Summary of Class

- Main topics
- Introductory Lectures – what is High Energy Astrophysics
- Physical Processes
- X-ray Detectors +Telescopes
- Cluster Lectures
- NS Lectures
- Black Hole Lectures
- SuperNova and SNR lectures
- Gamma-ray bursts
- Summary

- Unifiying theme: high energy processes in high energy objects

Basic physical processes
Black body radiation
Synchrotron radiation
Compton scattering
Line emission
Photoelectric absorption

Observational results strongly influenced by the properties of telescopes and detectors and need to get above the atmosphere (observatories need to be in space)
wide variety of detectors
can focus in the x-ray
γ-rays cannot be focused.

Please Fill In Your Evaluations

- Today the Department administrator said
- 'Our high-energy astrophysics classes seem to have low-energy students, especially ASTR 480 (only 27% responses (4 students) !!) '

What are High Energy Objects

- Compact objects (white dwarfs, neutron stars, black holes)- M/R is very large. Effects of gravity are dominant (GR is important)
- Objects dominated by high energy (x-ray, γ-ray emission)- clusters of galaxies, supernova remnants
- Objects that have both : gamma-ray bursts.
- Ability to probe cosmology: clusters, supermassive blackholes (active galaxies), gamma-ray bursts

How are 'high energy' photons produced

– Continuum

Thermal emission processes

  Blackbody radiation
  Bremsstrahlung

Non-thermal processes

  Synchrotron radiation
  Inverse Compton emission
  Non-thermal bremms

Line emission and absorption

  photoionization
  collisional excitation

How are Photons Generated/Absorbed

- Physical processes
  - **Black body radiation**- system is in equilibrium and all electromagnetic radiation falling on it is absorbed. At a particular temperature a black body emits the maximum amount of energy possible for that temperature.
  - **Synchrotron radiation**
    High energy (relativistic) particles 'spiraling' in a magnetic field (accelerated electrons)

Compton scattering
Electrons scattering of photons/photons scattering off electrons

Line Emission and absorption
Atomic transitions in atoms- x-rays mostly from K, L shell transitions

Photoelectric Absorption
Photons are absorbed by atomic transitions

•Difference between thermal (Maxwell-Boltzman distribution, equilibrium) and non-thermal (often power law distribution of particles)

•Collisional (bremmstrahlung, Compton scattering)

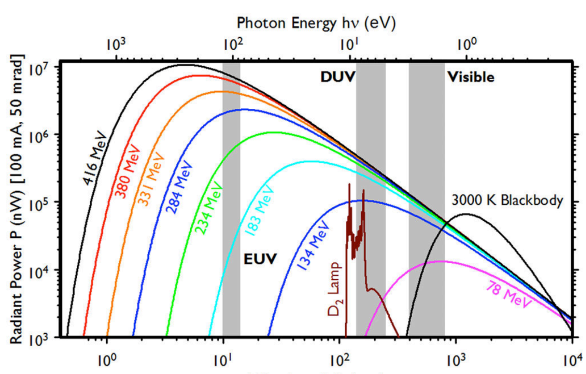
•Temperature sensitivities of different mechanisms give diagnostics

Synchrotron Emission

- Galactic radio emission (radiation from the halo and the disk),
- radio emission from the shell of supernova remnants
- X-ray synchrotron from PWN in SNRs
- Radio galaxies – lobes and jets
- Low Energy (radio-UV) Blazar continuum

Synchrotron

- For a power law input spectrum of particles $\longrightarrow$ a power law photon spectrum out to some maximum frequency
- **If particle spectrum is $dN/dE \sim N_0 E^{-p}$**
- **photon spectrum is $I_\nu \sim C_0 \nu^{-(p-1)/2}$**
  - **Higher energy particles radiate at higher energies $\nu \sim \gamma^2 qB/mc$**
- Where $C_0 \sim N_0 U_B \sigma_T$
  - **depends on the energy density of the B field $U_B \sim B^2$**
  - The Thompson cross section σ_T
  - and the number of particles N_0



NIST website
NIST SURF What is synchrotron radiation?

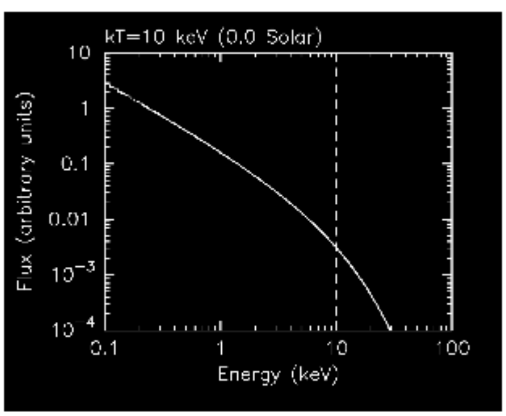
- continuum
  - blackbody- isolated neutron stars
  - synchrotron: some SNR (e.g. Crab)
  - bremsstrahlung: Clusters of galaxies
  - Compton scattering: X-ray continuum of AGN
- lines
  - fluorescence: AGN
  - thermal: clusters
  - photoionization : AGN

Which sources exhibit which processes?

