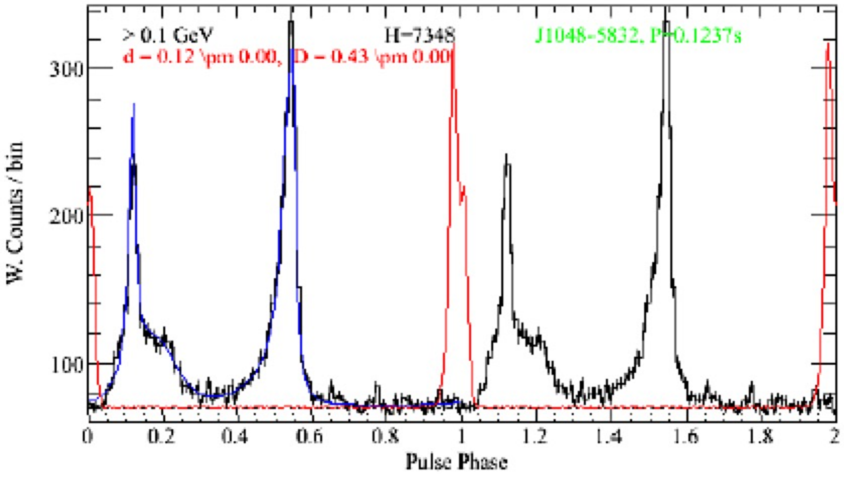
Neutron Stars

Accreting Compact Objects-

see Chapters 13 and 14 in Longair and Review article by Lattimer and Prakash 2004Sci...304..536L

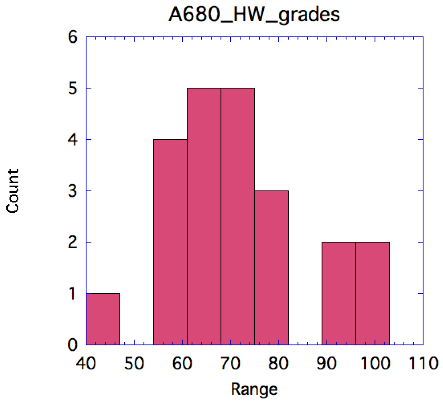


Radio (black) and γ-ray (red) pulse profiles from a neutron star

Mid-term

- Median~mean=71/110=64.5%- renormalize to 75% (multiply by 1.16)

A-A+	90	4
B+/A-	74-89	6
B	60-73	7
B-	55-59	4
C	<55	1



We will discuss options to 'adjust' grade include the mid-term in final grade

Origin and Basic Properties

- Neutron stars are the remnants of massive stars whose cores collapse during the supernova explosions at the end of their nuclear fusion lifetimes.
- Conservation of angular momentum and magnetic flux (?) of the progenitor star during the collapse gives the neutron star an extremely high spin rate and magnetic field.
- The collapse ends when the degeneracy pressure of neutrons balances the gravitational forces of the matter.
- The term neutron star refers to a star with a mass M on the order of 1.5 solar masses ($M_\odot$), a radius R of~12 km, and a central density as high as 5 to 10 times the nuclear equilibrium density

$(n_0 \fallingdotseq 0.16^*\ \mathrm{fm}^{-3=}2.7\mathrm{x}10^{17}\mathrm{kg})$ of neutrons and protons in 'normal' nuclei.

Nuclear density $n = A/\ (4/3\ \pi\ R_0{}^3\ ) = 3/4\ \pi\ (\ 1.25\ \ \mathrm{f\ m}\ )^3 = 0.122\ (\ \mathrm{f\ m}\ )^{-3}$

