model.

How exactly to make use of the black hole’s rotational energy has been in a similarly unsatisfactory state. Although Blandford & Znajek (1977) pointed out thirty years ago that magnetic fields can in principle efficiently convey black hole rotational energy from deep within the black hole’s ergosphere all the way to infinity, knowledge about this mechanism’s details has been almost as scanty as for accretion. The particular solution found by Blandford and Znajek and extended by Phinney (1984) assumes that the magnetic field is essentially force-free, with (almost) negligible matter inertia everywhere (including in the plane of the accretion disk) and is valid only for small spin parameter $a/M$. In addition, nothing in that theory specifies the strength of the magnetic field, or explains how it came to extend to infinity.

2. Genuine disk physics

I would not have painted such a gloomy picture if I did not intend quickly to adopt a very different attitude and report on some very significant recent progress. As a result of this progress, many of the mysteries bemoaned in the preceding section can now be substantially solved by the application of well-understood physical processes. In some cases, the main stumbling block is not lack of physics knowledge but lack of computing power. With this recently-gained understanding, it has become possible to outline a program by which the entire process, from mechanics of mass inflow to photon generation to jet launching, might reasonably be followed as a sequence of connected events.

The story behind these advances begins fifteen years ago when Steven Balbus and John Hawley pointed out that weak magnetic fields destabilize an orbiting disk and lead to the rapid growth of MHD turbulence (Balbus & Hawley 1991; Hawley & Balbus 1991). Orbital shear is what drives this “magneto-rotational instability”; orbital shear also enforces a correlation in the resulting MHD turbulence such that the magnetic stress $-B_r B_\phi/4\pi$ is always on average positive. That is, the shear itself ensures that the magnetic forces transmit angular momentum outward.

It is important to note that magnetic stress, unlike viscosity, is not intrinsically dissipative. The local rate of heat generation is not always proportional to the local stress. On the other hand, it is intimately connected to dissipation. Nonlinear mode-mode interactions can convey turbulent energy from the relatively large lengthscales on which the turbulence is stirred to much shorter lengthscales on which a variety of genuinely dissipative processes can act efficiently. When integrated over a large enough volume (vertically-integrated through the disk and wide enough to make averaging well-defined), the heating rate must agree with the one predicted by the time-steady disk picture described above, but there is no requirement for it to match up with the stress rate locally, either in time or space.
The radiative output can then be described by taking a position- and time-dependent heating rate from turbulence calculations and solving the radiation transfer equation using physical opacities. If the vertical structure of the disk is known well-enough, non-LTE effects in the disk atmosphere can be incorporated, and departures from locally Planckian spectra can be predicted.

To find the global radial profile of heating and radiation, it is still necessary to understand that inner boundary condition. Thirty years ago, heuristic arguments based on hydrodynamic intuition pointed toward a boundary condition requiring the stress to be zero at and inside the marginally stable orbit, but even then it was recognized that if magnetic fields were important, a different choice might be necessary (Page & Thorne 1974). Now that we know magnetic fields are essential to the entire accretion process, what Page and Thorne saw as a back-of-the-mind worry is now front-and-center. Fortunately, as we shall shortly see, it is now possible to calculate, rather than guess, what happens to the magnetic stress in the marginally stable region.

If we can compute the magnetic field in the marginally stable region, then we can also compute the magnetic field even closer to the black hole’s event horizon. Part of its nature is determined by dynamics within the accretion flow itself; part may be constrained by boundary conditions at infinity, where it is possible that some fieldlines are anchored.

3. Numerical simulations

The only fly in the ointment is that analytic methods for calculating the properties of any turbulent system are extremely limited in their power. Numerical simulation is really the only tool we have for examining fully-developed turbulence, and it has its own limitations. Nonetheless, some fifteen years after the first attempt to study numerically the properties of MHD turbulence in accretion disks, a great deal has been learned.

The simulations that have been done to date can all be divided into two classes: shearing boxes and global disks. To make a shearing box, imagine cutting out from a complete disk a narrow radial annulus of limited azimuthal extent. When its azimuthal length is small compared to a radian, it can be well approximated as straight along the tangential direction. Rather than describing the orbital motion by a rotational frequency \( \Omega(r) = \Omega_0 (r/r_0)^{-3/2} \) for radius \( r \) and annular central radius \( r_0 \), we can instead approximate it by writing the orbital speed as \( v_y = r_0 \Omega_0 \left[1 - (1/2)(r/r_0 - 1)\right] \), for \( r/r_0 - 1 \ll 1 \). The equations of motion can then be written in the rotating frame with appropriate centrifugal and Coriolis terms. At a similar level of approximation, the vertical gravity is \( g_z = z \Omega^2 \).

