High Energy Astrophysics

- Highly ionized plasmas
- Ionizing photons and particles
  \( \varepsilon > 13.6 \text{ ev} = 1 \text{ Ryd} \)
  \( \lambda < 912 \text{ Å} \)

- Photon wavebands
  EUV \( \rightarrow \) X-ray \( \rightarrow \) X-rays
  1000 Å \( \rightarrow \) 100 Å \( \rightarrow \) 0.1 Å

- 13 eV \( \rightarrow \) 1 keV \( \rightarrow \) 1 MeV
  \( 10^5 K \rightarrow 10^9 \rightarrow 10^{10} K \)

(High energy) particles radiate (copiously) all wavelengths: a full spectrum extending into X-ray & gamma-rays.
Relativistic processes play important role.

High energy excludes thermal radiation from most normal stars, except spectral tail of O stars. (34,000 - 10^5 K)
Involves compact objects which must be hot to be radiatively luminous:

\[ L_\odot = 4 \times 10^{33} \text{erg/s} \quad \text{if } T = 6000 \text{K} \]
\[ R = 7 \times 10^{10} \text{cm} \]

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

So \( L = L_\odot \Rightarrow T > 60,000 \text{K} \text{ for } R < 10^9 \text{cm} \)

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High luminosities \( \Rightarrow \) power available for bulk flows, can be radiation driven, magnetically driven, tidally driven, thermal wind, etc. Actually: gravity is the ultimate driver in all cases and e.g. mag fields are intermediary.

Supernova shocks/outflows \( V_{\text{ eject}} > 5000 \text{ km/s} \)

\[ E = \frac{1}{2} m_p V^2 \approx kT \]

\( \Rightarrow T > 10^8 \text{ K} \)

Collimated outflows - usually associated with accretion. More outflow power available the more compact the object: force density:
\[ f = \frac{GM_s}{R^2} \text{ for } s \propto \frac{1}{R^n} \]
Hot X-ray gas is common in Clusters of Galaxies:

1. Velocity dispersion of stars in cluster $\geq 1000 \text{ Kms}^{-1}$

2. $c_s = V_{\text{disp}}$ in virial equilibrium $\Rightarrow$

3. $T_{\text{gal}} \geq 3 \times 10^7 \text{ K}$ 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 discussed:

1. Compact objects (WD, NS, BH)
2. Supernovae
3. Cosmic rays
4. Solar Corona
5. Accretion Disks (AGN, YSO, compact objects)
6. AGN & galaxy clusters
7. 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 $E \geq 3$ keV

Note $1$ keV = $1.6 \times 10^{-9}$ erg = $k_B T_{\text{keV}}$

$\Rightarrow T_{\text{keV}} = 1.6 \times 10^9 \text{ K}$

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 $L_x > L_x \theta$

- 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 $F_0$ in X-rays (up to $10^{38}$ erg/s in $L_0$)

- 1971 Uhuru Satellite found Cen X-3 (Schreiner 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 cycles

Any guess?
[Rotating NS in binary]

- Companion is a BOI star
  - B = spectral class
  - O = highest luminosity subclass
  - I = supergiant

- 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 (≈10² times brighter than most 5 SNR)

1st x-ray extragalactic X-ray source detected was M87 in 1965

1st non-solar star capella: \( L_x = 10^4 L_x \odot \)
Hard X-ray Balloons

of X-ray sources

neutrons showed spectra 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 in

Moon occultation of Crab.

Spectral break in accreting NS

Cyg X-1 at temperature 2 x 10^7 K.

Cyclotron lines at 40 keV in

NS Her X-1 allowing B-field

to be measured 5 x 10^{12} G.

\[ m \nu^2 - e^2 / r = 0 \]

\[ w = eB / mc \] for particle of mass m

emission frequency: \[ \Delta \nu = \frac{1}{\tau} \frac{eB}{2 \pi mc} \]
X-ray satellites

- 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
  \[ \Rightarrow \text{black hole: too massive for NS} \]
  (more on this later)
Main features of satellite telescopes

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

- Einstein obs. was first: 10'' resolution
  (EO → image)
- X-ray sky surveys: (EO = HEAD-2)
  - HUTV: 350 sources 2-6 keV 7 deg²
  - HEAD-1: 840 sources 0.1-200 keV 4 deg²
- ROSAT: 1 year all sky survey 80,000
  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, spectrum X-Gamma
Beppo-SAX, ASCA, COS-X (on hold)
by 2005 with Chandra: ~500,000 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 1728-34° → thermonuclear hot spot on NS
  - Cat RA DEC

- X-ray burst from BeppoSAX, RXTE
  found 2.5 ms persistent flux, only LMXB showing bursts & persistent pulsations
  - BeppoSAX - 0.1 - 200 keV discovered

X-ray afterglows of Gamma-Ray bursts allowed better localization
- optical follow-ups → redshift detection
Rosat:
- 40% spectral resolution - position sensitive in 0.1 - 2.4 keV band (proportional counter)
- 5'' angular resolution images with plate detector "high resolution imager"

