ACTIVE GALACTIC NUCLEI

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OVERVIEW

PART 1

- *What are AGN?*
- *Why are they interesting?*
- *What are the observables?*
- *Is there a unified model for the various types?*

PARTS 2+3

- *2. How can we derive the physics of AGN from the observations*
- **3. What is the evidence for a black hole and accretion disk**

AGN III:MODELS

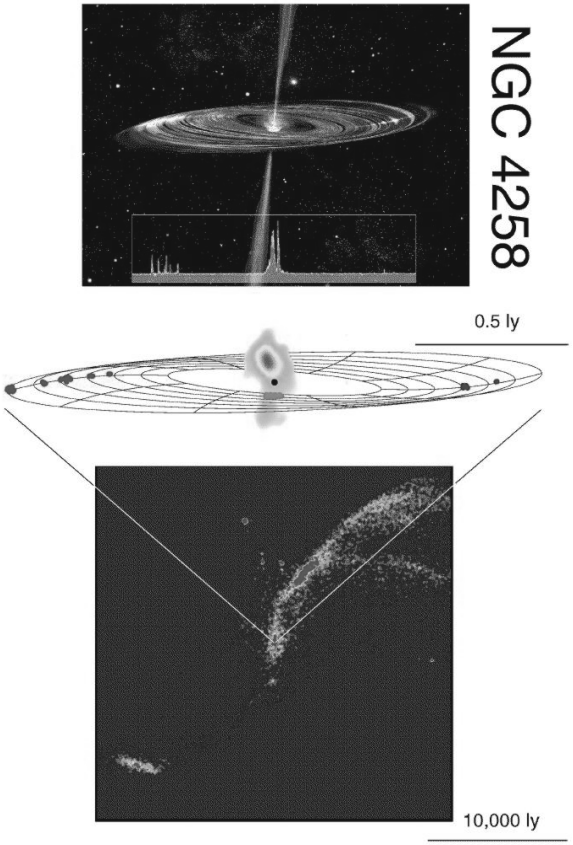
- Emission mechanisms
- Accretion and accretion disks
- X-ray emission mechanism
- Reprocessing
- Properties of black holes in AGN

GENERAL ARGUMENTS FOR ACCRETION IN AGN

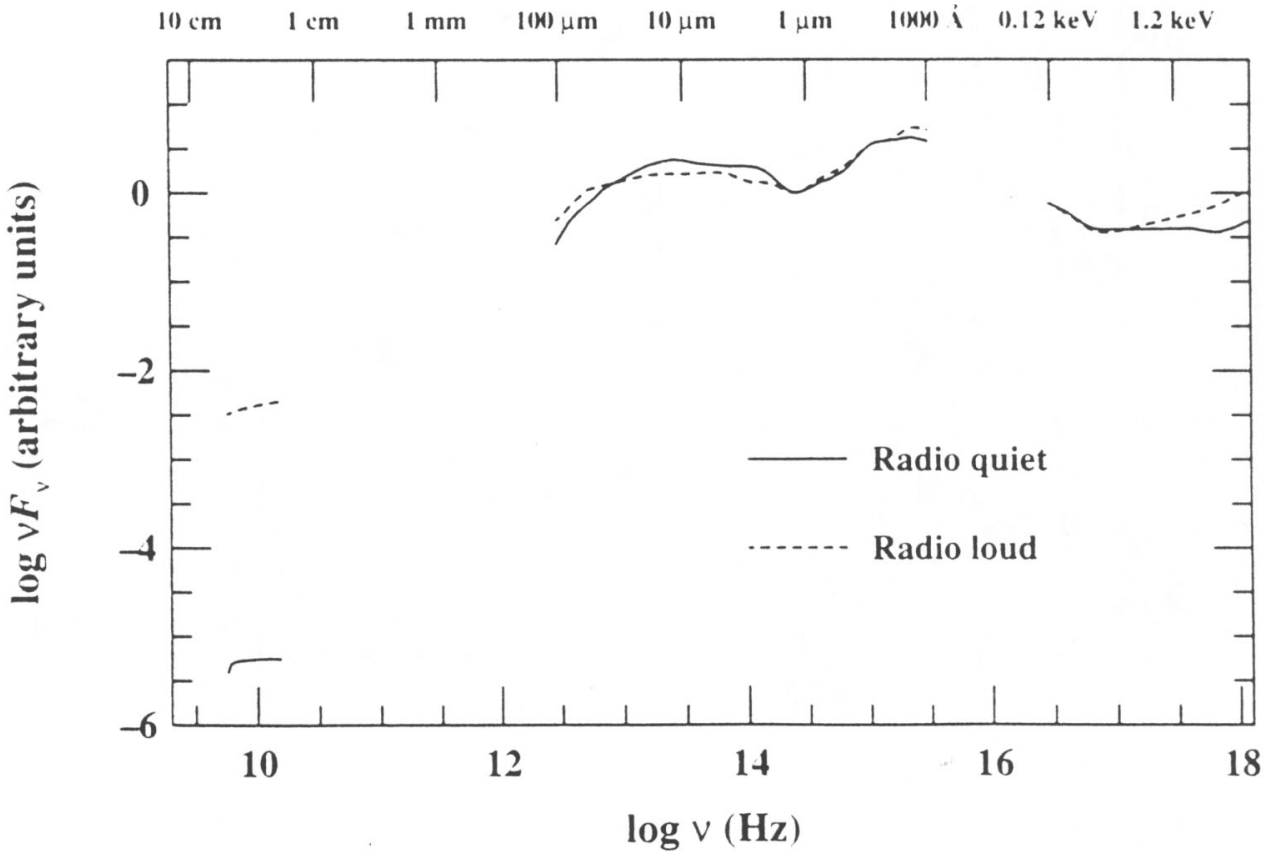
- Rapid variability (esp. X-rays) indicates that trillions of solar luminosities are generated in a region $<10^{13\text{-}15}$ cm.
- Source is extremely compact and highly efficient – usually too efficient for stellar processes.
- Accretion onto compact object much more efficient than fusions (10-100 times)
- Eddington limit implies mass $M>8 \times 10^5 L^{44} M_\odot$
- Dynamical studies show masses of $\sim 10^6\text{-}10^9 M_\odot$
- $\Rightarrow$ Compact object is a supermassive black hole

