Nuclei in the Cosmos School 2025

STELLAR EXPLOSIONS

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Prelude: Stellar Equation of State

$$P = P_{\text{ideal gas}} + P_{\text{radiation}} + P_{\text{degenerate e}^-\text{s}}$$

Stellar Equation of State

$$
\begin{aligned}
P &= P_{\text{ideal gas}} + P_{\text{radiation}} + P_{\text{degenerate e}^-\text{s}} \\
&= \frac{\rho k T}{\mu m_H} + \frac{1}{3} a T^4 + \frac{3\pi^2}{5}\frac{\hbar}{m_e}\left[\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{\frac{5}{3}} \quad \text{non-rel.} \\
&= \frac{\rho k T}{\mu m_H} + \frac{1}{3} a T^4 + \frac{\left(3\pi^2\right)^{1/3}}{4}\hbar c\left[\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{\frac{4}{3}} \quad \text{rel.}
\end{aligned}
$$

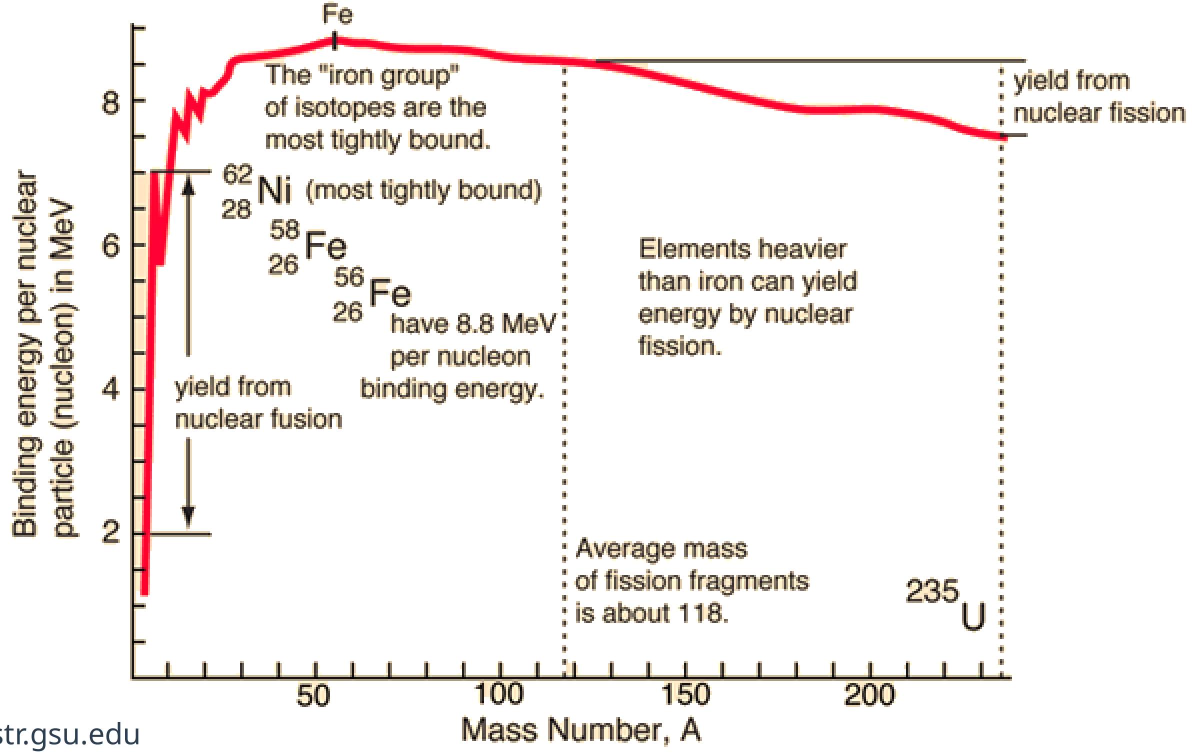
Stellar Equation of State

- All terms contribute, but depending on the conditions one will be the dominant term.
- How does each contribution to the pressure behave?

Stellar Equation of State

- All terms contribute, but depending on the conditions one will be the dominant term.
- How does each contribution to the pressure behave?
- What does this say about stellar explosions?

Prelude: The Curve of Binding Energy



http://hyperphysics.phy-astr.gsu.edu

Prelude: Simple burning model- the alpha chain

7 isotope network

$$^{4}\mathrm{He} \xleftrightarrow{(\alpha\alpha,\gamma)} {}^{12}\mathrm{C} \xleftrightarrow{(\alpha,\gamma)} {}^{16}\mathrm{O} \xleftrightarrow{(\alpha,\gamma)} {}^{20}\mathrm{Ne} \xleftrightarrow{(\alpha,\gamma)} {}^{24}\mathrm{Mg} \xleftrightarrow{(\alpha,\gamma)} {}^{28}\mathrm{Si} \xleftrightarrow{\mathrm{rcaag}} {}^{56}\mathrm{Ni}$$

Stellar Explosions

- Two main classes:
  - Cataclysmic Variables
  - Massive Star(s)

Stellar Explosions by Origin

- Cataclysmic Variables (binary system)
  - Novae
  - X-ray bursts
  - Thermonuclear (type Ia) supernovae
- Massive Star progenitors
  - Core collapse supernova
  - Electron capture supernovae
  - Gamma-ray bursts
  - Kilonovae
  - Pair production supernovae

General Binary System Orbits

- Obey a generalized form of Kepler's laws of planetary motion
  - orbits are ellipses
  - sweep out equal areas in equal time (conservation of angular momentum)
  - harmonic relation between the period and semi-major axis:

$$\frac{4\pi^2 a^3}{G} = (M_1 + M_2)P^2$$

- Center of mass condition:

$$M_1 a_1 = M_2 a_2$$
$$a = a_1 + a_2$$

What Are the Consequences?

- Hotter star can irradiate its companion → outer layers expand
- Tides can distort the stars
- Mass transfer
  - this is where things get fun
  - accretion luminosity is simply:

$$L_{\mathrm{acc}} = \frac{GM\dot{M}}{R}$$

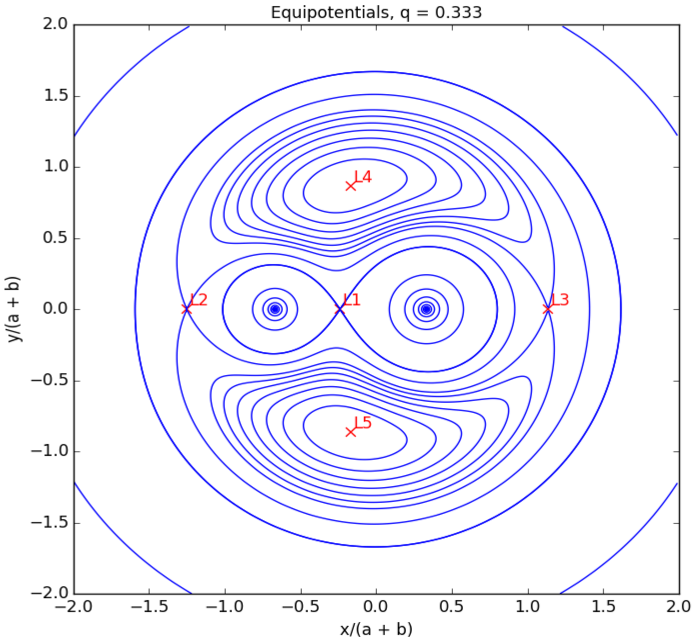
    - for compact objects, $R \ll R_\odot$, and this luminosity can be large (~ 100 $L_\odot$ for NS, ~1000 $L_\odot$ for a black hole)

Equipotentials

- Define an effective gravitational potential:

$$\Phi = U/m = -G\left(\frac{M_1}{s_1} + \frac{M_2}{s_2}\right) - \frac{1}{2}\omega^2 r^2$$

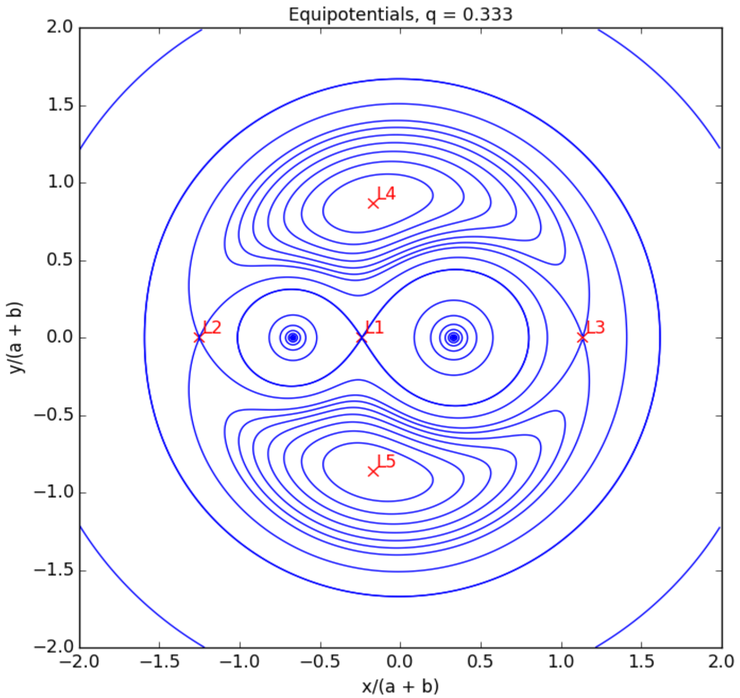
- 5 Lagrange points
  - On axis:
    - L1 between stars
    - L2 and L3 opposite the stars
    - All unstable
  - L4 and L5
    - Equilateral triangle with masses
    - Equilibrium
    - Trojan asteriods



https://github.com/zingale/astro_animations/tree/master/binary_exoplanets/equipotentials

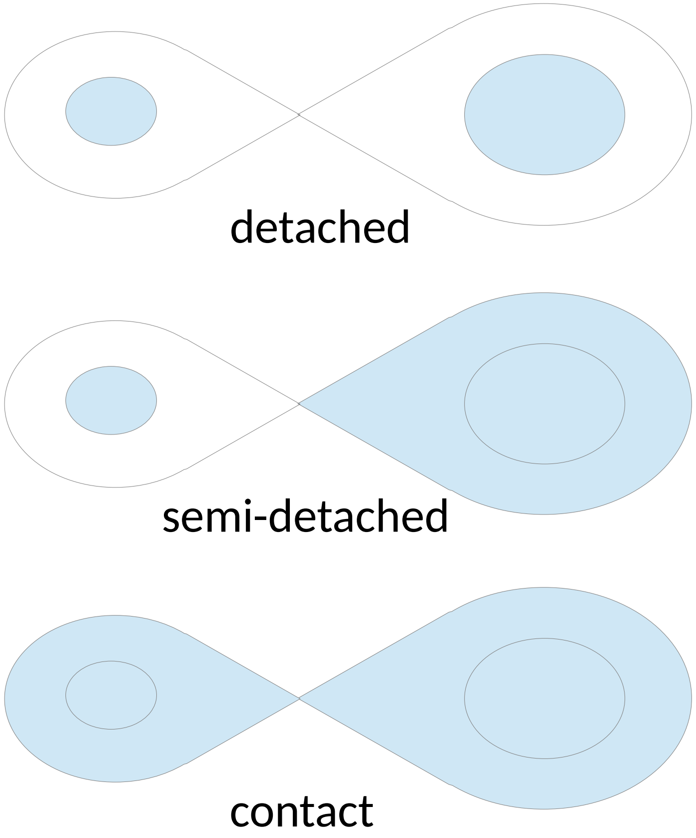
Equipotentials

- Moving along equipotentials requires no work
  - Effective acceleration normal to equipotentials
- General trends
  - Close to stars:
    - Gravity dominates
    - Equipotentials are spherical; centered on star
  - Far from stars:
    - Centrifugal force dominates
- Roche lobe
  - Each half of the figure-8

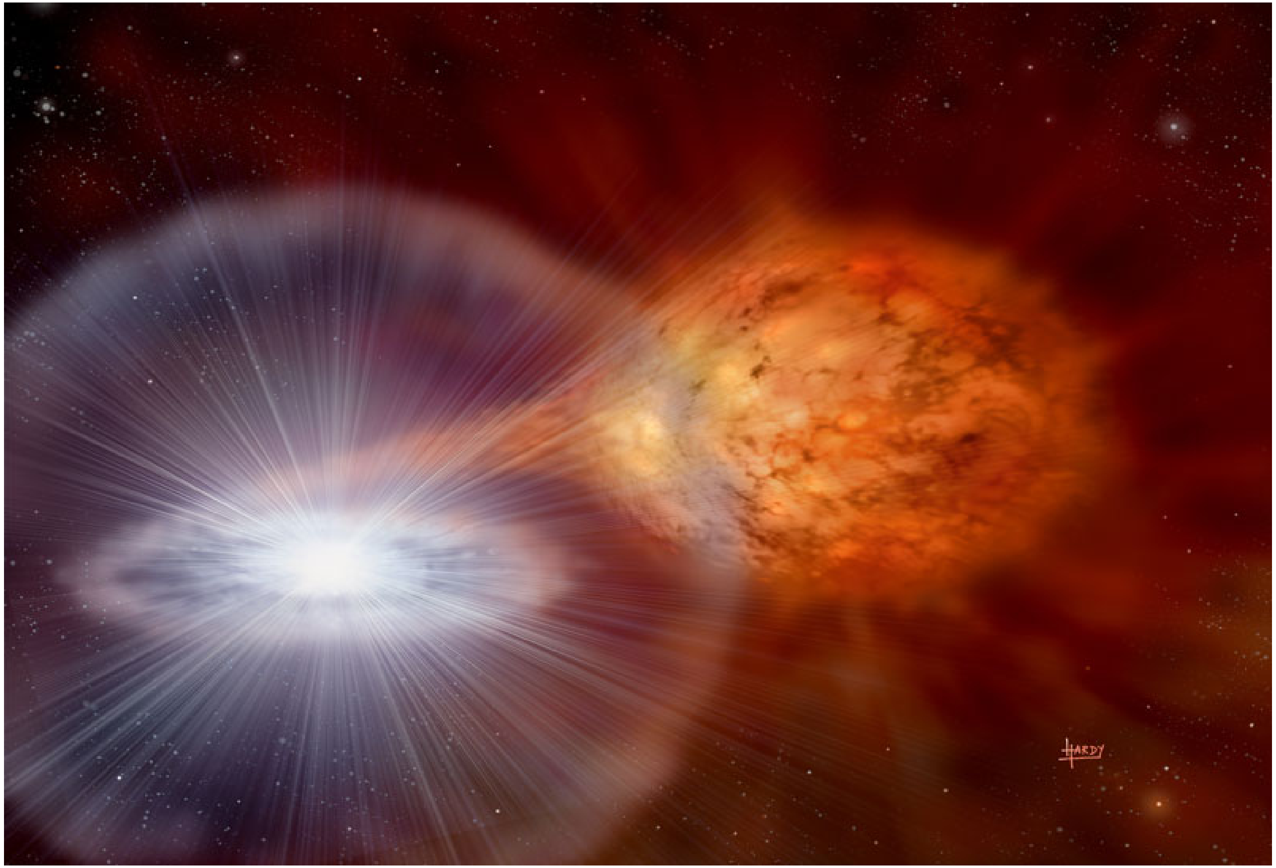


Classification of Close Binaries

- More massive star leaves MS first.
  - R can exceed Roche lobe when red giant
  - Material flows past the L1 point onto companion.
- Binary system classification:
  - Detached: both stars smaller than Roche lobes. Interact via gravity only.
  - Semi-detached: one star fills its Roche lobe. Mass can flow to companion.
  - Contact: both stars fill (or exceed) their Roche lobes. Can have a common envelope surrounding both stars.



What can happen next?



(David A. Hardy & PPARC)

Binary Explosion Taxanomy

- WD systems:
  - classical / recurrant nova: thermonuclear explosion of H layer on surface of WD
  - dwarf nova: instability in the accretion disk that dumps a lot of material onto WD surface at once
  - Type Ia supernova: thermonuclear explosion of an entire WD (or pair)
- NS systems:
  - X-ray burst: thermonuclear explosion of H layer on surface of NS
  - short gamma-ray burst: merger of two NSs
  - binary X-ray pulsar: accretion funneled onto magnetic poles of rapidly rotating NS
- BH systems:
  - accretion onto BH gives rise to X-ray emission (ms timescale rules out NS)

Nova V906 Car (née Carinae 2018)

https://apod.nasa.gov/apod/ap180325.html

Novae: General Properties

- Novae are not as intrinsically bright as supernova
  - Classical novae increase in brightness by ~ 10^6 x
- Appear to be associated with a white dwarf in a binary system (with a low mass main-sequence or Red Giant star as the companion)
- The system is not destroyed by the outburst
- Classical novae never recur over their observed lifetimes (estimated recurrence times of 1000 – 10000 years
- Recurrent novae are related to Classical novae and recur on the timescales of decades

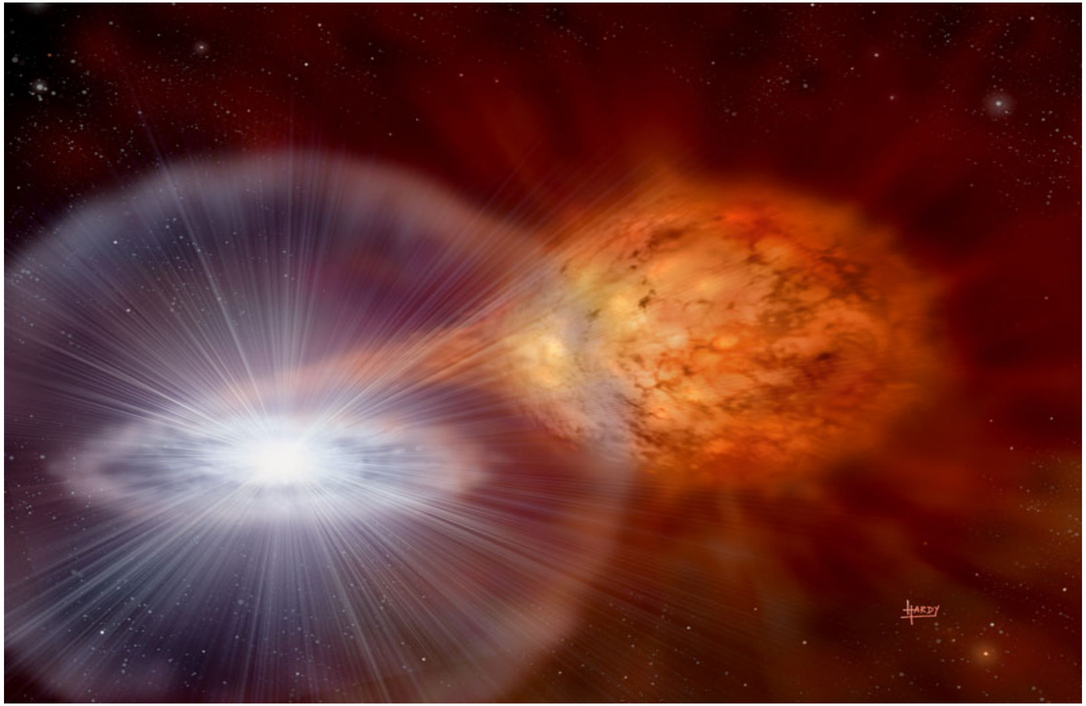
Recurrent Novae

- Similar mechanism as classical novae.
- But seen to recur.
- 10 known in Milky Way, 5 in LMC, and many in M31.
- Usually involve WD near Chandra limit and/or a red giant companion.
- Possible type Ia progenitors?
- Demonstration! T Coronae Borealis expected to erupt soon.

