High Energy Astrophysics

- highly ionized plasmas
- ionizing photons and particles

$(\mathcal{E} > 13.6 \text{ eV} = 1 \text{ Ryd})$

$\lambda < 912$ Å

- photon wavebands

	EUV	→	X-RAY	→	γ-RAYS
λ	1000 Å	100 Å →	12 Å	0.1 Å →	0.01 Å
ε	13 eV	0.1 keV →	1 keV	100 keV →	1 MeV
T	10^5 K	10^6 →	10^7 K	10^9 →	10^{10} K

- (High energy) particles radiate (copiously) all wavelengths: a full spectrum extending into X-ray & Gamma-rays

<u>relativistic processes</u> - play important role

"High Energy" excludes thermal radiation from most normal stars, except spectral tail of O stars. (34,000 - 10^5 K)

- Involves <u>compact objects</u> which must be <u>hot</u> to be radiatively luminous

$L_\odot = 4 \times 10^{33}$ erg/s ; $T \sim 6000$ K
$R \sim 7 \times 10^{10}$ cm

Blackbody: $L = 4\pi R^2 \sigma T^4 \Rightarrow T \propto R^{-1/2}$

So $L = L_\odot \Rightarrow$ <u>$T > 60{,}000$ K for $R < 10^9$ cm</u>

- High luminosities $\Leftrightarrow$ power available for <u>bulk flows</u>. Can be radiation driven, magnetically driven, tidally driven, thermal wind etc. Actually: <u>Gravity</u> is the ultimate driver in all cases and e.g. mag fields are intermediary

- <u>Supernova shocks/outflows</u> $V_{eject} > 5000$ km/s

$$\mathcal{E} \sim \frac{1}{2} m_p V^2 \sim kT$$

$$\Rightarrow T > 10^8 \text{ K}$$

- <u>Collimated Outflows</u> - usually associated with accretion

More outflow power available the more compact the object:

force density: $f = \frac{GM\rho}{R^2}$ for $\rho \propto \frac{1}{R^n}$

Hot X-ray gas is common in

Clusters of Galaxies:

→ Velocity dispersion of stars in cluster $\gtrsim 1000$ km/s

$c_s \sim v_{disp}$ in virial equilibrium ⇒

$T_{gal} \geq 3 \times 10^7$ K in clusters.

(X-ray gas in clusters is such a popular subject of study that "clusters" are often defined by their X-ray properties.)

- Sources of high energy astrophysics to be disussed
  - → compact objects (W.D, NS, B.H)
  - → Supernovae
  - → cosmic rays
  - → solar Corona
  - → Accretion Disks (AGN, YSO, compact objects)
  - → AGN & galaxy clusters
  - Gamma-Ray Bursts: highly relativistic sources

X-ray Astronomy History

- X-rays do not penetrate Earth's Atmos need to be above upper 1% of atmos to see 0.5 – 5 keV range
- attenuation decreases as X-ray photon energy increases
- Balloons ok for up to 40 km $E \geq 30$ keV
- rockets needed for > 80 km $E \gtrsim 3$ keV

(note 1 keV = 1.6×10^{-9} erg = $k_b T_{1keV}$
$\Rightarrow T_{1keV} = 1.6 \times 10^7$ K)

Balloons have advantage that they stay up longer

Rockets (as opposed to satellites) stay up for 5 min

Rockets

- German rockets captured in WWII
1949 geiger counters put on the rockets & sent up Sun was detected.
- 1950s technology would require 10^5 times more sensitivity if nearest stars emitted $L_X = L_{X\odot}$
- 1950s only sun was studied in X-rays
- 1962 American Science and Engineering launched rocket to detect X-rays from interaction of solar wind with moon –
- Instead, discovered Sco-X-1 (1st X-ray source in Scorpius constellation)
- much brighter than sun: reason not discovered earlier was "positioning" was only done passively, by spinning or precession of rocket
- what is Sco X-1 ?

