Probing Black Holes with Gravitationally Redshifted Emission Lines

by Andreas Müller

Abstract: The gravitational pull of black holes deforms emission in their vicinity such as spectral emission lines. Depending on distance the emission lines are shifted and even distorted close to the black hole. This is a common feature of all black holes of arbitrary mass. We show that gravitationally redshifted emission lines can be used to probe black hole properties such as mass and spin. We demonstrate that relativistic ray tracing simulations are consistent with optical and X-ray observations of the active galaxy Mkn 110. High-resolution observations allow in principle for probing gravitational redshift at unexpectedly high distances amounting to several 10,000 gravitational radii.

Model: Keplerian rotating, equatorial rings
In a simple model we assume that the emission lines originate from the Keplerian rotating rings that lie in the equatorial plane of a Kerr black hole (BH). Gravitational redshift of the spectral lines can be studied by shifting the rings successively towards the BH. The right figure sketches this set-up of the model.

Emissivity: We aim to study the emission lines in different distances to the BH. Therefore, the disk is sliced into narrow rings. A Gaussian emissivity profile as introduced in [1] peaks at $R_{\text{peak}}$ and selects a ring in each distance.

Line centroid: In this theoretical analysis (cf. [2] for details) there is no line specified, i.e. the line energy (horizontal axis) is specified by the general relativistic (GR) Doppler factor satisfying $g = v_{\text{law}} / c$. The line flux (vertical axis) is normalized to unity for the line exhibiting maximum flux. Let $F_1$ and $g_1$ be flux and $g$-factor for each energy bin. We characterize the emission of each line by the $g$-factor associated with the line centroid, i.e.

$$g_{\text{core}} = \sum g_i F_i$$

Line suppression

NLS1 Mrk 110: Observations vs. Model
The figure on the right-hand side displays the comparison of ray tracing simulations (blue dots) and redshift functions from theory (purple and green curves) with observational data from the active galaxy Mrk 110 (black, optical hydrogen and helium lines from broad line region [3]; red dot: X-ray line CIVIII [4]). Each simulated line is attributed with a centroid GR Doppler factor or centroid redshift according to $g = (1+z)^{2}$. Redshift $z$ increases as the emitting ring approaches the hole. Observations and simulations are consistent and define an inclination angle of the inner accretion disk of $i = 20^\circ$. The golden ring highlights the difference between Schwarzschild and Kerr, i.e. BH rotation can only be probed very close to the BH ($r < 4r_g$), e.g. with X-ray iron K lines.

Influence of radial drift towards the BH
The figure below shows an example that includes constant drift motion towards the BH with 0.02c. Infall motion enhances the red line wing and modifies the ratio of the Doppler peak fluxes. However, the position of the line core remains.

Kepler motion + radial drift

Kepler motion
Doppler peak ratios:

$$r_c = c \frac{\sin i}{r_{\ast}}$$

$$a = 0.998 \, M_\odot$$

$$i = 20^\circ$$

$$R_{\ast} = 40$$

Ring approaches BH: Line decays
The diagram on the left shows the deformation of emission lines by gravitational redshift for highly inclined rings (inclination angle of 75°) around a fast spinning Kerr BH with specific angular momentum of $a = 0.998M_\odot$. The ring radius with maximum emission is defined as $R_{\text{peak}}$ (in units of gravitational radii, $r_g = G M/c^2$).

Two effects are visible from the plot. First, the line flux is suppressed as the ring approaches the BH. At the event horizon the line vanishes (not shown here). Second, the line profile is deformed successively as the emitting ring comes closer to the BH. This is a typical signature of GR.

BH mass determination
A comparison of observed gravitationally redshifted lines with ray tracing simulations delivers $M_{\ast}$, i.e. distances in units of $r_g$. Absolute BH masses follow by a calibration, e.g. with time lag measurements from reverberation mapping.

Conclusions
Gravitationally redshifted emission lines are well suited to probe properties of black holes (mass and spin) and their surrounding inner accretion flow (inclination). As shown here, even at large distances around 10,000 $r_g$, the gravitational pull can be detected in optical BLR lines. Approaching the BH the amount of redshift of soft X-ray lines consistently attaches to the optical Iron K lines that originate from the BH vicinity even allow for probing BH spin. Drift motion towards the BH does not shift the line core but changes the line morphology by enhancing the red wing.

References

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