Astrophysics I: Stars and Stellar Evolution

AST 4001

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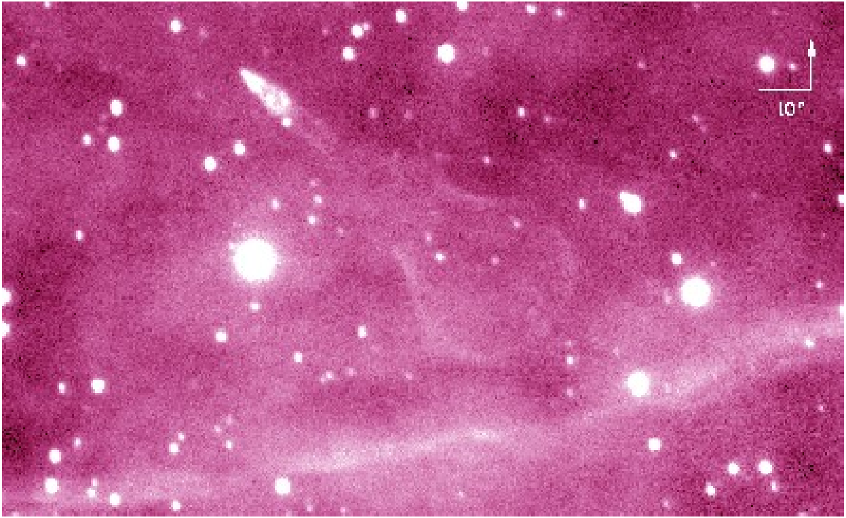
Stars and Stellar Evolution, Fall 2008

Overview

- Variations on Afterlife

1. Accretion Disks
2. Novae and X-ray Bursts
   - Classical Novae
   - Type I X-Ray Bursts

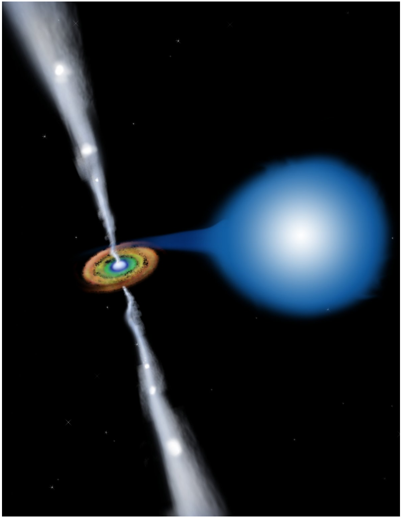
The Guitar Nebula



Compact Binaries

- compact remnants
  - white dwarf
  - neutron star
  - black hole
- types of systems
  - compact remnant + ...
    - main sequence star
    - evolved star - (red) (super) giant
  - two compact stars
    - double WD, double NS (double pulsar), double BH
    - WD+NS, WD+BH
    - NS+BH