- This will make sense after we discuss classical novae.

Classical Novae

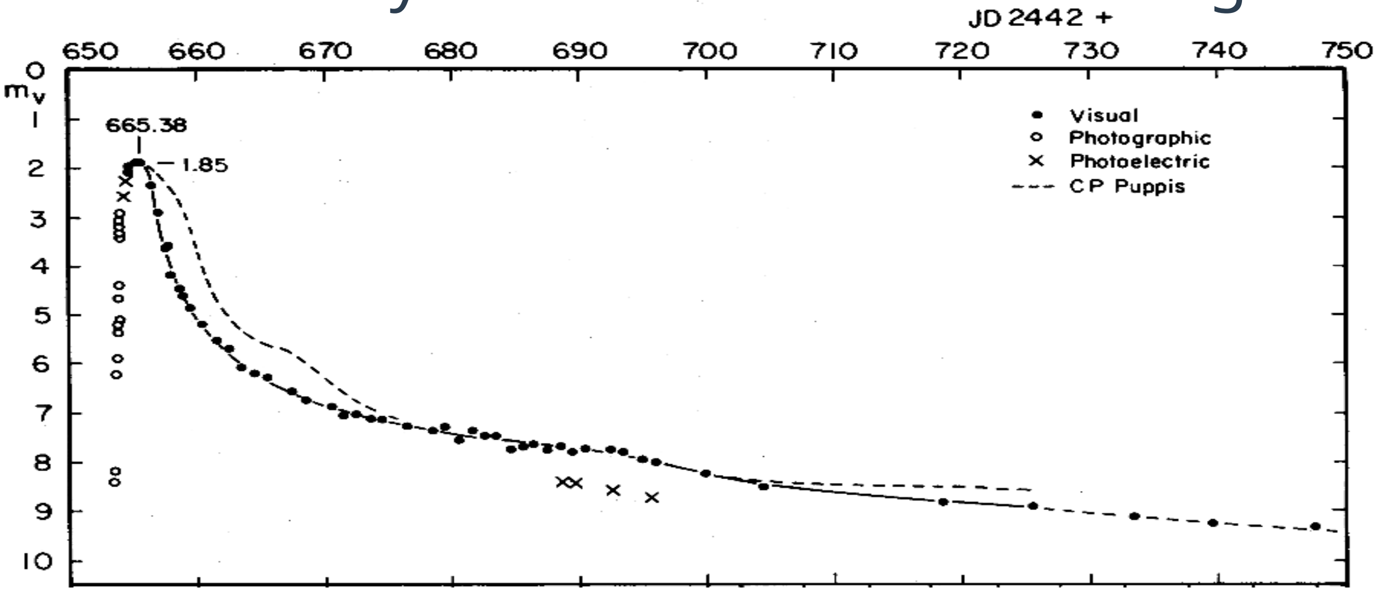
- Thermonuclear runaway of an accreted H layer on the surface of a white dwarf



An artists depiction of the RS Ophiuchi nova (David A. Hardy & PPARC)

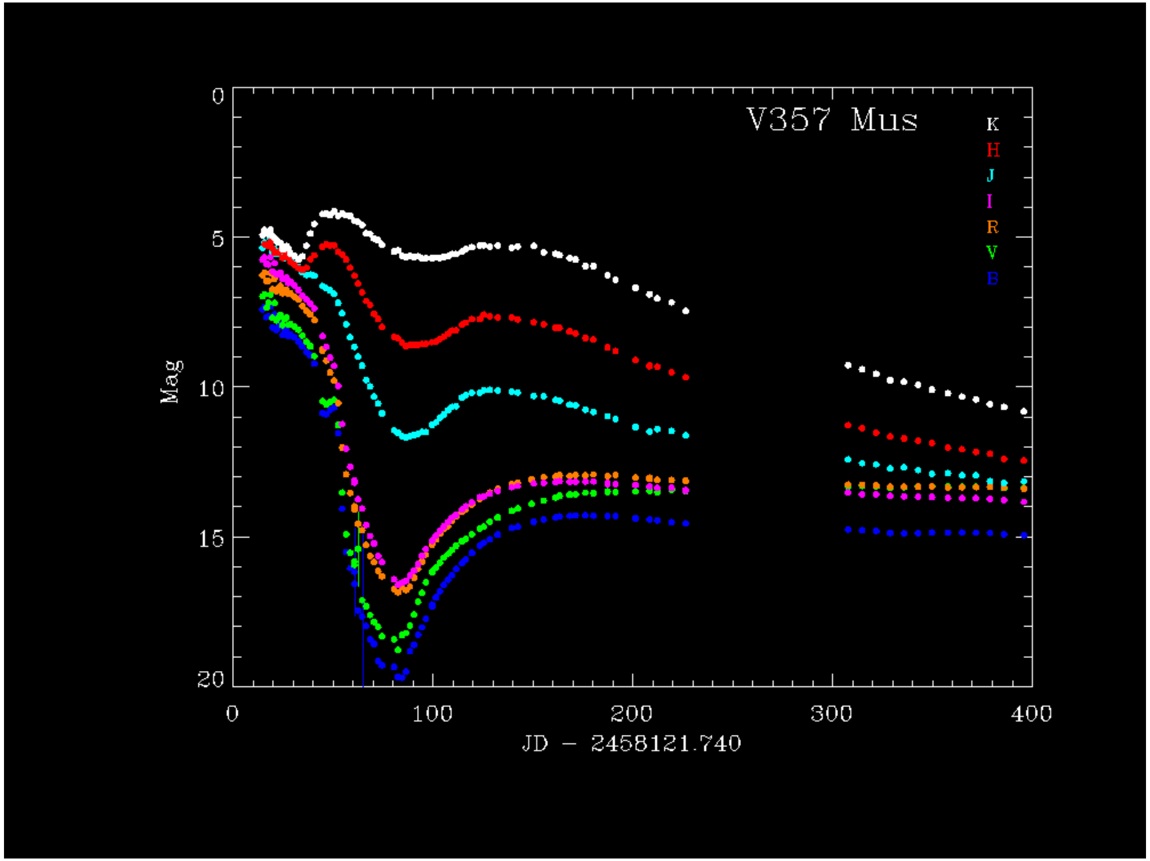
Classical Novae

- At peak brightness, nova can have $L \sim 10^5\, L_\odot$.
- Fast novae: brightness drops 2 mag in days.
- Slow novae: 100 days or more for the same brightness drop



(Young, Corwin, Bryan, and De Vaucouleurs)

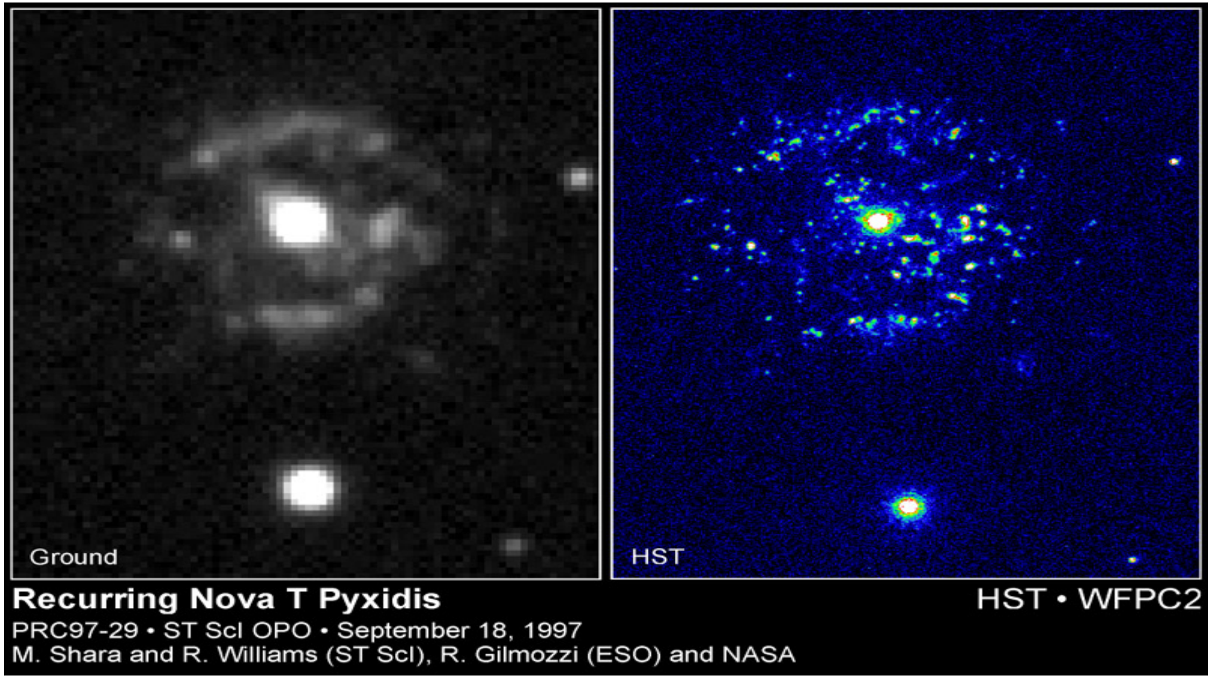
Classical Novae Light Curves



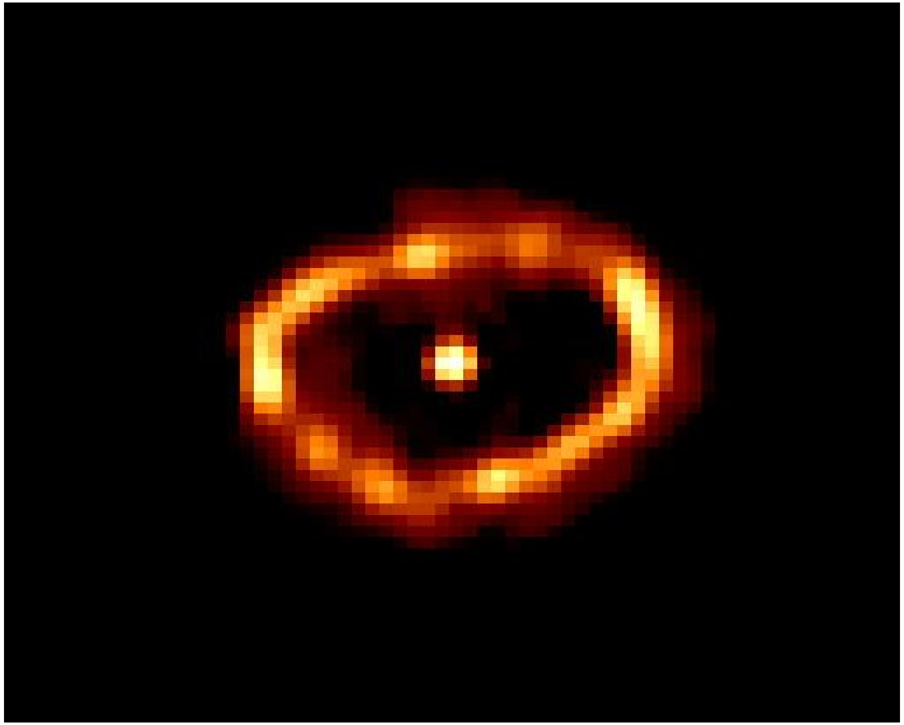
F. Walter

Classical Novae

- ~40 novae predicted / yr in our galaxy
- Some recur (P ~ decades)



Classical Novae



(F. Paresce, R. Jedrzejewski (STScI), NASA/ESA)

Nova Cygni 1992

Classical Novae

- General picture:
  - WD accretes H from companion at 10^{-9} to 10^{-8} $M_{\odot}$ yr^{-1}.
  - H layer builds up
  - Mixing takes place enriching envelope with CNO
  - Conditions at the base are degenerate—runaway!
  - Degeneracy lifted only once $T > 10^8$ K

Classical Novae

- Numerical modeling shows runaway occurs when a critical pressure is reached at the base

$$P_{\rm crit} \sim 2 \times 10^{19}\ {\rm erg\ cm^{-3}}$$

- HSE:

$$\frac{dP}{dr} = -\rho g$$

$$\frac{0 - P_{\rm crit}}{\Delta r} = -\rho g = -\frac{\Delta M}{4\pi R_{\rm WD}^2 \Delta r} \frac{GM}{R_{\rm WD}^2}$$

$$P_{\rm crit} \sim \frac{GM\Delta M}{4\pi R_{\rm WD}^4}$$

Burning

- This corresponds to T ~ 2×10^7 K
  - CNO cycle dominates the burning
  - Partially degenerate—P response is not great so T increases further
  - Convection sets in
- Above 10^8 K, hot CNO (beta-limited) kicks in
  - β+ decay rates are slow, T independent
  - ^{14}O and ^{15}O build up (these have slow decay times)
  - If we get hot enough, we can break out (rp-process). More on this later (w/ XRBs)
- Degeneracy is lifted here, which can quench the runaway
  - Expansion of the shell, T drops
  - Steady H burning can then ensue.
- Luminosity can be super-Eddington during the outburst.

Classical Novae

- About 10^{-4} $M_\odot$ is ejected to the ISM
- ~40 novae predicted / yr in the galaxy
  - Total ejected masses is ~4×10^{-3} $M_\odot$ yr^{-1}
- Supernovae occur about 1 every 50 yr, but eject ~3 $M_\odot$ per event, or 0.06 $M_\odot$ yr^{-1}
- Novae are a small part of nucleosynthesis
  - Except for the elements they overproduce

Classical Novae

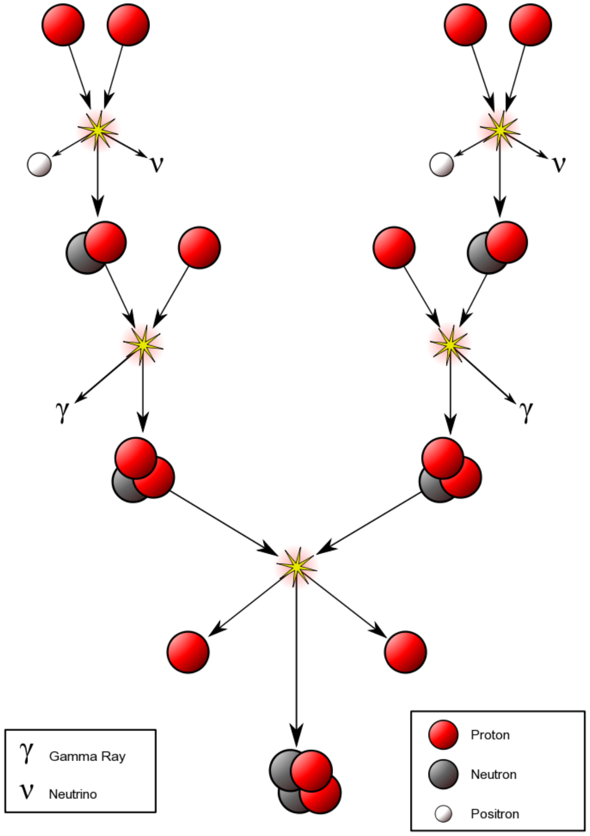
- Observations show lots of C, N, O and some with O, Ne, Mg, and Al in ejecta
- Two classes:
  - Correspond to CO and O/Ne/Mg WDs (determined by IR measurements)
- Ejecta reflects underlying WD, since it is unclear if T is ever hot enough to make heavy nuclei
  - This point is debated a lot in the literature
- CO novae show lots of dust
  - Formed in ejecta when T is cool
- It seems that CO novae have WDs with $M < 1.2\ M_\odot$
- ONeMg novae have WDs with $M > 1.2\ M_\odot$

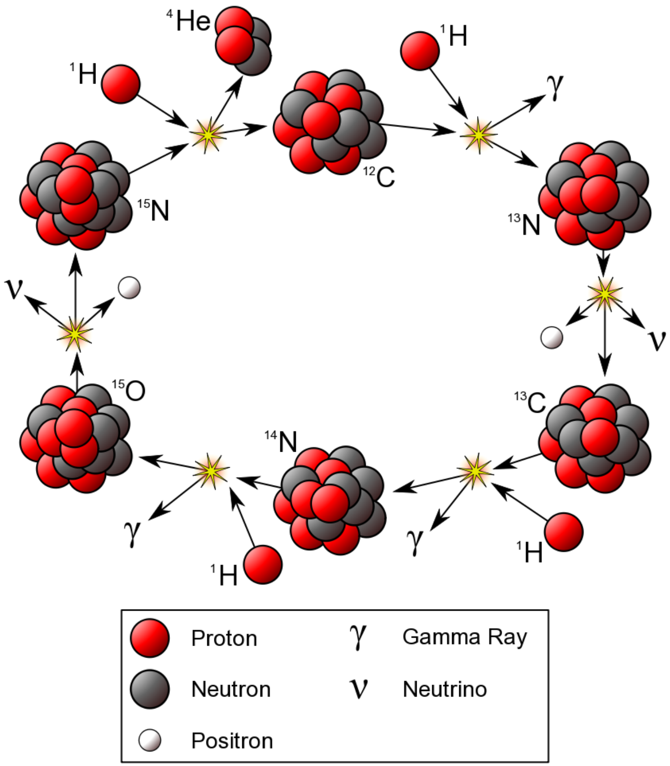
Classical Novae

- Novae are likely a major source of ^{13}C, ^{15}N, and ^{17}O.
- Also produce ^{7}Li.
- More controversial whether they produce lots of ^{22}Ne and ^{26}Al
- Overall, novae ejecta show lots of CNO and heavy elements. Nucleosynthesis alone cannot account for this.
- Also, only PP burning will not occur fast enough to power the outburst. Requires CNO burning.
  - WD material must be dredged up somehow.