- took 4-years from launch to locate object.
- object not understood until 1971 after Cen X-3 was discovered (see below)

Note: Sco X-1 looked bright in X-rays but not in opt
(100 stars brighter in opt / sq deg on ave.)

- Sco X-1 radiates 10^4 times $F_\odot$ in X-rays (up to 10^{38} erg/s $L_\odot$)
- 1971 Uhuru Satellite found Cen X-3 (Schreirer et al '71)

found
1. periodicity 4.84 seconds
2. period varied in time 2.09 days
3. X-rays disappeared completely for 11 hr in cyles

Any Guess?

→ [Rotating NS in binary]

: companion is a B0I star

(B = spectral class   I = supergiant
O = highest luminosity subclass)

→ energy to power X-ray source comes from accretion.

→ most early rocket discovered sources were accretion powered - binaries or Supernova Remnants

→ after 1973: CV's discovered
e.g. SS Cyg: CV's are accreting white dwarfs with low mass normal star companions

1st SNR to be discovered was Crab Nebula ($\simeq 10^2$ times brighter than most SNR)

1st X-ray extragalactic X-ray source detected was M 87 in 1965

→ 1st non-solar star Capella: $L_X = 10^4 L_{X\odot}$

Hard X-ray Balloons

- rockets showed spectra of X-ray sources were hard extending above 10 keV.
- Balloons could be used for ≥ 30 keV if above 40 km
- long duration observations made possible by balloons
- measurements up to 500 keV
- Crab up to 500 keV for example
- lunar occultation of Crab
- Spectral break in accreting NS Cyg X-1 at temperature 2×10^7 K,
- cyclotron lines at 40 keV in NS Her X-1 allowing B-field to be measured 5×10^{12} G

$$\frac{mv^2}{r} \sim \frac{eBv}{c} \Rightarrow$$

$$\Rightarrow \omega = \frac{eB}{mc} \text{ for particle of mass } m$$

emission frequency: $\nu_e = \frac{\omega}{2\pi} = \frac{1}{P} = \frac{eB}{2\pi mc}$

X-ray sattelites

- UHURU 1970 2-20 keV
  339 objects mostly X-ray binaries and Supernova Remnants
- Strong clustering near Galactic plane
- Fainter flux of isotropic seyferts & clusters
- Cen X-3 & Her X-1 proved accreting NS / binary
- Cyg X-1 : short time variability & source positions from rockets allowed determination of mass of accretor to be determined
  => black hole : too massive for NS (more on this later)

main features of satellite telescopes

raging:

- Wolter optics is main technique paraboloidal – hyperboloidal mirrors which reflect X-rays under grazing incidence (otherwise X-rays are absorbed!)

- Einstein obs. (EO) was first to image: 10" (arc sec) resolution (EO = HEAO-2)

X-ray sky surveys:

- UHURU 350 sources 2-6 keV
- HEAO-1 840 soures 0.1 - 200 keV

} 1 deg² res

- ROSAT ½ year all sky survey 80,000 sources 25" resolution. Also all sky map of X-ray background 12' res.
- total number of ROSAT sources: 150,000 8 year lifetime of ROSAT

- CHANDRA Recent deep field survey

Other instruments

XMM, RXTE, ~~ASTRO-E~~ (oops: lost), Spectrum X-Gamma

Beppo-SAX, ASCA, COS-X (on hold)

by 2005 with Chandra: ≃ 500,000 total known sources in X-rays

Important recent discoveries

→ Rossi Timing Explorer RXTE 2-200 keV

high spectral & temporal resolution

- 2.75 ms bursts of low mass X-ray binary (LMXB) 4U 17h28m-34° ⇒ thermonuclear hot spot on NS
  (4U = CAT, 1728 = RA, 34 = DEC)

- X-ray Burster from Beppo Sax, RXTE found 2.5 ms bursts + persistent flux. only LMXB showing bursts & persistent pulsations

- Beppo Sax - 0.1-200 keV discovered X-ray afterglows of Gamma-Ray bursts allowed better localization → optical followups .... → redshift detection

ROSAT & ASCA

ΔE/E

ROSAT: • 40% spectral resolution in 0.1 – 2.4 keV band (position sensitive proportional counter)

• 5" angular resolution images with plate detector "high resolution imager"

ASCA: • 0.5 – 10 keV CCD detectors superior energy resolution to ROSAT (2 %) at 5.9 keV but worse ∡ res (3').