Accreting Binary

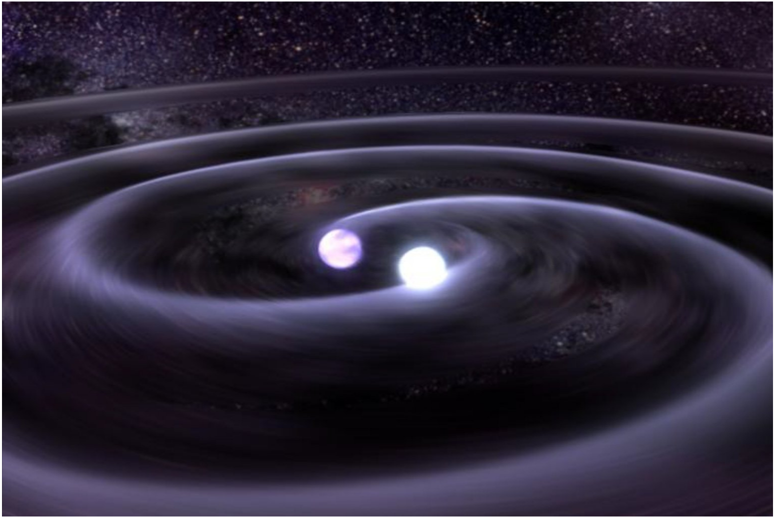


Evolution of Compact Binaries

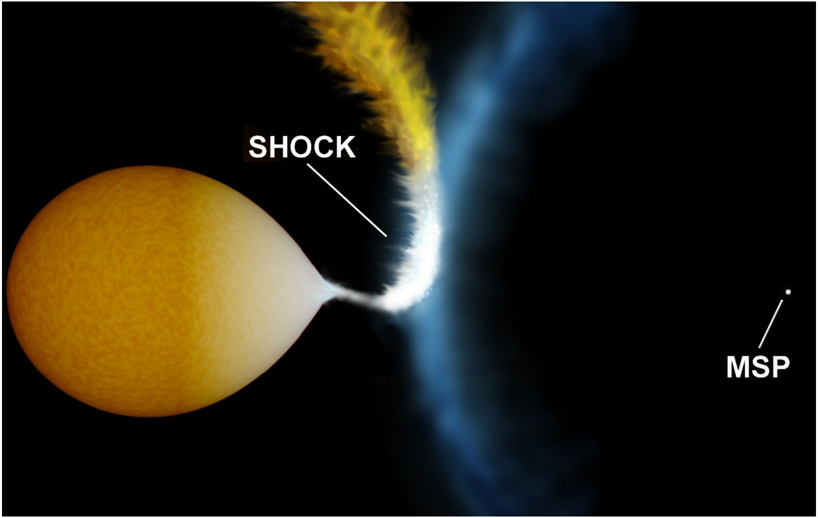
- mass transfer
  $\Rightarrow$ accretion disk
  $\Rightarrow$ X-ray binary
  What can it tell about the type of the compact star?
- loss of angular momentum (braking)
  - wind
  - magnetic fields
  - gravitational waves

  $\Rightarrow$ orbits gets increasingly tighter
  - merger
    $\Rightarrow$ gravitational wave signal
  - disruption of the less compact star
    $\Rightarrow$ accretion disk, . . .

Binary WD



Shock Wave in Millisecond Pulsar

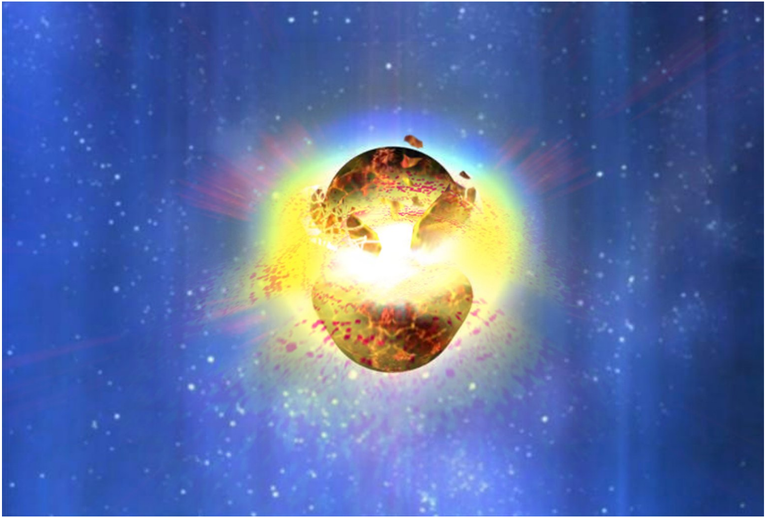


Evolution of Compact Binaries

accumulation of accreted material

- composition of accreted material?
- does accreted material burn?
- burning stable or not?
- thermonuclear runaway?
    - Novae
      how much material is ejected?
      does WD star grow?
    - detonation of "thick" H/He layer on WD surface?
    - supernovae
        - Type Ia - CO WDs
        - AIC - ONeMg WDs
    - (Type I) X-ray bursts
- stability of the accretion disk
    - outbursts from disk instabilities

