Lyman Edge Features from Accretion Disks Around Maximally Rotating Supermassive Black Holes

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Abstract

We calculate the amplitude of the Lyman discontinuity for an accretion disk around a maximally rotating black hole. The locally emitted disk spectrum is computed with a previously developed numerical model (Sincell & Krolik 1998) and then a new general relativistic ray-tracing code is used to determine the observed spectra as a function of inclination angle, $\theta_o$. We find that Lyman discontinuities are undetectable for disks viewed at inclinations $\cos \theta_o \lesssim 0.8$, but a significant feature remains for disks seen face-on.

1. Introduction

The ultraviolet (UV) spectrum of Seyfert galaxies is dominated by a quasi-thermal component (Shields 1978, Malkan & Sargent 1982, Malkan 1983) which extends into the soft x-ray band (Walter & Fink 1993). Although this feature is usually interpreted as thermal emission from a geometrically thin, optically thick accretion disk around a supermassive black hole, recent observations cast doubt on this simple explanation. A discontinuity at the Lyman edge, either in emission or absorption, seems to be a generic feature of theoretical models of accretion disks (e.g., Blaes 1998). However, partial absorption features have been detected in $\lesssim 10\%$ of observed AGNs (Antonucci, Kinney & Ford 1989, Koratkar, Kinney & Bohlin 1992).

Recently, Iwasawa, et al. (1996) detected extremely broad iron K-\(\alpha\) line emission from the Seyfert galaxy MCG-6-30-15. They interpret this emission as x-rays reflected by an accretion disk extending to $1.23\, R_g$, where $R_g = GM/c^2$, of the central black hole. For a stable accretion disk to exist this close to the central black hole this black hole must be rotating close to its maximal value ($\alpha = 0.92195\, \text{Meudon cedex, France}$, France).

This equation set can be reduced to six first-order equations by noting that the photon energy

$$E = -p_t$$

and angular momentum parallel to the symmetry axis

$$L = p_\phi,$$

where $p_t = \partial L/\partial \dot{x}^i$, are conserved along a null geodesic. It is possible to reduce the equation set further (see Bardeen, et al. 1972, Cunningham 1975, Agol 1997) but this introduces complicated bookkeeping into the ray-tracing calculation. The differential equations are integrated with a fourth-order Runge-Kutta routine (Press, et al. 1992).

There is one additional constant of the motion

$$Q^2 = p_\theta^2 + \cos^2 \theta \left[ -a^2 p_t^2 + p_\phi^2 / \sin^2 \theta \right]$$

which is needed to specify a particular photon geodesic. In this equation, $a$ is the black hole spin parameter and $\theta = \phi_0$ in Boyer-Linquist coordinates.

To compute the observed spectrum, we choose a particular inclination angle and a grid in the impact parameters ($\alpha$, $\beta$). The parameter $\alpha$, which is measured in units of $R_g$, is defined as the projected distance away from the black hole along an axis perpendicular to the spin axis of the black hole. The parameter $\beta$ is the projected distance parallel to the spin axis. The range of values for the impact parameters corresponds roughly to the inner and outermost radii of the accretion disk.

For each pair of impact parameters, the constants of motion of the corresponding geodesic are defined

$$L = -\alpha \sin \theta_0$$

$$Q^2 = \beta^2 + (\alpha^2 - a^2) \cos^2 \theta,$$

and $E = 1$. The equations of motion are then integrated inward from $r_o \gg M$, where $M$ is the mass of the black hole and we adopt geometriized units, and $\theta = \theta_o$. The integration is stopped when the geodesic either hits the disk ($\theta = \pi/2$), escapes to infinity or is captured by the black hole.
For a geodesic which intersects the disk at radius $r_e$, we can compute two important quantities: the total redshift of a photon emitted by the disk at $r_e$ and escaping to infinity

$$ g = \frac{\nu_e}{\nu_o}, \quad (8) $$

where $\nu_{e,o}$ are the frequency of the emitted and observed photon, and the angle at which the photon leaves the disk, $\theta_e$, measured in the rest frame of the orbiting material. Explicit equations for these quantities can be found in Cunningham (1975).

The observed spectrum is found by integrating the emitted intensity over the impact parameters of all the geodesics which reach the observer

$$ I(\nu_o, \theta_o) = \int I(\nu_e, r_e, \theta_e) g^3 \, d\alpha \, d\beta \quad (9) $$

where the factor $g^3$ arises from the invariance of the photon occupation number and $I(\nu_e, r_e, \theta_e)$ is the spectral intensity of the radiation emitted by the disk. For example, the intensity could be described by an analytic expression for the reflected iron line as a function of radius or a grid of numerical models of the continuum flux from an optically thick accretion disk.

3. Results

In figure 1 we plot the UV continuum of an optically thick accretion disk around a maximally rotating black hole. The black hole is assumed to have a mass of $2.7 \times 10^8 M_\odot$ and to accrete matter at $\dot{m} = 0.3 M_\odot / \text{yr}$, where $M_\odot$ is the Eddington critical accretion rate. The three curves represent three different values of the disk inclination angle, $\theta_o = \cos^{-1} \mu_o$.

We find that the Lyman edge discontinuity is unobservable when $\mu_o < \sim 0.8$, but that a significant absorption feature remains at smaller inclinations. If this model is typical of all accretion disks, then we would predict that Lyman edge features should be seen in $\sim 20\%$ of all AGNs. This is obviously only a very rough estimate, but it does indicate that black hole rotation is a plausible means of erasing the Lyman discontinuity in a large fraction of AGNs.

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Fig. 1.— A model of continuum emission from a disk around a Kerr black hole.