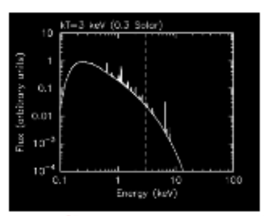
BREMSSTRAHLUNG SPECTRUM

$$I(E) = AG(E,T)Z^2 n_e n_i (kT)^{-1/2} e^{-E/kT}$$

exponential fall off at high E



A = normalization, G = Gaunt factor,
Z = charge of positive ions
n_e and n_i electron and ion densities
for $E << kT$ the spectrum is approximately a power law
for $h\nu >> kT$ there is an exponential cutoff



[In reality accompanied by recombination line emission]

Luminosity $L = 1.44\times10^{-27}\, T^{1/2} Z^2 n_e n_{ion} G\, V$ T = temperature, V = volume

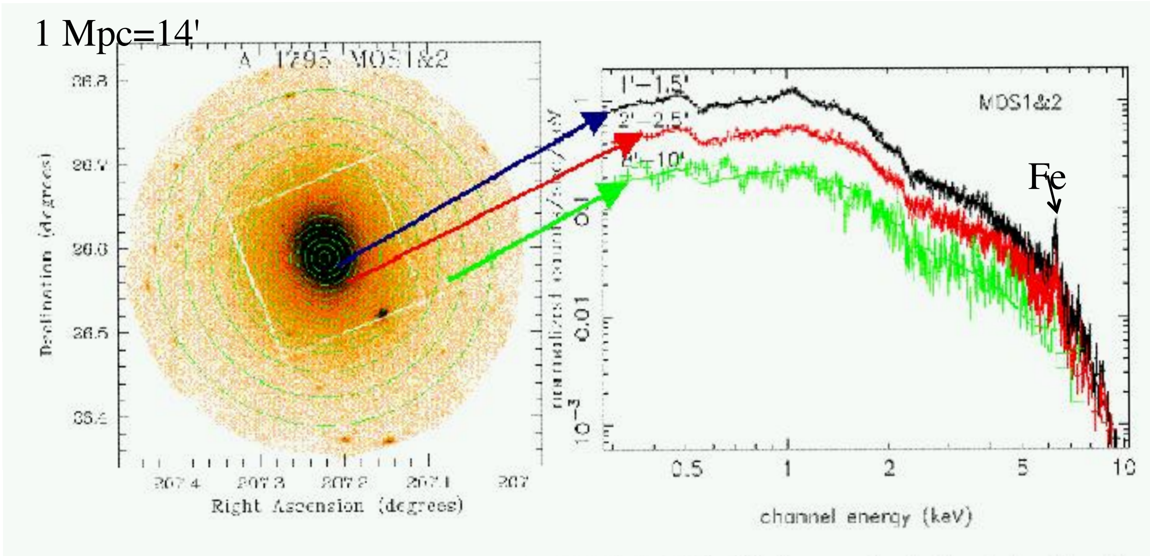


Figure 6: **Left:**Combined EPIC/MOS1&2 image of A 1795 in the [0.3−10]keV energy band. The circles define the

X-ray spectra of a Cluster

continuum due to bremmstrahlung - spectrum +geometry measure particle density and total mass of gas

Thompson/Compton Scattering

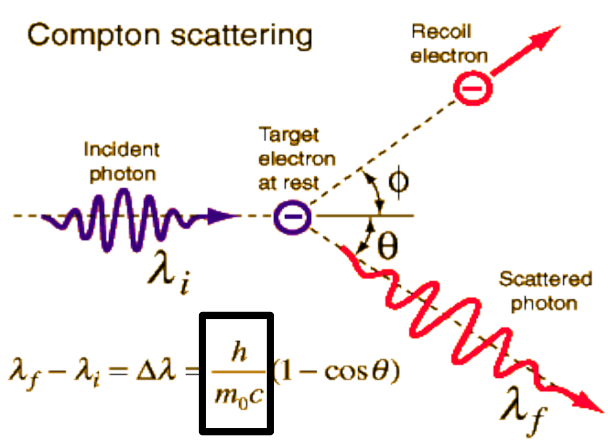
•Thomson scattering: elastic scattering of low-energy photons from low-energy electrons, with cross-section $\sigma_T = (8\pi/3)\,(e^2/m_ec^2) = 6.65\times10^{-25}$ cm^2

•Compton scattering: low-energy photon inelastically scatters off non-relativistic electron, *photon ends up with lower energy*

•Inverse Compton scattering: low-energy photon inelastically scatters off relativistic electron, *photon gains energy in observer rest frame*

Whether the photon gives energy to the electron or vice versa

Compton Wavelength $=h/m_ec=0.00243$ nm for an electron



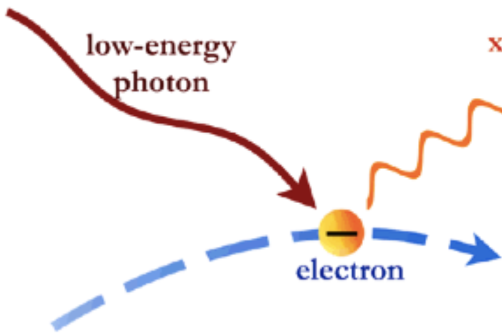
$$\lambda_f - \lambda_i = \Delta\lambda = \boxed{\frac{h}{m_0 c}}(1-\cos\theta)$$

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/compton.html

INVERSE COMPTON EMISSION

Compton scattering

- Photon $E_0 = h\nu$ boosted in energy by hot e^- at kT to e.g. X-rays



$$\frac{\Delta E}{E_0} = \frac{1}{m_e c^2}(4kT - E_0)$$

Examples in X-ray astronomy: active galactic nuclei (AGN), X-ray binaries

PHOTOELECTRIC ABSORPTION

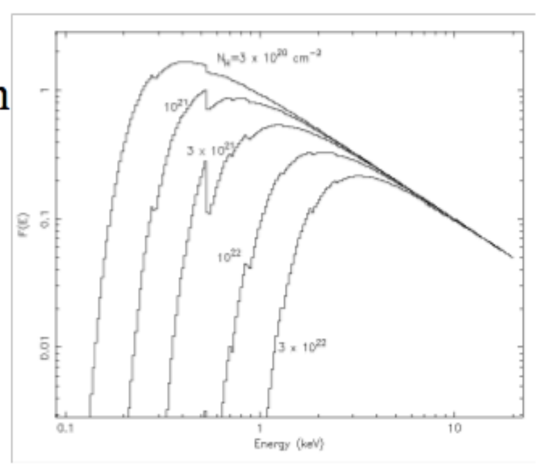
$N_H =$ Equivalent hydrogen column density (cm^{-2})