Neutron Star Merger

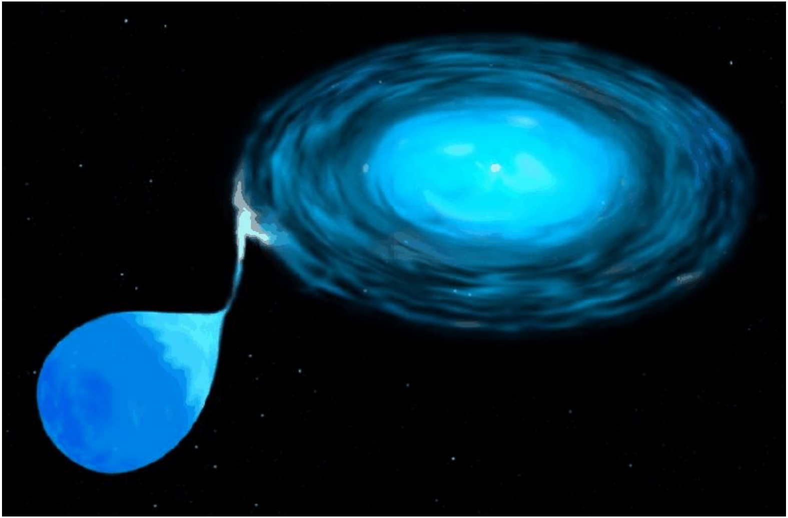


Final Fate of Compact Binaries

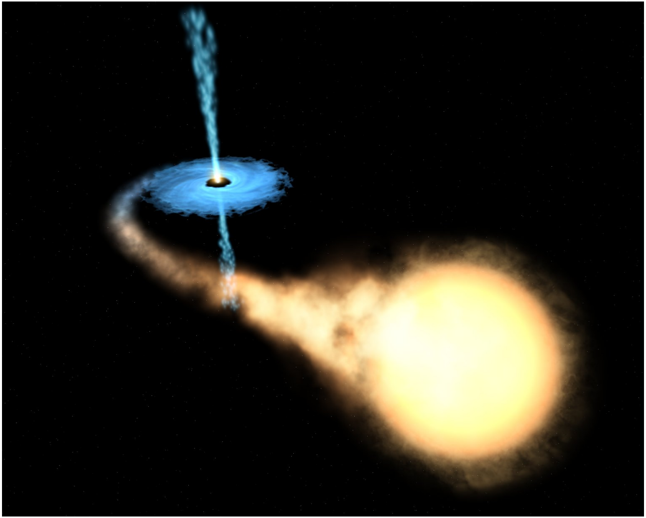
merger or disruption of one of the stars

- disruption
  - tidal disruption of less compact star
  - WD + MS/post-MS star: mass transfer
    - CO WD: ignition, Type Ia SN, no remnant
    - ONeMg WD: AIC $\Rightarrow$ NS:
      * "kick" during NS formation $\Rightarrow$ system separates
      * NS + MS/post-MS star
- merger
  - NS+NS $\Rightarrow$ short GRBs
  - WD+WD $\Rightarrow$ supernova?
  - WD+MS/post-MS star $\Rightarrow$ AIC
  - BH+BH $\Rightarrow$ GR wave signal
  - BH+NS $\Rightarrow$ accretion disk, GRB?
  - WD+NS/BH $\Rightarrow$ fast transient form accretion disk... NS$\rightarrow$BH collapse?

Accreting Binary



Accretion onto Black Hole



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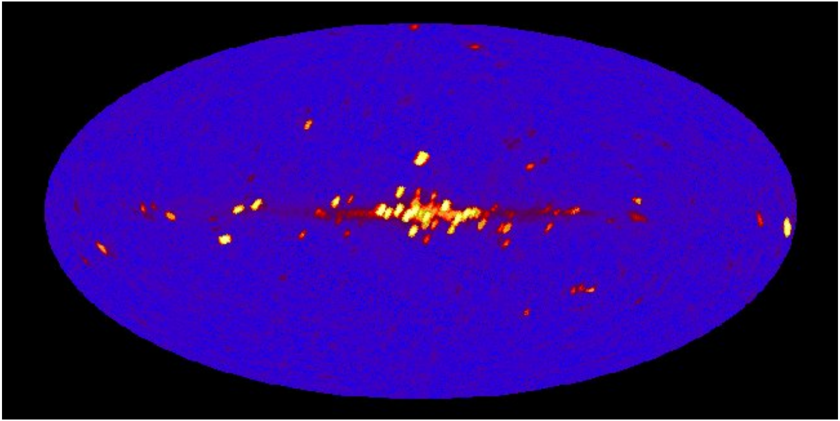
X-ray Sky