ROSAT took 1st X-ray picture of moon

→ note moon is X-ray bright from Thomson scattering off a thin layer near moon's surface; also flourescence from minerals produces spectral bump

→ ROSAT measured X-rays from comets unsolved problem to understand:

- scattering of solar X-rays?
- Bremsstrahlung between shock accel e^- & coma?
- Charge exchange between highly charged ions in <u>solar wind</u> and coma ← BEST

→ ROSAT found many stars with X-ray coronae

→ ROSAT pinpointed (via unidentified sources later followed up in optical) Several hundred T-Tauri stars way outside regions of star formation (T-tauri are extremely young stars of $M \sim M_\odot$)

→ ROSAT found Brown Dwarfs ⇒ Brown Dwarfs have hot coronae

→ ROSAT found X-ray emission from nuclear burning on surface of accreting WD binary systems (soft X-ray sources)

→ ROSAT found 200 SN remnants

→ ROSAT + ASCA 34 new pulsars
Can test NS cooling models

→ ROSAT 550 new X-ray sources in Andromeda

- ASCA spectroscopy of MCG-6-30-15
  Seyfert Galaxy with broad iron lines
  iron line shapes => black-hole because of gravitational redshift of line

- 50% of ROSAT sources are AGN

- 80% of X-ray background resolved by ROSAT (the remaining 20% by Chandra)

- Clusters: ROSAT showed hot X-ray plasma is 20% of cluster mass, and 4-5 times larger than mass in galaxies in clusters (the rest is dark matter)
- ASCA: Fe abundane in clusters is $\frac{1}{3}$ solar => primordial gas

- Several thousand clusters discovered by ROSAT => cosmology
  observed cluster evolution is much slower than predicted by simulations
  => universe is subcritical and wont close

X-ray binaries
Galaxies
Stars
AGN
Clusters
SNR
Gamma-Ray Bursts

} CHANDRA + OTHERS

X-ray Backround - resolved
Galactic ISM - diffuse
Galactic Coronae - diffuse
Planetary Nebulae - point sources + diffuse
Jets in Crab + Vela

} CHANDRA progress examples

→ Chandra 0.5" resolution
→ sources > 10 times fainter than previous scopes
→ very impressive imager
- pretty good for spectral resolution but not better than ASCA
- COS-X even better than Chandra, but not launched yet! (mission canceled)

Radio

- many high energy sources are radio sources

- radio astronomy started 1931
  Jansky measured Galactic Center

- 1944 2m all sky survey by Reber in his backyard

- "Radar echoes" from meteors in WW II

- Cas A SNR 1965 cambridge
  1 mile telescope 30" resolution

- Today: big arrays
  VLA ⇔ 20 km base lines in N Mexico
  VLBA ⇔ 8000 km base line
  VLBI ⇔ $\geq$ 10,000 km base line
  10^{-4} arc sec resolution!

Important radio results

- 21 cm line, galactic rotation curves
- radio galaxies: loud in radio faint in optical with jets / lobes up to $\simeq 1$ Mpc in scale
- quasars, first seen as "quasi-stellar radio sources"
- 150 SNR
- neutron stars first discovered as pulsating radio sources
- probes inner regions of AGN
- probes late time evolution of GRB

