Spectral and Temporal Variability Incorporating General Relativistic Effects

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Abstract. X-ray variability will arise from three components likely to be present in all active galactic nuclei: quasi-thermal emission from an accretion disk; direct emission from a power-law source; and photons from the latter, reprocessed and reflected from the former. Orbiting clumps within the disk produce some fluctuations in both overall flux and in the spectrum, as do motions of the power-law source. Here general relativistic effects are completely included, using the Schwarzschild metric, to find several new results. Among the most interesting are the possible disappearance of the reflection hump if viewed far from the symmetry axis and the possibility that rotation induced variability can be detected even for observers with nearly face-on views of the disk, as for Seyfert 1 galaxies.

1. Introduction

The model presented here has far more immediate implications for Seyfert galaxies and quasars than for most BL Lacs, in that the variability we discuss arises from phenomena directly related to the accretion disk and concerns the X-ray band. Nonetheless, these effects are probably present in many BL Lacs, even if these emissions are usually swamped by the relativistically enhanced synchrotron or inverse Compton processes, and they may be observable during low states when jet emission is weak.

The following characteristics of of AGN, especially Seyferts, and some X-ray binaries have been well established (e.g., Arnaud et al. 1985; Pounds et al. 1990): quasi-blackbody thermal bump in the EUV and soft X-ray spectra; a non-thermal power-law in the hard X-ray band; "reflection hump" from 10 keV to 100 keV; fluorescent lines around 6.4 keV; variability, sometimes on short timescales ($t < 1000$s) implying origins close to the central engine.

The usual interpretation is in terms of accretion disk phenomena. Non-thermal X-rays may be absorbed by an ensemble of gas clouds in and around the central engine (Guilbert & Rees 1988; Lightman & White 1988). If clouds (or disk regions) are dense enough to remain cold, they absorb much of the non-thermal power and re-radiate it (model fits indicate $\sim 1/2$). Such reprocessing models predict absorption edges, fluorescent lines and a Compton reflection hump (e.g., Ross & Fabian 1993; Nandra & George 1994). The width of the fluorescent iron line of both Galactic black hole candidates (e.g., Cyg X-1) and AGN is interpreted as arising from large Doppler and gravitational shifts, implying an origin in a disk.

2. General Relativistic Effects

Full general relativistic (GR) effects, including redshift, bending and focusing, have been considered in the study of the spectrum arising directly from the accretion disk, (e.g., Hollywood & Melia 1995). GR effects have not been employed when calculating "reflection" by the accretion disk (except in a special case, Reynolds & Begelman 1997). But the X-ray photons from a hard X-ray source have extra interactions with the strong gravity around the black hole; they are frequency shifted and focussed both as they impact the relativistic disk, and as they head away to the observer. Thus the reflected spectrum should carry more information on the gravitational field in the central engine, as well as the location of the primary X-ray source, than does the direct part of the spectrum.

Our first computations included: an accretion disk spectrum in its rest frame from Novikov and Thorne (1973); a power-law X-ray component in its rest frame expressed by $I_\nu = const.\ E^{-\alpha}\ \exp(-E/E_{cut})$, where E_{cut} is the effective upper cut-off energy of the spectrum (100 keV); a "reflected" spectrum computed similarly to Lightman & White (1988), assuming a covering factor of 0.5 — the atomic absorption and electron scattering are computed using F. Haardt's program; and double gravitational light bending and shifting. Details are given in Bao, Wiita & Hadrava (1998).

2.1. Basic formalism

Let $I_{\nu_{em}}$ be the local specific intensity at frequency ν_{em} at the disk and $I_{\nu_{ob}}$ the intensity observed at frequency ν_{ob} at infinity. Then

$$I_{\nu_{ob}} = g^3 I_{\nu_{em}} f(\mu) \qquad \text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{Hz}^{-1}\ \text{sr}^{-1}, \tag{1}$$

where $f(\mu)$ is a direction dependence function, determined by the local physics of scattering—for optically thick matter $f(\mu) = 1$. Here $g = E_{ob}/E_{em}$ is the ratio of the observed energy of a photon to that of the emitted energy (in the local frame); it includes both the gravitational shift and the disk rotation Doppler shift, and is given by (cf. Bao 1992)

$$g = \frac{\sqrt{(1-v_s^2)(1-2/r)}}{1-\Omega L_z}, \tag{2}$$

where $v_s = \Omega\ r\ (1-2/r)^{-1/2}$ is the velocity of the emitting matter measured in the local static frame, Ω is its angular velocity, and L_z is the component of its angular momentum about the z (symmetry) axis; (the angular dependence of the redshift factor g is contained in L_z).