A is the mean mass number ; $R_0 \sim 1.2\mathrm{fm}$

Stellar Evolution and Supernovae

- Stellar evolution – a series of collapses and fusions

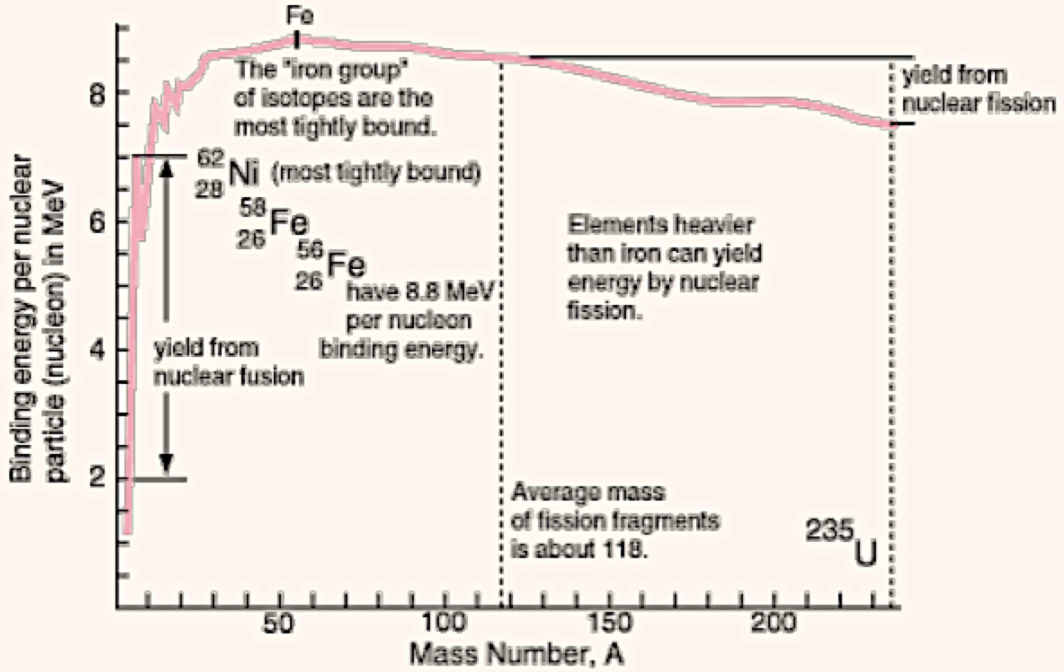
H => He => C => Ne => O => Si

- Outer parts of star expand to form opaque and relatively cool envelope (red giant phase).
- Eventually, Si => Fe: most strongly bound of all nuclei
- Further fusion would *absorb energy* so an inert Fe core formed
- Fuel in core exhausted hence star collapses

jlc@mssl.ucl.ac.uk
http://www.mssl.ucl.ac.uk/

Fission and fusion can yield energy

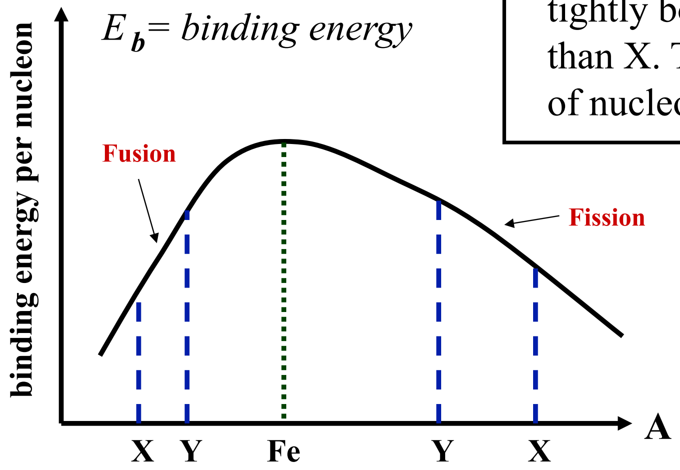
hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html



Binding energy of Nuclei - why stellar burning stops generating energy

A=total no. nucleons
Z=total no. protons
E_b= binding energy

Change from X to Y emits energy since Y is more tightly bound per nucleon than X. This is a function of nucleon mass