BLACK HOLE IN NGC 4258?

- Miyoshi et al. (1995) made MASER VLBA observations of disk in this inclined AGN
- Observed Keplerian rotation of disk at ~1 pc impling BH of mass 30 million solar masses



AGN SPECTRAL ENERGY DISTRIBUTION



ACCRETION DISKS

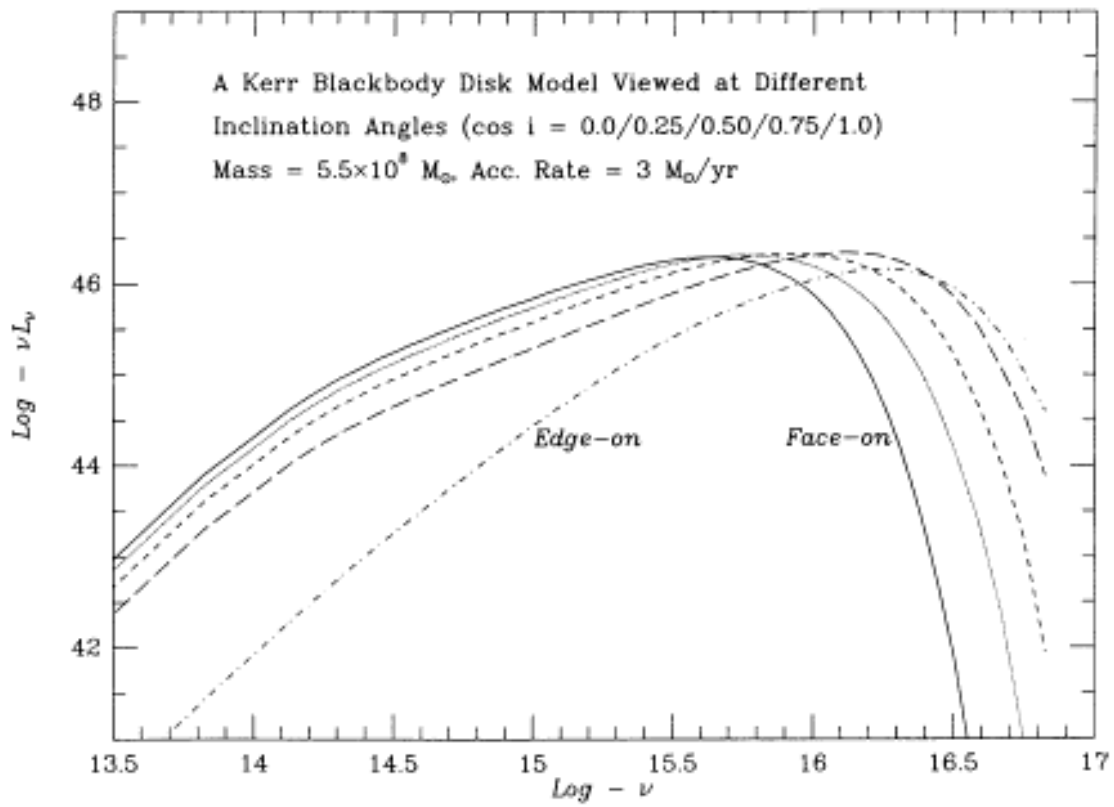
Luminosity is generated by viscous stresses (magnetic?)

- Mass accretion rate ($\dot{m}$) required to generate luminosity $L = \eta \dot{m} c^2$
  - $\dot{m} \sim 1.8 \times 10^{-3} L_{44} M_\odot \, yr^{-1}$
- If material has angular momentum (likely) it will form a disk
- Radial temperature profile $L \propto (GM\dot{m})/R \propto 2\pi R^2 T^4$ (local blackbody assumption)
- Hence $T(R) \propto \dot{m}^{0.25} M^{-0.25} R^{-0.75}$

Characteristic blackbody temperature is $T_{bb} = 5 \, 10^5 \, M_8^{-0.25}$ K

ACCRETION DISK SPECTRA

Theoretical accretion disk spectra can be fitted to actual data in the optical/UV. Generally they fit the spectra very well, and can be used to obtain M and $\dot{m}$. The parameters are model dependent, however, and sometimes not well constrained

