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Effects of Fluid Instabilities on Accretion Disk Spectra

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Abstract.
Numerical calculations and linear theory of radiation magnetohydrodynamic flows indicate that the photon bubble and magnetorotational instability (MRI) may produce large density inhomogeneities in radiation pressure supported media. We study the effects of the photon bubble instability on accretion disk spectra using 2-D Monte Carlo (MC) and 1-D Feautrier radiative transfer calculations on a snapshot of a 2-D numerical simulation domain. We find an enhancement in the thermalization of the MC spectra over that of the Feautrier calculation. In the innermost regions of these disks, the turbulent magnetic pressure may greatly exceed that of the gas. It is then possible for bulk turbulent Alfvénic motions driven by the MRI to exceed the thermal velocity making turbulent Comptonization the dominant radiative process. We estimate the spectral distortion due to turbulent Comptonization utilizing a 1-D MC calculation.

1. Introduction

The standard assumption central to most accretion disk models is that the turbulence responsible for angular momentum transport and gravitational energy release can be parameterized by an "α-viscosity" prescription (Shakura & Sunyaev 1973). The hypothesis that turbulence drives accretion has been borne out by the identification of the magnetorotational instability (MRI, Balbus & Hawley 1991) as a generic source for magnetohydrodynamic turbulence in differentially rotating flows. However, it is not yet known how accurately α-disk models describe real accretion disks. It is possible that both the structure and emitted spectrum of a disk in which the MRI is active may deviate significantly from the predictions of ad hoc α-disk models.

Numerical simulations of the radiation magnetohydrodynamic (RMHD) equations (Turner et al. 2003) show that MRI turbulence can produce a factor of 20 variation in density. In addition to the MRI, local linear analyses of the RMHD equations demonstrate that a radiatively driven photon bubble instability exists in radiation dominated accretion disks (Gammie 1998). This instability is present as long as the magnetic field is finite, but the growth rate for the instability is greatest when the magnetic pressure exceeds the gas pressure (Blaes & Socrates 2003). Numerical RMHD calculations of radiation pressure supported disks which neglect shear (Turner et al., in preparation) show that the non-linear development of the photon bubble instability does indeed produce large density variations. In section 2 we discuss the effects of these density inhomogeneities on the emergent spectrum.

Fluid motions associated with the MRI may also influence the emission. MRI turbulence is fundamentally magnetic in nature with a characteristic velocity v_w given by the Alfvén speed v_A which is less than the local sound speed c_s. Close to the hole, where the radiation pressure is dominant, c_s is given by the radiation sound speed which is larger than the sound speed of the gas. Thus, it is possible for the MRI turbulence to be *highly supersonic relative to the gas* and Compton scattering off of the turbulent eddies may produce a larger spectral modification than thermal Comptonization (Socrates, Davis, & Blaes 2003, hereafter SDB03). In section 3, we summarize these results.

2. Monte Carlo Results

We calculate a full-disk-thickness numerical solution of the RMHD equations in a stratified, radiation supported disk using the ZEUS-2D code with flux limited diffusion. Rapid photon diffusion creates large density inhomogeneities with relatively small temperature gradients. We then perform 2-D MC and 1-D Feautrier radiative transfer calculations through the uppermost quarter of the simulation domain. We horizontally average the domain to create a 1-D density and temperature input profile for the Feautrier calculation. Both methods model the effects of electron scattering and free-free emission and absorption. The optical depth at the base of the MC calculation was chosen to be several times the unit effective optical depth.

In figure 1, we compare the emergent spectrum from the MC calculation with the Feautrier spectrum and blackbody emission at a representative domain surface temperature. Though both of the calculated spectra resemble modified blackbody curves, the 2-D calculation's spectrum is more thermal (closer to blackbody) than the 1-D result. The stronger density dependence of absorption and emission relative to scattering is responsible for this difference. In the inhomogeneous 2-D MC domain, the surface flux is largest in the low density regions but is dominated by photons *emitted* in the densest regions where absorption is increasingly probable relative to scattering. Thus, on average, the photons escaping through the surface in the 2-D model will undergo fewer scatterings than those photons reaching the surface in the 1-D model resulting in a "less-modified" blackbody spectrum. This enhanced flux exceeds the local Eddington limit by a factor of order ten, consistent with predictions for highly inhomogeneous atmospheres (Begelman 2001).

3. Turbulent Comptonization

In order for turbulent Comptonization to be important in accretion disks, the bulk velocity of the turbulent eddies must exceed the thermal velocity of the electrons. To compare the turbulent and thermal velocities, it is convenient to define a turbulent wave temperature T_w in terms of the turbulent velocity on the outer scale. The wave temperature can then be related to thin disk parameters (SDB03)