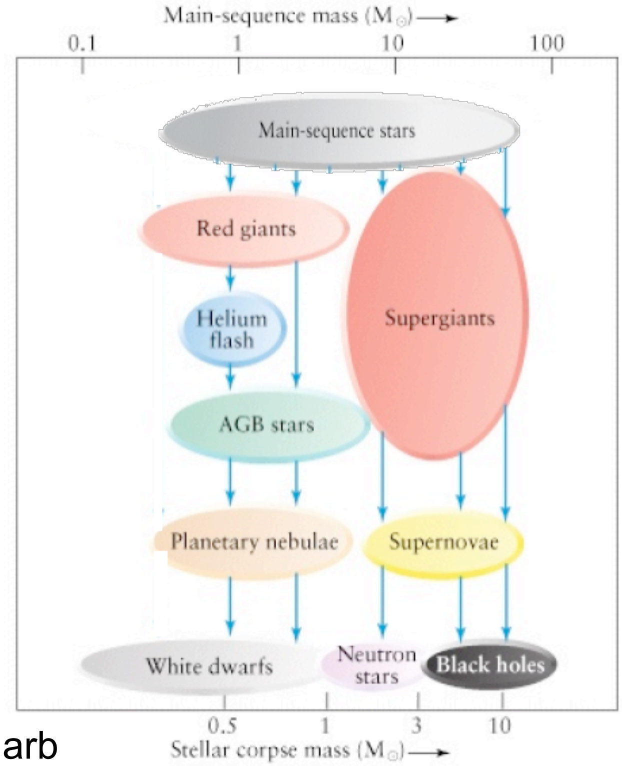


jlc@mssl.ucl.ac.uk
http://www.mssl.ucl.ac.uk/

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 have never got to white dwarfs)



Samar Safi-Harb

- Stars with a defined mass range evolve to produce cores that can collapse to form Neutron Stars
- Following nuclear fuel exhaustion, core collapses gravitationally; this final collapse supplies the supernova energy
- Collapse to nuclear density, in ≈ few seconds, is followed by a rebound in which the outer parts of the star are blown away
- The visible/X-ray supernova results due to radiation
  i. From this exploded material
  ii. Later from shock-heated interstellar material
- Core may
  i. Disintegrate
  ii. Collapse to a Neutron star
  iii. Collapse to a Black Hole

  according to its mass which in turn depends on the mass of the original evolved star

From L. Cominsky

Creation of Neutron Stars

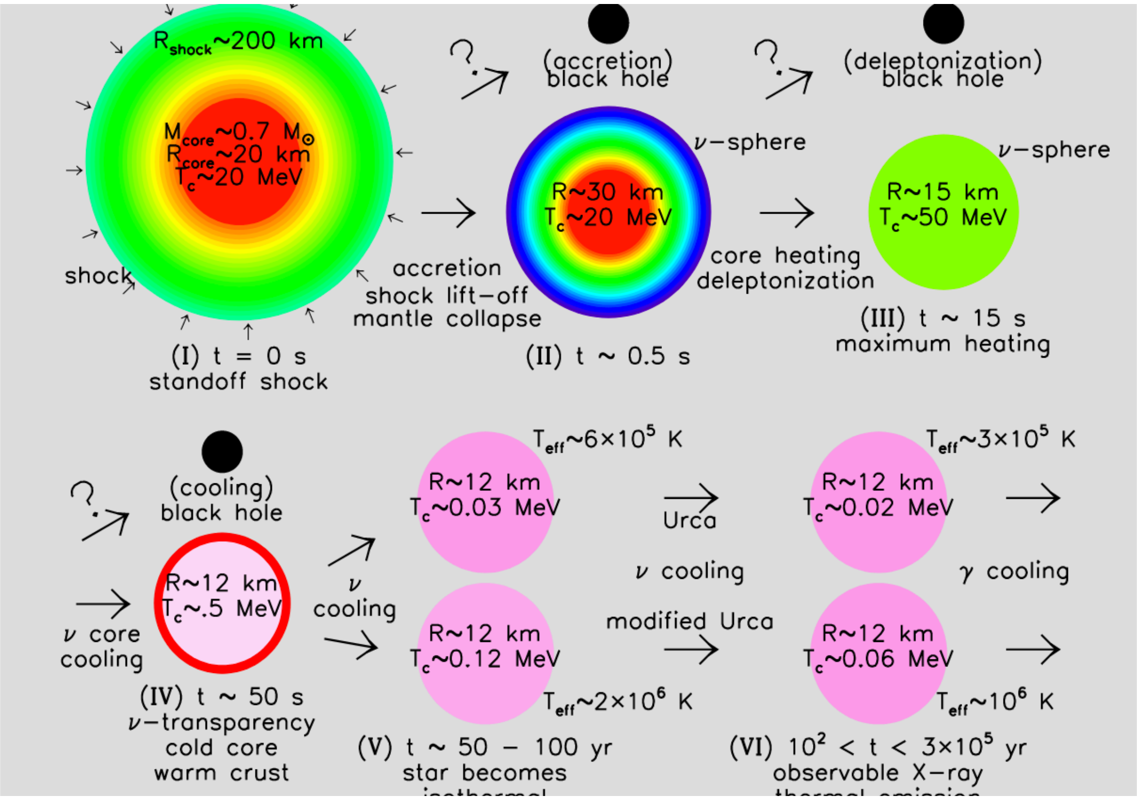
II/Ib/Ic Core-Collapse of Massive Progenitor at the end of its evolution