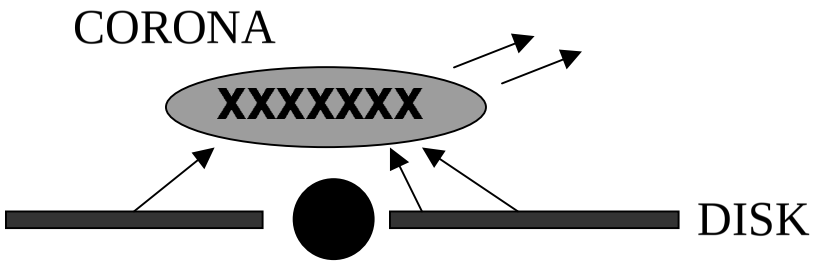


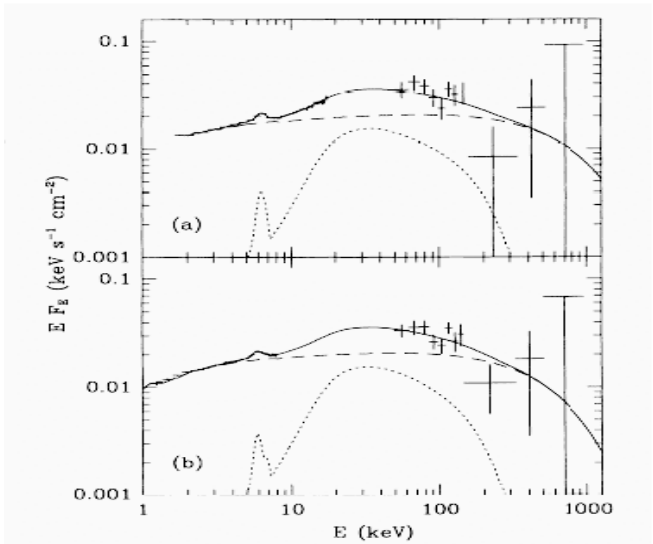
ACCRETION DISKS: PROBLEMS

- Though the models fit the spectra well, and a disk seems the most plausible geometry there are some outstanding questions
  - Jump in the UV spectrum is predicted at the Lyman edge (13.6 eV), but this is not usually observed.
  - Time lag predicted between UV and optical variations (as optical formed further out), but not observed.
  - Polarization
- This could mean the disk model is wrong, or alternatively that models of disks are simplistic

X-RAY EMISSION

- The accretion disk is not hot enough to give off X-rays, even in the innermost regions
- X-rays extend out to at least 100 keV in many objects
- Implies temperatures of 10^9K, but disk reaches only 10^6K
- Requires additional radiation mechanism AND an additional method of generating energy (dissipation)
- X-ray source often referred to as a “Corona”