Steady State Accretion Disks

- approximation for steady state "dust" accretion disks

$$\dot{M}(r) = \mathrm{const.}$$

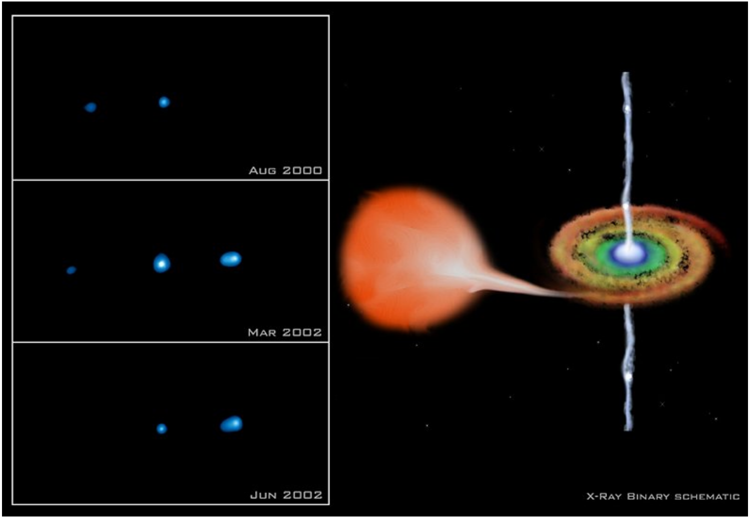
- angular momentum transport by viscosity or magnetic torques
- dissipate potential energy (minus kinetic energy) by radiation
- energy balance in steady state

$$-\dot{M}\frac{1}{2}\nabla\phi = \frac{GM\dot{M}}{2r^2} = \sigma T^4 \frac{\mathrm{d}A}{\mathrm{d}r} = 4\pi r \sigma T^4$$

$$T^4 = \frac{GM\dot{M}}{8\pi\sigma r^3}\,, \quad \text{more accurate derivation yields} \quad T^4 \approx \frac{3GM\dot{M}}{8\pi\sigma r^3}$$

- gravitational potential gradient highest close to object, where disk area is smallest $\Rightarrow$ disk hottest close to object
- see, e.g., W. K. Rose "Advanced Stellar Astrophysics", §9.2

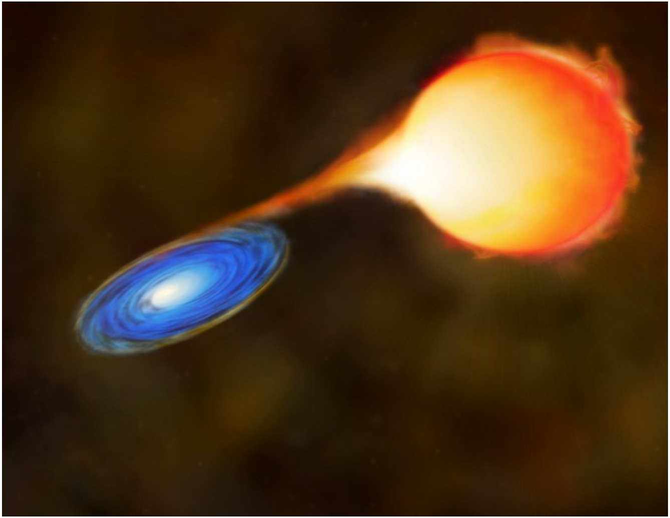
X-Ray Binary Jet



Steady State Accretion Disks

- hot accretion disk shies in X-ray band ⇒ X-ray binaries
- accreting compact object often (usually) out-shines companion star
  especially in low-mass X-ray binaries
- in high-mass X-ray binaries compact star may just accrete part of the wind of the companion star
- highest T reached can tell about inner radius of disk
  ⇒ type of companion star (or radius of inner edge where disk is disrupted)
- in systems with NS, inner disk can be disrupted by strong magnetic field of NS

Accreting Binary Star



Quiz

What is the Eddington luminosity for a WD, NS, and BH of $1\,\mathrm{M}_\odot$?