Collapse to nuclear density, in $\approx$ few seconds, is followed by a rebound in which the outer parts of the star are blown away

- Massive stellar progenitor core forms neutron star or black hole
- Explosive nucleosynthesis products near core (Si and Fe) plus hydrostatically formed outer layers (O, Ne) are expelled
- *Most of the explosion energy is carried away by neutrinos*
- Uncertain explosion mechanism details involve neutrinos, probably large-scale shock instabilities, rotation, possibly magnetic fields
- Star must be at least $8M_\odot$; core at least $1.4\ M_\odot$.

(U. Hwang 2007)

NS- Formation Lattimer and Prakash 2004



The Previous Slide in Words....pg 3,4 in L&P

- Neutron stars are created in the aftermath of the gravitational collapse of the core of a massive star ($>8M_{\odot}$)
- Newly-born neutron stars or proto-neutron stars are rich in leptons, mostly e^- and ν_e
- The gravitational binding energy released is $\sim 3GM/5R^2 \approx 3\text{x}10^{53}$ erg ~ 10% of Mc^2. The kinetic energy of the expanding remnant is on the order of $\sim 10^{51}$ erg to and the energy radiated in photons is $\sim 10^{49}$ erg
- The proto-neutron star left behind rapidly shrinks because of pressure losses from neutrino emission- which forces electrons and protons to combine, making the matter neutron-rich

- Once dead core exceeds $1.4M_{sun}$, electron degeneracy pressure cannot support it.
- Core starts to collapse
  - $\rho \approx 10^9$ kg/m^3 - Density of core when collapse begins (onset of relativistic effects in electron motions)
  - $\rho \approx 10^{10}$ kg/m^3 - Fermi energy exceeds neutron-proton mass difference…

Inverse beta decay becomes energetically preferable to normal beta decay

$$p + e^- \rightarrow n + \nu$$

- Nuclei become very neutron rich… neutronization

And then...

– $\rho \approx 10^{14}$ kg/m^3 - Individual nuclei are so neutron rich that they start to fall apart

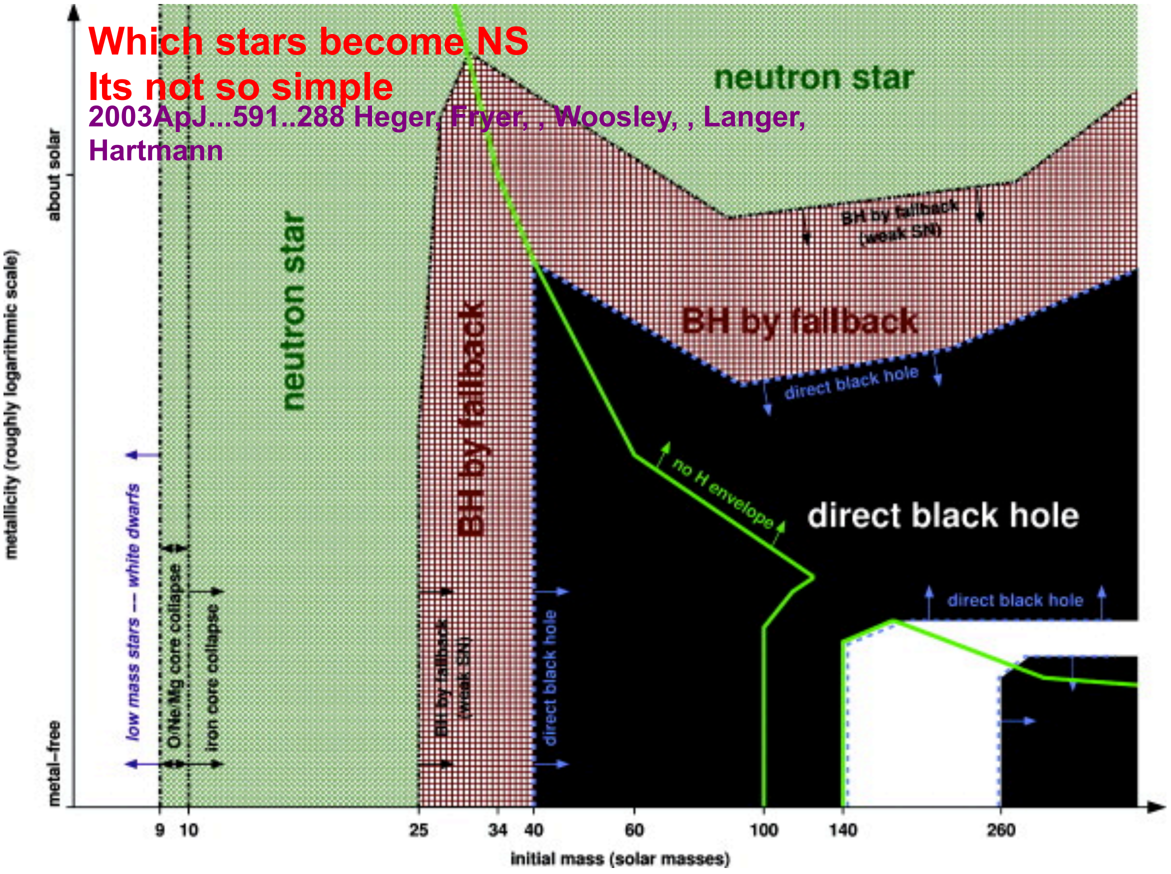
- Remaining nuclei surrounded by sea of free neutrons