The observed spectrum can be written as

$$F_{\nu_{ob}} = \int I_{\nu_{ob}} d\Pi \quad \text{erg cm}^{-2}\ \text{s}^{-1}\ \text{Hz}^{-1}, \tag{3}$$

where Π is the solid angle the emitting matter subtends at the observer; this directly measures the bending or lensing effect. Here

$$d\Pi \;=\; BdBd\phi' D^{-2}, \tag{4}$$

where D is the distance between the observer and the emitter, B is the total impact parameter and ϕ' is the position angle of the photon. We find $d\Pi$ can be rewritten in terms of the coordinates of the disk, r and $\varphi_{\rm s}$; it is calculated as in Bao, Hadrava, & Østgaard (1994).

The above equations are fine for computing the observed spectrum of direct disk emission, but they must be modified to calculate the reflected spectrum. The power-law intensity measured *on the disk* will be inversely proportional to the redshift factor to the third power and and the solid angle at infinity. But the reflected intensity measured by the *observer at infinity* will be proportional to $(g_{out}/g_{in})^3(d\Pi_{out}/d\Pi_{in})$. The key difference between this work and earlier computations is that GR effects are considered *both* for the incoming and outgoing photons, and not just for the outgoing photons. (Reynolds & Begelman 1997 also considered this effect using a different formalism but only for on-axis irradiation.) The impact parameters B of the incoming and outgoing X-ray photons are different. Most of our computations were simplified to assume parallel rays from the power-law source, implying an origin at relatively large distances (say $R > 200m$). The outgoing photons can extract rotational energy from the disk and be boosted to higher energies.

3. Resulting Spectra

Models were computed for a $10^6 \mathrm{M}_\odot$ black hole, with an accretion rate of 0.01 $\dot{M}_{\rm Edd}$, a viscosity parameter, $\alpha_{\rm vis} = 0.01$, and were set so the total power of the power-law plus its reflected power equals 11.26 times the total power from the thermal disk (integrated between $6.1m \le r \le 100m$). The power-law parameters were taken as $\alpha = 0.9$ and $E_{cut} = 100$ keV. The angle between the disk axis and the incoming power-law photons is called i_0, the angle between the axis and the outgoing reflected photons is i_1, and the azimuthal angle between the incoming and outgoing photons is Δ (i.e., $\Delta = 0$ has both on the same side of the BH).

We first saw how the gravitational shifts alone affect the observed spectra by considering a case where the relativistic rotation of the accretion disk and the gravitational focusing have their minimum influences, e.g., $i_1 \approx i_0 \approx 0$. The spectrum from the disk in Schwarzschild spacetime is softer than that observed in flat spacetime; and gravitational effects cancel in reflected spectra with the primary X-ray photons sent back in the same direction. If one examines higher source inclinations, the reflection "hump" is amplified by gravitational focusing. This is understood because for fixed i_1, the observed solid angle is also fixed, but as i_0 increases the incident solid angle decreases, so the ratio of the solid angles for each element of the disk increases, and thus the amplitudes of the reflected components grow; of course, the direct disk spectrum is independent of i_0. We also examined the effect of azimuthal orientation and find that the reflection effect is clearly stronger when the source is on the same side of the BH as is the observer, independent of i_0. See Bao et al. (1998) for details.

Changing the observer's viewing angle produces changes in both the directly observed disk spectrum and (more substantial) changes in the reflected hump. The reflection hump is reduced at greater inclinations to the disk axis, as shown in Figure 1. Within the unified scheme for AGN, Seyfert 1 galaxies are viewed closer to the line of sight while Seyfert 2's are seen through an obscuring torus

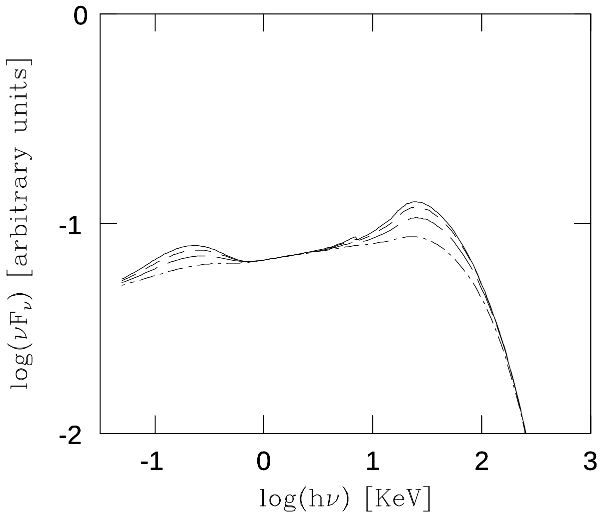

Figure 1. Composite spectra where the inclination of the source is fixed at $i_0 = 40°$ and the inclinations of the observer are $i_1 = 1°$ (solid line), 40° (short-dashed line), 60° (long-dashed line), and 80° (dot-dashed line).

because they are viewed at a higher inclination (e.g., Antonucci 1993). Part of the difference between the harder X-ray spectra of Seyfert 1's and Seyfert 2's could be due to this angle dependent GR effect on the reflection hump.

