The Structure and Energetics of Active Galactic Nuclei

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The AGN Paradigm

• The black-hole + accretion-disk model is finally fairly secure
  – Black-hole mass measurements have unknown systematic uncertainties
• No generally accepted models for emission and absorption regions, though disk-related outflows seem most promising
Major AGN Questions

• What are the masses AGN black holes?
• What are the energetics of the accretion process?
  – Accretion rate
  – Radiative efficiency
  – Kinetic energy (jets, absorbing gas)
• How does the AGN mass function evolve over time?
• What is the nature of the line emitting and absorbing gas in AGNs?

\[ L = \eta \dot{M} c^2 \]

- Mass accretion rate
- Efficiency
AGN Black Hole Masses

- Measured for nearly 40 AGNs via reverberation mapping
- Secondary methods are tied to these
- Evidence these are meaningful estimates:
  - Virial relationship between line widths and time delays

Onken and Peterson 2002
Peterson and Wandel 2000

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Hubble Science Legacy
AGN Black Hole Masses

- Evidence these are meaningful estimates:
  - $M_{\text{BH}} - \sigma$ relationship same in AGNs and quiescent galaxies

- What we need:
  - Direct comparison of reverberation and stellar dynamical masses
  - Two-dimensional reverberation-mapping to understand kinematics and geometry of line-emitting region

Ferrarese et al. 2001
Direct Comparison of Reverberation and Stellar Dynamical Masses

• Requires spatially resolving the black-hole radius of influence \( r_* = \frac{GM_{\text{BH}}}{\sigma^2} \).
  – Impose criterion on diffraction limit and use \( M_{\text{BH}}-\sigma \) relationship (\( \sigma \propto M_{\text{BH}}^{2/9} \)):

\[
\phi_{\text{diff}} < \frac{r_*}{D} \propto \frac{M_{\text{BH}}}{\sigma^2 D} \propto \frac{M_{\text{BH}}^{5/9}}{D}
\]

  – This gives minimum dynamically measurable \( M_{\text{BH}} \) as a function of distance.
Why Must This Be Done From Space?

- A ground-based large telescope should be able to attain comparable resolution with adaptive optics (AO)
- However, AO Strehl ratios are still too small: the faint stellar absorption features are swamped by scattered nuclear light
X-ray/UV Absorption

- Ubiquitous property of AGNs
- Large column densities, multiple velocity components, massive outflows
- Analogs to outflows in young stars?
- Connection to BALs in luminous QSOs?
- How much mass and kinetic energy is involved?
- How do these vary with AGN properties?

Chandra: Kaspi et al. 2002
HST: Crenshaw et al. 2002
FUSE: Gabel et al. 2002
Why Is A Large Space Telescope Needed?

• Resolution needs to reach thermal width (~10 km s\(^{-1}\), or \(R = 30,000\)) to resolve velocity components

• Large collecting area since these are faint sources

• Must be done in the UV (resonance lines), must be done at low redshift (complex absorption structures in lower luminosity objects)

• Variability and weak fine structure lines probe physical conditions in absorbing gas
Extended Structures

- AGNs show small-scale structures at the highest spatial resolution
- 8-m diffraction limit yields spatial resolution on scales of several parsecs, where outflow and fueling structures might become apparent
- Evolution of AGN host galaxies out to $z \approx 1$ can also be probed in rest-frame optical

NGC 3393
WFPC2 F606W
Spatial resolution ~30 pc
Formation and Evolution of Galaxies

• Bulges and supermassive black holes are intimately related
• A small percentage of current SMBHs are active, but these are important as tracers and as examples of how the accretion process works
• We need to understand the energetics of the process, both the radiative and kinetic output, to understand galaxy evolution
• *Understanding galaxy evolution requires understanding black-hole evolution*
Comment on Space Astronomy Infrastructure

• To make efficient use of very large telescopes, we must off-load essential work that can be done with smaller telescopes
  – A generally recognized principle in ground-based astronomy
  – UV data are too critical to do without
  – We need smaller workhorse facilities as part of the space astronomy infrastructure
  – A 1-m class UV spectroscopic telescope fits into a MIDEX funding envelope (~$200M) and ELV (e.g., Delta II with 10-ft fairing)