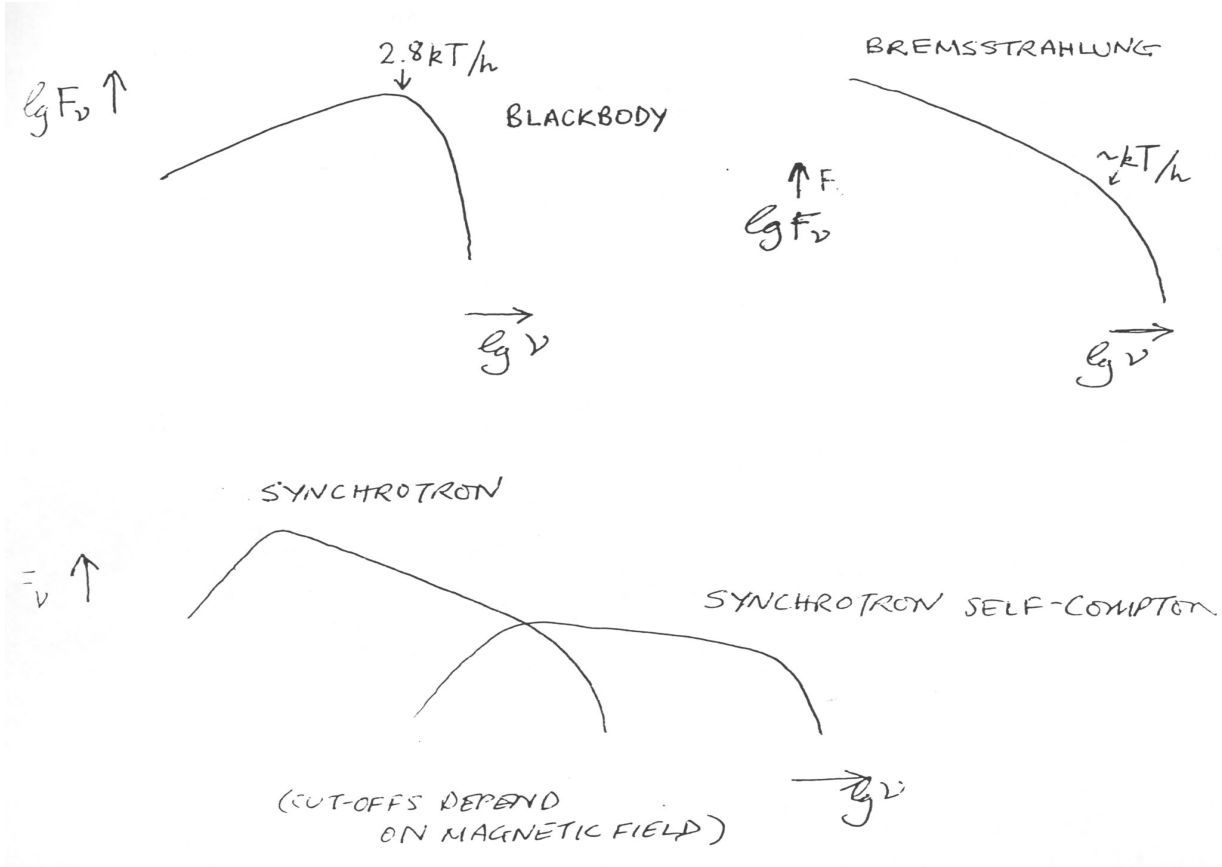




TYPES OF PRIMARY EMISSION MECHANISM

- **Synchrotron:** Electrons move around in a magnetic field. Accelerating electrons produce radiation. Likely mechanism for radio emission in AGN.
- **Synchrotron Self-Compton (SSC):** As above but the synchrotron photons are Compton scattered from the electrons. This makes the observed spectrum extend to much higher energies.
- **Bremsstrahlung:** Thermal motion of electrons in optically thin plasma. Acceleration/deceleration due to interaction with ions. Photons escape without much interaction with electrons
- **Black body:** As above but medium is optically thick to scattering. Photons scatter many times before emerging.

SCHEMATIC SPECTRA



COMPTON SCATTERING

Secondary emission mechanism

- Photons interact with electrons. Energy is transferred in the process. If photons give electrons energy on average this is known as Compton scattering. If electrons give photons energy this is inverse Compton.
- Photons change direction. New direction is random but drawn from a particular probability distribution. Precise shift for a given angle.
- Thermal distribution of electrons with low energy photons injected into it produces approximate power law form, cutoff at approximately kT
- For inverse Compton scattering in thermal plasma, the mean energy shift is: $\Delta E/E = 4kT/m_e c^2$
- PROBABLE SOURCE OF X-RAYS IN AGN

Accretion disk provides "seed" photons

COMPTONIZATION SPECTRA

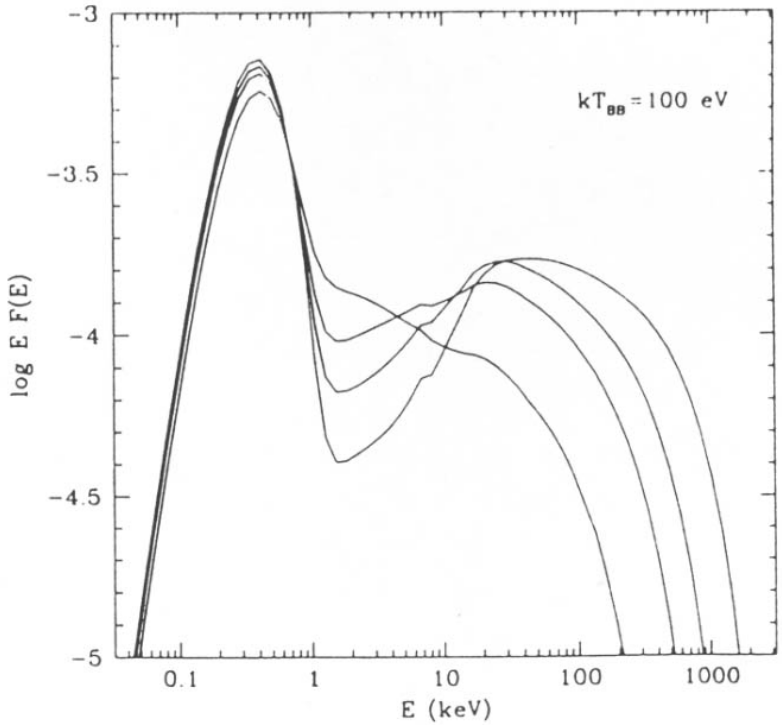


FIG. 6.—Comptonized spectra for different values of (τ, Θ) equilibrium values [(0.63, 0.11), (0.32, 0.21), (0.2, 0.3), (0.1, 0.5)]. kT_{BB} is set to 100 eV, and a face-on line of sight is considered.

REPROCESSING

- X-rays from corona illuminate the accretion disk. One of three things can happen
  - Complete photoelectric absorption (thermalization)
  - Compton scattering
  - Absorption followed by line emission (recombination or fluorescence)
- Thermalized photons are reradiated in optical/UV or infrared. How much of this “reprocessed” emission is there?
- Scattered/line photons come back in the X-ray, but with a very different spectrum to the incident one

X-ray reflection spectrum

- Most low energy photons absorbed before they escape
- Higher energy photons tend to scatter
- If matter is cold, photons lose energy so downscatter
- Resulting spectrum is very flat and peaks at ~30 keV
- Fluorescence lines from heavy elements – most prominent is Fe Kα