Burning

- PP vs CNO





(Wikipedia)

Modeling Novae

- Modeling novae is hard because of the large amount of expansion in the envelope
  - Late stages, R ~ 10^{12} cm
- Major theoretical issue: dredge-up
  - How to we enrich the burning layer with CNO from the underlying WD?
  - Algorithmic issues may mask physical effects here

Nova Dredge-Up

- How can we dredge-up material from the underlying WD?
  - Diffusion layer
    - H diffuses down into WD during accretion
    - Deep H ignites first, with lots of metals surrounding it
    - Convection driven by this heating brings metals into the H envelope
  - Shear mixing
    - Accretion disk extends to the WD surface
    - Kelvin-Helmholtz instability ensues and mixed
    - Can this work with a magnetic field?
  - Convective overshoot
    - Burning begins at the base of the H layer
    - Convection is driven
    - Overshoot of the convective eddies mixed CO into the envelope

Novae: Mixing Simulations

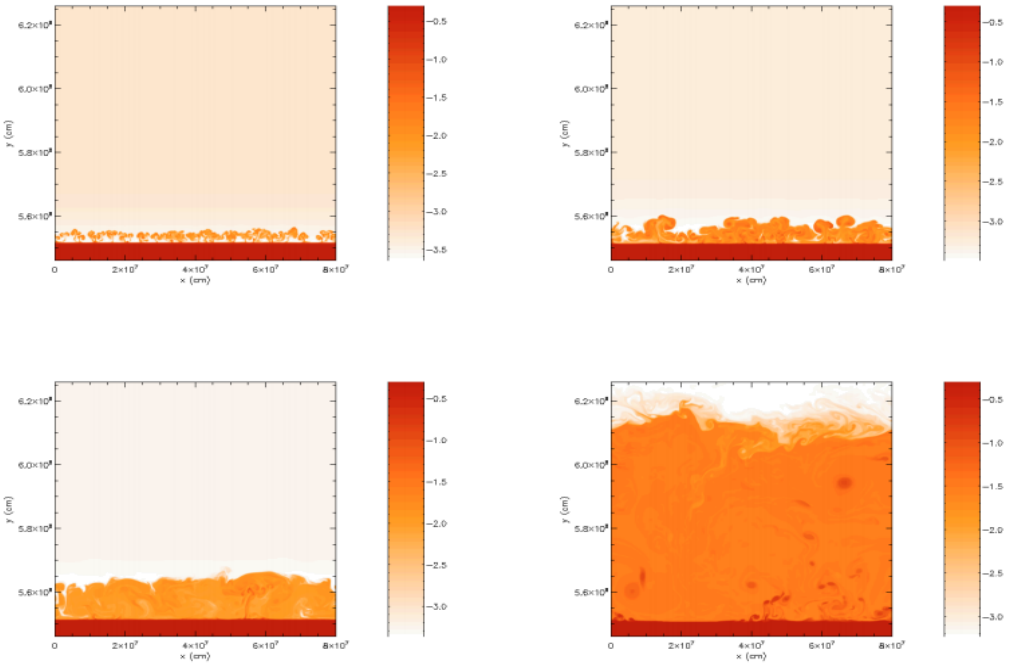


Fig. 1. Snapshots of the development of KH instabilities at t = 215 s (*upper left panel*), 235 s (*upper right*), 279 s (*lower left*), and 498 s (*lower right*), shown in terms of ^{12}C mass fraction (in logarithmic scale). The injection of core material driven by the KH instabilities translates into a mass-averaged abundance of CNO-nuclei in the envelope of 0.079, 0.082, 0.089, and 0.17, respectively. The mean CNO abundance at the end of the simulations reaches 0.30, by mass.

(Casanova et al. 2010)

Neutron Star Systems

- What about a system with a neutron star as the compact object? Can we form such a system?
- A lot of energy is released in a core-collapse supernova.
  - Explosion of a massive star (10s of $M_\odot$) leaves behind a neutron star remnant of < a few $M_\odot$.
  - Explosion drives away about ½ of the mass of the system.
  - Neutron star can be given a strong kick.
- If enough mass is transferred from the massive star to the companion during evolution, the system can remain bound.
- Or an accreting white dwarf collapses into a neutron star.

XRBs

- Neutron stars also can accrete H/He from companion
  - Much higher surface g
  - Only a depth of meters is needed for runaway
  - X-ray burst: explosive burning gives X-ray flash (minutes long)
  - Recurrence time of hours
- Satellites can see repeated bursts from a single source

XRB Energetics

- Gravitational energy release / baryon:

$$\frac{GMm_p}{R} = \frac{(6.67 \times 10^{-8}\ \mathrm{cm}^3\ \mathrm{g}^{-1}\ \mathrm{s}^{-2})(1.4 \cdot 2 \times 10^{33}\ \mathrm{g})(1.67 \times 10^{-24}\ \mathrm{g})}{10^6\ \mathrm{cm}}$$

$$= 3.1 \times 10^{-4}\ \mathrm{erg} \approx 200\ \mathrm{MeV}$$

- Thermonuclear burning (H) releases ~ 5 MeV / baryon
- Burning is overwhelmed by accretion
  - Fuel must be stored and then burned on short timescale
- Thin-shell instability
  - Fuel accreted for hours – days
  - Burned in 10 – 100 seconds
- ~70 XRB sources known (some with > 100 individual bursts)

XRB Bursts

- H burning
  - As with novae, start with PP and CNO.
  - Once we are hot enough, breakout reactions move us beyond hot CNO cycle
  - Proton captures build heavy nuclei
  - H can be exhausted before He burning is done: C can build up
- Pure He bursts are different
  - Energy release is rapid (no waiting on weak interactions)
  - Eddington limit is likely exceeded
  - Photosphere radius expansion burst can occur
  - These have become popular lately as a means to determine NS mass and radii

XRB Burning

- As the burning proceeds, we can break out of the CNO cycle and build up proton-rich nuclei

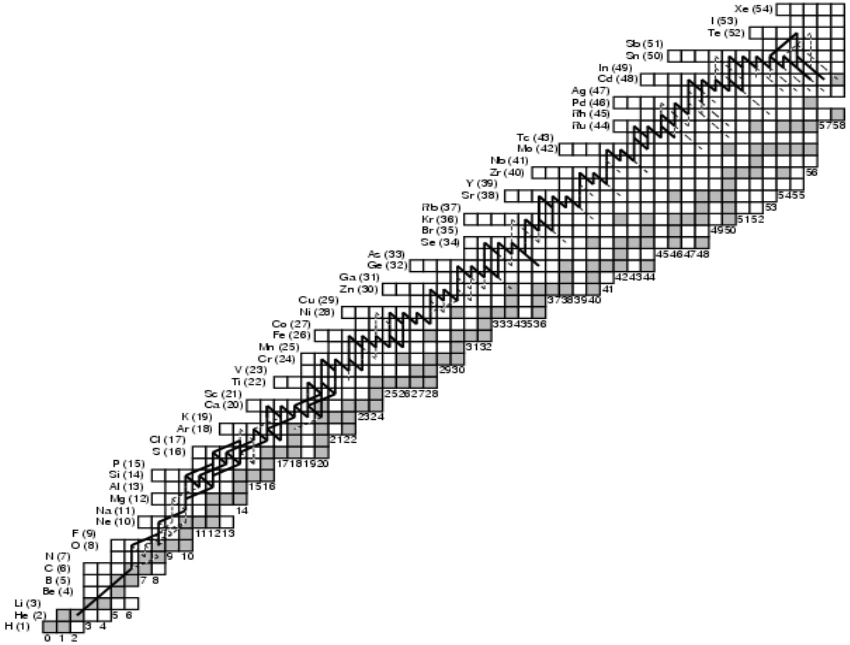
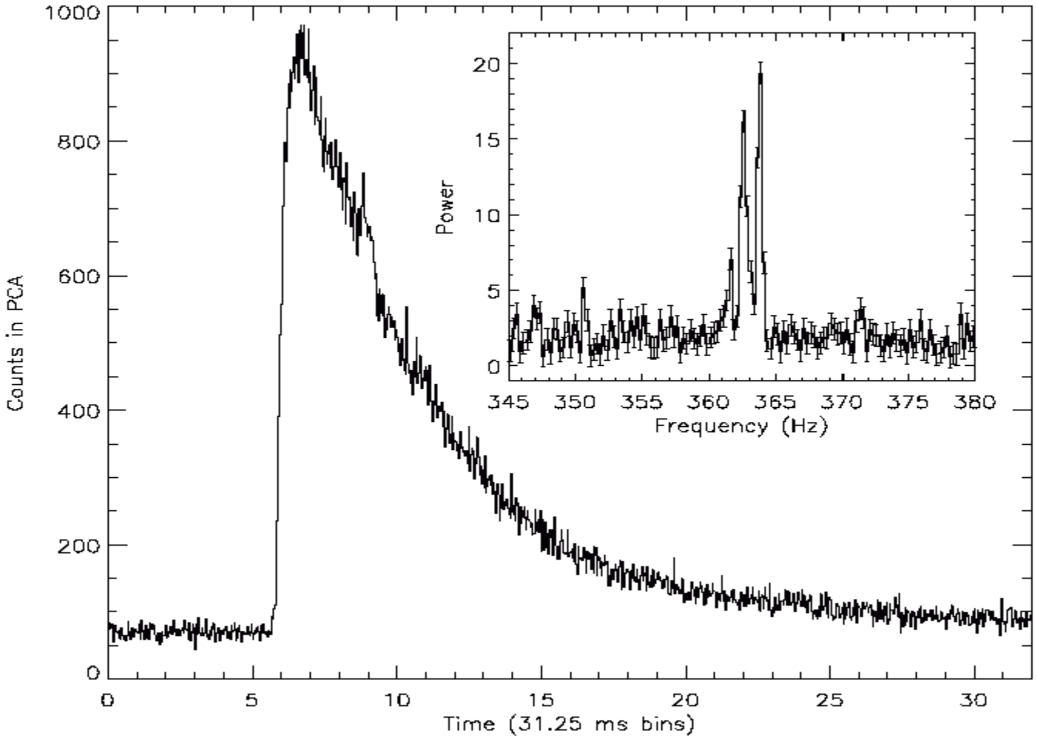


Fig. 3.1. Schematic showing the dominant pathways of the nuclear reaction flows during the rp process. Elements far beyond ^{56}Fe can easily be reached. Filled squares denote stable nuclides (after Schatz et al. 2001).

Strohmayer & Bildsten 2003

XRBs

- A pure He lightcurve



Strohmayer et al., 1996, ApJ, 469:L9

XRBs

- Multiple bursts from the same system

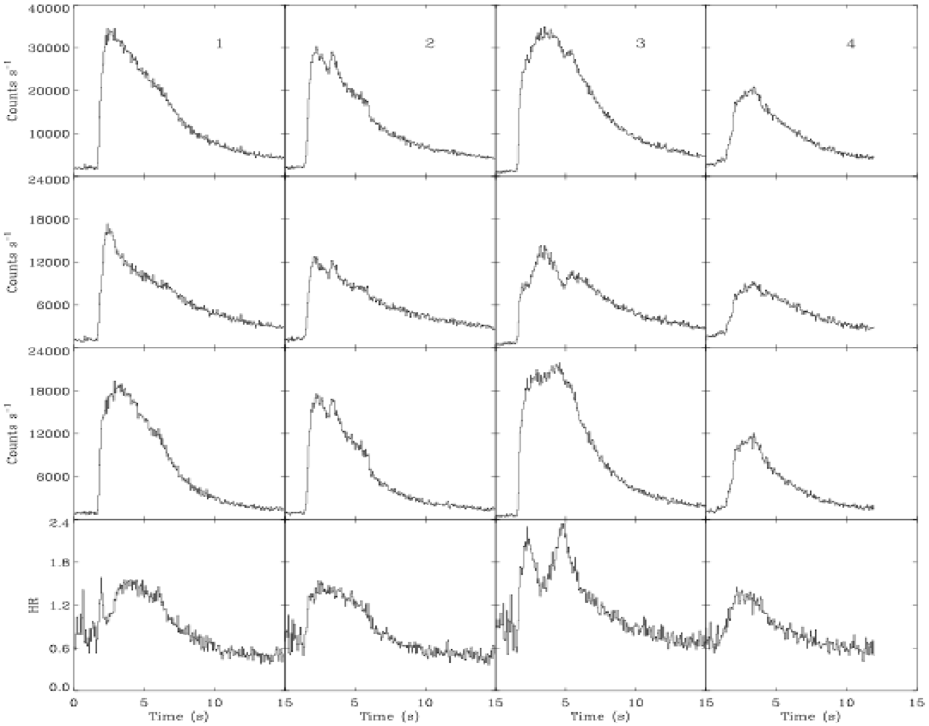


Fig. 3.4. A sample of four X-ray bursts from the LMXB 4U 1728–34 as observed with the RXTE/PCA. Each sequence shows, from top to bottom, the total 2 - 60 keV countrate, the 2 - 6 kev countrate, the 6 - 30 keV countrate, and the hardness ratio (6 - 30 keV) / (2 - 6 keV). Bursts 1 and 3 show clear evidence for PRE based on the hardness ratio evolution.

from Strohmayer and Bildsten 2003

XRBs

- A hydrogen burst—note the longer timescales because of the waiting points with H burning

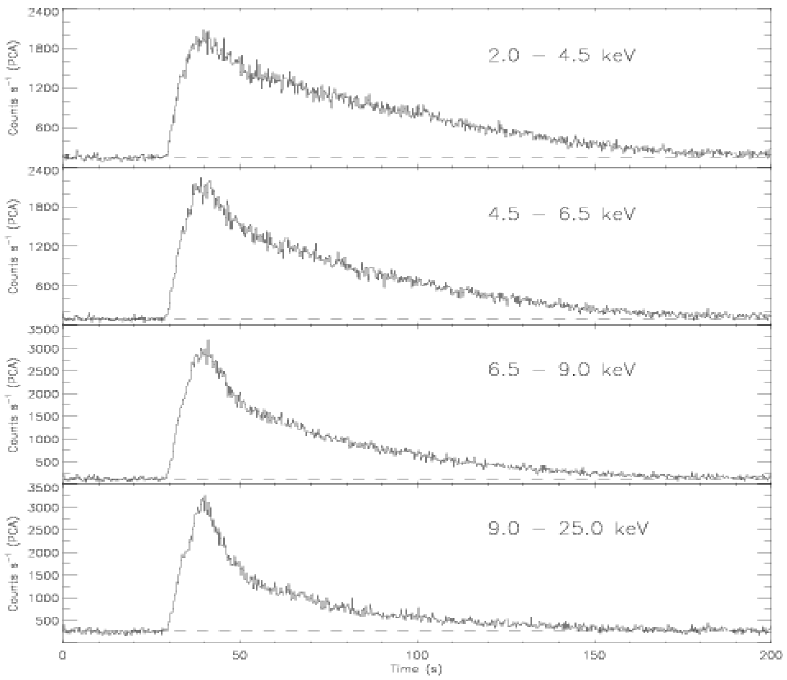
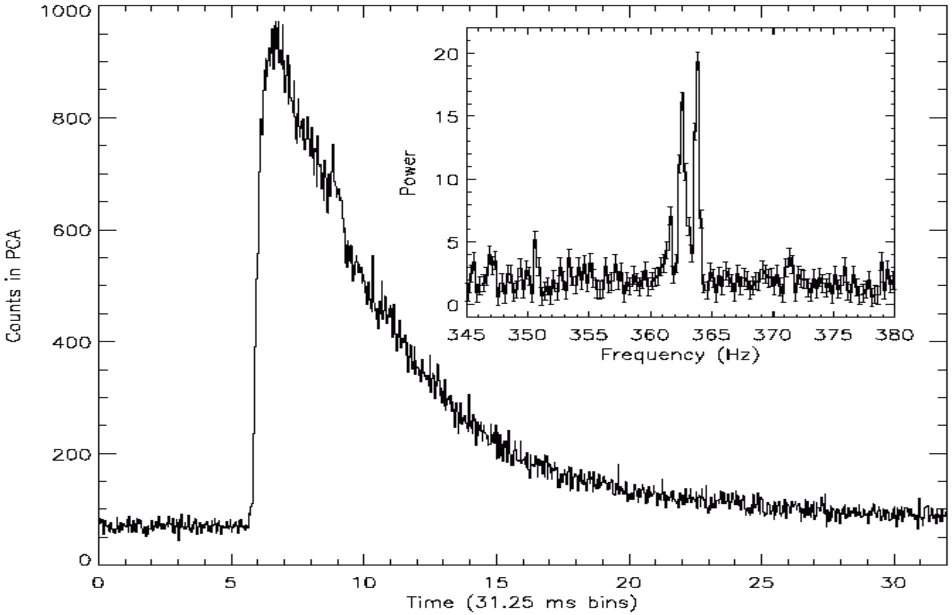


Fig. 3.3. An X-ray burst from GS 1826–238 seen with the RXTE/PCA. The burst is shown in four different energy bands. The long duration is indicative of the delayed energy release from the rapid proton (rp) process. The dashed line marks the preburst flux level (see also Kong et al. 2000).

from Strohmayer and Bildsten 2003

XRB Observations

- Light curve has a fast rise
- Decay is slower—this is the thermal diffusion timescale
- X-ray luminosity can be at the Eddington limit
  - Photosphere can lift off
- Brightness oscillations are observed (300 to 600 Hz)
  - Evident in power spectrum of lightcurve
  - Spin must be at play here
  - Evidence for non-uniform burning—perhaps localized ignition?