  This is called the neutron drip phase

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

– $\rho \approx 10^{18}$ 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



Which stars become NS

Its not so simple

2003ApJ...591..288 Heger, Fryer, , Woosley, , Langer, Hartmann

UpDated Plot of NS Progenitor Mass

- Raithel, et al 2018 arXiv:1712.00021
- NS masses in purple, black hole in gray
- (progenitor star mass in **orange,** core in **green**)

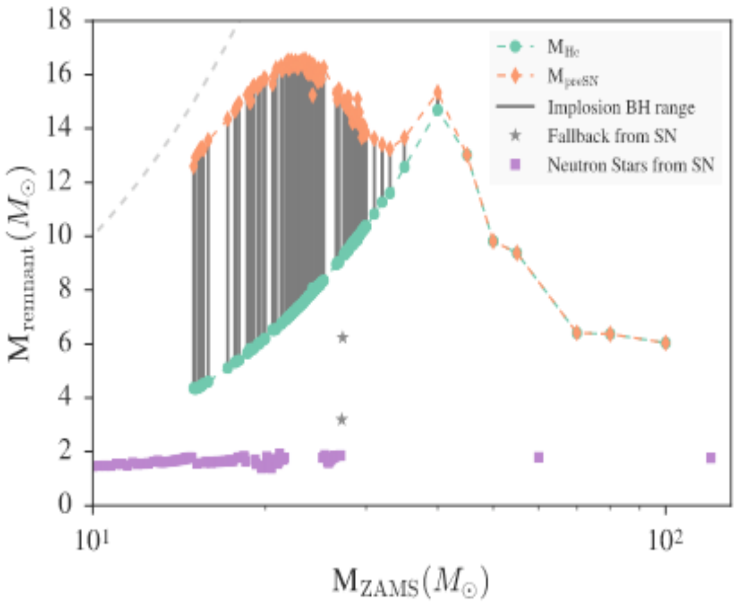


FIG. 1.— Baryonic remnant masses as a function of the progenitor ZAMS mass, for the central engine W18. Neutron star remnant masses from successful explosions are shown in purple. The range

Neutron Stars- see **The Physics of Neutron Stars**

J.M. Lattimer, M. Prakash Science 2004

- 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 pulsars periods always increase (slow down)
  - **All characteristic timescales scale as $\rho^{-1/2}$ (ρ is density)**

    $\omega=1/\mathrm{sqrt}(GM/r^3) =1/\mathrm{sqrt}(G\rho)$

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 (radio pulsars) need $\rho \sim 10^{14}$ gmcm^{-3}** the maximum spin rate is governed by the density profile of neutron stars
- What are the sources of energy?
  - Spin down
  - accretion
  - magnetic field