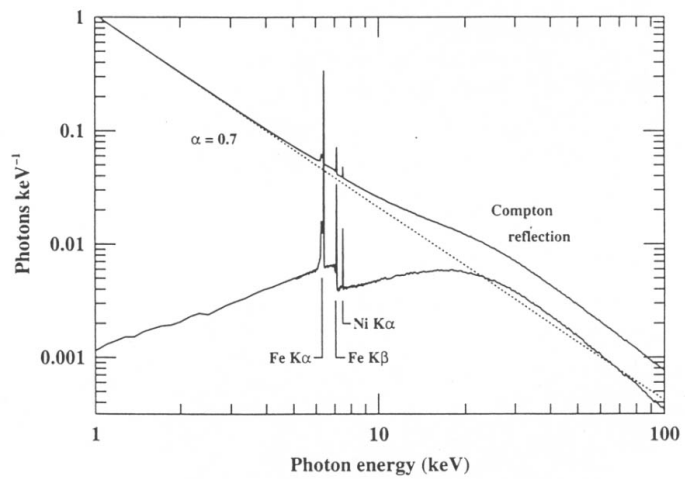
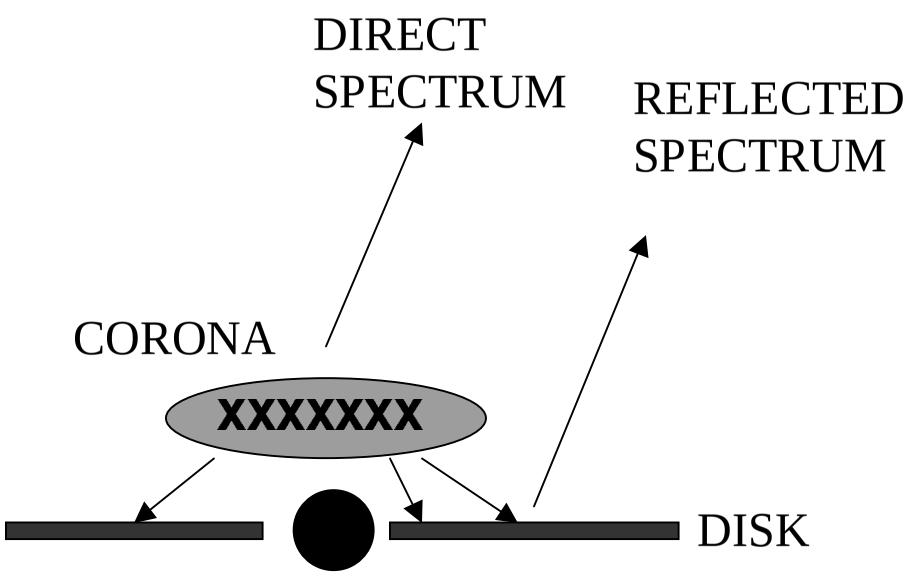
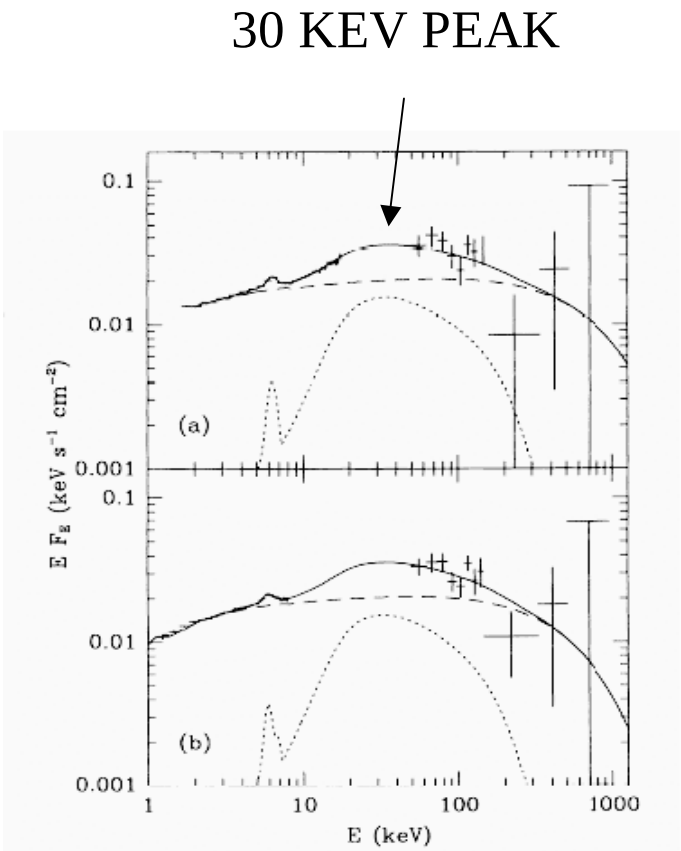


Fig. 4.4. An X-ray 'reflection' model (George and Fabian 1991). An input power-law continuum with energy index $\alpha = 0.7$, shown as a dotted line, irradiates a plane parallel slab of 'cold' (i.e., $T \lesssim 10^6$ K) gas. The lower spectrum shows the reflected X-ray spectrum, which contains the Fe Kα (6.4 keV), Fe Kβ (7.06 keV), and Ni Kα (7.48 keV) fluorescence lines, along with the Fe K-shell absorption edge at ~7.11 keV. (The corresponding Ni K-shell absorption edge at 8.34 keV is too weak to be visible.) The effects of Compton 'down-scattering' within the slab (whereby photons interact with and recoil off lower-energy electrons, losing energy in the process) can be seen in the fall-off in the reflected continuum at high energies, in the smearing of the Fe K-shell absorption edge, and in the lower-energy wings of the fluorescence lines (which is most easily seen in the Fe Kα line). The combination of Compton down-scattering of higher-energy photons on the one hand and photoelectric absorption of lower-energy photons on the other gives rise to a broad hump in the 'reflected' continuum over the range ~20–100 keV. Data courtesy of I. M. George.

