AGN Physics with the Sloan Digital Sky Survey
*ASP Conference Series, Vol. **VOLUME***, 2004*
G.T. Richards and P.B. Hall

Accretion Disks Based on Real Physics

Omer Blaes

Department of Physics, University of California at Santa Barbara, Santa Barbara, CA 93106

Abstract. I briefly summarize the problems with current accretion disk models of AGN, and stress the need for *detailed* empirical guidance from SDSS on how the continuum spectral energy distribution depends on black hole mass and Eddington ratio. I also describe recent, first-principles physics work on the dynamics and thermodynamics of the inner, most luminous parts of the accretion flow, fully incorporating the effects of diffusive photon transport. I comment briefly on the implications of this work for observed spectra in the optical/ultraviolet/X-ray regions of AGN.

1. Introduction

I was asked by the organizers to review accretion disk theory as it applies to bright AGN and quasars, but to do this subject real justice would require much more space than I have here. I will therefore limit my discussion to just two topics. First, I will pose a question that SDSS must try and definitively answer. Second, I will describe some of the important physical effects that have recently been discovered to operate in the innermost parts of the accretion flow.

Almost all of the basic predictions that current accretion disk models of AGN make are not in agreement with observation. Examples include the shape of the continuum spectral energy distribution, the dearth of observed edge features associated with bound-free opacities in accretion disk atmospheres (but see Antonucci et al., these proceedings, for evidence of Balmer edges), polarization, and variability. For a review of the situation as of a few years ago, see e.g. Koratkar & Blaes (1999).

Practically the only success is the prediction that the bolometric power should be dominated by ultraviolet emission, as the effective temperature of optically thick material on the scale of a gravitational radius is given by

$$kT_{\rm e} \sim 50{\rm eV}\eta^{-1/4}\left(\frac{M}{10^8{\rm M}_\odot}\right)^{-1/4}\left(\frac{L}{L_{\rm Edd}}\right)^{1/4}. \tag{1}$$

Even this "success" is qualified: it merely explains why accreting stellar mass black holes typically radiate most of their power in the X-rays, but the much bigger black holes in AGN radiate in the ultraviolet. Note that at fixed Eddington ratio and fixed radiative efficiency, the characteristic effective temperature should *decrease* with increasing black hole mass M.

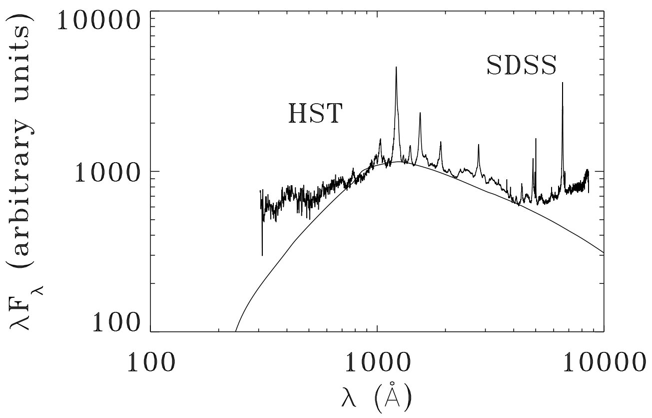

Figure 1. Best fit accretion disk model (Hubeny et al. 2000) to the combined SDSS (Vanden Berk et al. 2001)/HST (Telfer et al. 2002) composite spectrum. The model parameters are $a/M = 0.9$, $M = 10^{10}$ $M_\odot$, $L/L_{\rm Edd} = 0.1$, $\cos i = 0.6$ ($i = 53°$), and $\alpha = 0.01$. The local, vertically-averaged stress is assumed to be α times the total vertically-averaged pressure in the model.

2. Accretion Disk Spectral Energy Distributions and Colors

Accretion disk models of the big blue bump have had a long history (e.g. Shields 1978, Sun & Malkan 1989, Laor 1990). An example of a fit of such a model to the SDSS/HST composite spectrum is shown in figure 1. Accretion disks *can* have colors as red as those observed in the optical/near ultraviolet, and they can produce a spectral break in the vicinity of the Lyman limit of hydrogen, as observed. However, the black hole mass required to achieve this fit is probably unreasonably high. In addition, it is unclear why this particular spectral shape is picked out by nature, when generic accretion disks would give rise to a much broader distribution of spectra. As noted by Laor (1997), simple thermal accretion disk models also cannot explain the power-law like extension into the soft X-rays, as shown in figure 2. It may be that there is an additional Comptonizing medium (e.g. Czerny & Elvis 1987), a point to which I will return shortly.