$\sigma(E) =$ cross section (cm^2)

$\tau = \sigma(E) N_H =$ optical depth

$F(E) = AE^{-\Gamma} e^{-\sigma(E) N_H}$

$\sigma(E) \approx E^{-3}$



Profile dominated by bound-free edges of abundant elements

X-ray photoelectric absorption is important in measuring the material in the line of sight to the x-ray source

- Gas in the Milky Way towards x-ray binaries
- Material in the accretion stream in high mass x-ray binaries
- The 'torus' in AGN

X-rays are penetrating and photoelectric absorption can effectively measure column densities over 4 orders of magnitude from ~10^{20}-10^{24} atms/cm^2

How Does One Obtain Spectral/Imaging Information

How do we measure the position, energy, and arrival time of an X-ray photon?

- What we observe depends on the instruments that one observes with !
- In x and γ-ray spectroscopy we have a wide variety of instruments with different properties
- In both fields one is driven by rather low fluxes (count rates) compared to radio-UV data and so high quantum efficiency is a major goal

γ-ray spectroscopy is dominated by continuum processes (lines are rare-nuclear lines) the main stress is on broad band pass and high quantum efficiency

In the x-ray band there are numerous atomic transitions and so one wants "good" energy (wavelength) resolution in addition

X-ray CCD

2009 Nobel Prize in Physics

- x-ray is absorbed in silicon of the CCD, resulting in the production of multiple electron-hole pairs
- If this absorption occurs within the depletion region of the CCD, the electrons and holes are separated by the internal electric field, with the holes rapidly undergoing recombination whilst the electrons are 'trapped' in the pixel until being read-out

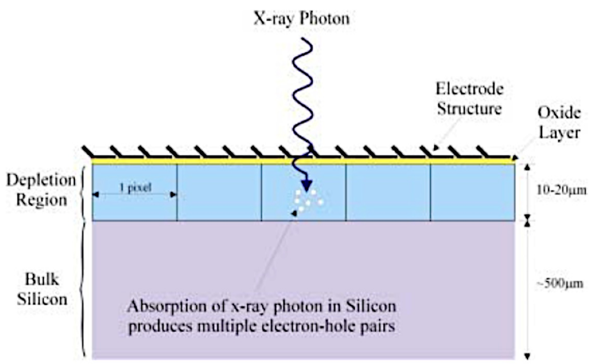


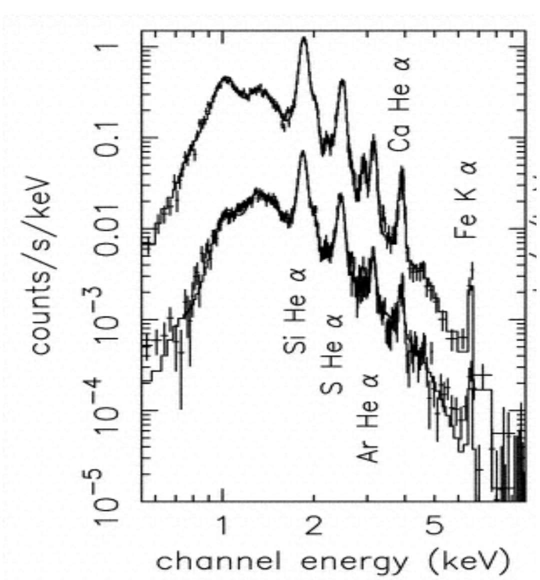
Figure 3: Schematic illustration of the direct detection of an X-ray photon.

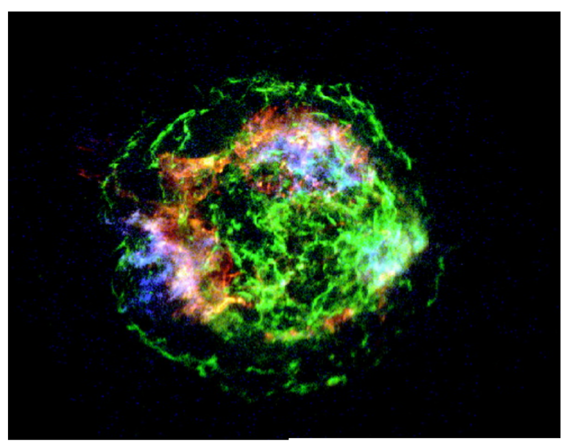
7 October 2009—Willard Boyle and George Smith, formerly of Bell Telephone Laboratories, in Murray Hill, N.J., shared half of the Nobel Prize in Physics "for the invention of an imaging semiconductor circuit-the CCD," the basis for digital imagery in everything from mobile phones to the Hubble Space Telescope.