Maximum Spin

- An absolute upper limit to the neutron star spin frequency is the mass-shedding limit:
  - *the velocity of the stellar surface equals that of an orbiting particle suspended just above the surface.*
  - For a rigid Newtonian sphere this frequency is the Keplerian rate
  - $\nu_K = (2\pi)^{-1}\sqrt{GM/R^3} = 1833\ (M/M_\odot)^{1/2}(10\ \mathrm{km}/R)^{3/2}\mathrm{Hz}$.
- However, both deformation and **GR** effects are important
- The highest observed spin rate, 641Hz from pulsar PSR B1937+21 implies a radius limit of 15.5 km for 1.4 $M_\odot$

Lattimer and Prakash 2004

Observational Intro to Neutron Stars

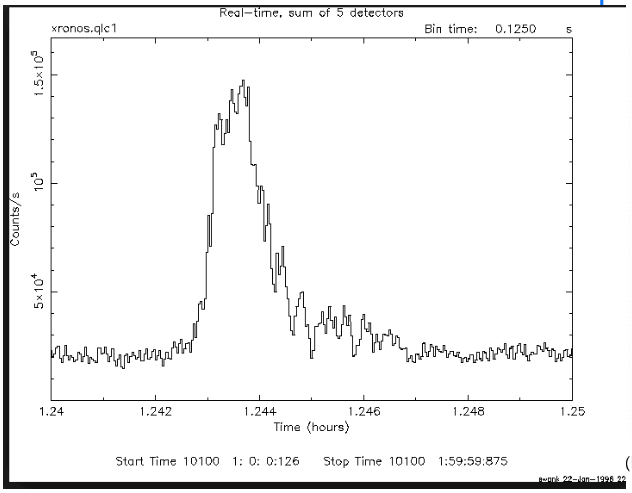
- Neutron stars are a very diverse population, both in their observational and their physical properties.
- They radiate most of their energy at X-ray and gamma-ray wavelengths.
- Their electromagnetic emission can be powered by rotation, accretion, heat, magnetic fields or nuclear reactions,
- **But all are a subset of the same sort of object**
- They show an amazing variety of pulsating and bursting behaviors.
- The 'zoo' of names is base on observational properties classified according to the primary power source for their emission and spin evolution.

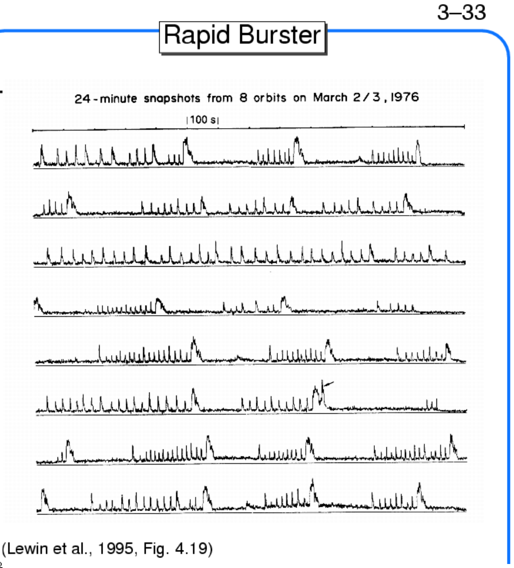
A. Harding 2013

"Classes' of Neutron Stars

- Rotation-powered pulsars (RPP) derive their energy primarily from the rotation of the NS
- Magnetars from magnetic field energy,
- Isolated NSs (INS) from the latent heat of the NS matter from the SN
- Accretion-powered NSs from the energy released by matter accreting onto the NS from a binary companion.
  - A subclass of accreting NSs are X-ray bursters whose bursts are powered by thermo-nuclear explosions or a instability in the magnetosphere (will not cover in class) pg 481-483 in Longair
- Central Compact Objects (CCO), are soft X-ray point sources inside supernova remnants and are dim at all other wavelengths.