Compute Eddington accretion rate for WD ($R = 10,000\,\mathrm{km}$), NS ($R = 10\,\mathrm{km}$), and BH ($R = 3\,\mathrm{km}$)

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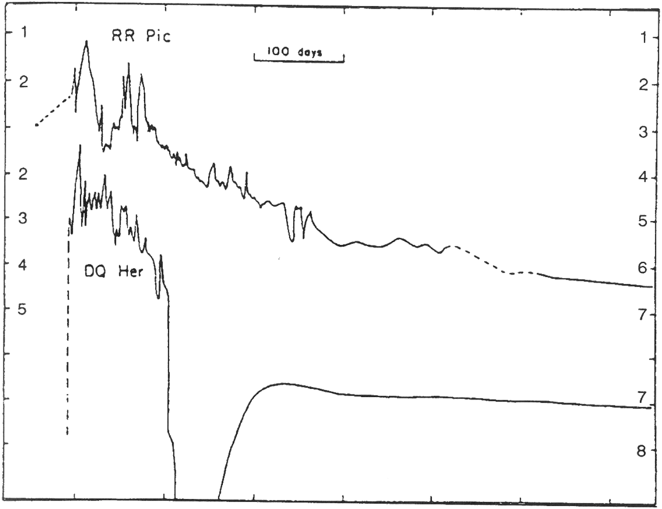
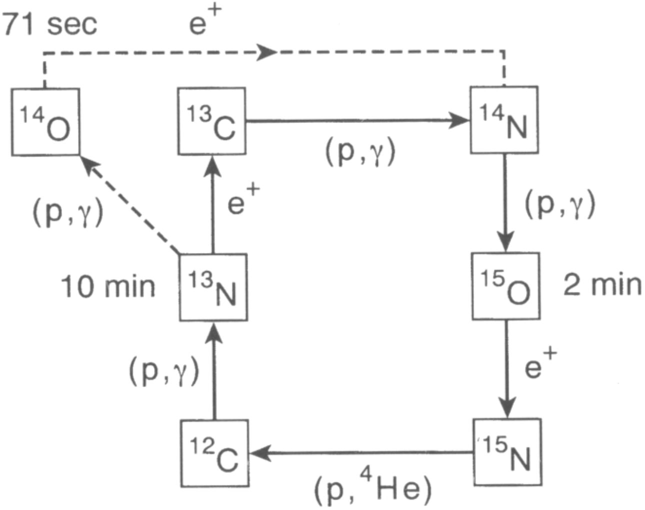
Classical Novae

- Accretion of H-rich material on WD in binary star system
- thermonuclear runaway of degenerate hydrogen layer
- "hot" CNO burning, possibly "breakout" from CNO cycle
- expansion of envelope, possibly engulfing of companion star
- enrichment of envelope in material of underlying WD "dredge up"
  $\Rightarrow$ Can CO WD grow?
  $\Rightarrow$ Can systems with Novae be progenitors of Type Ia SNe?
- We observe novae on CO WD and on ONeMg WDs