Strohmayer et al., 1996, ApJ, 469:L9

XRB Observations

- Oscillations can be observed in the rise of the burst
  - Amplitude is higher when X-ray flux is lowest
  - Likely due to small hot spot spreading across the entire NS.
- Oscillations during decay
  - Usually smaller amplitude than during rise
  - Some bursts show oscillations both during rise and decay
  - Not clear how to explain with the spreading hot spot idea
- Frequency changes during bursts
  - Frequency (usually) increases during the burst to some limiting value
  - Cause: angular momentum conservation expanded shell contracting back to the NS surface (?)
    - Can't account for all of the observed frequency increase

XRB Frequency Evolution

3.4 Millisecond variability during X-ray bursts **23**

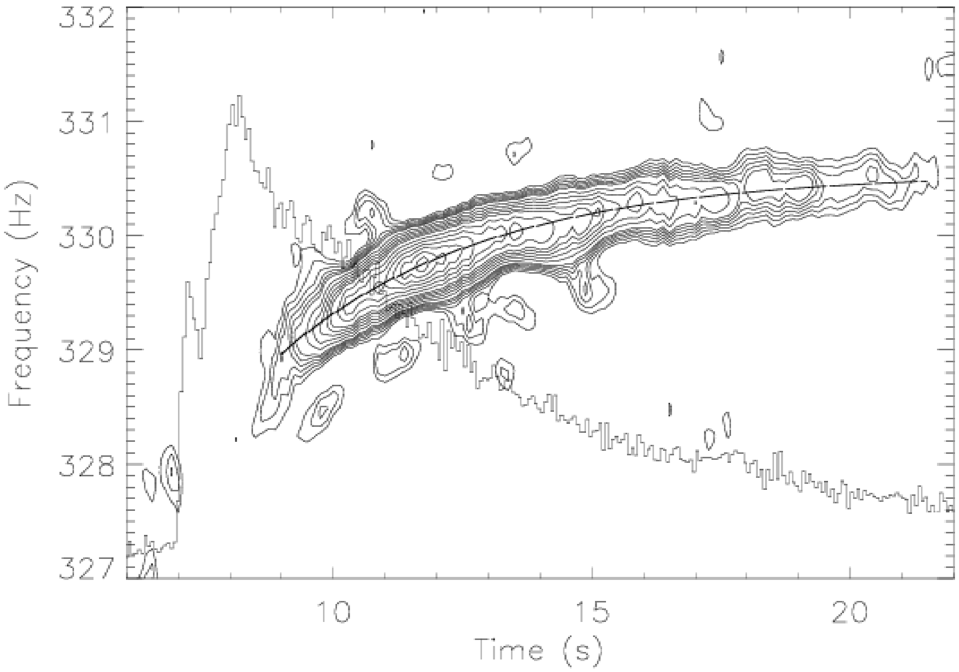
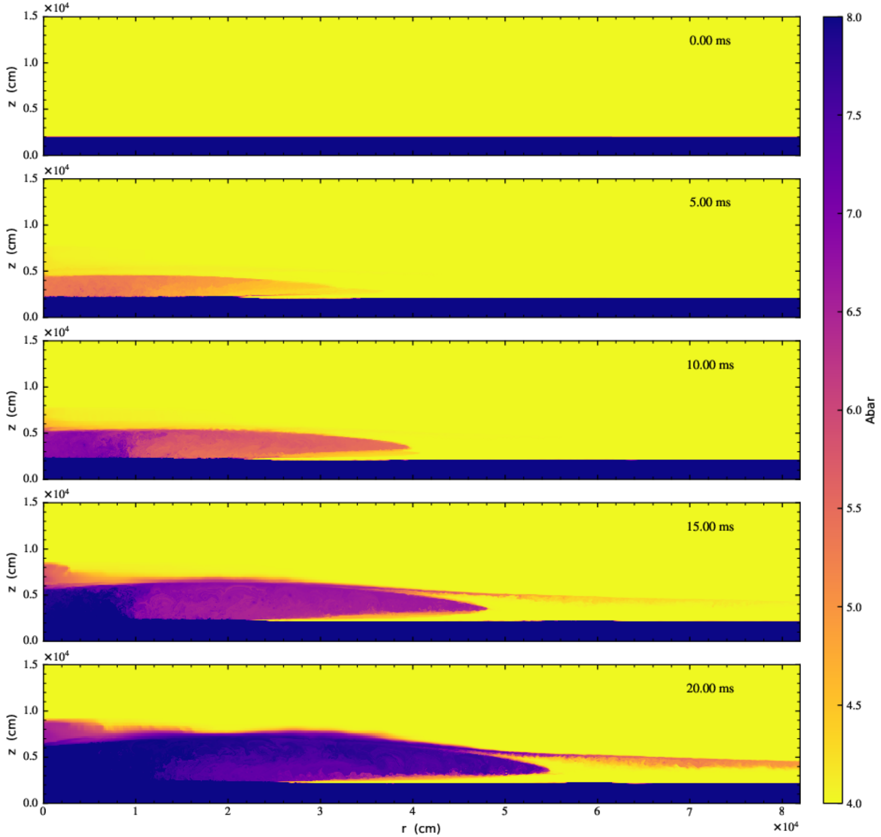


Fig. 3.9. An X-ray burst from 4U 1702–429 observed with the PCA onboard RXTE. Shown are contours of constant power spectral density as a function of frequency and time. The solid curve shows the best fitting exponential model. The burst time profile is also shown (after Strohmayer & Markwardt 1999).

from Strohmayer and Bildsten 2003

Modeling XRBs

- Most of what we know comes from 1-d (or even 1-zone) models
  - Able to use large networks to explore the nucleosynthesis
- Multi-d simulations show that rotation is important



Eiden et al. 2020

Summary of XRB Calculations

- 1-d models successfully reproduce multiple bursts, get the recurrence time right, etc. (see, e.g. Woosley et al. 2004)
  - Spherically symmetric
  - Simple approximation of convection
- 2-d shallow water hydro calculations show the importance of rotation in confining the burning
- Some progress modeling pure He bursts with low Mach algorithms (Lin et al. 2006 and Malone et al. 2011)
  - Differing approaches show differences in dynamics, resolution requirements, etc.
- Recent calculations using simplified hydrostatic vertical structure and high-aspect ratio zones showed effects of rotation on flame speed (Cavecchi 2012)
  - Doesn't capture turbulence interactions, not really hydrodynamics vertically

What Can We Learn In Multi-D

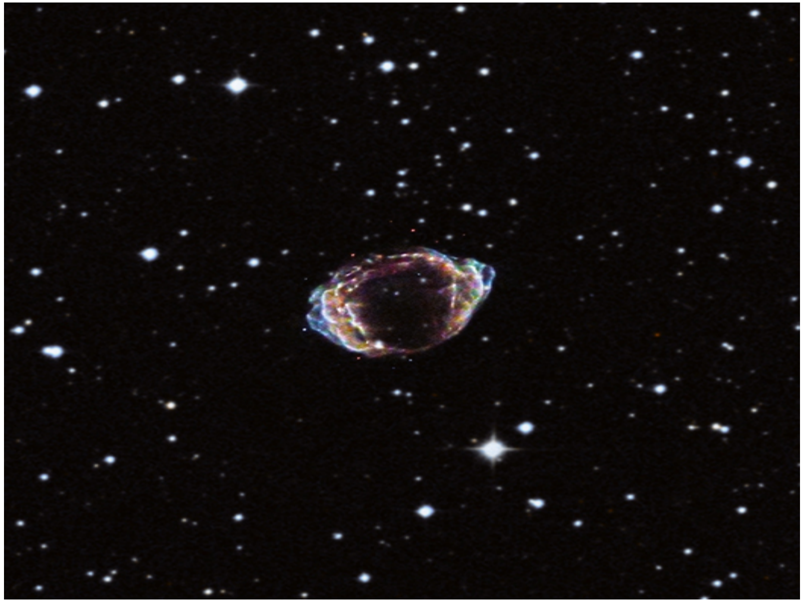
- How does the fuel spread over the surface?
- How does the ignition begin?
  - Convection is likely important in the moments leading up to the ignition — this is a 3-d problem.
  - How many locations does the burning begin at?
- Is the burning localized?
  - If so what localizes it?
  - How does it spread?
  - How fast does the burning spread?
- Does convection modify the nucleosynthesis?
- What are the effects of rotation?

What Can We Learn In Multi-D

- Does convection bring ash to the surface?
  - Potential for escape greater
- Do multi-dimensional effects offer a mechanism for brightness oscillations?
- How much of the initial fuel layer is burned?
- What does the (laterally propagating) burning (front) look like?
- Are there any other multidimensional effects that have not been thought of that are important to the evolution of the burst?

Supernovae

- G1.9+0.3, most recent galactic SN.
  - 28,000 light years away
  - Obscured by dust because it is in the direction of the center of the galaxy.
  - Would have been seen ~120 yrs ago.



http://chandra.si.edu/photo/2013/g19/

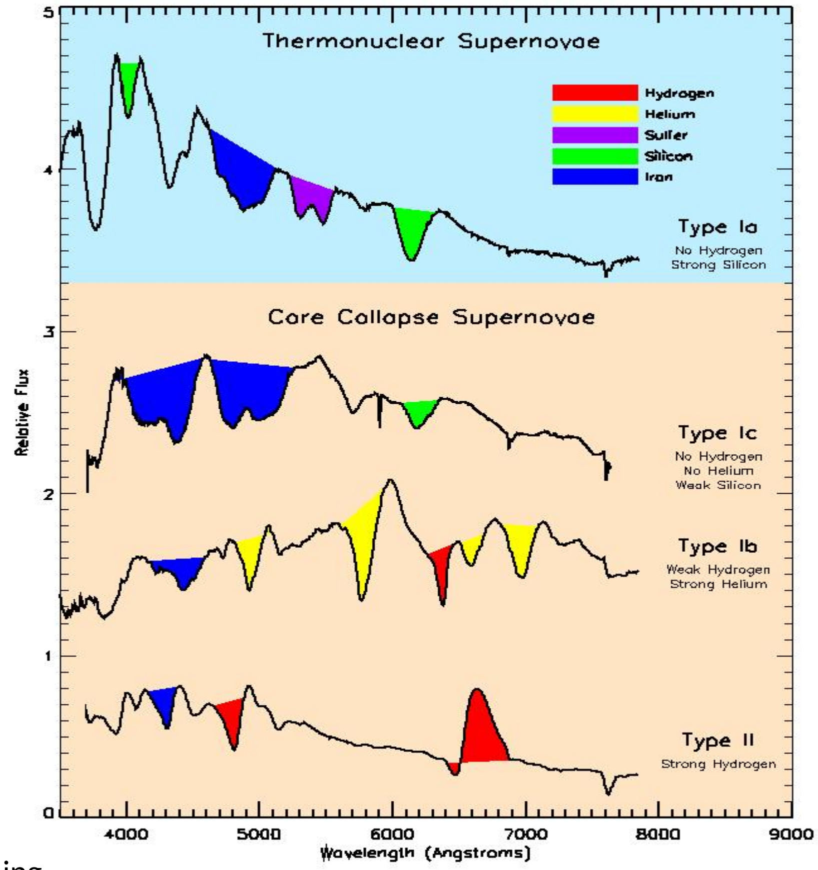
Supernovae

- Supernova 1987a

ESO

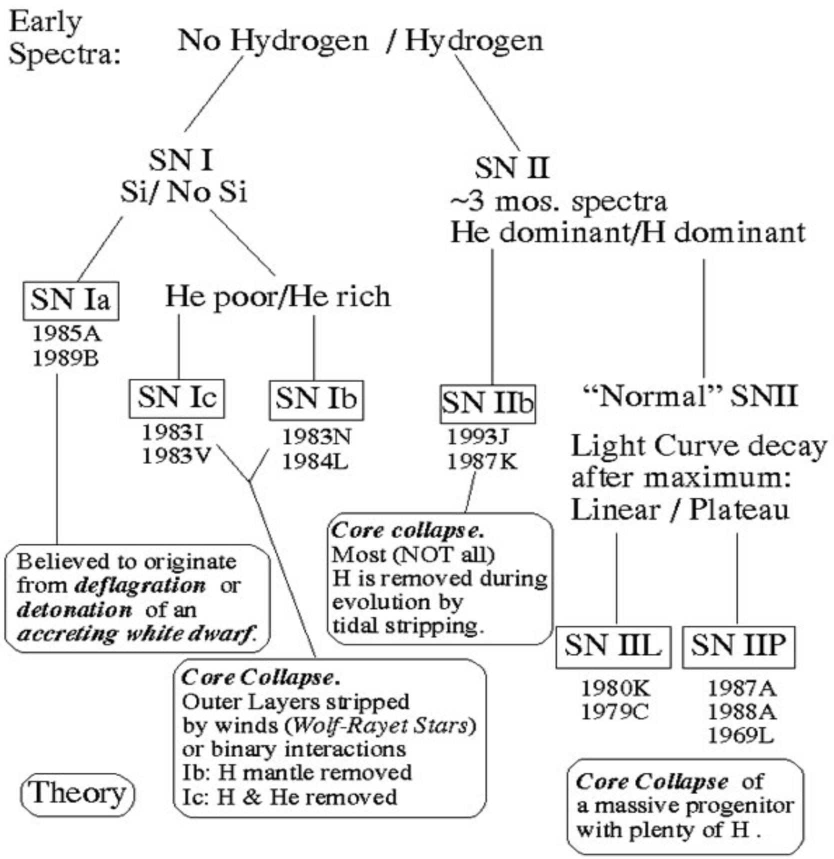
Supernovae

- Fundamentally two types:
  - Gravitationally powered
  - Thermonuclear powered
- Observational classification more complicated
  - Type I: no H in spectrum
    - Ia: strong Si lines
    - Ib: strong He, weak Si
    - Ic: weak He
  - Type II: strong H in spectrum
- Observational pace is accelerating:
  - 1 per century in our galaxy
  - 1 – 10 per second in the observable Universe



Dan Kasen http://panisse.lbl.gov/~dnkasen/tutorial/graphics/sn_types.jpg

Supernova Taxonomy



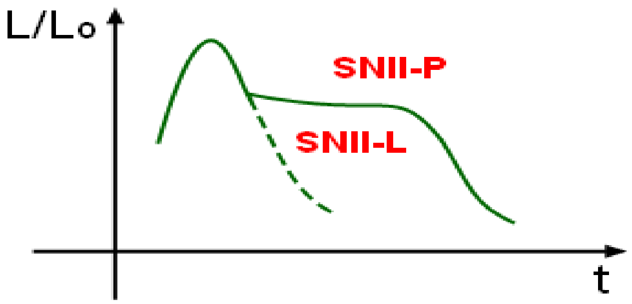
"Abnormal" SNII

SN IIn

SN IIp

M. Montes

Supernovae



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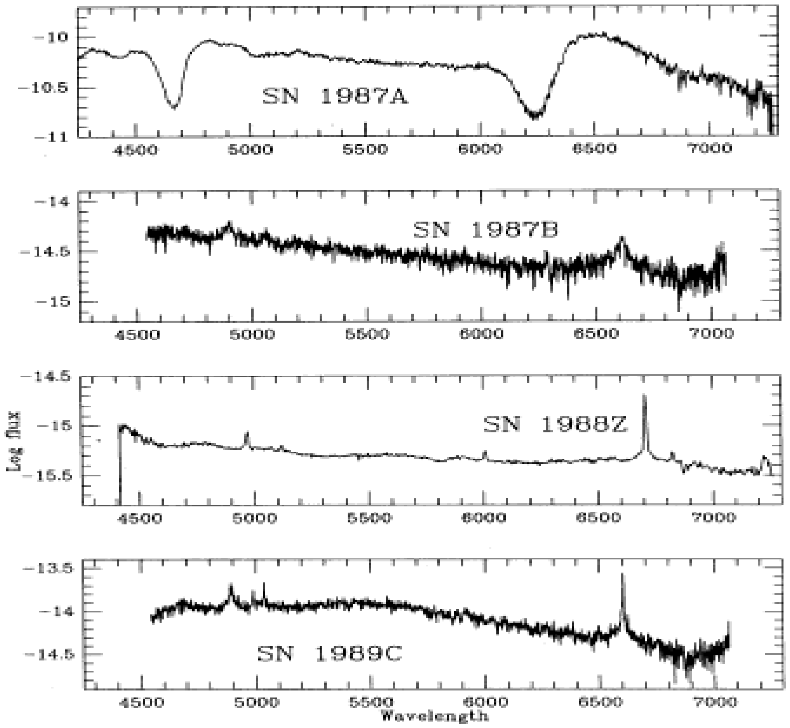


Sclegel (1990)