Two Types of Bursters

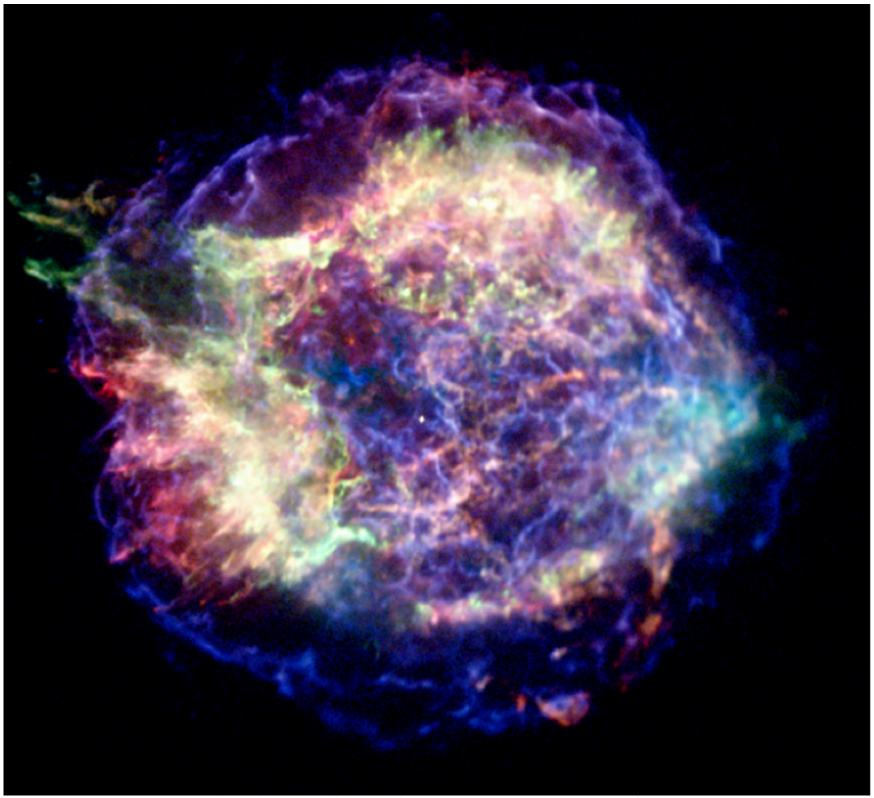




(Lewin et al., 1995, Fig. 4.19)

'regular' burster- 36 sec of data J.Swank

Rapid Burster Lewin et al 1995



NASA/CXC/MIT/UMass Amherst/
M.D.Stage et al.

Basic Properties of Each Class (see Harding 2013 arXiv: 1302.0869) Focus of Class in Red

- Central Compact Objects (CCO):
  - X-ray sources detected close to the centers of young (SNRs) , have no apparent emission in other wavebands and no binary companions. (see DeLuca 1711.07210.pdf)
- **Rotation Powered Pulsars:**
  - Neutron stars that are spinning down due to torques from magnetic dipole radiation and particle acceleration
  - broad-band pulsations from radio to gamma-ray wavelengths
  - more than 2000 radio pulsars are now known,> 100 detected at X-ray energies and > 130 gamma-ray pulsars
  - two main populations of RPPs: **normal pulsars** having characteristic ages
  - P= 2/(dP/dt) < 100 Myr, and **millisecond pulsars** (MSP) with 'ages' > 100 Myr.
- MAGNETARS
  - NSs primary power source is the tapping of energy stored in their magnetic fields
  - steady X-ray luminosities are100x t spin-down luminosities, requiring a source of power way beyond the magnetic dipole spin-down
  - Have bursts ~0.5 sec long average energy 10^{40} - 10^{41} erg, giant superflares of total energy 10^{45}-10^{47} erg,

More Classes

- Isolated neutron stars
  - thermally cooling with no emission outside the soft X-ray band,
  - lack any observable associated supernova remnant or nebula.
  - INS very nearby, cooling middle-aged NSs.
- **Accreting neutron stars**
  - NSs in binary systems accreting matter from their companion stars,
  - gravitational energy from the infalling matter provides the energy for the observed radiation and accretion torques dominate the spin evolution.
  - accreting NSs display a wide variety of behaviors, depending on the NS magnetic field strength, mass of the companion and nature of accretion.
  - two general classes**, low mass (LMXB) and high mass (HMXB)**, referring to the mass of the companion
    - LMXBs a NS (or black hole) in a binary with a low-mass star, fills its Roche Lobe, transferring matter onto the compact object through an accretion disk- ms pulsations
    - HMXB the compact object accretes material from the wind of the companion star- periods of 1 - 1000 s.