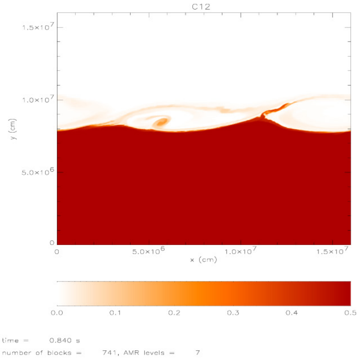
Light Curve of a Classical Nova

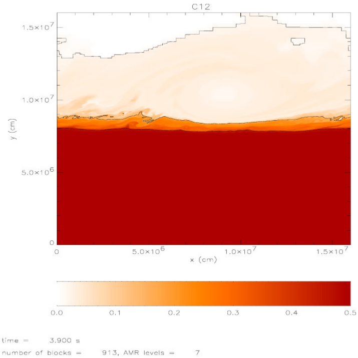


Nuclear Burning in a Classical Novae

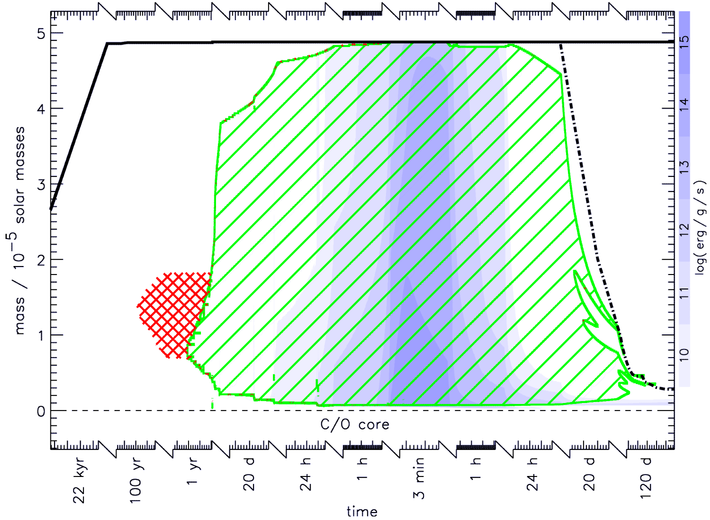


Mixing in Nova Surface Layer





Nuclear Burning in a Classical Novae

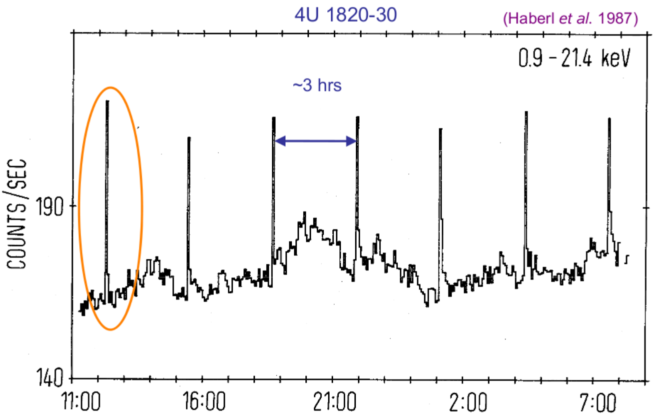


Type I X-Ray Bursts

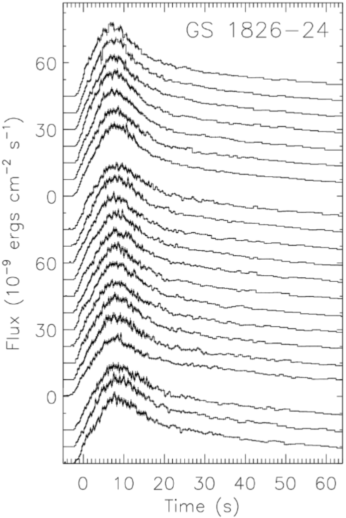
- Accretion of H-rich or He-rich material on NS in binary star system
- β-limited CNO cycle burning of accreted material if accretion rate is high enough, otherwise built up of degenerate H layer
- if all H burns before burst, built up of degenerate He layer
- thermonuclear runaway of degenerate hydrogen/helium layer
- burning by α, αp and *rp*-processes
- recurrence time hours to days