www.lot-oriel.com/site/site_down/cc_notesxray_deen.pdf

An Elemental Map of Cas-A- Exploded in ~1670 But not seen

- Red=He-like Si, blue=Fe complex
- Bottom right- ratio of Si to Fe+Mg

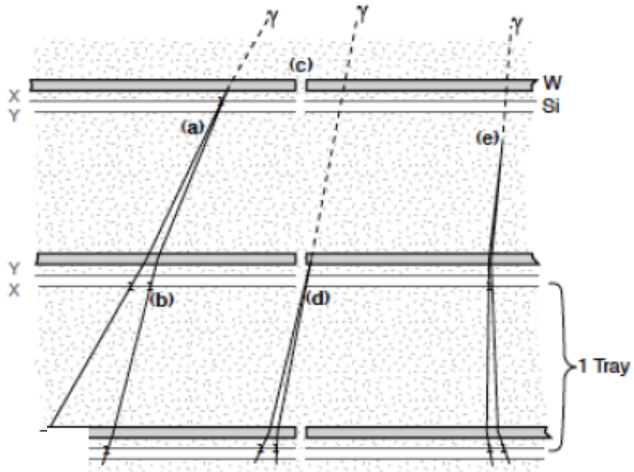


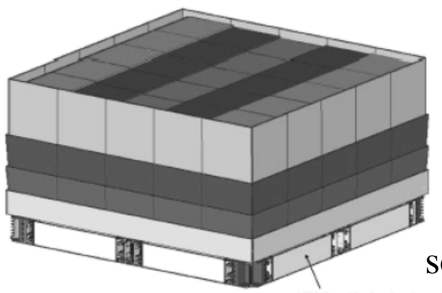


Spectrum of 2 regions in SNR

γ-ray Detectors

- High-energy γ-rays "cannot" be reflected or refracted
- they are detected at E>30 Mev by their interaction via the conversion of the γ-ray into an e^+e^- pair
- A major concern is rejecting the much larger number of cosmic rays (need 0.9997 efficiency in rejection)





Full coverage of anti-coincidence detectors

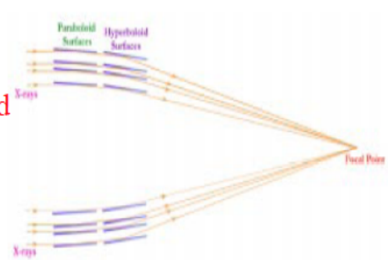
see http://imagine.gsfc.nasa.gov/science/toolbox/gamma_detectors2.html

X-Ray Reflection: Zero Order Principles:

Refs:

Gursky, H., and Schwartz, D. 1974, in "X-Ray Astronomy," R. Giacconi and H. Gursky eds., (Boston: D. Reidel) Chapter 2, pp 71-81;

Aschenbach, B. 1985, Rep. Prog. Phys. 48, 579. * very detailed



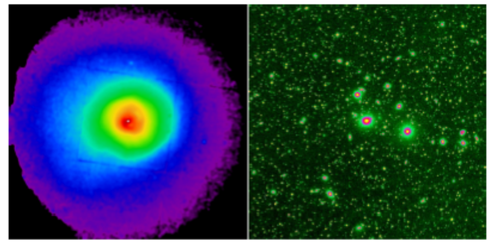
X-rays reflect at small grazing angles.

An analogy is skipping stones on water.

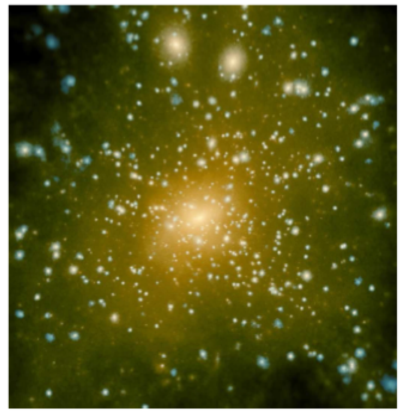
Scattering of any wave by an ensemble of electrons is coherent only in very special directions; namely, the familiar Angle of Incidence equals Angle of Reflection, $\phi_i = \phi_o$.

Clusters of Galaxies

- Clusters of galaxies are the largest gravitationally bound systems in the Universe.
- At optical wavelengths they are over-densities of galaxies with respect to the average density: 100-1000's of galaxies moving in a common gravitational potential well (a smaller assembly is defined a galaxy group).
- The typical masses ~ 10^{13}- $10^{15} M_{sun}$ (10^{46} - 10^{51} gm) and
  sizes ~ 1 - 4 Mpc (10^{24}-10^{25} cm).
- The combination of size and mass leads to velocity dispersions/ temperatures of 300-1200km/sec; 0.5-12 keV
- $M \sim (kT)R$; $\sigma^2 \sim kT$



X-ray optical
Perseus cluster d~73Mpc



Dark matter simulation
V.Springel

WHY ARE CLUSTERS INTERESTING?

- Largest, most massive systems in the universe
- Probes of the history of structure and galaxy formation
  - Dynamical timescale are not much shorter than the age of the universe
  - -clusters retain an imprint of how they were formed
- Provide a history of nucleosynthesis in the universe
  - - as opposed to galaxies, clusters probably retain all the enriched material
- Fair samples of the universe- laboratory to measure dark matter
- The gravitational potential is dominated by dark matter on all scales
- Most of the baryons are in the hot gas (80%)

Theoretical Tools

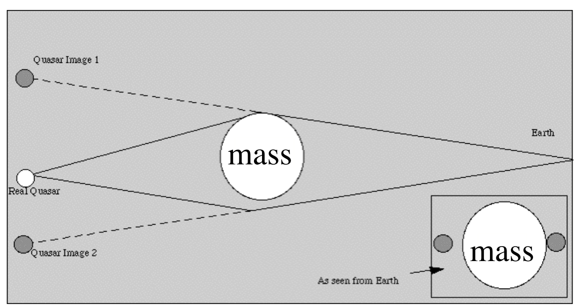
- Physics of hot plasmas
  - Bremmstrahlung
  - Collisional equilibrium
  - Heat transport
  - Etc
- Formation of structure
- Evidence for feedback processes
- How to use lensing to measure gravitational potential (mass)
- Measurement of dark matter, total mass and their distribution via hydrostatic equilibrium
- Determination of chemical abundances