4. Variability

We now consider the additional features introduced by reflection off an orbiting "clump" in the disk. The instabilities to which the inner portion of the disk is subject (e.g., Shakura & Sunyaev 1976; Wiita 1996) should produce significant internal variations in the density and temperature of these parts of the disk. In our computations, the clump is assumed to remain "cold", but its motion yields different beaming effects, and thus changes in flux. In a realistic model, the non-thermal source(s) above the disk is (are) also unlikely to be static. If the power-law arises from a jet, there will probably be wiggles and irregularities that imply that the maximum of the emission at any one time is likely to be at least somewhat off-axis. Similarly, if the power-law arises from flares within the disk corona, the location of peak emission will change. In these new calculations we have generalized our results so as to consider not only parallel illumination, but also nearby (but physically compact) non-thermal sources.

When examining only the reprocessed component we find that the maximum amplitude of the spectrum corresponds to the the case when the clump moves towards the observer and the minimum to the case when it moves away from the observer. This is partially because of the standard Doppler effect, but it is enhanced because scattered photons extract energy from the relativistically rotating disk, in a bulk analogy to inverse Compton scattering. Unsurprisingly,

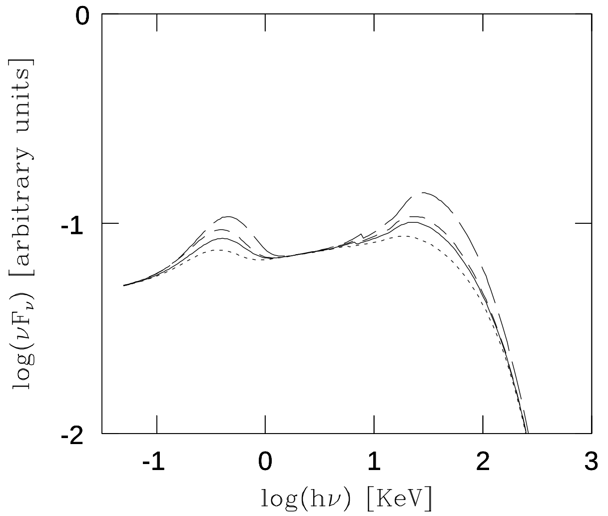

Figure 2. Composite spectra where the clump is at $r = 20m$, $i_1 = 30°$, and $i_0 = 50°$. The clump moves from orbital phase 0° (solid line), to 90° (dotted line), to 180° (short-dashed line), and 270° (long-dashed line).

this effect is stronger for larger values of i_0. Lightcurves arising from a single reflecting clump show stronger variations at higher energies.

For the composite spectra one generally sees changes in both the disk and reflected components as the orbital phase of the clump changes (Figure 2). Gravitational focusing causes the flux to be slightly stronger when the reflecting region is behind the BH than when it is in front. However, the highest fluxes come when the clump is approaching and the lowest when it is receding. If the viewing angle is nearly along the axis ($i_1 \sim 0°$) then variations will be seen only in the reflected components, as there will be no motion induced changes from the clump itself; however, there will be variations arising from the way in which it reprocesses the power-law emission.

In our examinations of sources located at different distances from the disk we unsurprisingly find that the intensity of the reflection hump decreases when sources move away from disk. Different values of Δ seem to produce no fundamental difference in the spectrum variability. Finally, if the illuminating source is near the axis, the reflection humps vary but there are no changes in the lower energy components which come directly from the disk.

5. Conclusions

A model involving non-thermal sources illuminating an accretion disk explains many features of Seyfert galaxy spectra. We have included more complete GR effects which modify the outgoing spectra in non-trivial ways. Thermal photons come directly from the disk, and so experience a single path through a strong gravitational field, while many non-thermal high energy photons reach the observer through twice bent and focussed paths. The resulting spectra depend upon the geometry of the source and observer, and weaker reflection humps are expected for disks viewed at larger angles, e.g., Seyfert 2 galaxies.

Variability can be introduced from rotating spots or moving power-law sources, as well as from the absolutely intrinsic fluctuations in emission from warm-spots in the disk (e.g., Abramowicz et al. 1989, Mangalam & Wiita 1993; Wiita 1996). These fluctuations can be very different for the direct and reprocessed components as well. Within unified models for AGN, Seyfert 1 galaxies are viewed at relatively low inclinations, $i_1 < 45°$; some rotational modulation in their flux can still occur and be observable even for very low values of i_1 as long as the non-thermal source is off-axis. Greater variability at higher observed energies is consistent with this picture.

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