Asca:
- 0.5 - 10 keV CCD detectors
- superior energy resolution to Rosat
- but worse x res (3')
- at 5.9 keV

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 fluorescence from minerals produces spectral bump

Rosat measured X-rays from comets
- unsolved problem to understand:
  - scattering of solar X-rays?
  - Bremsstrahlung between shock and e- & coma?
  - charge exchange between highly charged ions in solar wind and coma
ROSS found many stars with x-ray coronae

ROSS 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 ≈ Mo)

ROSS found Brown Dwarfs → Brown Dwarfs have hot coronae

ROSS found x-ray emission from nuclear burning on surface of accreting WD binary systems (soft x-ray sources)

ROSS found 200 SN remnants

ROSS + ASCA 34 new pulsars can test NS cooling models

ROSS 550 new x-ray sources in Andromeda
- ASCA spectroscopy of Mrk-6-30-15
  - Seyfert galaxy with broad iron lines
  - Iron line shapes \( \Rightarrow \) 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 abundance in clusters is \( \frac{1}{3} \) solar \( \Rightarrow \) primordial gas
- Several thousand clusters discovered by ROSAT \( \Rightarrow \) cosmology
- Observed cluster evolution is much slower than predicted by simulations \( \Rightarrow \) universe is subcritical and won't close
X-ray binaries

Galaxies
Stars
AGN
Clusters
SNR
Gamma-Ray Bursts

X-ray background - resolved
Galactic ISM - diffuse
Galactic Corona - 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!
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 WWII

- Cas A SNR 1965 Cambridge 1 mile telescope 30" resolution
- Today: big arrays
  VLA ↔ 20 km base lines in NM
  VLBA ↔ 8000 km base line
  VLB1 ↔ ≥ 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 ~1 Mpc in scale

quasars, first seen as "quasi-stellar radio sources"

ISO 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, P-Cygni profiles
- Wolf-Rayet stars
- Blue shifted absorption lines \( \gtrsim 3000 \text{ km/s} \)

\( 10^{-5} \text{ M}_\odot/\text{yr} \) loss rates
(Sun loss rate is \( 10^{-14} \text{ M}_\odot/\text{yr} \) by comparison)
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 $\beta=0.5$ down to the radius of marginal stability $r=1.23 \ GM/c^2$. 
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.
Table 1. Observatories and instruments that have been important for studies of X-ray reflection from black sources

<table>
<thead>
<tr>
<th>Observatory (lifetime)</th>
<th>Instrument</th>
<th>Area (cm²)</th>
<th>Band (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXOSAT (ESA) May 1983–April 1986</td>
<td>GS</td>
<td>100</td>
<td>2–20</td>
</tr>
<tr>
<td>Ginga (Japan) February 1987–November 1991</td>
<td>LAC</td>
<td>4000</td>
<td>1.5–3'</td>
</tr>
<tr>
<td>ASCA (Japan+NASA) February 1993–March 2001</td>
<td>GIS</td>
<td>2 × 50 @ 1 keV</td>
<td>0.8–1</td>
</tr>
<tr>
<td>ASCA (Japan+NASA) April 1996–April 2002</td>
<td>SIS</td>
<td>2 × 100 @ 6 keV</td>
<td>0.5–10</td>
</tr>
<tr>
<td>RXTE (NASA) December 1995–present</td>
<td>PCA</td>
<td>6500</td>
<td>2–60</td>
</tr>
<tr>
<td>BeppoSAX (IT+NL) April 1996–April 2002</td>
<td>LECS</td>
<td>22 @ 0.28 keV</td>
<td>0.1–10</td>
</tr>
<tr>
<td></td>
<td>MECS</td>
<td>150 @ 6 keV</td>
<td>1.3–10</td>
</tr>
<tr>
<td></td>
<td>PDS</td>
<td>600 @ 80 keV</td>
<td>15–30</td>
</tr>
<tr>
<td>Chandra (NASA) July 1999–present</td>
<td>ACIS</td>
<td>340 @ 1 keV</td>
<td>0.2–10</td>
</tr>
<tr>
<td></td>
<td>HETG</td>
<td>59 @ 1 keV</td>
<td>0.4–10</td>
</tr>
<tr>
<td>XMM-Newton (ESA) December 1999–present</td>
<td>EPIC-MOS</td>
<td>2 × 920 @ 1 keV</td>
<td>0.2–10</td>
</tr>
<tr>
<td></td>
<td>EPIC-PN</td>
<td>1220 @ 1 keV</td>
<td>0.2–10</td>
</tr>
</tbody>
</table>

Note that some of these observatories possess other instruments/detectors that we have not listed since not of direct relevance to iron line studies. Instrument abbreviations: ACIS: AXAF Charged Coupled Imagi...
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 Ka fluorescent line at 6.40 keV and a "Compton reflection hump" peaking at \( \sim 30 \) keV. Figure from [178].