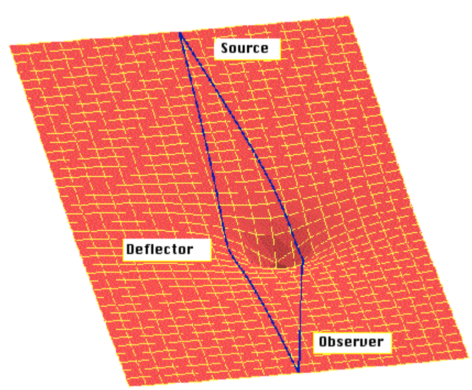
Basics of Gravitational Lensing

- Massive clusters can produce **giant arcs** when a background galaxy is aligned with the cluster core.
- Every cluster produces weakly distorted images of large numbers of background galaxies.
  - These images are called arclets and the phenomenon is referred to as weak lensing.
- The deflection of a light ray that passes a point mass M at impact parameter b is

$$\Theta_{def} = 4GM/c^2 b$$

Also important for studies of AGN





Lensing

- Einstein radius is the scale of lensing
- For a point mass it is
- $\theta_E = ((4GM/c^2)(D_{ds}/D_d D_s))^{1/2}$

- or in more useful units
- $\theta_E = (0.9")M_{11}^{1/2} D_{Gpc}^{-1/2}$

- Lens eq

$\beta = \theta-(D_{ds}/D_d D_s)4GM/\theta c^2$.

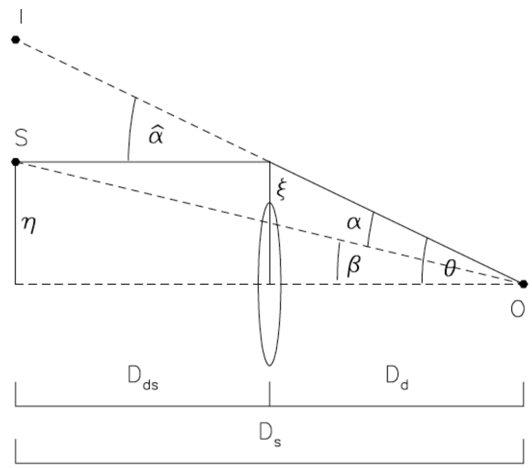
or

$\beta = \theta-\theta^2_E/\theta$

2 solutions for θ_E

Any source is imaged twice by a point mass lens

Gravitational light deflection preserves surface brightness because of the Liouville theorm



What can be measured with X-ray Spectra

- Temperature profile, redshift, and abundances of the most common elements (heavier than He).

- Using symmetry assumptions the X-ray surface brightness can be converted to a measure of the ICM density.

- Using the assumption of hydrostatic equilibrium the cluster total mass (dark+baryonic) can be estimated.

Deriving the Mass from X-ray Spectra

For spherical symmetry eq of hydrostatic equilibrium reduces to

$(1/\rho_g)\, dP/dr = -d\phi(r)/dr = GM(r)/r^2$

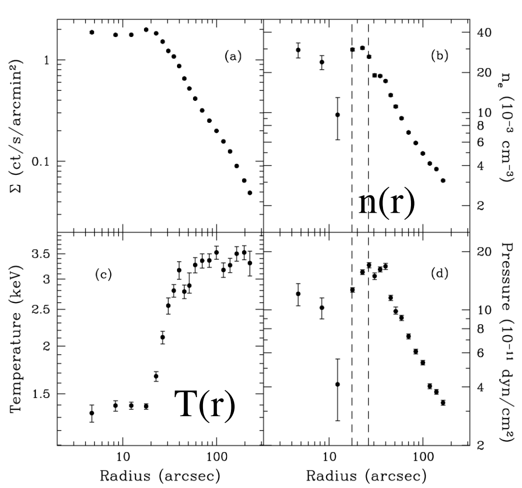
With a little algebra and the definition of pressure - the total cluster mass can be expressed as

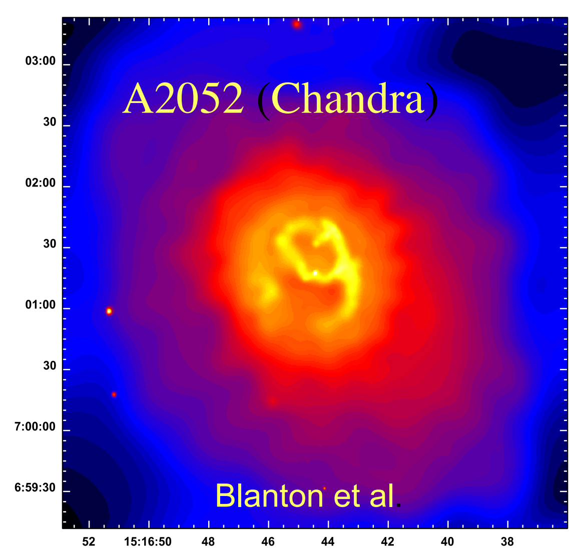
$$\boxed{M(r) = kT_g(r)/\mu G m_p)\mathbf{r}\ (d\ln T/dr + d\ln\rho_g/dr)}$$

k is Boltzmans const, μ is the mean mass of a particle and m_H is the mass of a hydrogen atom
Every thing is observable
The temperature T_g from the spatially resolved spectrum
The density ρ_g from the knowledge that the emission is due to bremmstrahlung
And the scale size, **r**, from the conversion of angles to distance

Effects of Feedback in Image and Temperature

the hot gas can apparently be strongly affected by AGN activity- direct evidence of the ability of SMBHs to influence environment on large scales





How do Clusters Form- Mergers

- As time progresses more and more objects come together- merge
- Hierarchical growth of structure in ΛCDM universe
- Clusters as most massive objects tend to form late