REPROCESSING GEOMETRY





Fe Kα most important diagnostic of black hole

BLACK HOLES

- Solution of Einstein field equations of general relativity for point mass by Karl Schwarzschild.
- Gravitational radius $r_g = GM/c^2 = 1.48 \times 10^{13} M^8$ cm.
- Event horizon or Schwarzschild radius (no light or matter can return when crossed) is at $2 r_g$
- Marginally stable orbit for matter = $6r_g$
- High velocities close to black hole
- Also gravitational redshift: time appears to slow down close to black hole. $E_{obs} = E_{emitted} (1-2r_g/r)^{0.5}$

When do GR effects become noticeable?

KERR BLACK HOLES

- In general, the black hole can have angular momentum – solution (metric) found by Kerr
  - Spin parameterized by dimensionless parameter a=0 reduces to Schwarzschild, a=1 maximum spin
  - Event horizon at $2r_g$ for a=0; r_g for a=1
  - Marginally stable orbit depends on a. $6r_g$ for a=0 but only 1.24 r_g for a=1 (for a=-1 ie. retrograde $9r_g$)
- Accretion disk can approach closer to black hole, therefore redshifts and velocities are larger

IMPORTANCE OF IRON Kα EMISSION

- Only emission originating close to the black hole (<100 rg) can give information about non-Newtonian gravity
- X-ray photons are generated there
- Continuum alone not adequate – no fiducial energy marker – so need emission line
- Soft X-ray lines absorbed by the disk on the way out, and if not are blended with several other lines.
- Fe Kα line strong, and isolated from other features – IDEAL!

LINE BROADENING

- For a monochromatic line generated in an accretion disk rotating around a black hole, the line profile will be determined by a combination of gravitational and Doppler shifts.
- These depend on (at least):
  - Inclination of the disk
  - Inner radius
  - Outer radius
  - Spatial distribution of line emissivity

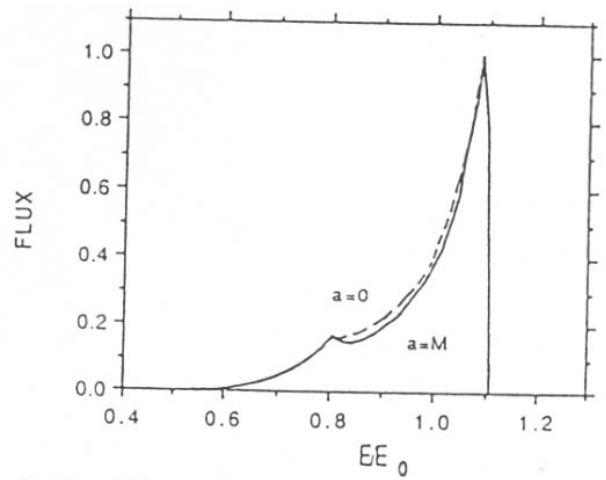


Figure 2. The difference in the line profile due to the Kerr parameter. Comparison between $a = 0$ and $a = M$ is given. The other parameters are common, ($r_{in} = 6\,M$, $r_{out} = 20\,M$, $q = -2$, $\theta_{obs} = 45°$). The solid line is the result for $a = M$ and the dashed line is that for $a = 0$.

THEORETICAL PROFILES

LINE BROADENING NEAR A BLACK HOLE

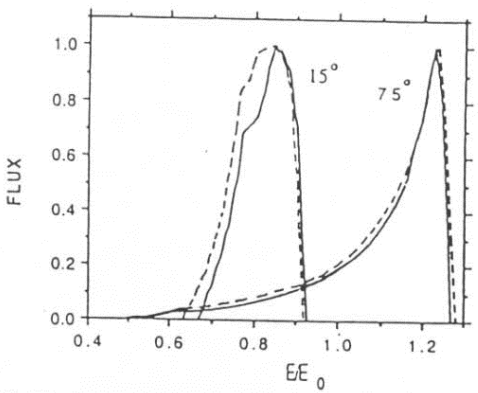


Figure 5. The difference in the line profile due to the inclination angle θ_{obs}. Results are given for $\theta_{obs} = 15°$ and 75°. The other parameters are common, ($r_{in} = 6\,M$, $r_{out} = 10\,M$, $q = -2$). The solid line is the result for $a = M$ and the dashed line is that for $a = 0$.