Supernovae

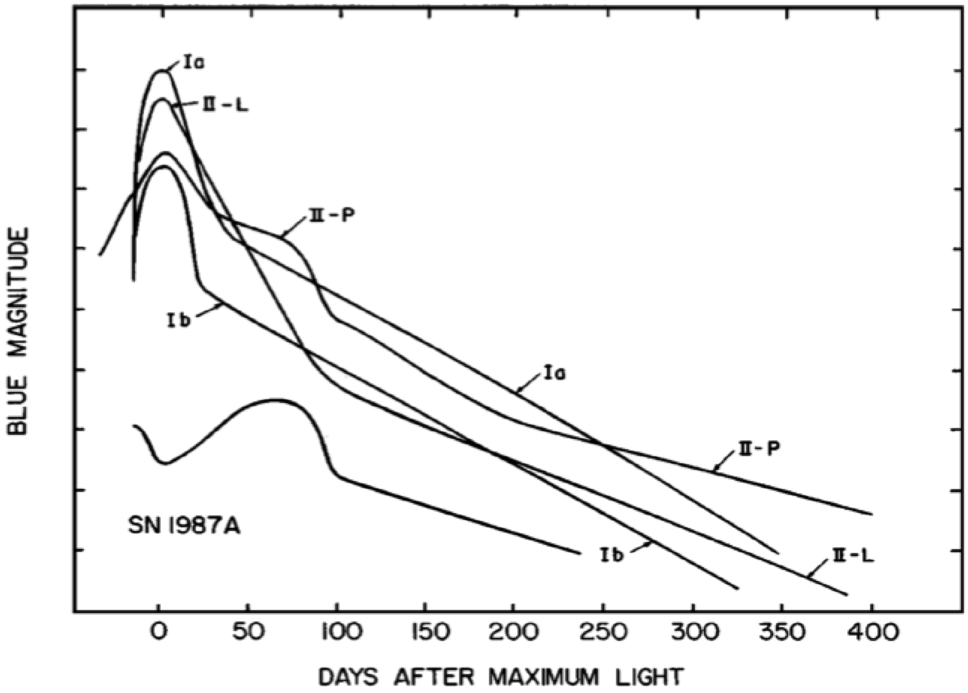
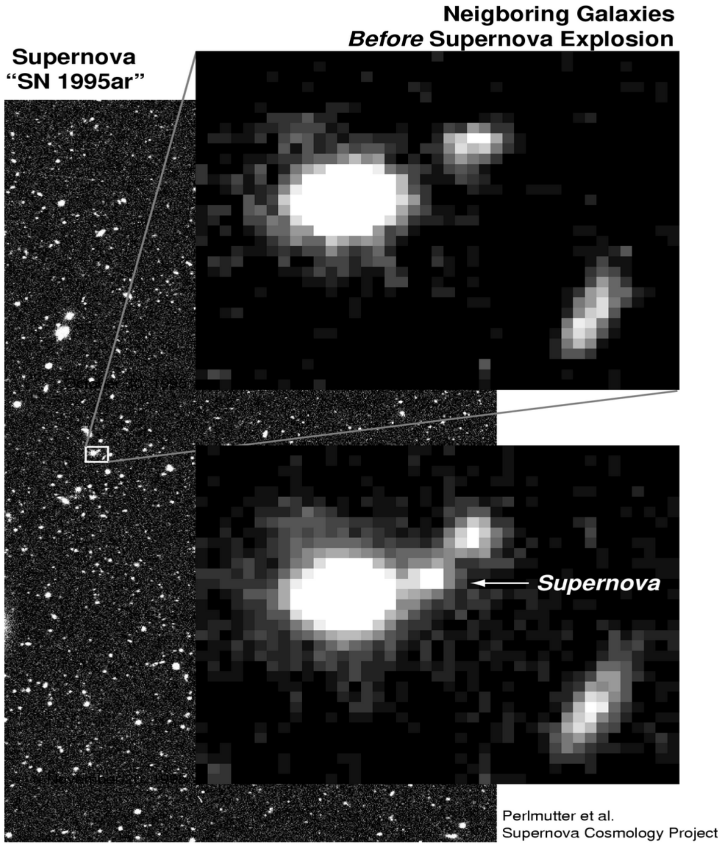


Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous.

Figure Credit: Wheeler, J. C., & Harkness, R. P. 1990, RPPh, 53, 1467

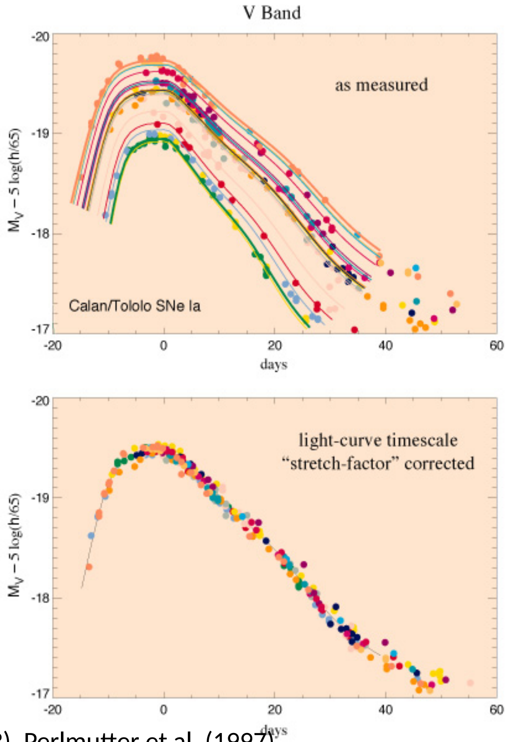
Supernovae Searches

- Observers look for a sudden increase in the brightness of a galaxy.
- Follow-up observations tell whether it is a Type Ia supernova or core-collapse
- → time domain astronomy



Type Ia Supernovae

- Brightness rivals host galaxy, L ~10^{43} erg s^{-1}
- Radioactive ^{56}Ni powers the lightcurve



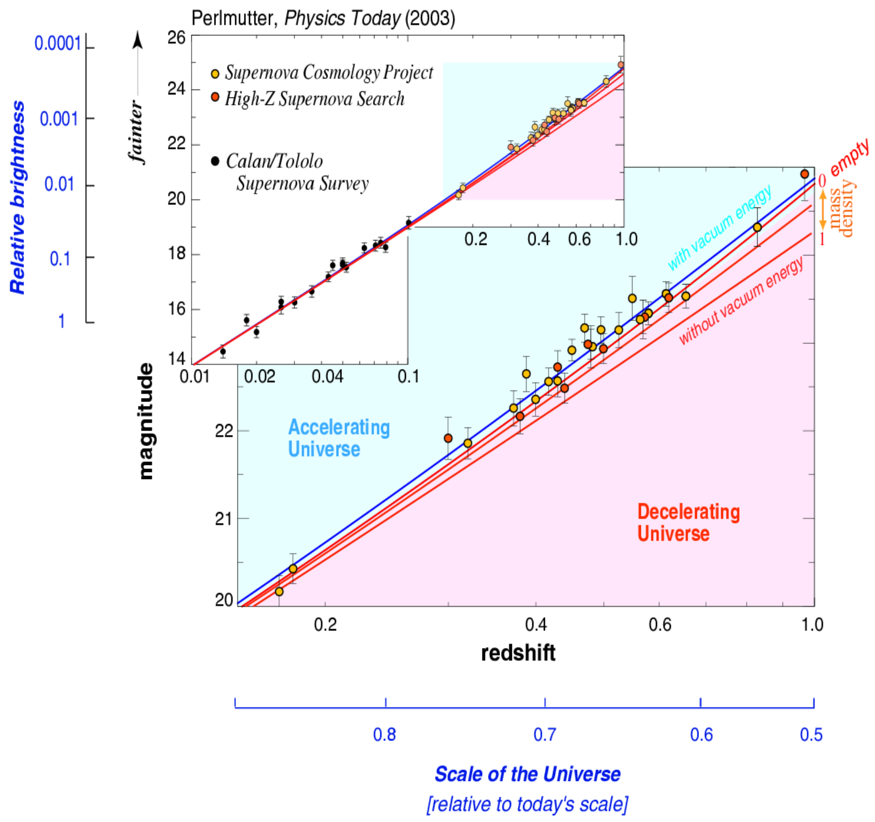
SN 1994D (High-Z SN Search team)

- Allows calibration- SNe Ia act as standard candles.
- No H in spectra, but strong Si, Ca, and Fe lines
- Occur in old stellar populations
- No compact remnant

Phillips (1993), Perlmutter et al. (1997)

Type Ia Supernovae

- Observations give a distance vs redshift relation.
- Allows us to determine the cosmological parameters.
- In 1998, this led to the discovery that the expansion rate of the Universe is accelerating.



SNe Ia: Back of the Envelope

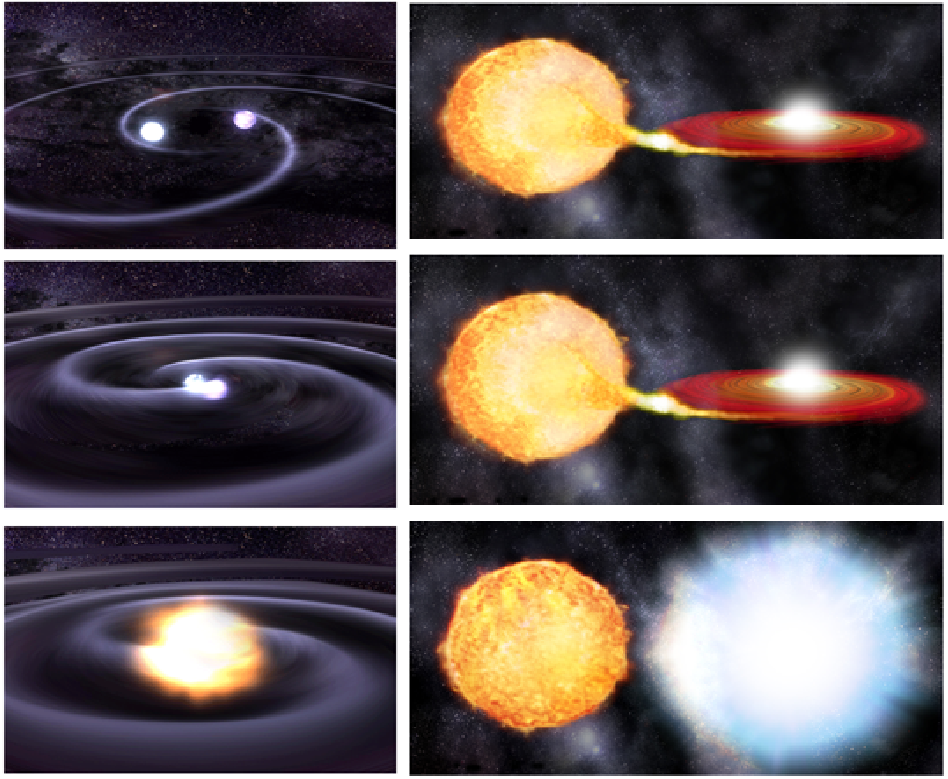
- We can get a feel for the energetics involve through a simple back of the envelope calculation
  - Chandra mass WD has a radius of ~2000 km
  - Gravitational PE: $\Omega \sim \frac{GM^2}{R} \sim 2.6 \times 10^{51}\ \mathrm{erg}$
  - Nuclear energy from burning all the C:
    - Simplified reaction: $14\,{}^{12}\mathrm{C} \longrightarrow 3\,{}^{56}\mathrm{Ni}$
      - Binding energy of ^{12}C nucleus: 92.172 MeV
      - Binding energy of ^{56}Ni nucleus: 484.008 MeV
    - Burning 14 C gives off 162 MeV

$$E_{\mathrm{nuclear}} \sim \frac{M}{14 \cdot 12 m_p} 162\ \mathrm{MeV} = 2.6 \times 10^{51}\ \mathrm{erg}$$

SNe Ia: Back of the Envelope

- Caveats:
  - WD is a mix of C/O, so energy / gram from burning is slightly lower
  - Not all C/O burns, and not everything will burn to Ni
  - Gas has internal energy, so nuclear energy release needed to unbind the star is lower than Ω
- This gives us a sense that the basic picture can work:
  - Burn ~ a Chandra mass of C/O and you can unbind the WD
- To be sure: SNe Ia are bright because ^{56}Ni radioactively decays—this powers the lightcurve

SNe Ia Progenitors- 3 ways in 2 settings



from astrobites.org (http://astrobites.org/2015/04/07/super-bright-supernovae-are-single-degenerate/) via Wikipedia/Discover

SNe Ia Progenitors- 3 ways in 2 settings

- Single degenerate Chandrasekhar-mass
  - C/O WD accretes mass until it approaches $M_{Chandra}$
  - Ignition of a flame starts runaway (not collapse)
  - Traditional model
- White dwarf mergers
  - A pair of WDs merges (or collides)
- Sub-Chandrasekhar (aka Double Detonation)
  - Variation on the single degenerate model
  - An accreted He layer detonates, triggering a detonation in the underlying C/O WD.

Diversity of Observations

- We see a lot of these events and are beginning to understand sub-classes
  - Superluminous: some showing more than a Chandra-mass of Ni
  - Subluminous events?
  - SNe Iax:
    - low photosphere velocity, hot, peak L very low
    - Maybe 20-50 of these per 100 normal SNe Ia (Foley et al. 2013)
    - Perhaps these are deflagrations?
- We've never see the progenitor system before explosion though!
- Delay time distribution: time between star formation and SNe Ia explosion
  - DD can give broad range of delay times (merger-time relates to post-common envelope separation)

Single vs. Double Degenerate

- Single degenerate
  - Pros:
    - Some SNe Ia show circumstellar material (PTF11kx) that can only be explained in SD context
    - Some nuclei require high densities (e- captures favored), e.g. SNR 3C 397
    - UV pulse seen in early lightcurve (4 days; Cao et al. 2015) suggests interaction with companion
  - Cons:
    - We don't see surviving companion in remnants
    - Observations and population synthesis don't produce enough $M_{Chandra}$ WDs.
    - Spectra/Phillips relation from simulations don't match observations well.

Single vs. Double Degenerate

- Sub-chandrasekhar
  - Pros:
    - A range of masses naturally allow for a range of brightnesses.
    - Nature makes plenty of sub-Chandra mass Wds.
    - Spectra/Phillips relation from models agrees well with observations.
  - Cons:
    - Mass (thickness) of accreted layer possibly an issue
    - May not produces observed elements that require high-density burning.

Single vs. Double Degenerate

- Double degenerate
  - Pros:
    - We can explain the entire SNe Ia rate just based on the observed number of WDWD systems we see
    - SN 2011fe was one of the most intensely studied supernova—no features in its spectra suggesting a companion
    - SN 2007if and SNLS 03D3bb are super-Chandra—more than 1.4 M of Ni produced
  - Cons:
    - Theoretical models show the potential for accretion-induced collapse to a neutron star
    - Recent studies allay this concern some.

Outstanding Questions in SNe Ia

- General consensus: thermonuclear explosion of ~ $1M_\odot$ degenerate C/O
- What is the progenitor?
  - Diversity of observations suggests multiple progenitor channels
  - Single white dwarf or merging white dwarf?
  - Chandra or sub-Chandra mass?
- Single degenerate channel:
  - What are the initial conditions?
  - Does the burning front remain subsonic?
- Double degenerates:
  - Can we avoid the accretion induced collapse?
  - Can we get an explosion that looks like a SNe Ia?
- What is the physical basis for the width-luminosity relationship in the lightcurve?
  - Some variation in the explosion is needed to account for the diversity in explosions.

No single code can address all of these questions!

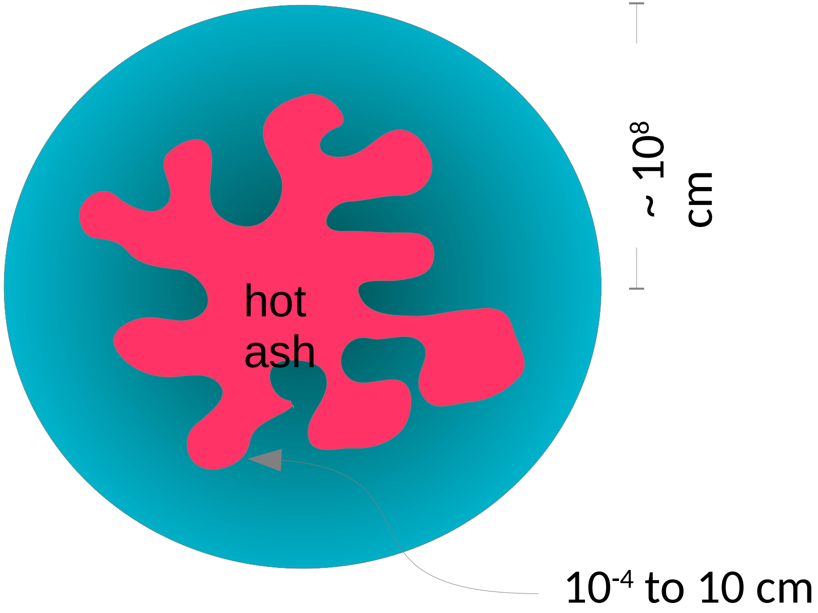
SNe Ia—A Multi-scale Problem

A wide range of length scales are represented

- Stellar scale: 10^8 cm
- Flame scale: 10^{-4} to 10 cm

The temporal scale is equally impressive

- Convective phase: 100 yr
- Explosion phase: 1 s



No single algorithm can address all parts of this problem

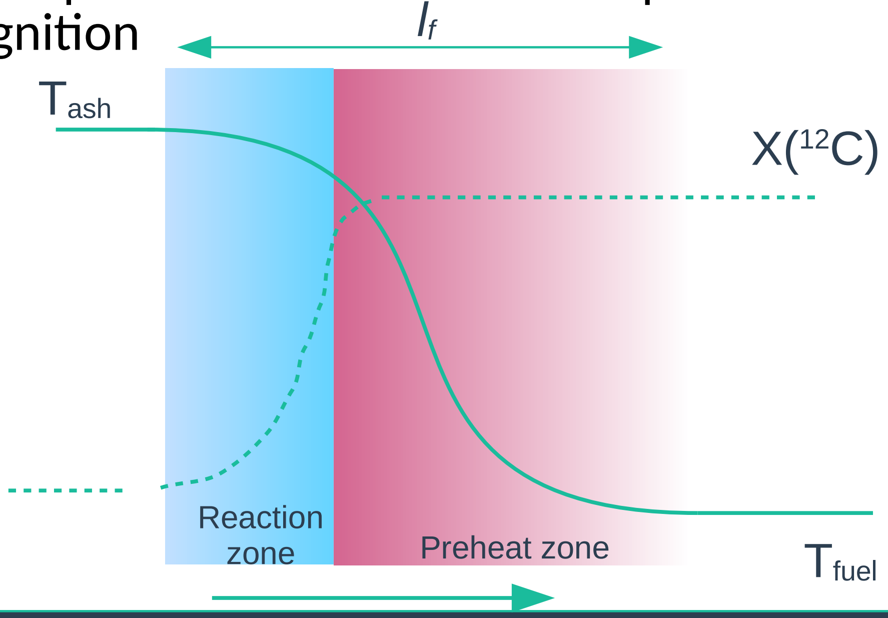
To address the open questions, it is not enough to move to bigger and bigger computers—we need algorithms tuned to the conditions in the star.