Now

10^{10} yrs ago

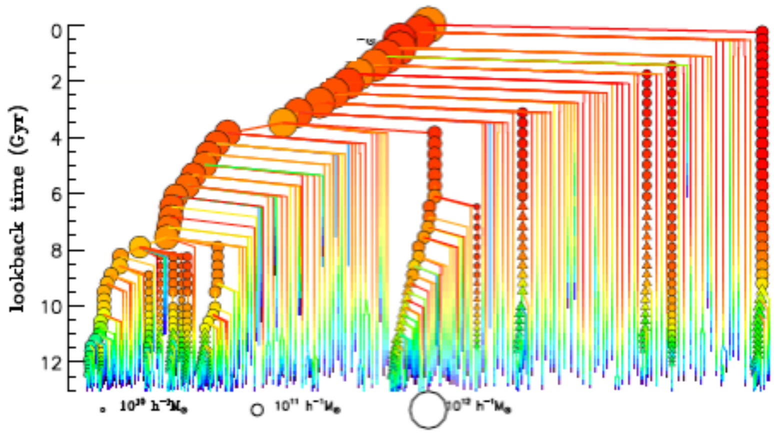
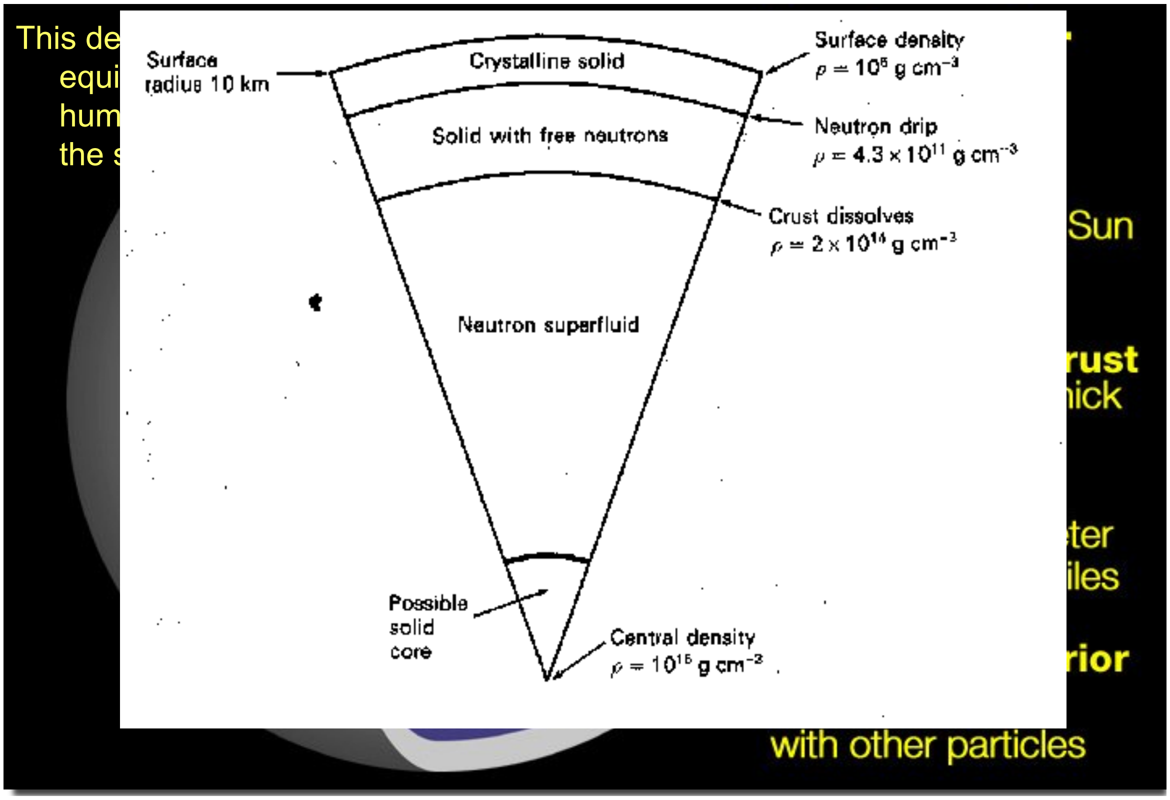