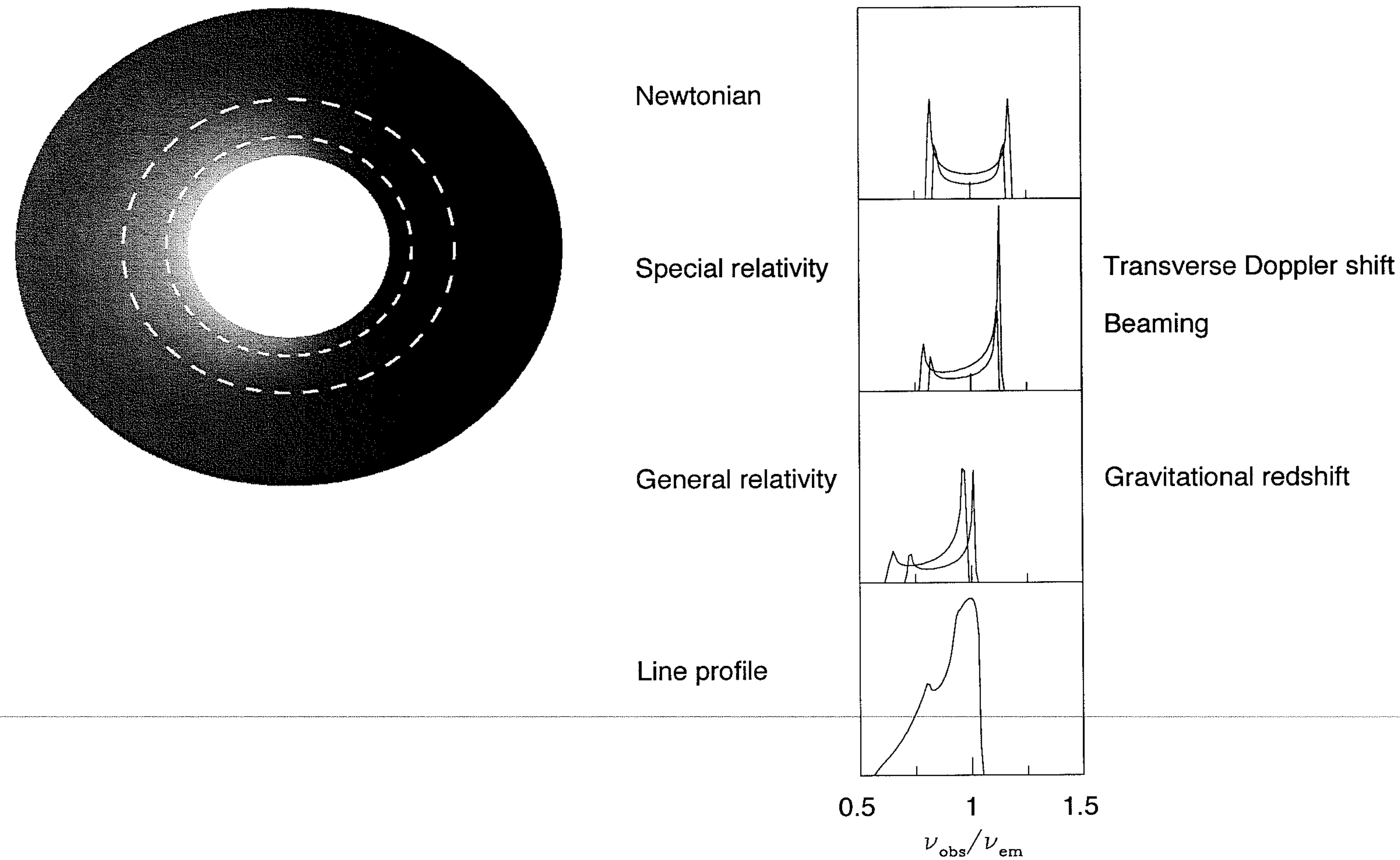
UV

- 100 - 3000 Å
- Ionization potential of hydrogen
- heavily blocked by dust
- Instrumentation "easier"
- plasma diagnostics at few x 10^5 K temps.
- White Dwarfs, Planetary Nebulae
- transition between photosphere and Corona of Sun
- absorption lines in spectra indicate Hot ISM
- Winds from O stars, Wolf-Rayet stars — P-cygni profiles