Figure 3 depicts predicted optical/near ultraviolet spectral indices as a function of black hole mass, spin, and Eddington ratio, all at fixed viewing angle. Again, it is possible to reproduce the observed SDSS colors, but only for rather large black hole masses and/or low spins (this trend is identical to that seen in fits to Seyfert 1 spectra by Wandel, Peterson, & Malkan 1999). Note that at fixed Eddington ratio, the colors tend to get redder as the black hole mass increases, consistent with expectations from equation (1).

I have measured the spectral indices from the KPNO/HST/FUSE sample of Brotherton et al. (2001), for which black hole masses (and therefore Eddington ratios) have been measured from the Hβ photoionization method (Kaspi et al. 2000). The results, shown in figure 4, are not encouraging. While I might have made mistakes which resulted in some of the scatter, the impression is that at least at high Eddington ratios, the colors get bluer with increasing black hole

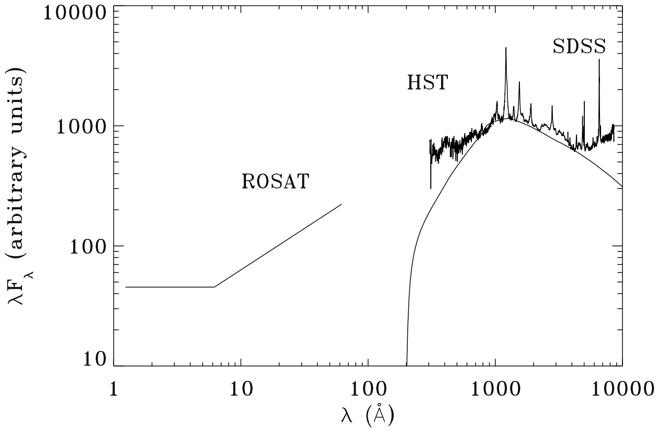

Figure 2. Same model as in figure 1, extended to X-ray wavelengths in order to compare with the ROSAT composite of Laor et al. (1997).

mass! There are numerous ways in which the theoretical colors predicted by accretion disk models might be wrong, many of which have been discussed in the literature: reprocessing (which we know must be going on in view of the simultaneity of optical/ultraviolet continuum variability), nonstationary accretion disks, slim disks, truncation of the inner disk, or an additional red contribution to the big blue bump that is due to some other process. It is not obvious, however, whether these would give the observed color trends. The observational data might be influenced by internal reddening in the source, but this cannot be the dominant factor in the color trends of "normal" quasars observed by SDSS (Richards et al. 2003). Could it perhaps be that the black hole mass determinations using this technique are not sufficiently accurate or have systematic trends with luminosity or color? A comprehensive study of color trends with *black hole mass and Eddington ratio* with the huge statistics of SDSS would be extremely interesting in shedding light on what is going on in these sources.

3. Progress Toward a Genuine First Principles Theory of Accretion Disks

Despite over thirty years of work, models of accretion disks in AGN still continue to suffer from some fundamental theoretical uncertainties that plague any attempt to use them to predict observables. The Shakura & Sunyaev (1973) prescription for the vertically-averaged anomalous stress, $\tau_{R\phi} = \alpha P$, has always left us in the dark as to what to take for the vertically averaged pressure P in the innermost, radiation pressure dominated regions of the flow. A number of combinations of radiation pressure $P_{\rm rad}$ and gas pressure $P_{\rm gas}$ have been employed over the years: $P = P_{\rm rad} + P_{\rm gas}$, $P_{\rm gas}$, $(P_{\rm rad} P_{\rm gas})^{1/2}$. These choices are not really driven by any physics, but merely by whether or not the modeler wants the disk to be thermally and "viscously" stable.