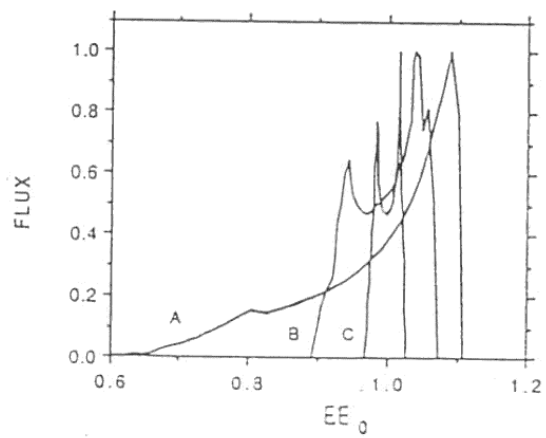
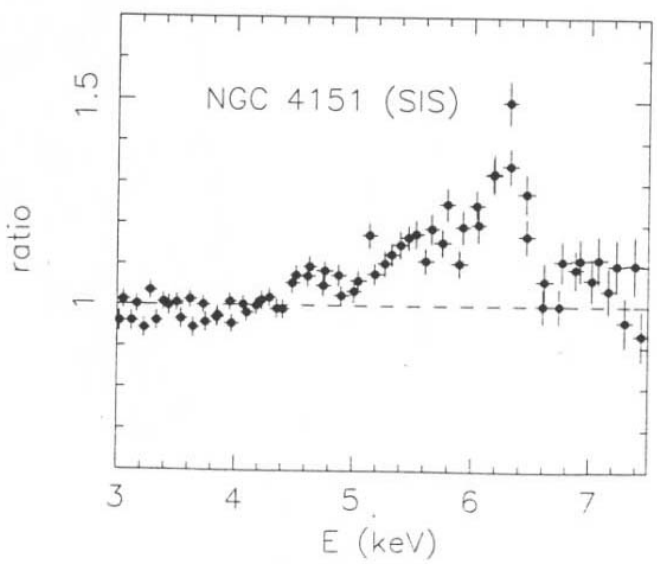


Figure 1. The difference in the line profile due to the location of emitting region. The case (A) is (r_{in}, r_{out}) = (6 M, 20 M), the case (B) (r_{in}, r_{out}) = (60 M, 200 M) and the case (C) (r_{in}, r_{out}) = (600 M, 2000 M). The other parameters are common, ($q = -2$, $a = M$, $\theta_{obs} = 45°$).

Fe K profile in NGC 4151



Fe K PROFILE IN NGC 4151

RELATIVISTIC DISK MODEL SPECTRAL FITS

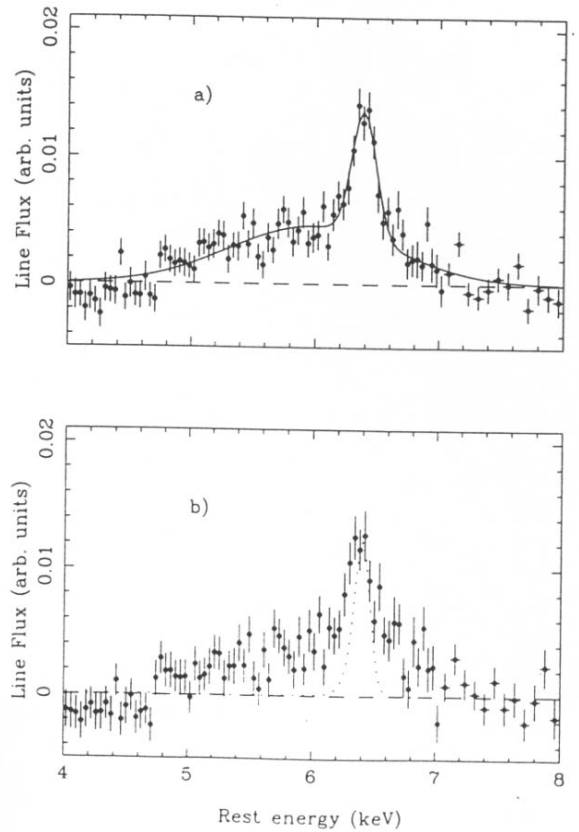
Parameter	Obs 1	Obs 2	Obs 3
χ^2	1230	1193	1689
Degrees of freedom	1261	1137	1550
E_D (keV)	$6.60^{+0.07}_{-0.09}$	$6.48^{+0.05}_{-0.06}$	$6.50^{+0.06}_{-0.08}$
I_D[a]	$5.8^{+1.8}_{-1.7}$	$6.1^{+1.9}_{-1.9}$	$7.2^{+1.6}_{-2.0}$
EW_D (eV)	307^{+93}_{-90}	245^{+75}_{-75}	241^{+53}_{-67}
q	2.63 (f)	2.63 (f)	$2.63^{+0.19}_{-0.28}$
θ_{obs}	0°0 (f)	0°0 (f)	$0°0^{+19.0}_{-0.0}$
r_i/r_g	6.0 (f) (<9.0)	6.0 (f) (<7.8)	6.0 (f) (<7.8)

NOTES.—Errors correspond to 90% confidence for six, five, and eight interesting parameters for Obs 1, Obs 2, and Obs 3, respectively (see notes for Table 1). Fixed parameters are indicated by (f). The model for Obs 1 has two fewer free parameters than Obs 3 because q and θ_{obs} are fixed at their best-fitting values for Obs 3. These are also fixed in Obs 2, which also has κ fixed (see Table 1). The upper limits for r_i/r_g correspond to 90% confidence for seven, six, and nine interesting parameters for Obs 1, Obs 2, and Obs 3, respectively.