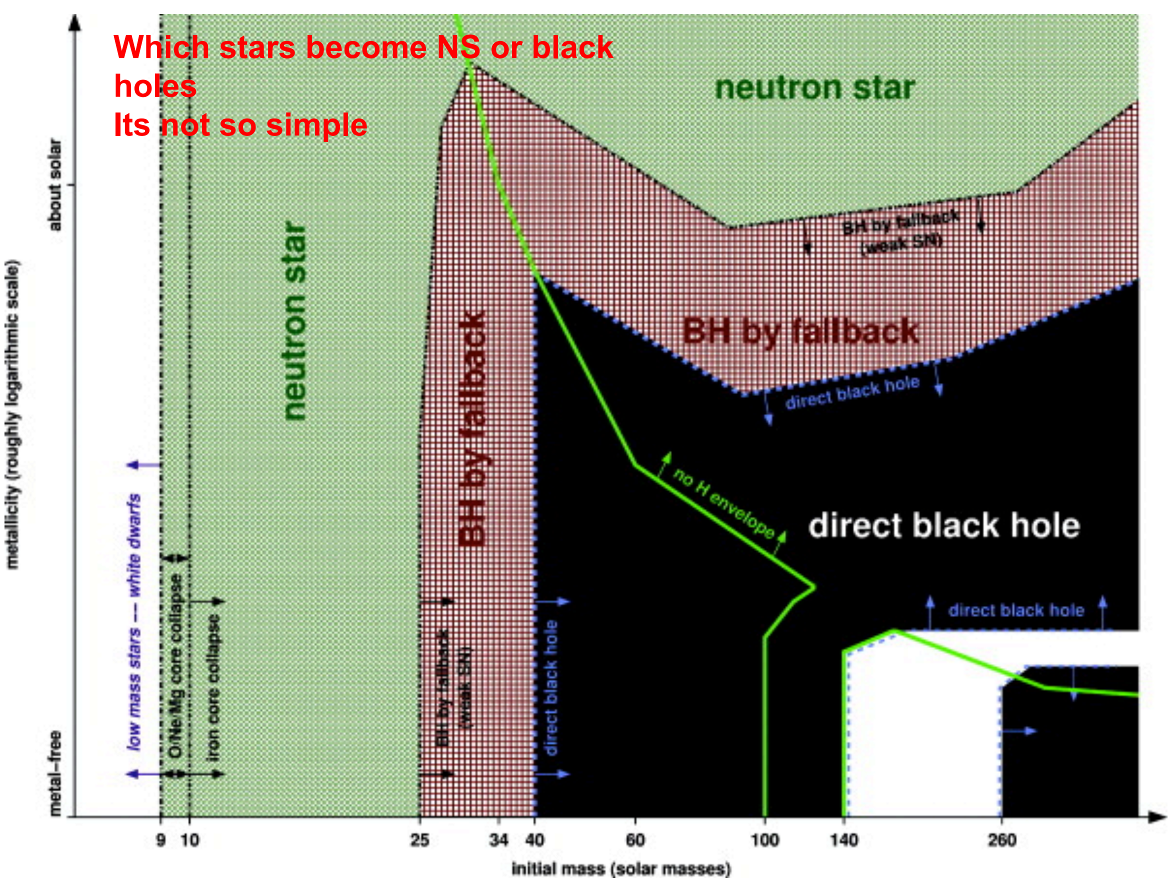
Figure 1. BCG merger tree. Symbols are colour–coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than 10^{10} $M_\odot$ h^{-1} are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch. Triangles show galaxies that have not yet joined this FOF group.

Neutron Stars

- Predicted theoretically by Volkoff and Oppenheimer (1939)
- First 'discovered' by Hewish et al 1967 (Noble prize) as the counterparts to radio pulsars
  - short period from radio pulsars (<1s) can only be obtained from a compact object via either rotation or oscillations; also the period derivatives are small and for radio pulsar periods always increase (slow down)
    - All characteristic timescales scale as $\rho^{-1/2}$ (ρ is density)
      rotation frequency ω=sqrt(GM/r^3) =sqrt($G\rho$)
    - Shortest periods ~1.5ms- light travel time arguments give a size (ct~ 500km)
- White dwarfs with $\rho \sim 10^7$–10^8 gmcm^{-3} maximum rotation periods $P = 2\pi/\Omega \sim 1$–10 s
- **To get periods of ~1ms need $\rho \sim 10^{14}$ gmcm^{-3} much denser than normal stars or white dwarfs**
- What are the sources of energy?
  - Spin down
  - accretion

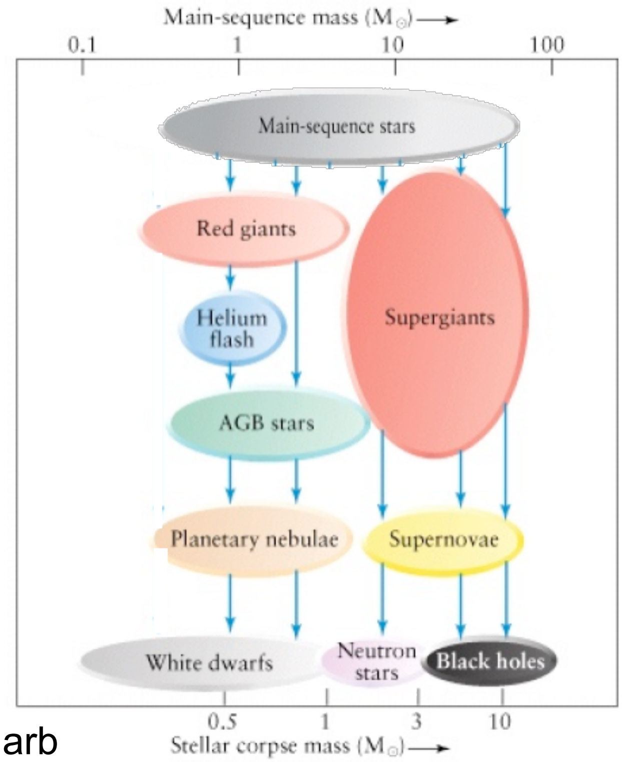
Inside Neutron Stars





Progenitors of Compact Objects

- Main sequence stars evolve and at the end of their 'life' (period of nuclear burning) end up as compact objects
- $t_{MS}/t_{sun} \sim (M/M_{sun})^{-2.5}$
- The most massive end up as black holes
- The least massive as white dwarfs (the main sequence lifetime of stars less than 1/2 M_{sun} is greater than the Hubble time so they never get to white dwarfs)



Samar Safi-Harb

Degneracy and All That- Longair pg 395 sec **13.2.1**

- In *white dwarfs*, internal pressure support is provided by **electron degeneracy pressure** and their masses are roughly the mass of the Sun or less
- the density at which degeneracy occurs in the non-relativistic limit is proportional to $T^{3/2}$
- This is a quantum effect: Heisenberg uncertainty says that $\delta p \delta x > h/2\pi$

For Neutron stars

– $\varrho \approx 10^{16}$ kg/m^3 - Neutron degeneracy pressure starts to become important