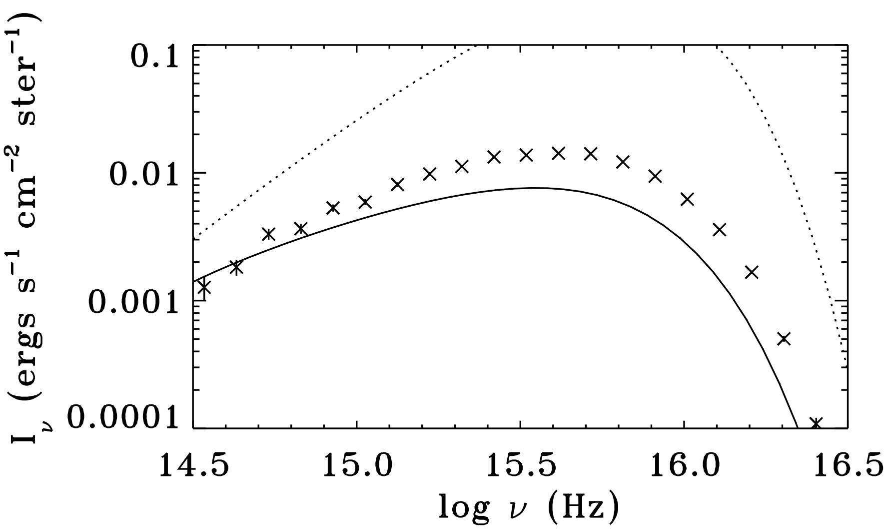

Figure 1. The output of 2-D MC calculations (x's) and 1-D Feautrier method (solid line) are compared with a 1.06×10^5K black body (dotted line).

$$T_w \equiv \frac{m_e}{3K_B}\left\langle v_w^2 \right\rangle \simeq 9.0\times10^9\,\frac{\alpha}{\epsilon^2}\left(\frac{L}{L_{edd}}\right)^2 r^{-3}\,\mathrm{K} \qquad (1)$$

Here, L is bolometric luminosity, L_{edd} is the Eddington luminosity, ϵ is the radiative efficiency, r is the cylindrical radius in units of gravitational radii $r_g = GM/c^2$, α is the standard viscosity parameter, and the effects of general relativity and no-torque inner boundary conditions have been neglected. It can be seen from eq. (1) that the wave temperature dominates the thermal temperature near the inner radius of the disk for sufficiently high accretion rates. The photons can only sample the velocity field on scales of order the photon mean free path such that the relevant wave temperature is generally less than that given by eq. (1). Our lack of understanding of turbulent dissipation in accretion disks hinders our ability to model their vertical structure. This uncertainty is further compounded by the possibility that turbulent Comptonization may itself be a dominant means of energy release. Therefore, we adopt a simple homogeneous model to estimate the reduction in wave temperature appropriate for the reduced velocities.

1-D MC calculations show that for sufficiently high turbulent stresses, turbulent Comptonization may account for a significant amount of the far-UV and X-ray power of accreting sources. For example, the spectrum shown in figure 2 has significant power up to ~1 keV and resembles soft X-ray excesses observed in many Seyfert 1 galaxies and QSO's. If soft excesses in these sources are due to turbulent Comptonization, they provide a direct means for probing the turbulence.

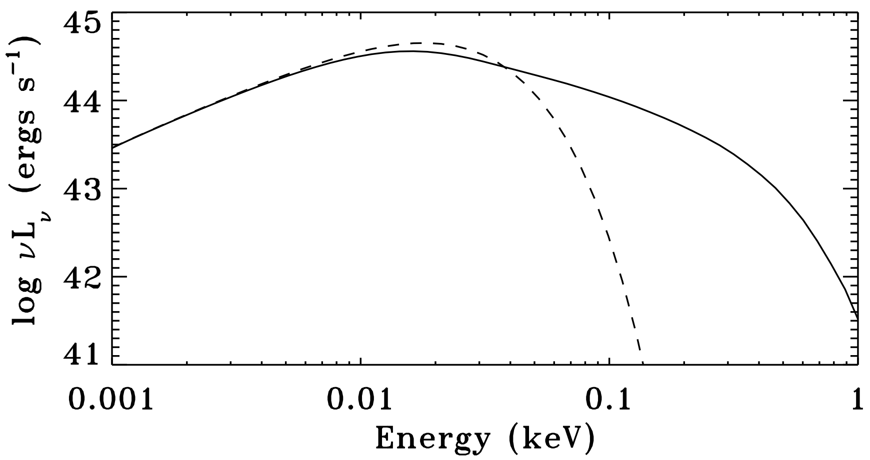

Figure 2. A spectral energy density produced by 1-D MC calculations for an accretion disk around a $10^8 M_\odot$ maximally spinning Kerr black hole. The dotted line is the thermal disk spectrum neglecting the effects of turbulent Comptonization.

4. Conclusions

Large density fluctuations due to the photon bubbles instability may alter the spectrum emitted in radiation pressure dominated accretion disks. These results are based on calculations which neglect shear. If shear is not neglected the MRI may affect the photon bubble instability, possibly altering the disk structure. However, for sufficiently large v_A, the MRI may be compressible in radiation dominated regions and may produce significant inhomogeneities on its own (Turner et al. 2003).

We also analyze the interactions of photons with turbulent eddies and show that for sufficiently large turbulent stresses, a prominent spectral component in the far UV and X-ray bands emerges. Observations of accreting systems may provide a means to directly probe the mechanism responsible for angular momentum transport in these sources.

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