→ blue shifted absorption lines $\gtrsim 3000 \frac{km}{s}$

10^{-5} $M_\odot$/yr loss rates

(Sun loss rate is 10^{-14} $M_\odot$/yr by comparison)



Fabian et al. PASP 2000
112 1145

RN '03

CLOSE

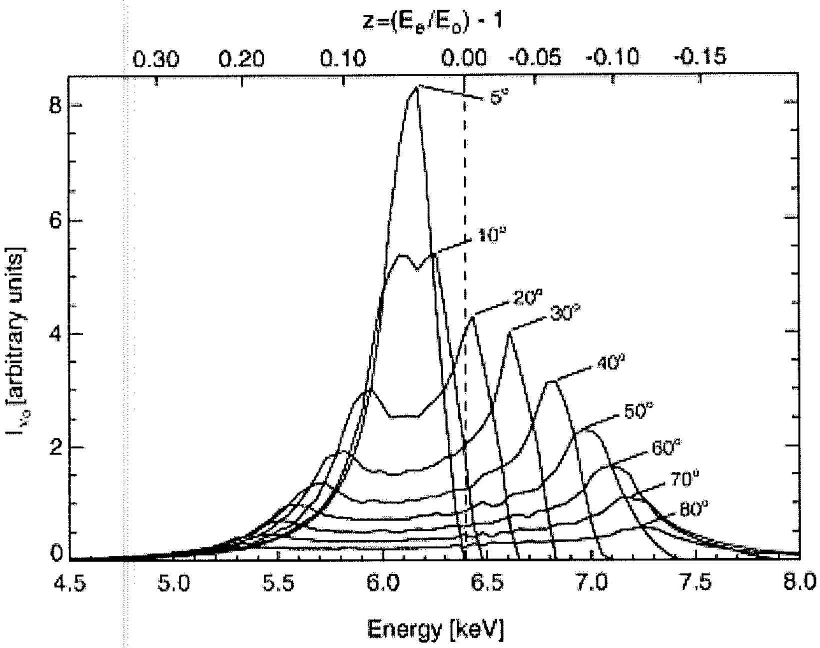


Fig. 9. Iron line profiles from relativistic accretion disk models as a function of disk inclination (as measured by the angle between the normal to the disk plane and the observers line of sight). The black hole is assumed to be rapidly rotating (a=0.998), and the disk is assumed to possess a line emissivity index of β=0.5 down to the radius of marginal stability $r \approx 1.23\ GM/c^2$.