How Can A Burning Front Propagate?

Deflagration

Subsonic → fuel and ash are in pressure equilibrium

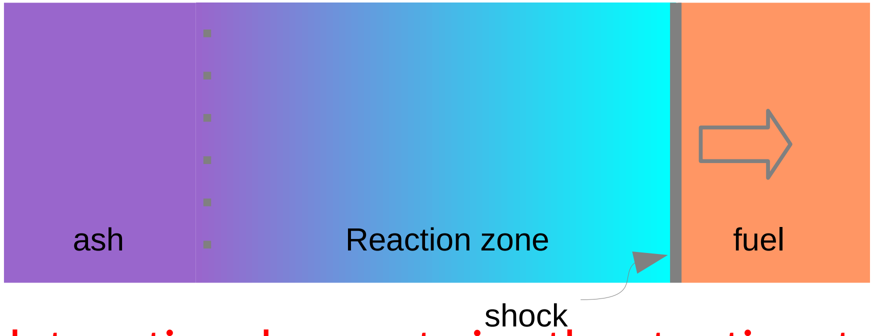
Heat diffusing from the hot ash raises the temperature of the fuel to the point of ignition



Detonation

Supersonic → shock heats fuel to point of ignition

heat release in fuel sustains detonation



A detonation does not give the star time to expand

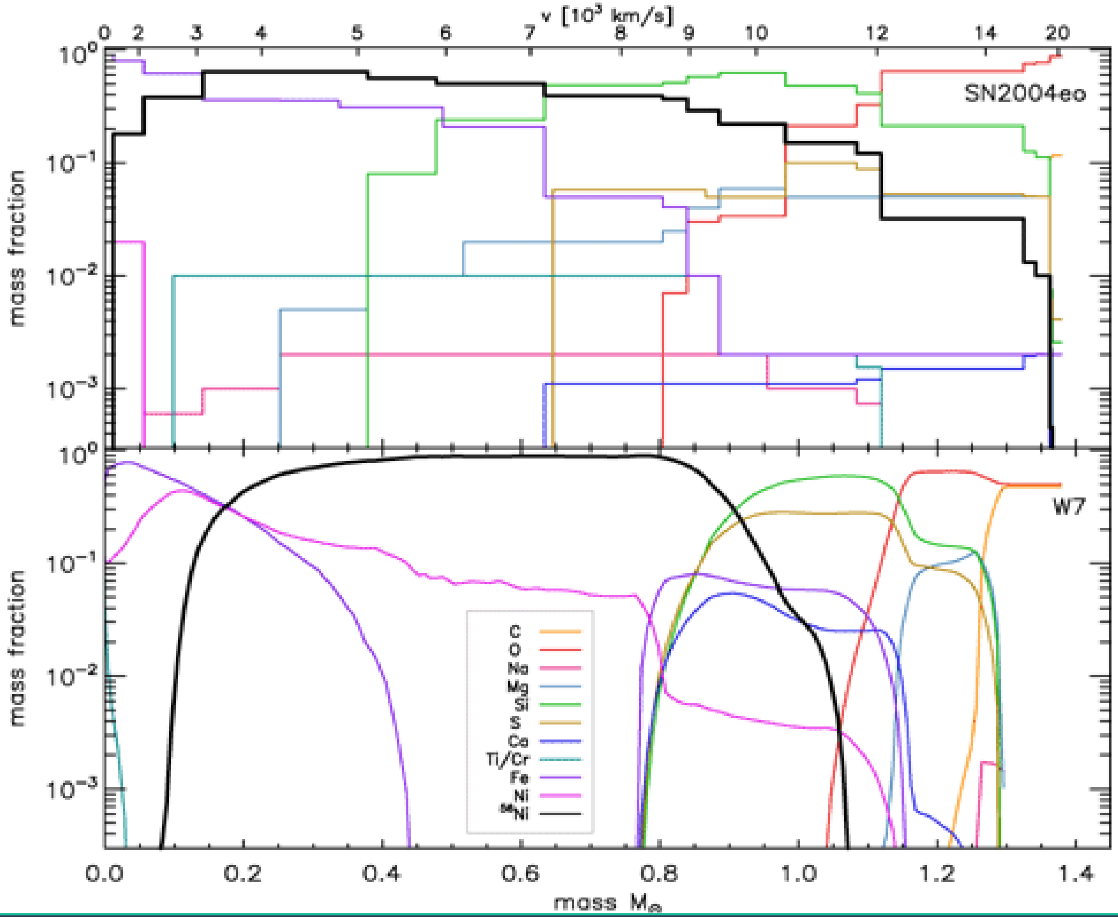
All the C+O will burn at high density to nickel. No intermediate mass elements produced!

Type Ia Supernovae

- Early favored picture: single Chandra-mass WD
- Cannot detonate from start to finish
  - This was shown in 1970s by Arnett
  - Detonation is supersonic → outer layers don't know a burning front is coming, so they cannot pre-expand
  - Burning takes place at too high of a density, over produces Ni-group, doesn't make intermediate mass elements
- Pure deflagration is also unlikely
  - Models show that this can leave behind unburned carbon near the center
- Deflagration-detonation transition?

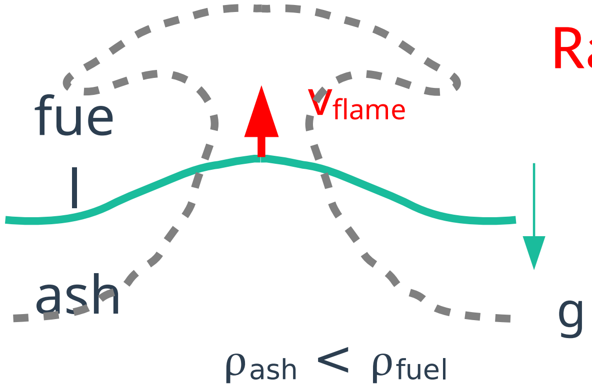
Type Ia Supernovae

Observation vs W7 model



Mazzali et al. (2008)

Wrinkling the Flame



Rayleigh-Taylor Instability:

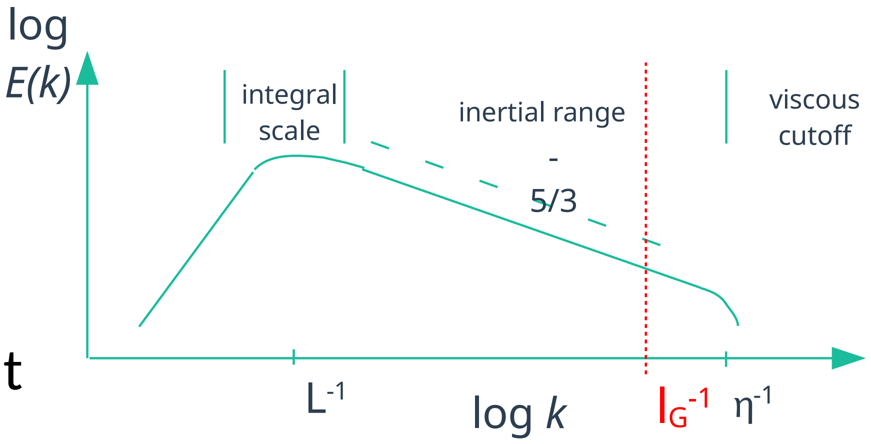
This is a buoyancy driven instability. The hot ash behind the flame rises and the cool fuel ahead of the flame falls downward.

Large amounts of surface area generated.

Turbulence:

Turbulence is characterized by random motions. Instabilities create vorticity on the large scales that cascades down to smaller and smaller scales.

Kolmogorov: KE dissipation rate is constant across scales: $u^3/l = \epsilon$



adapted from Peters (2000)

Transition to Distributed Burning

- Gibson scale—flame speed is comparable to the turbulence speed
  - turbulence can directly affect the flame structure
  - Kolmogorov turbulence:

$$l = L\left(\frac{u}{U}\right)^3$$

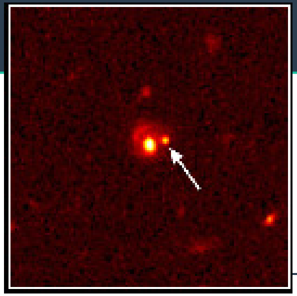
    - here, L is the integral scale and U is the turbulent intensity at the integral scale

$$l_G = L = \left(\frac{v_f}{U}\right)^3$$

  - Flames get thicker as they encounter lower densities
  - For C/O flames, we are at the Gibson scale at densities of ~ 10^7 g/cc

Modeling SN Ia in near-Chandra mass scenario

Mark A. Garlick



P. Garnavich/CfA

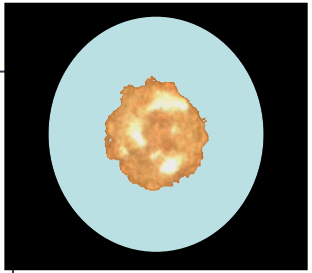
- free expansion of envelope
- multi-group (non-LTE) radiation transport

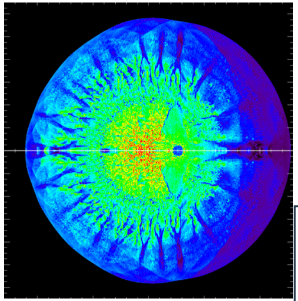
Accretion

- stellar evolution code with accretion/binary evolution code

$>10^8$ yr

~ seconds





Smoldering

- subsonic convection in core of white dwarf
- low Mach number flow solver
- conductive heat transport

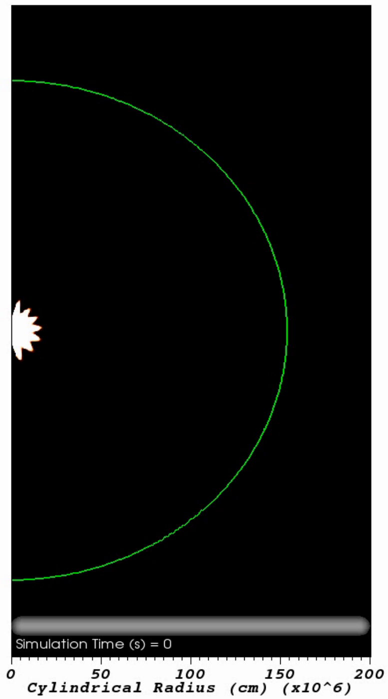
~ 1000 yr

ignition

Flame/Explosion

- initial deflagration
- DDT or expansion/recollapse
- Compressible hydro with subgrid model for flame.

DDT Scenario



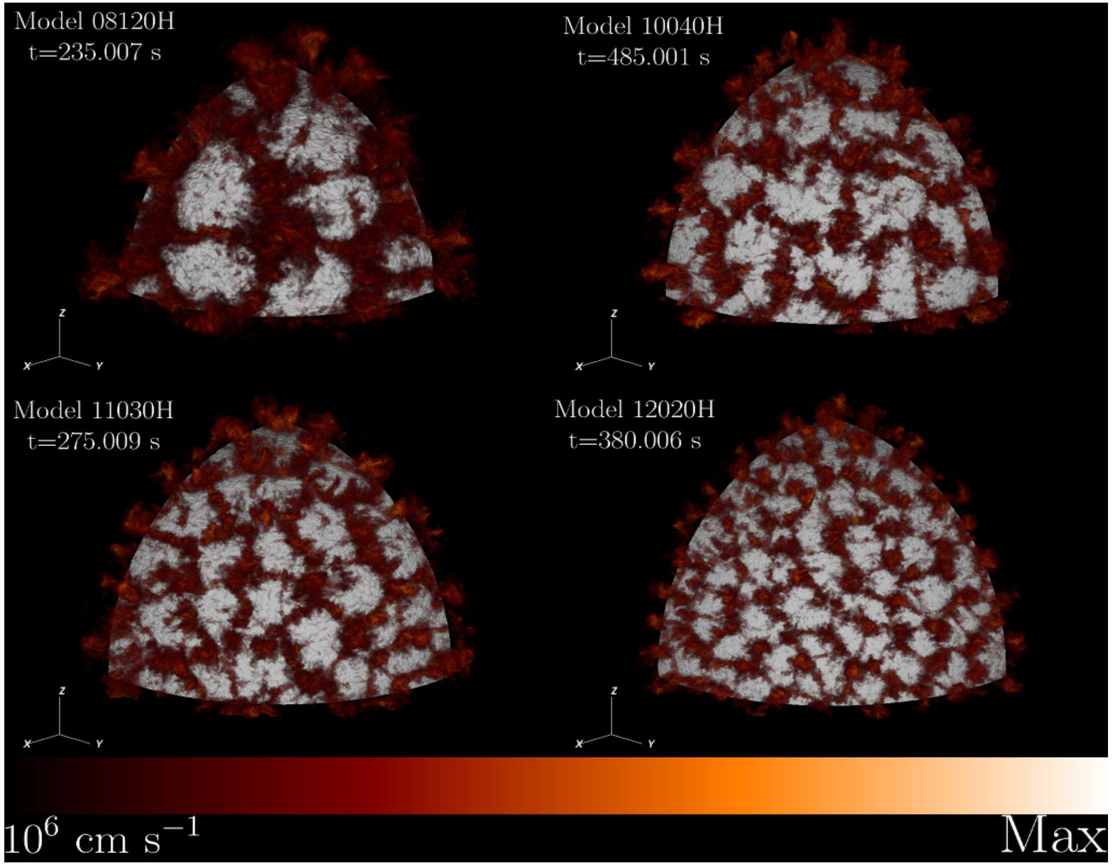
Jackson et al. 2010

sub-Chandra SNe Ia Models

- Basic idea:
  - Burning begins in an accreted helium layer on the surface of a low(er) mass white dwarf
  - Detonation
- How does the burning transfer to the C/O core?
  - Edge lit: direct propagation of detonation across interface. May require ignition at altitude
  - Double detonation: compression wave converges at core, ignites second detonation at the center of the WD
- Main problem: how much surface He is too much?
- Potential progenitors: Iax class SNe (Foley et al. 2013)
  - Lower velocity, lower peak magnitude, hot photosphere

Sub-Chandra He Convection

- Suite of different initial models run
  - Some required multiple levels of refinement
- Three types of outcomes
  - Localize runaway on short timescale
  - Nova-like convective burning
  - Quasi-equilibrium (?)



Jacobs, et al. ApJ 827 84 2016

WD Mergers

- First question to ask: are there enough WD+WD systems that can merge in a reasonable time frame to account for SNe Ia?
  - Answer appears to be “yes”:
    - Badenes & Maoz (2012) looked at 4000 WDs in SDSS data and model the merger rate (based on radial velocity measurements)
    - Find merger rate of 1.4 x 10^{-13} yr^{-1} $M_{\odot}^{-1}$ (consistent with measured Ia rate), but most likely they are sub-Chandra mergers

WD Mergers

- Next question: if two WDs inspiral, are you guaranteed to get a Ia?
  - Not necessarily
  - Saio & Nomoto (1985): C ignites at edge of C/O WD and burns inward, converting it into O/Ne/Mg WD
    - Accretion induced collapse
  - Models show that the only way to avoid AIC is for the C/O from the disrupted secondary to accrete slowly, so heating doesn't ignite C
- No simulations to date have followed the inspiral, disruption, coalescence, and explosion
  - Special cases exist: head-on collisions, equal mass WDs, ...