Shearing boxes are best for wide dynamic range studies of the turbulent cascade, well-resolved exploration of internal vertical structure within the disk, and tracing disk thermodynamics. The advantage for the latter subject is that the relatively large dynamic range in lengthscale for turbulent dynamics allows one to localize comparatively well where dissipation occurs and then follow the diffusion of radiation away from its source regions.

In a global disk simulation, one places a large amount of mass on the grid in an initial state of hydrodynamic equilibrium. To avoid noise propagation across the boundary of the problem area, the outer boundary is placed well outside the outer edge of the initial mass distribution. When angular momentum begins to flow outward through the disk as a result of the MHD turbulent torques, matter from the inner part moves inward while a small amount of mass on the outside moves outward, soaking up the angular momentum that has been carried outward to it. Thus, these global disks are truly “accretion disks” only in their inner portions. For this reason, it is necessary to locate their initial centers...
far enough outside the innermost stable circular orbit (the ISCO, i.e., the radius of marginal stability) that there can be a reasonable radial dynamic range for the accretion flow proper.

In the current state-of-the-art, shearing box simulations employ 3-d Newtonian dynamics in the MHD approximation including radiation forces. By means of integrating both an internal energy and a total energy equation, they can track the numerical dissipation rate as a function of time in each cell of the simulation; this numerical dissipation rate is assumed to mimic the physical dissipation and is used to increase the heat content of the cells where and when it occurs. Radiation transfer is computed in the approximation of flux-limited diffusion, using thermally-averaged opacities (Hirose et al. 2006).

Global disk simulations are best for following the inflow dynamics, the radial profile of magnetic stress, the surface density profile that the stress produces, and non-local magnetic field effects. They also permit identification of typical global structures (the main disk body, disk “coronae”, etc.) and the study of jets.

The most physically complete global disk simulations now available use 3-d fully general relativistic dynamics in the MHD approximation, but they take no account of radiation. In one version (Gammie et al. 2003), the total energy equation is integrated, so energy is rigorously conserved; in another (De Villiers & Hawley 2003), an internal energy equation is solved, permitting numerical energy losses. The advantage of the former method is that numerical dissipation does not lead to energy loss; its disadvantage is that physical radiation losses don’t occur either. The advantages and disadvantages of the latter method are more or less reversed, if one is willing to accept numerical energy losses as approximating genuine radiative losses.

In all cases, both shearing box and global simulations, the magnetic field is nearly always assumed to have zero net flux. This choice is made largely because it’s the simplest and involves the smallest number of arbitrary choices: the initial field on the boundary of the simulation is always zero. On the other hand, it is possible that there can be large-scale fields running through real accretion flows, and they may have substantial effects on the character of those flows; this question remains to be investigated.

4. Selected Results

The body of this talk will be devoted to a brief summary of some of the principal achievements of these simulations. Consistent with my title, I will focus on three topics: what we have learned from the global simulations about the radial profile of stress (and possibly of dissipation); what shearing box simulations have shown us about the vertical structure of disks, and how that can influence the character of the emitted spectrum; and how magnetically-driven accretion can (or maybe not) launch relativistic jets.

4.1. Radial stress profiles

The De Villiers-Hawley simulation code is designed to do an excellent job of conserving angular momentum and propagating magnetic fields reliably, but is less good at conserving energy. Consequently, we believe its description of the electromagnetic stress and its relation to mass inflow should be reliable, but it is much more difficult to use the data from these simulations to predict dissipation and the radiation that may follow from it. For the time being, then, we can discuss the stress with some confidence, while using it as an indirect and approximate indicator of dissipation.

Figure 1 shows the instantaneous shell-integrated electromagnetic stress (i.e., \(-b^r b_\phi + |b|^2 u^r u_\phi\), for magnetic four-vector \(b_\mu\) and four-velocity \(u_\mu\)) evaluated in the local fluid-frame at late-times in two simulations, one with a non-rotating black hole, the other
with a black hole having spin parameter $a/M = 0.9$. For comparison, the figure also shows the stress predicted by the Novikov-Thorne model (i.e., a time-steady disk with a zero-stress inner boundary condition) when the accretion rate is the same as the time-averaged value in the corresponding simulation. As can readily be seen, the zero-stress boundary condition fails drastically to describe what actually happens. In both cases, the electromagnetic stress continues quite smoothly inward through the marginally stable region. In the Schwarzschild case, the stress rises slowly inward until just outside the event horizon, and then plummets as the event horizon is approached. In the Kerr case, the stress rises sharply upward and does not diminish even very near the horizon.