RN '03

CLOSE

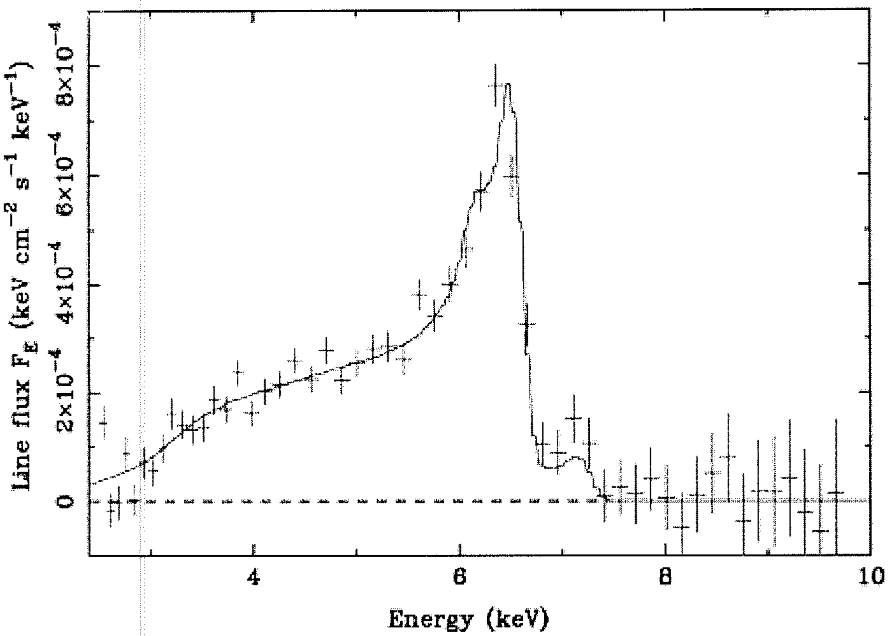


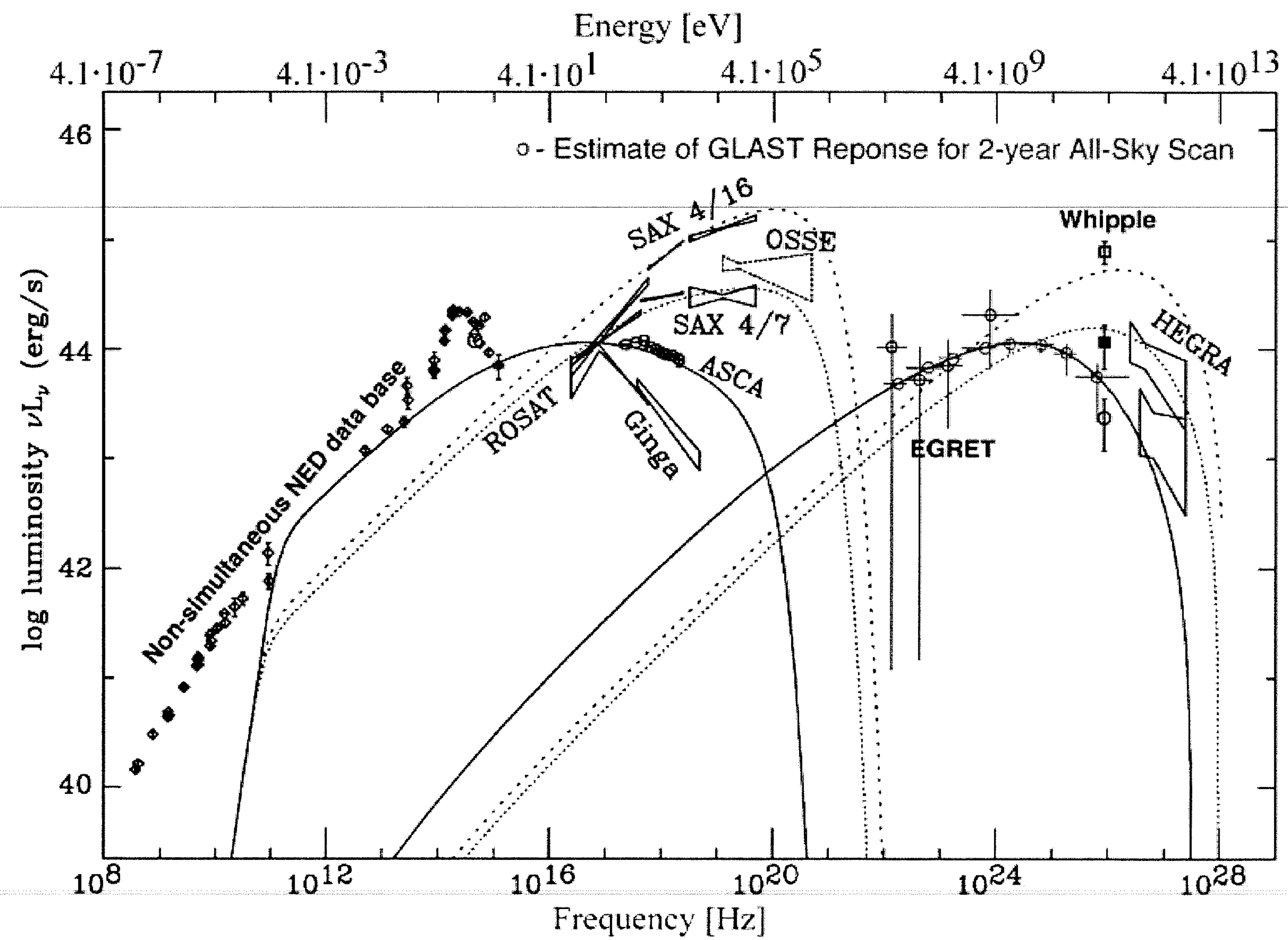
Fig. 15. Continuum subtracted iron line profile from the second XMM-Newton observation of MCG–6-30-15 [220]. This is the highest signal to noise relativistic line profile yet measured.