X-Ray Bursts

Thermonuclear Origin of X-ray Bursts



X-Ray Bursts

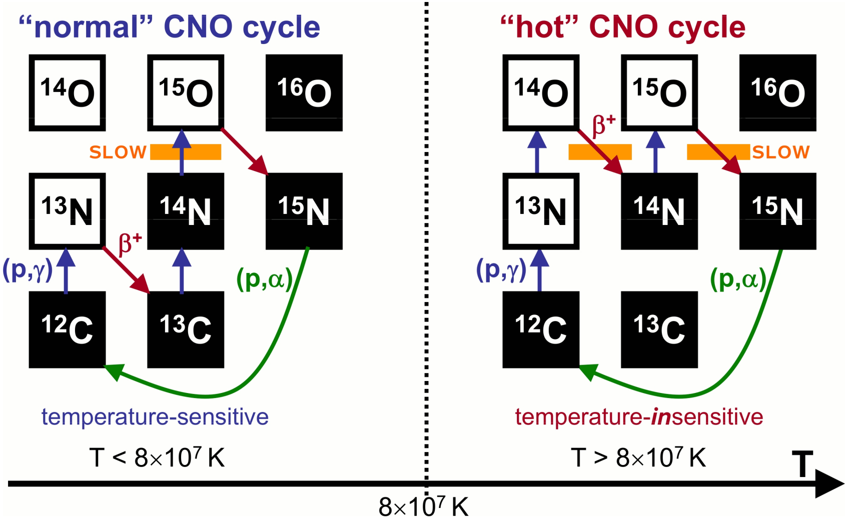


XRB Observations

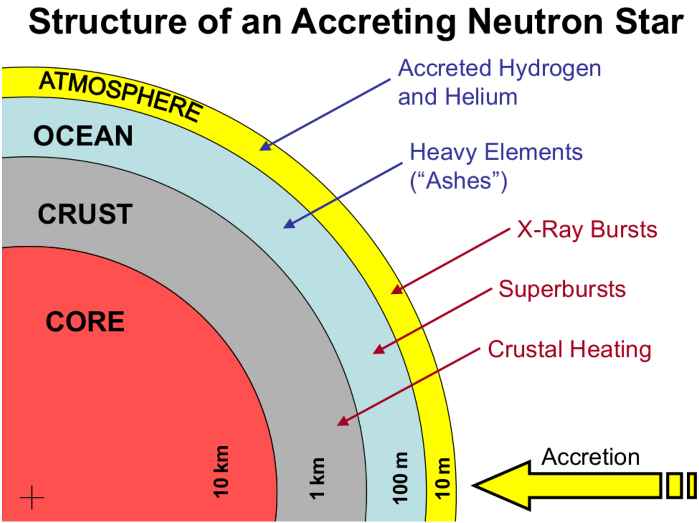
- Repeated burst of X-rays
- tens of seconds duration
- repeat time hours to days
- inferred luminosity close to Eddington

***The most common* thermonuclear explosion in nature!**

Hot CNO cycle



X-Ray Bursts


Structure of an Accreting Neutron Star
ATMOSPHERE
OCEAN
CRUST
CORE
Accreted Hydrogen and Helium
Heavy Elements ("Ashes")
X-Ray Bursts
Superbursts
Crustal Heating
10 km
1 km
100 m
10 m
Accretion

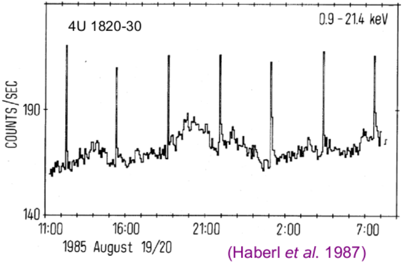
X-Ray Bursts

Energetics of Bursts

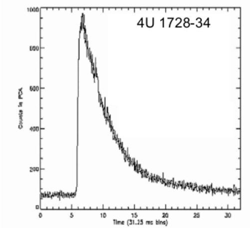
nuclear energy release $Q_{nuc} \approx (1\text{-}5)$ MeV / nucleon

gravitational energy release $\frac{GM}{R} \approx 200$ MeV / nucleon

ratio of energies $\alpha = \frac{\int F_p dt}{\int F_b dt} \approx \frac{GM/R}{Q_{nuc}} \approx 40 - 100$

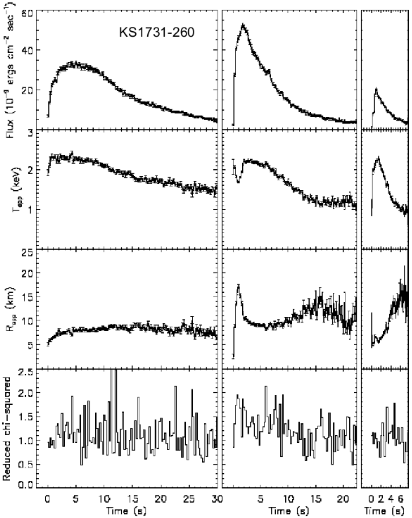


(Haberl *et al.* 1987)



(Strohmayer *et al.* 1996)

X-Ray Bursts



Flux

Temperature

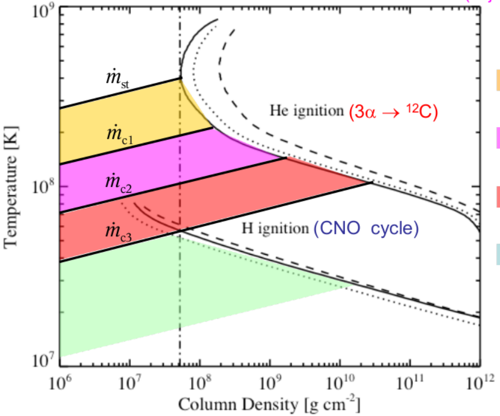
Radius

(Muno *et al.* 2001)