It is easy to understand qualitatively both stress profiles. Because there is no reason for the magnetic field to disappear suddenly at the ISCO, while orbital shear continues to stretch any radial components in the azimuthal direction, there is no physical mechanism to eliminate magnetic stress there (Krolik 1999, Gammie 1999); rather, the stress continues and, if anything, strengthens. The contrast in behavior between the spinning and non-spinning cases can just as easily be understood when one thinks of stress as momentum flux. The electromagnetic stress is nothing else than an outward flux of angular momentum, carried in the electromagnetic field. A non-rotating black hole has no angular momentum to give up, so it cannot act as a source for outgoing electromagnetic angular momentum flux; on the other hand, the angular momentum of a rotating black hole can be tapped, and we see this process in action here. Those concerned by an outflow of anything from an event horizon should have their qualms removed by the recognition that there is nothing to prevent a rotating black hole from swallowing negative angular momentum, i.e., angular momentum corresponding to rotation in the opposite sense. This is, of course, completely equivalent to releasing positive angular momentum. Indeed, deep in the ergosphere, the electromagnetic energy-at-infinity is frequently negative (Krolik et al. 2005).

As previously discussed, although the work done by magnetic stress does not necessarily correspond to any particular local rate of heating, there is a relationship on a more globally-averaged level. Thus, the curves of integrated fluid-frame stress shown in Figure 1 hint that dissipation may also continue smoothly across the marginally stable orbit, also contrary to the guessed boundary condition of the Novikov-Thorne model.

A further suggestion that this is so comes from a different argument. Many of the specific physical mechanisms of dissipation in this context are associated with regions of high current density. If, for example, there is a (small: we make the MHD approximation, after all) uniform resistivity $\eta$ in the fluid, the local heating rate is $\eta ||J||^2$, where $J^\mu$ is the electric current four-vector and $||J||$ is its scalar magnitude. In fact, the dissipation may be even more closely associated with $||J||^2$ than this simple guess would suggest because there are a number of plasma instabilities that create anomalous resistivity precisely where the current is strong. Maps of the current density show that it is strongly concentrated toward the center of the accretion flow, rising rapidly into the plunging region inside the ISCO (Hirose et al. (2004)). To the degree that current density indicates candidate regions for rapid magnetic energy losses, this signal, too, suggests that there may be a great deal of dissipation in and within the marginally stable region.

The continuation of stress through the plunging region can also be looked at from a different point of view: in the language of the Shakura-Sunyaev $\alpha$ model. Their argument from dimensional analysis was that the time-averaged vertically-integrated stress should be comparable to the time-averaged vertically-integrated pressure. Our data confirm that this is so, provided one interprets “comparable” loosely. In the disk body, that is, at radii well outside the ISCO and well inside the initial pressure maximum (beyond which there is no accretion), the time-average ratio at a single radius of vertically-integrated
stress to vertically-integrated pressure is generally in the range $\sim 0.01-0.1$. However, the instantaneous value of this ratio can easily change by factors of several over an orbital period. Moreover, if one tracks this ratio from somewhat outside the ISCO to well inside, there is a consistent trend for the ratio between stress and pressure to increase. As shown in Figure 1, the stress generally increases inward in this region; because the radial speed of the accretion flow also increases inward, the vertically-integrated density and pressure of the matter tend to decrease. The result is that the ratio of stress to pressure increases sharply, often rising by factors of 10–100 from the disk body to deep inside the plunging
Figure 2. Heating and radiative output from two shearing box simulations. Left panel shows a case in which \( p_r/p_g \approx 0.2 \) (taken from Hirose et al. 2006); right panel a case in which \( 0.5 \leq p_r/p_g \leq 2 \), depending on the time within the simulation Krolik et al. 2007). In both figures, the solid curve shows the volume-integrated dissipation rate, while the dashed curve shows the radiative output. After initial transients, heating and radiative flux are nearly identical.

region. Thus, a description of inflow dynamics near the ISCO in terms of a constant \( \alpha \) parameter is strongly in conflict with the results of these simulations. Claims (as are often made) based on assuming a constant value of \( \alpha \) within this region are therefore on very shaky ground.