Reynolds & Nowak Phys. Reports (2003)

Table 1. Observatories and instruments that have b important for studies of X-ray reflection from black sources

Observatory (lifetime)	Instrument	Area (cm^2)	Band (keV)
EXOSAT (ESA)	GS	100	2–20
May 1983–April 1986	ME	1600	1–50
Ginga (Japan)	LAC	4000	1.5–3'
February 1987–November 1991			
ASCA (Japan+NASA)	GIS	2×50 @ 1 keV	0.8–1
February 1993–March 2001	SIS	2×100 @ 6 keV	0.5–1
RXTE (NASA)	PCA	6500	2–60
December 1995–present	HEXTE	2×800	15–25
BeppoSAX (IT+NL)	LECS	22 @ 0.28 keV	0.1–1
April 1996–April 2002	MECS	150 @ 6 keV	1.3–1
	PDS	600 @ 80 keV	15–30
Chandra (NASA)	ACIS	340 @ 1 keV	0.2–1
July 1999–present	HETG	59 @ 1 keV	0.4–1
XMM-Newton (ESA)	EPIC-MOS	2×920 @ 1 keV	0.2–1
December 1999–present	EPIC-PN	1220 @ 1 keV	0.2–1

Note that some of these observatories possess oth instruments/detectors that we have not listed since not of direct relevance to iron line studies. Instrum abbreviations: ACIS: AXAF Charged Coupled Imagi



Energy [eV]
4.1·10^-7
4.1·10^-3
4.1·10^1
4.1·10^5
4.1·10^9
4.1·10^13
o - Estimate of GLAST Reponse for 2-year All-Sky Scan
SAX 4/16
OSSE
Whipple
SAX 4/7
HEGRA
ASCA
ROSAT
Ginga
EGRET
Non-simultaneous NED data base
log luminosity νLν (erg/s)
46
44
42
40
10^8
10^12
10^16
10^20
10^24
10^28
Frequency [Hz]