However, no matter what the assumption, we do *not* understand whether the disk is thermally (or "viscously" stable). This is because we do not yet

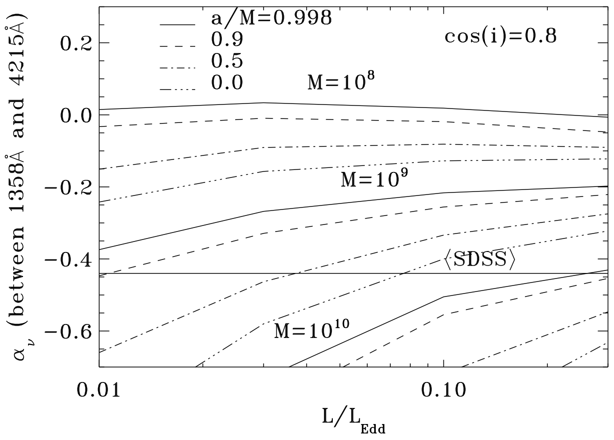

Figure 3. Theoretical spectral indices for relativistic accretion models as a function of black hole mass and spin and Eddington ratio. All models shown are similar to those of Hubeny et al. (2000), and assume $\alpha = 0.01$.

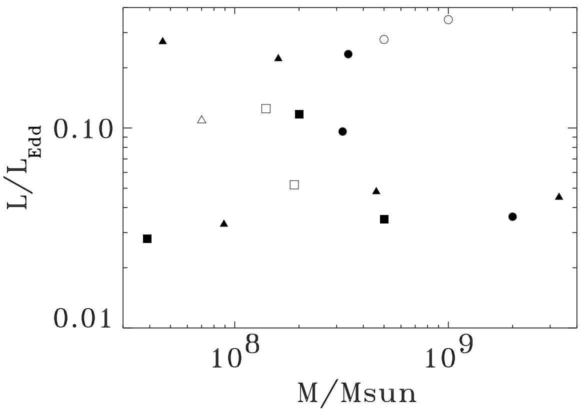

Figure 4. Continuum spectral indices ($F_\nu \propto \nu^{\alpha_\nu}$) measured between rest wavelengths 1358 and 4215 Å, as a function of black hole mass and Eddington luminosity ratio for the KPNO/HST/FUSE sample of AGN of Brotherton et al. (2001). Different point types represent different ranges in the spectral index: $-0.2 > \alpha_\nu > -0.4$ (circles - the bluest indices), $-0.4 > \alpha_\nu > -0.6$ (squares), and $-0.6 > \alpha_\nu$ (triangles - the reddest indices). Filled points indicate spectra for which the continuum is reasonably well-represented by a power-law between 1358 and 4215 Å, while open points indicate spectra which have significant curvature between these two wavelengths. I excluded two obviously red quasars IR 07546+3928 and PG 1351+640 from the sample. I also excluded the Seyfert 1 galaxy NGC 5548, for which there is evidence (Chiang et al. 2000) that the putative disk in this source is truncated.

understand how turbulence driven by the MRI (Balbus & Hawley 1991) behaves in a radiation pressure dominated environment. We do not understand how this turbulence dissipates the accretion power, particularly its spatial distribution and the partitioning of the power into heat or other forms. We do not understand whether heat is transported radiatively or by bulk motions in the turbulence.

Radiation pressure alters both the dynamics and thermodynamics of the inner accretion flow, in ways that are much more subtle than merely accounting for it in the equation of state. While photons provide the dominant pressure support on large scales, rapid photon diffusion destroys this support on small scales. This makes the plasma highly compressible, even for subsonic motions with respect to the radiation sound speed (as expected for MRI turbulence). Such motions can still be supersonic with respect to the much smaller gas sound speed, leading to very large density compressions and rarefactions on small scales. Large density inhomogeneities appear to be the rule in non-stratified shearing box simulations of MRI turbulence with radiation MHD (Turner et al. 2003).

The fact that the turbulence is supersonic with respect to the gas sound speed can imply that it is also suprathermal with respect to the electron thermal velocity. In this case Comptonization by bulk motions in the turbulence itself may produce a high energy power-law tail to the big blue bump (Socrates et al. 2003, Davis et al., these proceedings), perhaps explaining why EUV/soft X-ray excesses are so ubiquitous in quasars.