4.2. Internal vertical structure

Having thus emphasized the consequences of magnetically-driven accretion in the inner part of the accretion flow, it is now time to turn to its implications for the internal structure of accretion disks at larger radii. The best tool for studying this problem is shearing box simulations that both accurately conserve energy and follow radiation transfer (as described in Hirose et al. 2006). In this review, we will briefly discuss two of the principal results of these simulations: their implications for thermal stability in disks and the fact that disk upper layers are generically supported primarily by magnetic fields.

In their classic paper on the \( \alpha \)-model, Shakura and Sunyaev (1973) also predicted that the inner regions of all disks surrounding black holes in which the accretion rate is more than a small fraction of the Eddington rate should be dominated by radiation pressure. Three years later (Shakura & Sunyaev 1976), the same two authors demonstrated that, within the approximation scheme of the vertically-integrated \( \alpha \)-model, radiation pressure dominance leads directly to thermal instability. If so, the standard equilibrium solution for the region from which most of the light is generated in the brightest accreting black hole systems is unstable. To this day, no satisfactory resolution to the question of, “What actually happens in these circumstances?” has emerged.

One of the principal motivations for our program of simulating shearing boxes with radiation generation and transport is to answer this question. At this stage, there is progress to report, but not yet any firm answer to the big question. When the gas pressure is dominant, it is clear that a truly stable steady-state can be found. Figure 2 illustrates this point by showing the “light-curve” of a shearing box disk segment in which the radiation pressure \( p_r \) is only about 20% of the gas pressure \( p_g \). The fluctuations in radiative output are only at the tens of percent level.

On the other hand, increasing radiation pressure does tend to drive fluctuations. When
Figure 3. Vertical profiles of several kinds of pressure in a simulation whose volume- and time-averaged ratio of radiation pressure to gas pressure was ≃ 0.2 (Hirose et al. 2006). The thick curves are time-averaged over fifty orbital periods starting from the end of initial transients; the thin curves are the initial conditions. Magnetic pressure is shown by the solid curves, radiation by the dotted curves, and gas pressure by the dash-dot curves.

the radiation and gas pressures are comparable (Fig. 2b), the output flux varies over a range of a factor of 3–4. Intriguingly, although $p_r/p_g$ at its greatest is above the threshold for instability suggested by Shakura and Sunyaev, and stays there for as long as 5 cooling times, the disk exhibits large limit-cycle oscillations, but no unstable runaway. We are actively investigating whether the instability remains under control at still higher values of $p_r/p_g$ (Hirose et al., in preparation).

A consistent result of all vertically-stratified shearing box studies is that their upper layers are magnetically-dominated (Miller & Stone 2000; and as shown in Fig. 3 taken from Hirose et al. 2006). Although the data shown here are from a particular gas-dominated simulation, more recent work studying shearing boxes with radiation pressure comparable to gas pressure (Krolik et al. 2007) and radiation pressure considerably greater than gas pressure (Hirose et al., in preparation) shows very much the same pattern: independent of whether gas or radiation pressure dominates near the midplane, by a few scale-heights from the center, magnetic pressure is larger than either one.

A somewhat surprising corollary of magnetic dominance in the upper layers is that “coronal” heating is rather limited. Strong hard X-ray emission is so commonly seen from accreting black holes, no matter whether the central black hole has a mass $\sim 1M_\odot$ or $\sim 10^9M_\odot$, that somewhere in the system there must be a region of intense heating with only small matter density and optical depth. Otherwise, there would be no way to heat electrons to the $\sim 100$ keV temperatures required to produce the X-rays. This region is generally called the accretion disk “corona”, and it is often thought of in conceptual terms derived from experience with the Solar corona: it is imagined that somehow magnetic field loops emerge buoyantly from the nearby disk, twist and cross, and release energy at reconnection points.

Unfortunately for this popular scenario, these simulations, the first to treat the dynamics of the upper layers of disks in a consistent fashion, show no sign of anything
Figure 4. Time-averaged vertical profiles of the dissipation rate in a shearing box simulation. In this simulation, the mean gas and radiation pressures were comparable, but there were order unity fluctuations. The solid curve pertains to those times when the radiation pressure was particularly high, the dashed curve to those times in which it was particularly low.