– $\varrho \approx 10^{18}$ kg/m^3 - Neutron degeneracy finally halts the collapse provided that $M < 3M_{sun}$

– End up with a neutron star… typical mass of $1.4M_{sun}$ with a radius of 10km- theoretical mass radius relation is not well understood due to the effects of QCD

Radius of NS

- Use the 'known' density of nuclear matter

($\varrho_{Neutron}$~$1.2x10^{14}$g/cm^3) and

the Chandrasekar mass

gives a radius

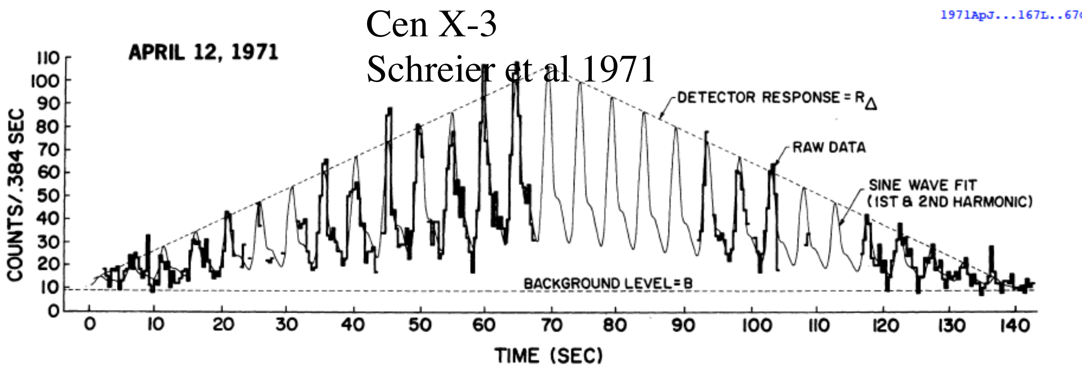
- R_{NS}~$(3M_{Chandra}/4\pi\varrho_{Neutron})^{1/3}$ ~10km

consistency between the observed spin periods,

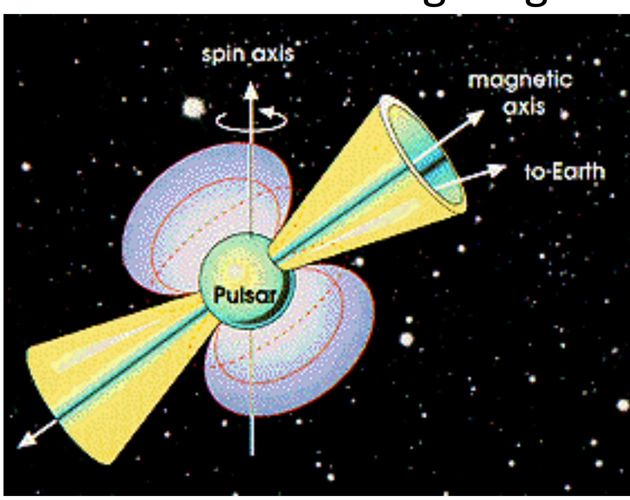
and neutron stars

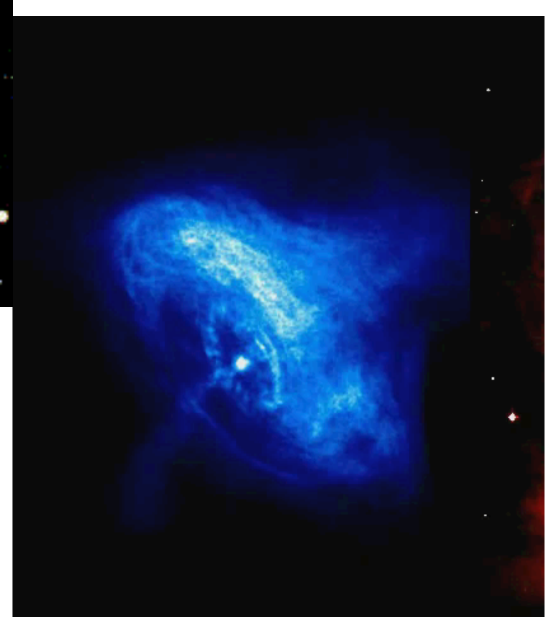
Cen X-3

Schreier et al 1971



Rotating magnetic field model





- Emission from isolated, non-accreting neutron stars

Radiation Mechanism

a magnetic dipole with magnetic dipole moment p_m radiates electromagnetic radiation at a rate

$-dE/dt \sim [\ \Omega^4\ p^2_{m0}]/[6\pi c^3\ ]$.eq 13.33

- Where p_{m0} is the magnetic moment is the component of the magnetic dipole perpendicular to the rotation axis
- Magnetic dipole radiation extracts rotational energy from the neutron star.
- If I is the moment of inertia of the neutron star,
- $-d/dt[I\Omega^2]=I\Omega d\Omega/dt= \Omega^4 p^2_{m0}/6\pi c^3$ and so $d\Omega/dt \propto \Omega^3$
- The age of the pulsar can be estimated if it is assumed that its deceleration can be described by a a law $d\Omega/dt \propto \Omega^n$ if n is constant throughout its lifetime It is conventional to set n = 3 to derive the age of pulsars ***τ;*** so $\boldsymbol{\tau = P/(2\, dP/dt\ )}$.
- Using this relation the typical lifetime for normal pulsars is about 10^5–10^8 years.

- Where radio pulsars lie in the P,dP/dt plot.
  - the lines correspond to constant magnetic field and constant age.
- If magnetic braking mechanism slows-down of the neutron star then (see eqs 13.40-13.42)
- $B_s \approx 3\text{x}\ 10^{15}(PdP/dt\ )^{1/2}$ T .