Resolving the Space-Time Around Black Holes

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Image from Dovciak et al. (2004)
Introduction

- Black holes are defined by their mass, charge, and angular momentum (spin)
- Determining the spin is important for mapping the metric of the black hole
- Fe K emission line in the X-ray band is an important probe of the region near the black hole
- We investigate the capabilities of future missions to robustly measure spin independent of spatial emissivity of the disk (e.g. the effects of spatial emissivity are degenerate with spin)
- We discuss the accuracy of currently available spectral fitting routines to measure spin from future observations
Fe K Line Profiles

Radially Integrated Disk Emission

- What can be measured?
  - Disk Inclination Angle: mainly from blue wing
  - BH Spin: mainly from red wing
- BUT the measurements also depend on:
  - Radially emissivity of the disk
  - Ionization state of Fe
  - Complex continuum modeling
  - Inclusion of possible emission from inside marginally stable orbit

Measuring Black Hole Spin

- Suppose there is a local magnetic flare ("hot spot") within tens of gravitational radii or less from the black hole.

- If the hot spot co-rotates with the disk for at least one orbit forming a thin annulus ⇒ two sharp spikes from enhanced region over the time-averaged line profile (corresponding to extreme red- and blue-shifts of hot spot)
  - Each peak is a function of radius, spin, and disk inclination angle
  - Independently measure inclination ⇒ constrain radius and spin

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Annulus
Accretion Disk
Black Hole

Sample Profile for an Annulus of Emission
Dovciak et al. (2004)
Hot Spot Emission

Keplerian Orbital Timescales

<table>
<thead>
<tr>
<th>Radius (r_g)</th>
<th>$10^6 M_\odot$</th>
<th>$10^7 M_\odot$</th>
<th>$10^8 M_\odot$</th>
<th>$10^9 M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6$r_g$</td>
<td>140 s</td>
<td>1.4 ks</td>
<td>0.17 d</td>
<td>1.7 d</td>
</tr>
<tr>
<td>10$r_g$</td>
<td>320 s</td>
<td>3.2 ks</td>
<td>0.37 d</td>
<td>3.7 d</td>
</tr>
<tr>
<td>20$r_g$</td>
<td>894 s</td>
<td>8.9 ks</td>
<td>1.0 d</td>
<td>10.4 d</td>
</tr>
<tr>
<td>100$r_g$</td>
<td>10 ks</td>
<td>1.2 d</td>
<td>11.6 d</td>
<td>115.7 d</td>
</tr>
<tr>
<td>1000$r_g$</td>
<td>3.7 d</td>
<td>36.6 d</td>
<td>366 d</td>
<td>10 years</td>
</tr>
</tbody>
</table>
• Simulation of 5 ks observation, $I = 10\%$ of main line ($5 \times 10^{-6}$ ergs s$^{-1}$)

• Measurement of line energy in this example is dominated by energy scale systematics ($\sim 1$ eV), not statistics
Observational Evidence of Hot Spots

- Many cases of claimed “hot spot” emission in AGN spectra:
  - MCG -6-30-15 (Iwasawa et al 1999)
  - ESO 198-G24 (Guainazzi 2003)
  - NGC 3516 (Turner et al 2002, Iwasawa et al 2004a)
  - IRAS 18325-5926 (Iwasawa et al 2004b)
  - Mkn 766 (Turner et al 2006)

- Simulations show Constellation-X will easily be able to measure the energies of the spikes ($E_{\text{min}}$ and $E_{\text{max}}$), even for weak hot spots
• Year-long observation campaign of **NGC 2992** with **RXTE**

• Flux varied by a factor of \(~10\) on short timescales (days-weeks)

• During the 3 highest-flux observations, a highly redshifted \((E\sim5.6\text{ keV})\), broadened Fe K\(\alpha\) line dominated \(\Rightarrow\) emission originated close to the black hole

*Murphy et al (2007)*
R = R_{Horizon}

Uncertainty in ionization state of Fe: ± 4.2%

⇒ a/M > 0.75,
1.0 < R - R_H < 1.5
$\theta = 30^\circ$

$g^- = 0.5 \ 0.55 \ 0.6 \ 0.65 \ 0.7 \ 0.75 \ 0.8 \ 0.85 \ 0.9 \ 0.95 \ 1.00$

$R_{\text{MS}} - R_{\text{Horizon}}$
$\theta = 60^\circ$

![Graph with labeled axes and curves](image)
Blue Peak (g+) Contours

- As $g^+$ increases, spin vs. distance contours get wider.
- Energy shifts become less sensitive to spin at larger radii.
For high resolution spectroscopy, accuracy of calculations must be improved.
Conclusions

- It is difficult to constrain BH spin independent of assumptions about radial emissivity and emission inside the marginally stable orbit.

- We quantified the uncertainties on spin in terms of key observational measurements and found that, although distance to localized emission can be constrained, the spin remains elusive.

- Combined with temporal analysis, this may be the most accurate way to measure BH mass.

- To measure other parameters of accretion disks (inclination, ionization state, emissivity, spatial scales), numerical models of the Kerr metric must be improved in parallel with improved instrumentation.