WD Mergers

- E.g.: Yoon et al.
- Merger remnant leads to slow accretion onto core, can avoid AIC

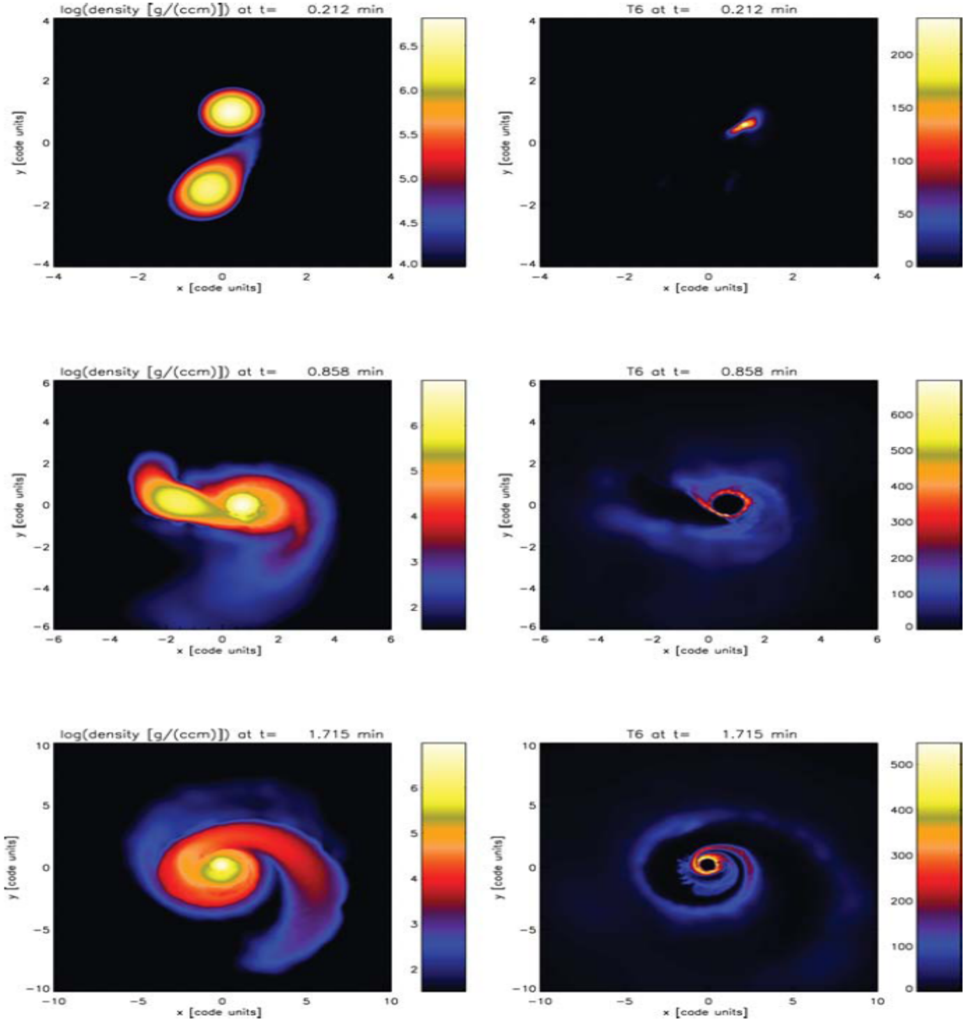
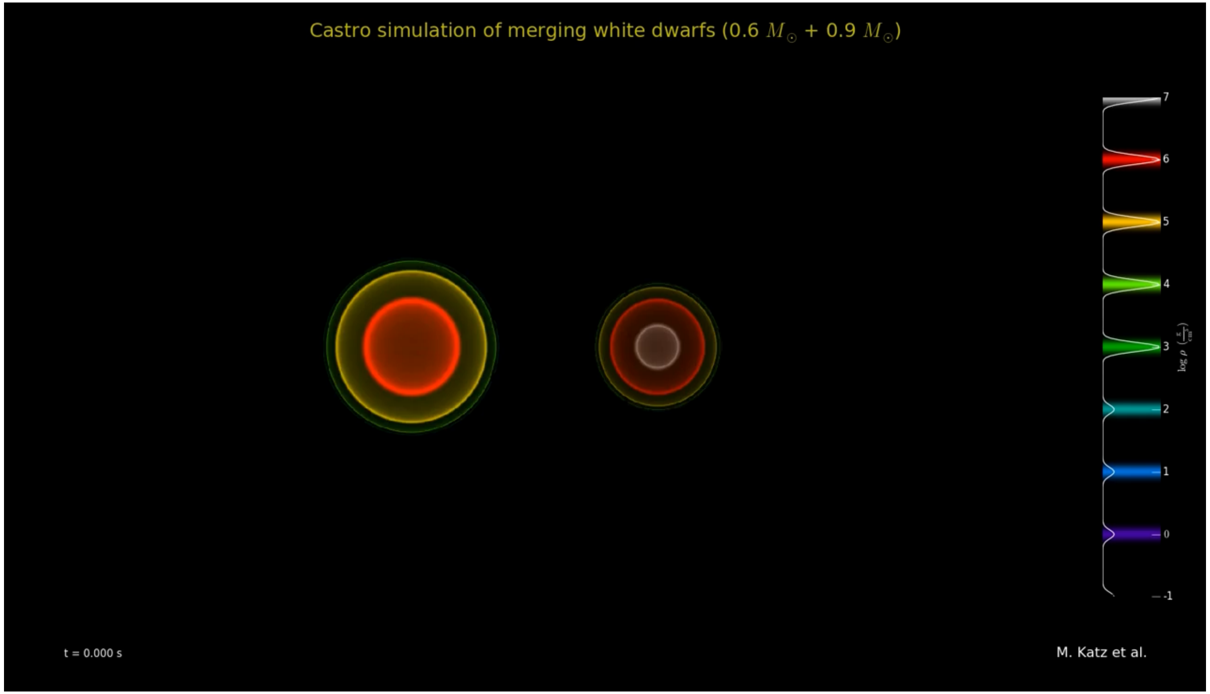


Figure 2. Dynamical evolution of the coalescence of a 0.6 $M_\odot$ + 0.9 $M_\odot$ CO white dwarf binary. The panels in the left-hand column show the density in the orbital plane, the panels in the right-hand column the temperature in units of 10^6 K. Lengths are in code units (= 10^9 cm).

(Yoon, Podsiadlowski, and Rosswog, 2007)

SBU Merger Simulation (Katz et al.)



https://www.youtube.com/watch?v=0AAPwsST9WQ

https://www.youtube.com/watch?v=nsdOrP2cQPM

Violent Mergers

- Maybe the merger can avoid an accretion phase and instead violently merge when the two stars make contact
- Works best for mass ratios near 1
- E.g. Pakmor et al. 2012

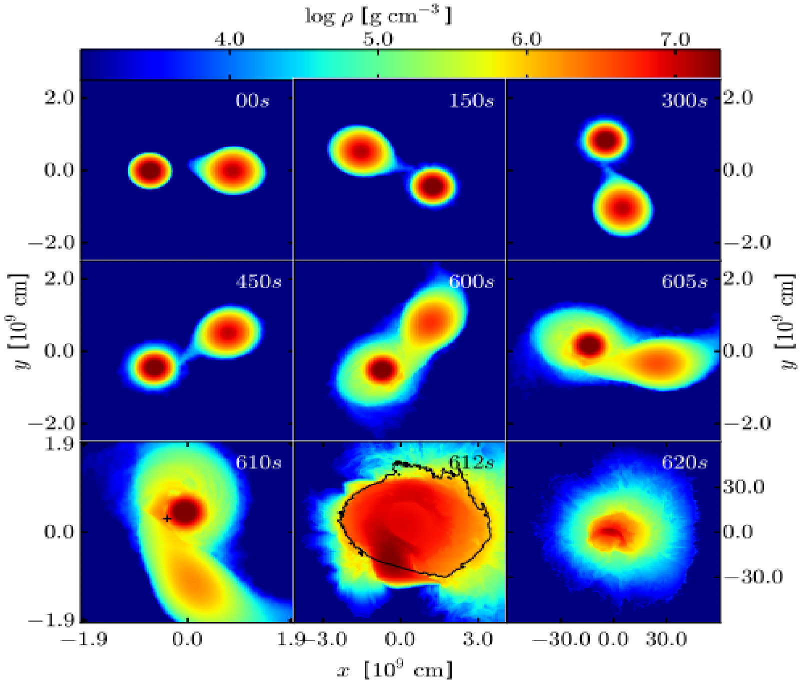


Figure 1. Snapshots of the merger of a 1.1 $M_\odot$ and a 0.9 $M_\odot$ carbon–oxygen white dwarf and the subsequent thermonuclear explosion. At the start of the simulation the binary system has an orbital period of ≈35 s. The black cross indicates the position where the detonation is ignited. The black line shows the position of the detonation front. Color coded is the logarithm of the density. The last two panels have a different color scale ranging from 10^{-4} g cm^{-3} to 10^{6} g cm^{-3} and 10^{4} g cm^{-3}, respectively.

Violent Mergers

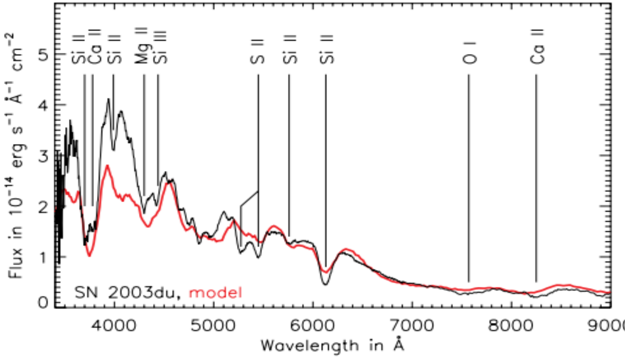


Figure 4. Maximum light spectrum of our model. The red line shows the spectrum of our model one day after maximum light in the *B* band. The black line shows the observed spectrum of SN 2003du (Stanishev et al. 2007) at the same time.

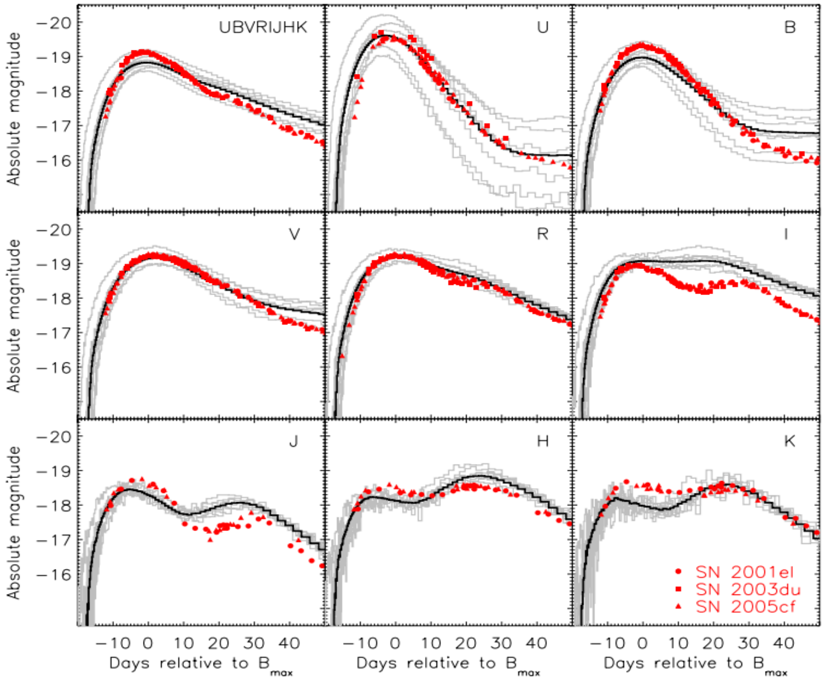
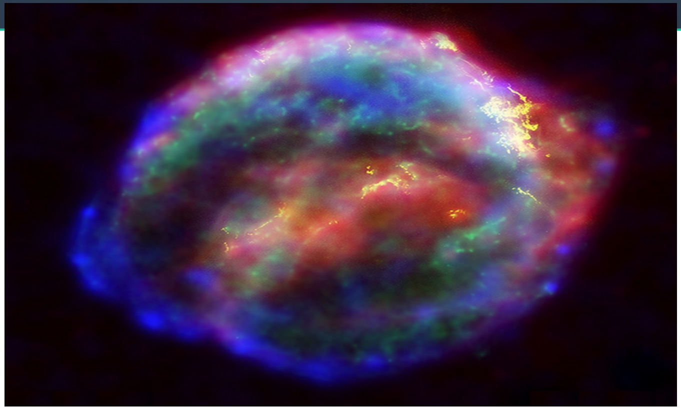


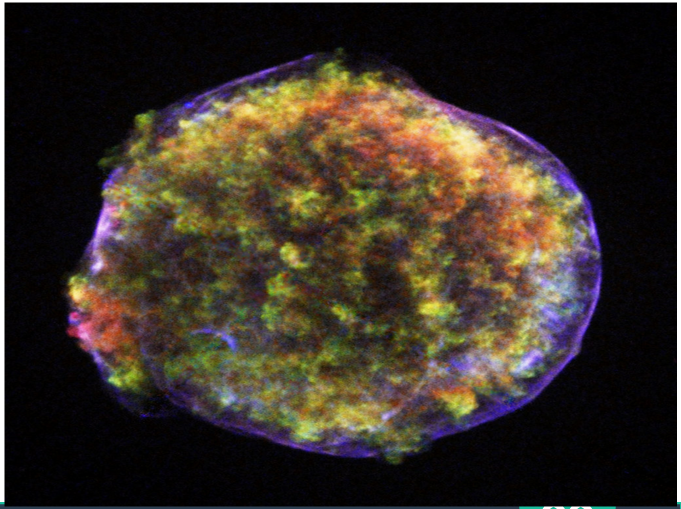
Figure 3. Light curves of our model. The panels from top left to bottom right contain *UBVRIJHK* bolometric and broadband *U,B,V,R,I,J,H,K* light curves. The black line corresponds to the angle average of the model. Gray histograms show light curves along seven different lines-of-sight representative for the scatter caused by different (100) viewing angles including the most extreme light curves. The time is given relative to *B*-band maximum. The red symbols show observational data of three well-observed normal SNe Ia, SN 2001el (Krisciunas et al. 2003), SN 2003du (Stanishev et al. 2007), and SN 2005cf (Pastorello et al. 2007).

What's Left Behind?

- Mostly spherical remnant
- No compact object left behind
- No evidence for a companion star
- Some clumping and high-velocity metal features suggest slight asymmetries in the explosion



SN 1604 (Kepler's supernovae) in our galaxy.



A Note On Systematic Effects

- For all Ia settings, the composition of the WD (e.g. metallicity) and the conditions under which burning occurs (e.g. density) significantly influence the yields.
- Exploring these parameters (that follow from things like age of host galaxy) is a topic of contemporary research.
- Example: Change in electron fraction due to metallicity or electron capture (density dependent).

Prelude: Simple burning model- the alpha chain

7 isotope network

$$^{4}\mathrm{He} \xleftrightarrow{(\alpha\alpha,\gamma)} {}^{12}\mathrm{C} \xleftrightarrow{(\alpha,\gamma)} {}^{16}\mathrm{O} \xleftrightarrow{(\alpha,\gamma)} {}^{20}\mathrm{Ne} \xleftrightarrow{(\alpha,\gamma)} {}^{24}\mathrm{Mg} \xleftrightarrow{(\alpha,\gamma)} {}^{28}\mathrm{Si} \xleftrightarrow{\mathrm{rcaag}} {}^{56}\mathrm{Ni}$$

Isotopes of Ni

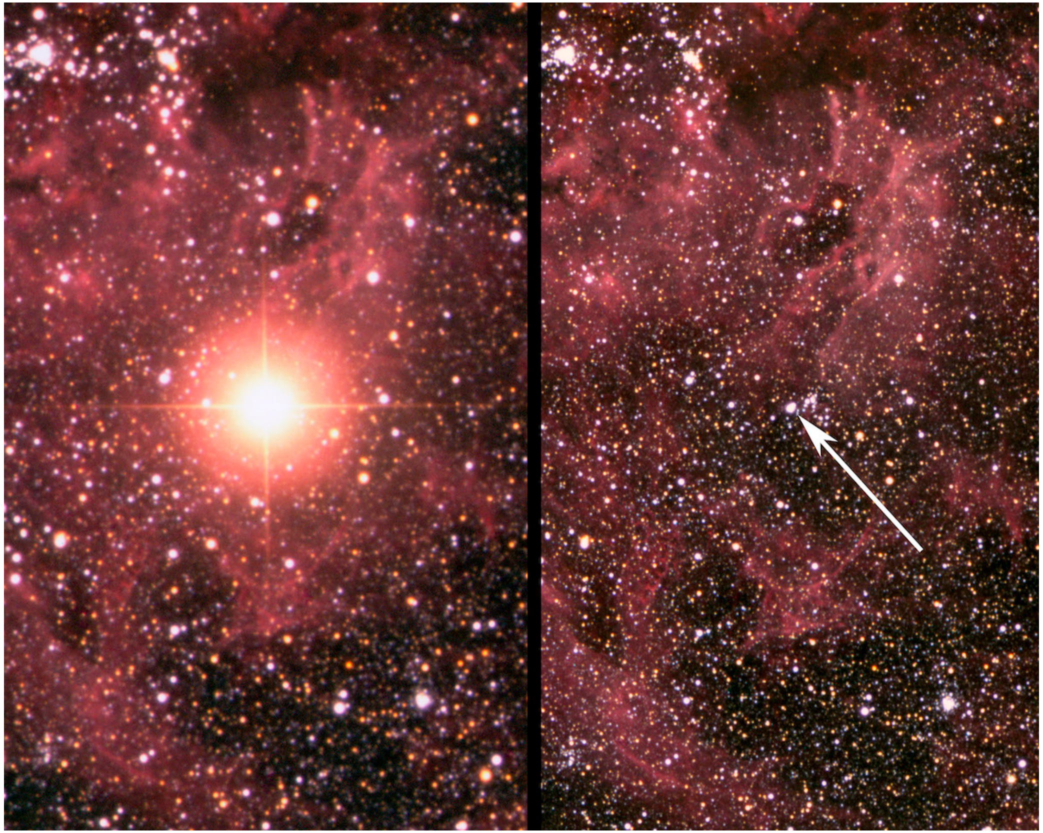
Isotope	half life
^{56}Ni	6.1 days
^{58}Ni	stable
^{59}Ni	76,000 years
^{60}Ni	stable
^{61}Ni	stable
^{62}Ni	stable
^{63}Ni	101 years
^{64}Ni	stable

Systematic Effect on the Brightness

- The mass of ^{56}Ni synthesized in the explosion controls the brightness of a SN Ia.
- The mass of ^{56}Ni depends on the composition because more metals mean more neutron-rich nuclei. Burning at high density also neutronizes via e- capture.