Indeed, the dissipation in shearing box segments of accretion disks is typically confined to the central regions of the disk. Figure 4 (Krolik et al. 2007) illustrates this fact in a shearing box whose radiation and gas pressures were, on a time-averaged basis comparable, but in which the ratio of radiation to gas pressure fluctuated over the range 0.5–2. Whether the energy content of the disk was high (and the radiation pressure dominated the gas pressure) or low (and the ratio went the other way), the dissipation was still confined to the inner few scale-heights of the disk.

Although magnetic dominance in the upper layers of disks likely does not lead to strong coronal heating, it does have other potentially important observational consequences. Chief among them is the fact that when magnetic pressure gradients replace gas pressure gradients as the matter’s principal support against gravity, the density of the gas must fall. Because the photosphere of the disk is located where magnetic support is so important, we immediately infer that previously-estimated photospheric densities were too high, and that LTE may not be enforced as thoroughly as previously thought (Blaes et al. 2006). The locally-emitted spectrum may therefore have larger deviations from Planckian, and if these features are sufficiently strong, may be visible in the disk-integrated spectrum. An example is shown in Figure 5 when magnetic support is properly included in the atmosphere structure, a prominent CVI edge appears. Still further departures from conventional spectral predictions may arise from the fact that at any given moment, the atmosphere can depart substantially from the usual picture of plane-parallel symmetry.
Figure 5. Output spectrum from a gas-dominated shearing box at 55° from the local vertical direction. The solid curve shows the spectrum predicted when the atmosphere is magnetically-supported, the dashed curve shows the predicted spectrum when magnetic support is neglected (Blaes et al. 2006).

The surprising quietness of the magnetically-dominated regions of shearing box atmospheres motivates a search for other places to supply the intense heating required to explain the observed hard X-ray emission. Better places to look might include the plunging region, which is both strongly magnetized and highly dynamical, and the region just above it from which jets are launched.

4.3. Jet launching

For many years, two models have dominated thinking about the launching of jets: the Blandford-Znajek mechanism (Blandford & Znajek 1977) and the Blandford-Payne scheme (Blandford & Payne 1983). The two models share two central elements: large-scale poloidal magnetic fields that extend from infinity and pierce the midplane of the accretion flow; and dynamically-enforced rotation. They are distinguished by whether the rotation is enforced by space-time frame-dragging (Blandford-Znajek) or the orbiting matter of the accretion disk (Blandford-Payne). Because the latter depends in an essential way on accretion, whereas the other (at least in principle) does not, they are also distinguished by whether the inertia of matter is significant. Lastly, they differ in the source of power for the jets: orbital energy of accreting matter for Blandford-Payne, the rotational kinetic energy of the black hole itself for Blandford-Znajek.

Both models’ dependence on externally-imposed large-scale fields is problematic because the most natural way to bring magnetic fields into either the inner parts of accretion disks or all the way to the black hole event horizon is by advection along with accreted fluid. However, we have no way of knowing whether such large-scale connections might survive the many orders of magnitude in compression suffered by the matter; reconnection might destroy large-scale connections far from the black hole. On the other hand, if even a small fraction of the flux survives, over time it might still build up to be significant. This remains an open question.

The simulations we have done so far have all assumed zero large-scale field, primarily as a result of our effort to minimize the number of arbitrarily chosen free parameters.
Interestingly, we have found that even when the magnetic field in the accreting matter has no net flux at all, and therefore no externally-imposed connections to infinity, under the right circumstances it can spontaneously create such connections within a limited volume.

To be specific, when the accretion flow contains closed dipolar field loops large enough that the outer ends are accreted long ($\gg 10^3 GM/c^3$) after the inner ones, a jet is automatically created from the flux provided by the inner half of the field loop (McKinney & Gammie 2004, Hawley & Krolik 2006). When flux is brought toward the black hole along with the accretion flow, as soon as field lines begin to thread the event horizon, matter drains off them, and the field lines, freed of the matter’s inertia, float upward. Because a centrifugal barrier prevents any matter with non-zero angular momentum from penetrating into a cone surrounding the rotation axis, there is little inertia above these field lines. The field lines then rapidly expand upward. This process of filling the region around the rotation axis with magnetic field ceases only when there is enough field intensity that the magnetic pressure distribution reaches equilibrium. If the central black hole spins, the portions of the field lines within the ergosphere are forced to rotate along with the black hole, imposing a twist on the field lines. The result is Poynting flux travelling outward through the evacuated cone around the rotation axis.