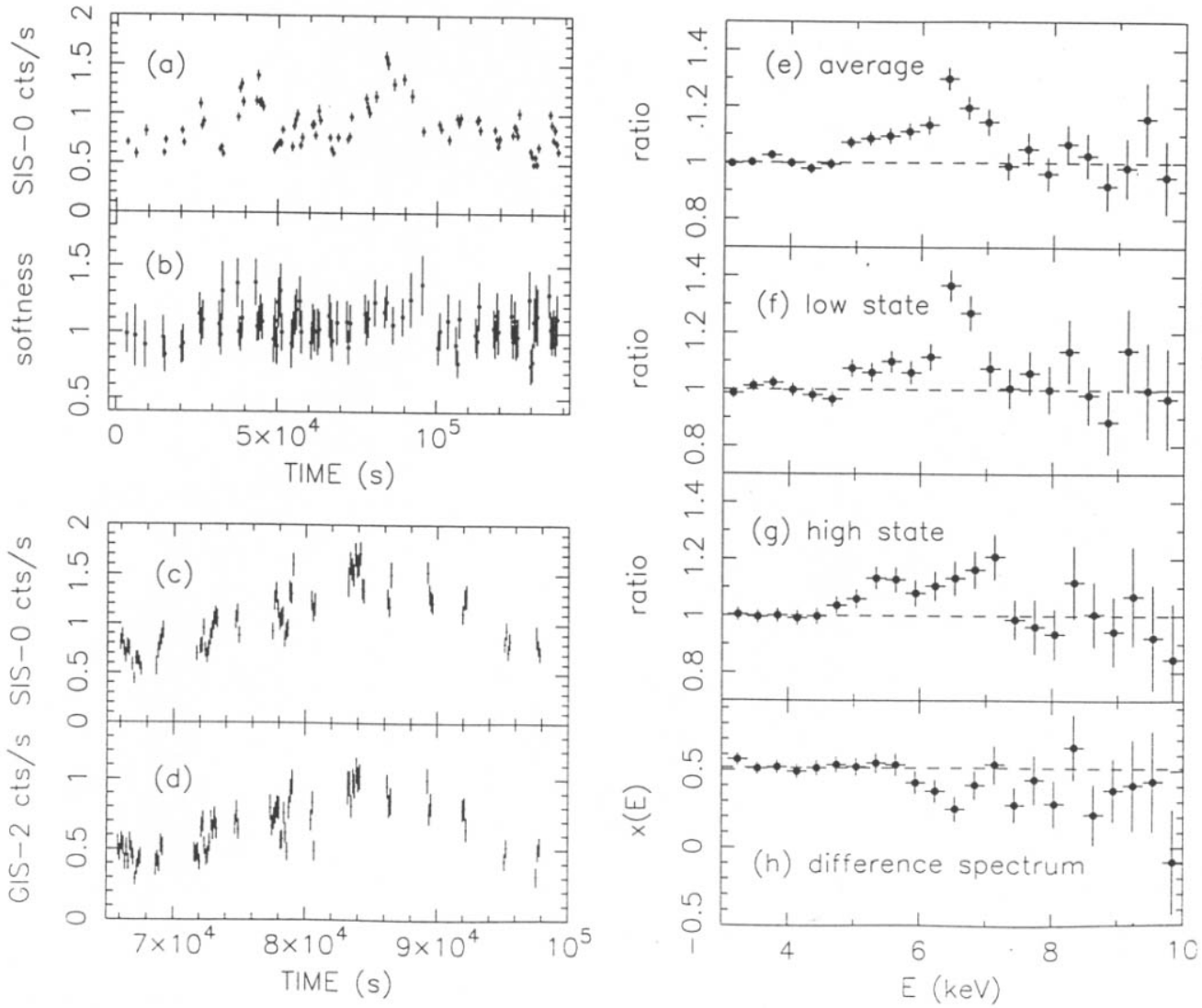
[a] Disk iron line intensity in units of 10^{-4} photons cm^{-2} s^{-1}.

AVERAGE PROPERTIES

- FWZI~100,000 km s^{-1}
- Inclination = 30 deg
- Inner radius = 6 r_g
- Outer radius = 100 r_g
- Emissivity $r^{-2.5}$
- Equiv. width 200 eV



NGC 7314 LINE VARIABILITY



FE K PROFILE VARIABILITY: NGC 7314

- Say red wing responds to continuum changes in a time Δt.
- Size of line-emitting region smaller than $c\Delta t$.
- But the size of the line-emitting region must be bigger than last stable orbit so $c\Delta t > 6r_g$ (or $1.24r_g$ for extreme Kerr).

Thus for a Schwarzschild BH:

$$M_8 < \frac{\Delta t}{2960} \tag{7}$$

and for a maximally rotating Kerr BH:

$$M_8 < \frac{\Delta t}{612} \tag{8}$$

For NGC 7314 we get $M_8 = 47$ and 230 for Schwarzschild and Kerr metrics respectively.

OBSERVATIONAL EVIDENCE FOR BLACK HOLES IN AGN

- Measurement of mass of $>10^7$ $M_\odot$ inside 0.13pc in NGC 4258 (and similar for some other sources): very difficult to fit in the requisite number of stars inside that volume and not get gravitational collapse to form black hole
- Extreme gravitational and Doppler energy shifts in the Fe Kα profile in the X-rays

SOME OUTSTANDING PROBLEMS

- What is the correct unification model? Radio quiet/loud and Seyfert 1 and 2.
- What is the physical structure of the accretion disk?
- What is the origin of the viscosity in the disk?
- What is the origin of the high energy emission and where is it produced?
- What is the origin of the rapid X-ray variability
- Can we get accurate measurements of the black hole mass?
- Is the black hole spinning?
- What is the connection between AGN and normal galaxies?
- How do AGN evolve with cosmic time?