eg. Reynolds & Nowak '03

CLOSE

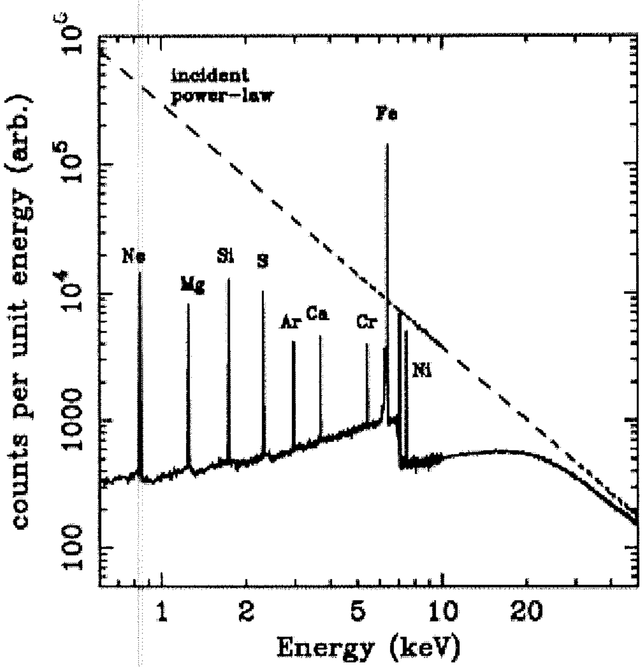
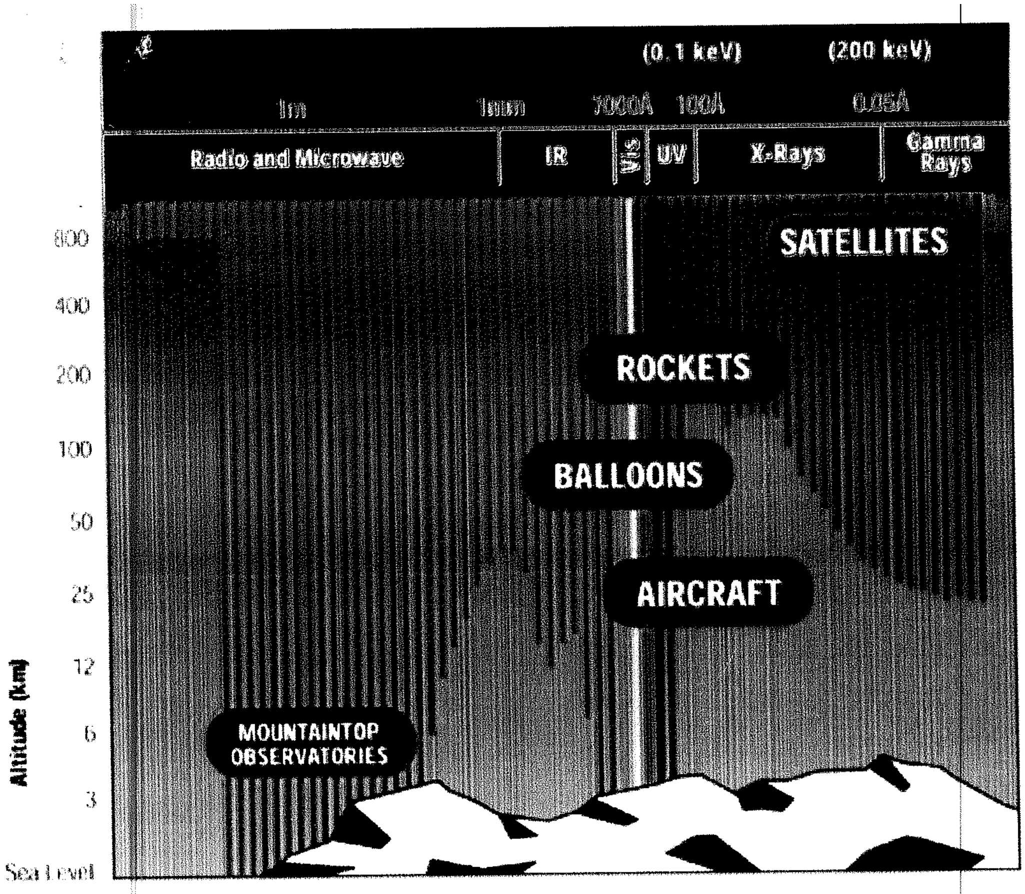


Fig. 7. Results of a simple Monte Carlo simulation demonstrating the "reflection" of an incident power-law X-ray spectrum (shown as a dashed line) by a cold and semi-infinite slab of gas with cosmic abundances. In the accretion disk setting, one would observe the sum of the direct power-law continuum and the reflection spectrum—the principal observables are then the cold iron Kα fluorescent line at 6.40 keV and a "Compton reflection hump" peaking at ∼30 keV. Figure from [178].



(0.1 keV)
(200 keV)
1m
1mm
7000Å
100Å
0.05Å
Radio and Microwave
IR
Vis
UV
X-Rays
Gamma Rays
SATELLITES
ROCKETS
BALLOONS
AIRCRAFT
MOUNTAINTOP OBSERVATORIES
800
400
200
100
50
25
12
6
3
Sea Level
Altitude (km)