When the black hole rotates rapidly, the electromagnetic luminosity can be quite sizable. Table 1 presents that luminosity, normalized by the rest-mass accretion rate, as a function of black hole spin. The radiative efficiency predicted by the Novikov-Thorne model is also given in that table in order to provide a standard of comparison. As can be seen, when the black hole rotates rapidly, the jet efficiency becomes comparable to the putative radiative efficiency. Thus, consistent with what many have long speculated, black hole rotation does seem to enhance jet luminosity.

On the other hand, black hole spin may not be the only relevant parameter. For example, large dipolar loops are not the only imaginable field structure for an accretion flow. One could just as easily imagine narrower dipolar loops, or quadrupolar loops (loops that don’t cross the equatorial plane) or toroidal loops. These other geometries are in general less favorable to jet support than the initial form explored, the large dipolar loops (Beckwith, Hawley & Krolik, in preparation). Real systems are likely to exhibit some mixture of these sorts of field topologies, and that mixture could easily vary from one object to another, or from one time to another in a single object. Some of the observed variability in jets may conceivably reflect varying field structures in the matter fed to the central black hole.

### Table 1. Jet Poynting flux efficiency in rest-mass units $\eta_{\text{EM}}$, as a function of black hole spin parameter $a/M$ (Hawley & Krolik 2006). These numbers can be compared with the radiative efficiency predicted by the Novikov-Thorne model, i.e., the specific binding energy of a particle in the innermost stable circular orbit.

| $a/M$ | $\eta_{\text{EM}}$ | $\eta_{\text{NT}}$ |
|-------|------------------|------------------|
| -0.9  | 0.023            | 0.039            |
| 0.0   | 0.0003           | 0.057            |
| 0.5   | 0.0063           | 0.081            |
| 0.9   | 0.046            | 0.16             |
| 0.93  | 0.038            | 0.17             |
| 0.95  | 0.072            | 0.18             |
| 0.99  | 0.21             | 0.26             |
5. Conclusions

Thanks to the fundamental discovery that stresses in accretion disks come from correlated MHD turbulence, driven by the magneto-rotational instability, we can now begin to speak with confidence about a number of aspects of their operation. With the aid of ever-more-detailed and realistic numerical simulations, we have taken the first steps toward connecting their internal dynamics with observable properties.

In this talk, advances in this direction in three areas have been reported:

- We now see that angular momentum transport is accomplished quasi-coherently, by magnetic stress. Because this mechanism is not a kinetic process like viscosity, it is not intrinsically dissipative, although the associated MHD turbulence does eventually dissipate. Moreover, far from ceasing at the innermost stable circular orbit, as has been generally assumed for more than thirty years, magnetic stress continues through the marginally stable region and deep into the plunging region. When the black hole spins, the stress can be continuous all the way to the event horizon. At the very least, the ability of electromagnetic stresses to carry angular momentum away from the black hole and into the accretion flow means that the spin-up rate of black holes can be rather less than would have been estimated on the basis of accreting matter with the specific angular momentum of the last stable orbit. It is also possible, although quantitative determination of this effect remains a job for the future, that these extended stresses lead to extended dissipation as well, augmenting the radiative efficiency of black hole accretion beyond the traditional values.

- Detailed study of the vertical structure of disks subject to the MRI has shown that their upper layers are supported primarily by magnetic pressure gradients. In addition, these upper layers can be far from the smooth time-steady plane-parallel condition in which they are commonly imagined. As a result, the density at the photosphere is likely to be rather smaller than previously estimated, and the locally-emitted spectrum may have significant departures from black-body form. Ongoing work promises to clear up the long-standing mystery of whether radiation-dominated disk regions are thermally unstable, and if they are, what happens in the nonlinear stage of this instability.

- As had been initially pointed out in the mid-1970s, when large-scale magnetic fields pass close by rotating black holes, it is possible for very energetic relativistic jets to be driven, deriving their energy from the rotational kinetic energy of the black hole itself. We can now begin to compute the detailed structure of these jets, as functions of both space and time. In addition, we now see that it is possible to create large-scale magnetic field threading the ergosphere of the black hole and stretching out to infinity from much smaller-scale field embedded in the accretion flow—but not all small-scale field structures are capable of doing this.

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