In addition to the turbulence, radiation pressure can itself drive instabilities (Gammie 1998, Blaes & Socrates 2003) that amplify acoustic waves into shocks, as shown in figure 5. These shocks can permit locally super-Eddington radiative cooling without exerting the expected average radiation pressure force that would drive an outflow (Begelman 2001). This breaks the connection between the radiation flux that is responsible for cooling and thermal balance, and the radiation flux that is responsible for providing hydrostatic equilibrium against the tidal gravitational field of the black hole. The shape of the inner disk surface could therefore be altered from the flat profile expected in standard models, possibly enhancing the role of reprocessing.

4. Conclusions

SDSS should permit an exquisitely detailed analysis of how optical/ultraviolet continuum spectral energy distributions are related to fundamental parameters such as black hole mass and luminosity. This will provide a much-needed guide to how accretion flow models need to work in reality. In the meantime, slow but steady theoretical progress is being made in understanding the basic physics of accretion disks. Most interesting from the point of view of AGN is the increased understanding of the subtle effects that radiation magnetohydrodynamics may have on the flow and its resulting spectrum.

Acknowledgments. I am very grateful to my collaborators Ski Antonucci, Shane Davis, Ivan Hubeny, Julian Krolik, Aristotle Socrates, and Neal Turner for their scientific insights. I also thank Randall Telfer for supplying me with the data of the HST/SDSS composite spectrum, and Mike Brotherton for sharing their broadband quasar spectra with me. This work was supported in part by NASA grant NAG5-13228 and NSF grant AST-0307657.

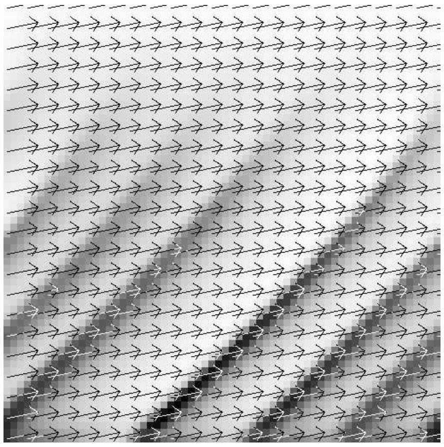

Figure 5. Snapshot of the density distribution produced in a simulation of the nonlinear development of the photon bubble instability (Turner et al., in preparation). Arrows indicate the direction of the magnetic field.

References

Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 214

Begelman, M. C. 2001, ApJ, 551, 897

Blaes, O., & Socrates, A. 2003, ApJ, 596, 509

Brotherton, M. S., Green, R. F., Kriss, G. A., Alexander, T., Kim, J. Kaiser, M. E., Zheng, W., Oegerle, W., & Hutchings, J. 2001, AAS 199th meeting, 138.01

Chiang, J., et al. 2000, ApJ, 528, 292

Gammie, C. F. 1998, MNRAS, 297, 929

Hubeny, I., Agol, E., Blaes, O., & Krolik, J. 2000, ApJ, 533, 710

Kaspi, S., et al. 2000, ApJ, 533, 631

Koratkar, A., & Blaes, O. 1999, PASP, 111, 1

Laor, A. 1990, MNRAS, 246, 369

Laor, A., et al. 1997, ApJ, 477, 93

Richards, G. T., et al. 2003, AJ, in press

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Shields, G. 1978, Nature, 272, 706

Socrates, A., Davis, S. W., & Blaes, O. 2003, ApJ, in press (astro-ph/0307158)

Sun, W.-H., & Malkan, M. A. 1989, ApJ, 346, 68

Telfer, R. C., Zheng, W., Kriss, G. A., & Davidsen, A. F. 2002, ApJ, 565, 773

Turner, N. J., Stone, J. M., Krolik, J. H., & Sano, T. 2003, ApJ, 593, 992

Vanden Berk, D. E., et al. 2001, AJ, 122, 549

Wandel, A., Peterson, B. M., & Malkan, M. A. 1999, ApJ, 526, 579