X-Ray Bursts

Ignition and Accretion Rate Dependence

(Fujimoto et al. 1981 ; Bildsten 1998)



stable H burning
→ unstable H/He ignition

stable H burning
→ unstable He ignition

unstable H burning
→ unstable He ignition

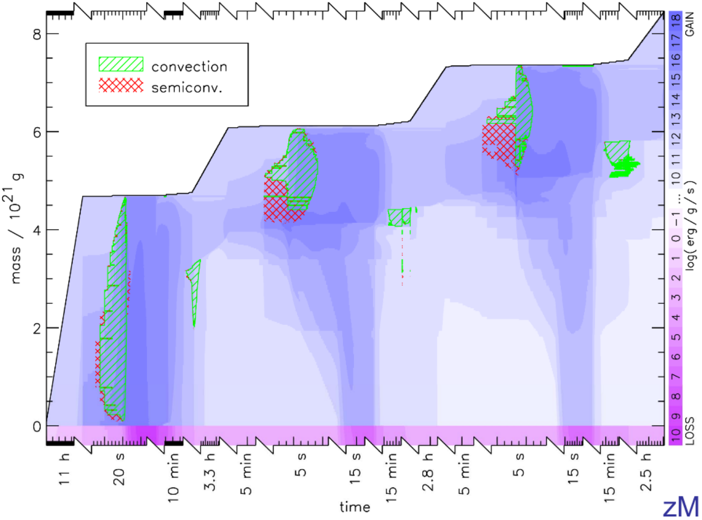
unstable H burning
→ unstable H/He ignition

$$\dot{m}_{st} \sim \dot{m}_{Edd}$$

$$\dot{m}_{c2} \sim 0.01\,\dot{m}_{Edd}$$

(courtesy to Fang Peng)

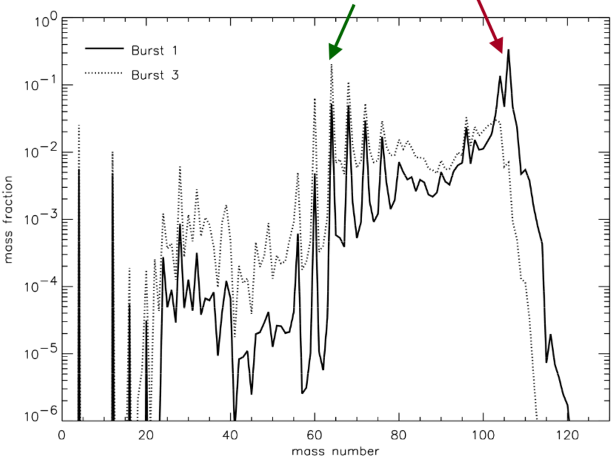
X-Ray Bursts


convection
semiconv.
mass / 10^{21} g
0
2
4
6
8
11 h
20 s
10 min
3.3 h
5 min
5 s
15 s
15 min
2.8 h
5 min
5 s
15 s
15 min
2.5 h
time
GAIN
18 17 16 15 14 13 12 11 10 ... −1 0 1 2 3 4 5 6 7 8 9 10
log(erg / g / s)
LOSS
zM

X-Ray Bursts

Comparison of ashes of "first" burst and later bursts

→peak moves to A=64 from A=106

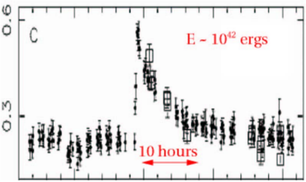


X-Ray Super-Bursts

Superbursts

Observations

- similar peak luminosity
- hours of duration (1000x longer)
- ➔ Energy is 1000 x higher
- recurrence time is years (only 6 bursts have been seen so far, two in the same system)



Model Paradigm

- Occurs in ashes layers of some 1000 XRBs
- Toy models of a heated layer reproduce basic lightcurve features
- Superburst ignited by ^{12}C burning
- For ignition a mass fraction of ~10% of ^{12}C is needed
- Once ignited, other light fuels, like ^{16}O and ^{28}Si, can burn
- Possible contribution to energy generation by photodisintegration of heavy nuclei