Core-Collapse Supernovae

- SN 1987A



Massive Star Evolution

- Massive stars ($M > 8\text{-}10\ M_\odot$) ignite He and C under non-degenerate conditions
  - Stars above 11 $M_\odot$ also ignite heavier fuels up to carbon non-degenerately
  - Some uncertainty due to mass loss
- Stellar winds are significant for high mass stars ($M > 15\ M_\odot$)
  - Mass loss can have extreme dynamical effects on the evolution

$$M/\dot{M} < t_{\rm nuc}$$

  - Mass loss is parameterized in stellar evolution codes—there is a lot of uncertainty

Mass Cuts

- Mass plays a big role in the outcome of stellar evolution

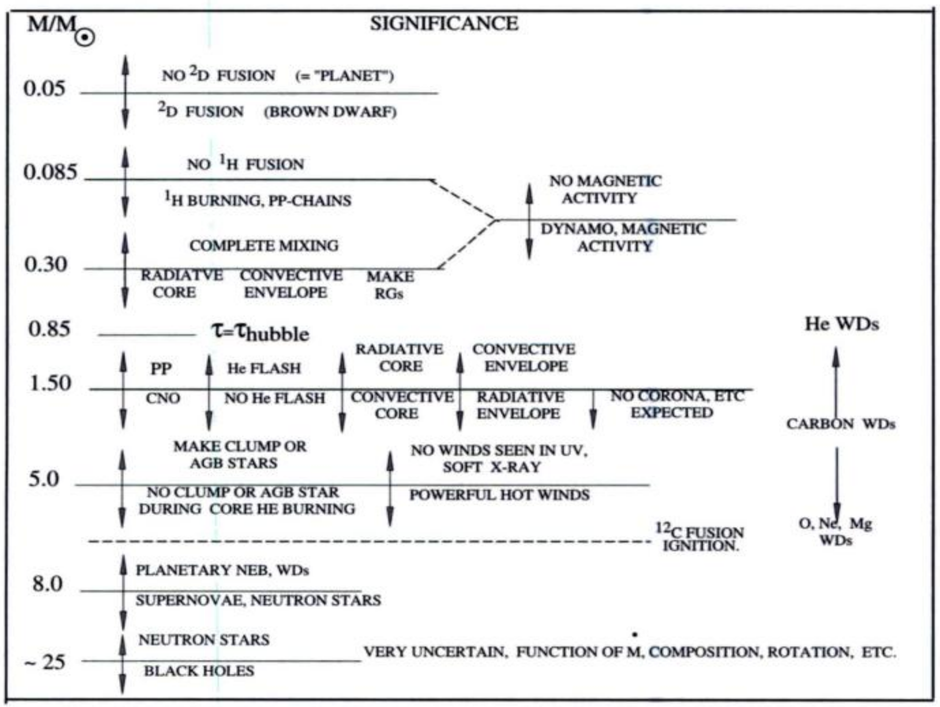


Fig. 2.4. Our "Mass Cut" diagram showing the fate of single stars in various mass classes. See text.

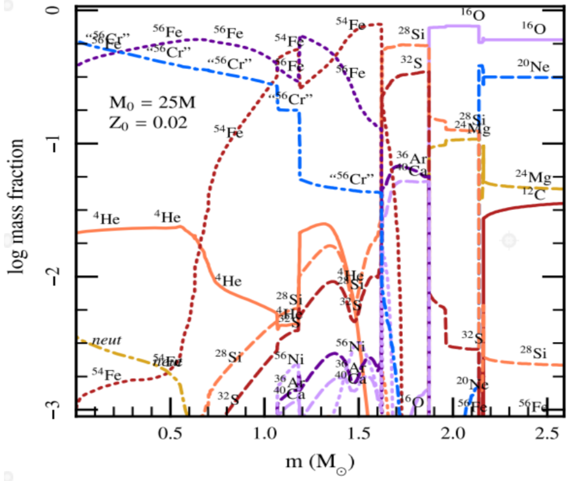
(Hansen, Kawaler, Trimble)

High Mass Evolution

core burning state	*9 $M_\odot$ star*	*25 $M_\odot$ star*	*core temperature*
H burning	20 million years	7 million years	$(3\text{-}10) \times 10^7$ K
He burning	2 million years	700,000 years	$(1\text{-}7.5) \times 10^8$ K
C burning	380 years	160 years	$(0.8\text{-}1.4) \times 10^9$ K
Ne burning	1.1 years	1 year	$(1.4\text{-}1.7) \times 10^9$ K
O burning	8 months	6 months	$(1.8\text{-}2.8) \times 10^9$ K
Si burning	4 days	1 day	$(2.8\text{-}4) \times 10^9$ K

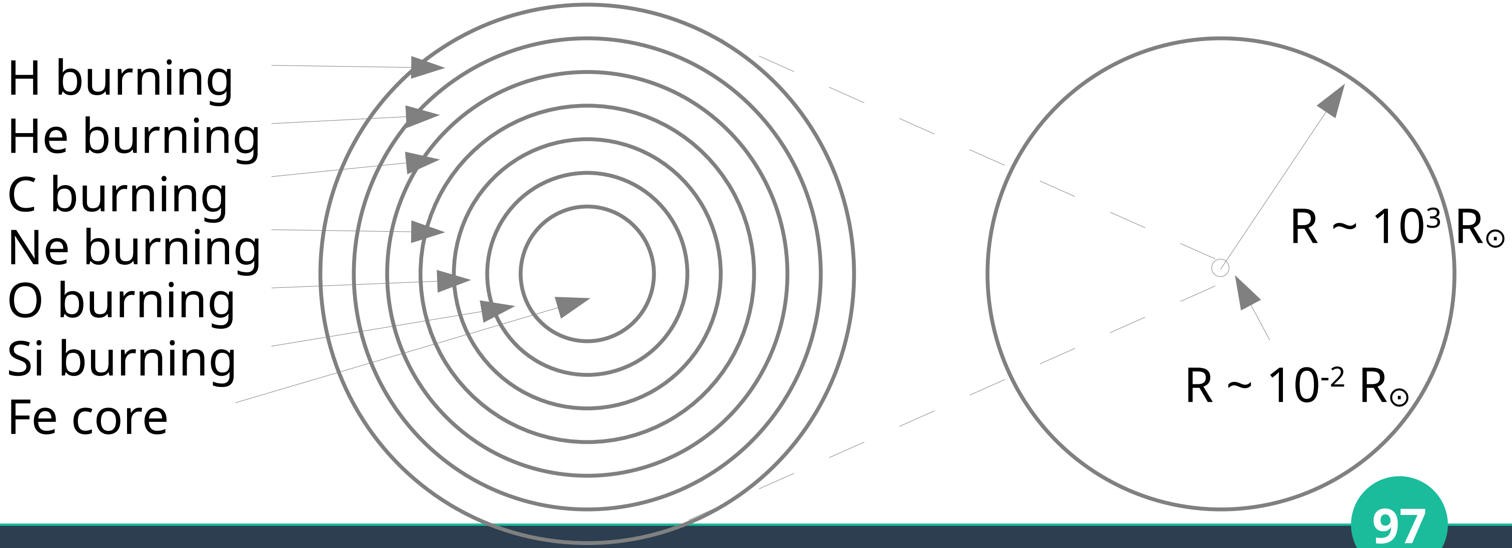
(table from Hester et al. Ch. 17)

High Mass Evolution



(from Bill Paxton, MESA.)

- Advance burning stages lead to a "onion-skin" layering of nuclei



Core-Collapse Supernovae

(Pols, Ch 13)

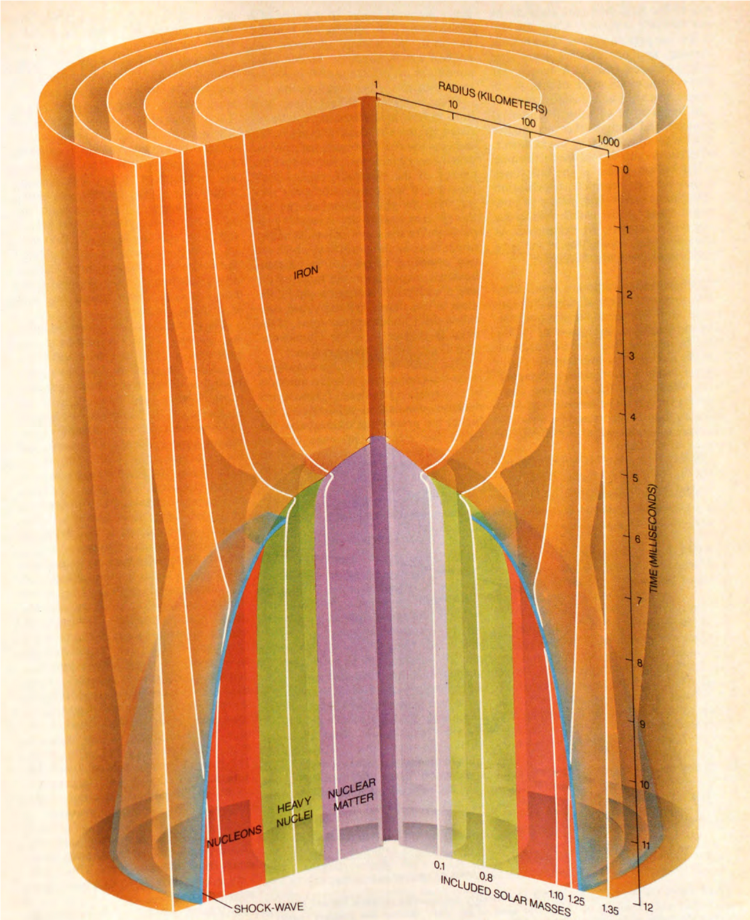
- Since the star has run out of energy sources, it begins to cool.
  - Core is degenerate and relativistic
  - Chandra mass is slightly lower because of higher μ_e—$M_{Ch} \sim 1.2\ M_\odot$
  - There is nothing to stop the contraction
- Relativistic degenerate gas has $\gamma = 4/3$— not dynamically stable

Core-Collapse Supernovae

- Electron captures come into play
  - Free electrons capture onto β-unstable nuclei (inverse β-decay) and protons combine to neutrons
    - Material becomes more neutron-rich
    - Degenerate e pressure decreases
  - This leads to the collapse of the core (helped by decreasing Chandra mass)
- Photo-disintegration
  - At 10^{10} K, photon energies are comparable to the binding energy of nuclei
  - Heavy nuclei are broken apart:

$$^{56}\mathrm{Fe} + \gamma \leftrightarrow 13\,^{4}\mathrm{He} + 4n$$

Core Collapse Supernovaa



Bethe and Brown, Sci. Am. 1985

Electron-capture SNe

- Note that stars that are < 10 $M_\odot$ don't make it to Fe.
  - Make O/Ne/Mg cores (from C burning)
  - Electron degeneracy kicks in before Ne burning occurs
  - Electron capture becomes favorable → collapse is triggered.

Core-Collapse Supernovae

- Collapse is rapid (~ 10 ms)
  - Dynamical timescale is

$$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho}} \approx \frac{2100\ \mathrm{s}}{\sqrt{\rho}}$$

  - Continued electron captures occur
    - Full dissociation of Fe into p + n does not occur during the collapse
- Collapse halts when nuclear densities are reached
  - Core is mostly neutrons now
  - Neutron degeneracy is part of the story, but strong nuclear force also comes into play
  - Equation of state "stiffens"
  - Proto-neutron star is formed

Core-Collapse Supernovae

- Strong force resists the collapse.
  - Outer layers of the core do not know that the inner core stopped.
- Outer layers of the core hit the compact inner core and bounce—shock wave moves outward through the star.
- Neutrinos are produced at high rates during collapse.
  - Core is dense—neutrinos are trapped.
  - They create a bubble of hot gas behind the shock, which pushes the shock outward—this is really not well understood.
  - Most of the energy is carried by neutrinos
- R-process may take place here?

Core Collapse SNe

- Back of the envelope
  - When the iron core collapses, it goes from the size of a WD down to ~ 20 km

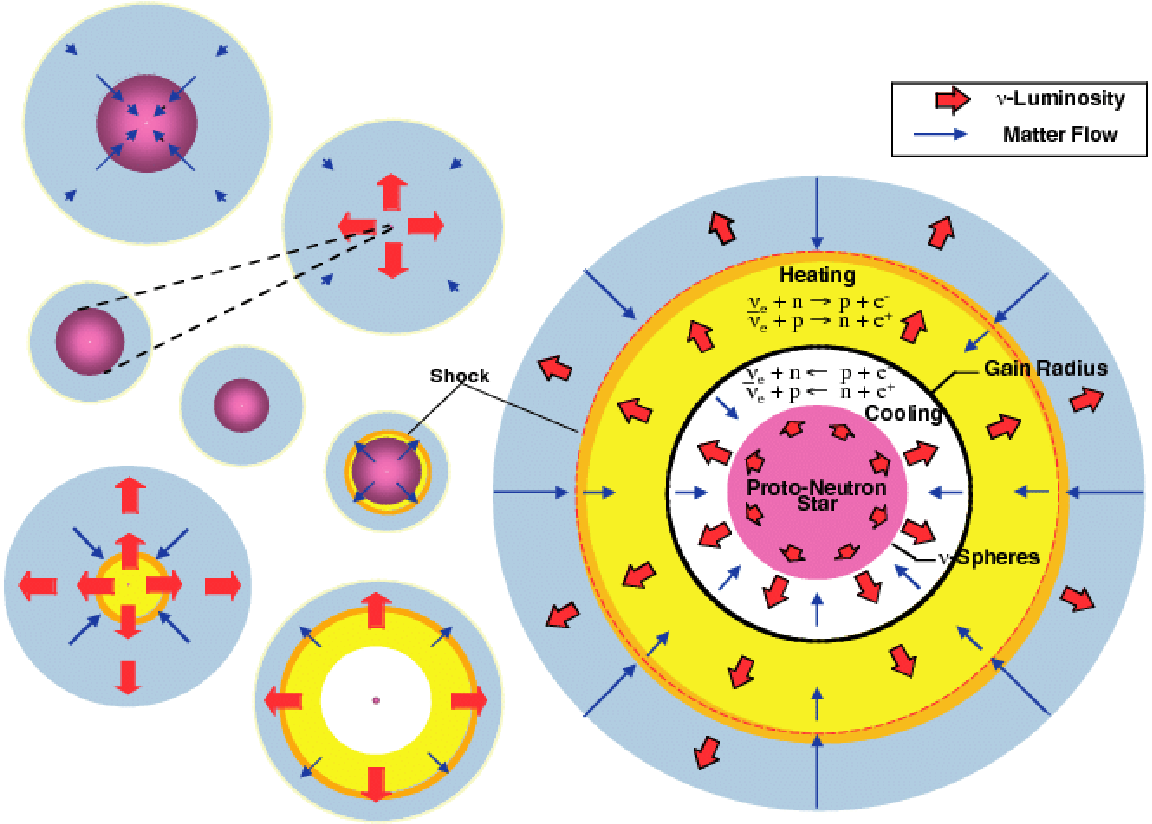
$$\Delta\Omega = -\frac{GM^2}{R_{\rm WD}} + \frac{GM^2}{R_{\rm NS}} \approx \frac{GM^2}{R_{\rm NS}} \sim 10^{53}\ {\rm erg}$$

  - Note: not all this energy will come out in photons
- The envelope does not have time to follow the collapse all the way down
  - About 0.1% of the collapse energy is needed to blow off the envelope
  - Photon energy is 0.01 KE ~ $10^{-4}\,\Omega$
- The details of the explosion mechanism are not well understood
  - Some of that gravitational binding energy needs to be converted into kinetic energy

Explosion Mechanism

- Inner core bounces due to stiffness, rebounds
- Expanding inner core hits still free falling outercore
  - Outward propagating shock forms
  - Not enough energy for the shock to make it out through the entire star (a prompt explosion)
- Shock dissociates infalling matter (mostly Fe) into p + n
  - This consumes a large fraction of the gravitational binding energy released
  - Electron captures onto p create lots of neutrinos
    - Star is opaque to the neutrinos!
    - Neutrinos heat the material behind the shock—it becomes convective
    - Believed to revive the stalled shock

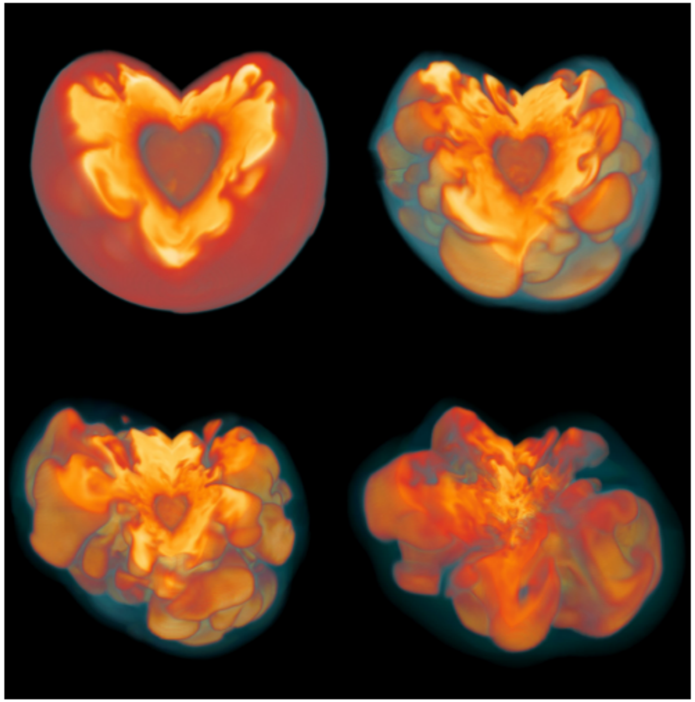
Core Collapse Supernovae



Tharrington, Messer, and Hoffman Overview of NLCF FY 2006 Allocations

Modeling Core-Collapse Supernovae

- Most of what we know about core-collapse supernovae comes from computer simulations
- Exceptionally difficult simulations
  - Need to follow the matter, neutrinos, and the interactions between them to get it right
- We are only now at the point where 3-d models give explosions (and not all the time, and not for everyone...)



(Woosley and Janka)

Figure 2: *Looking into the heart of a supernova (14). Four snapshots show the vigorous boiling of the neutrino-heated, convective region around the nascent neutron star. Buoyant bubbles of hot matter moving outwards appear bright red and yellow. These are bounded by a shock wave, which expands outwards, disrupting the star. The images, from top left to bottom right, show the structure at 0.1, 0.2, 0.3, and 0.5 seconds after the shock is born. At these times, the shock has an average radius of about 200, 300, 500, and 2,000 kilometers, respectively.*

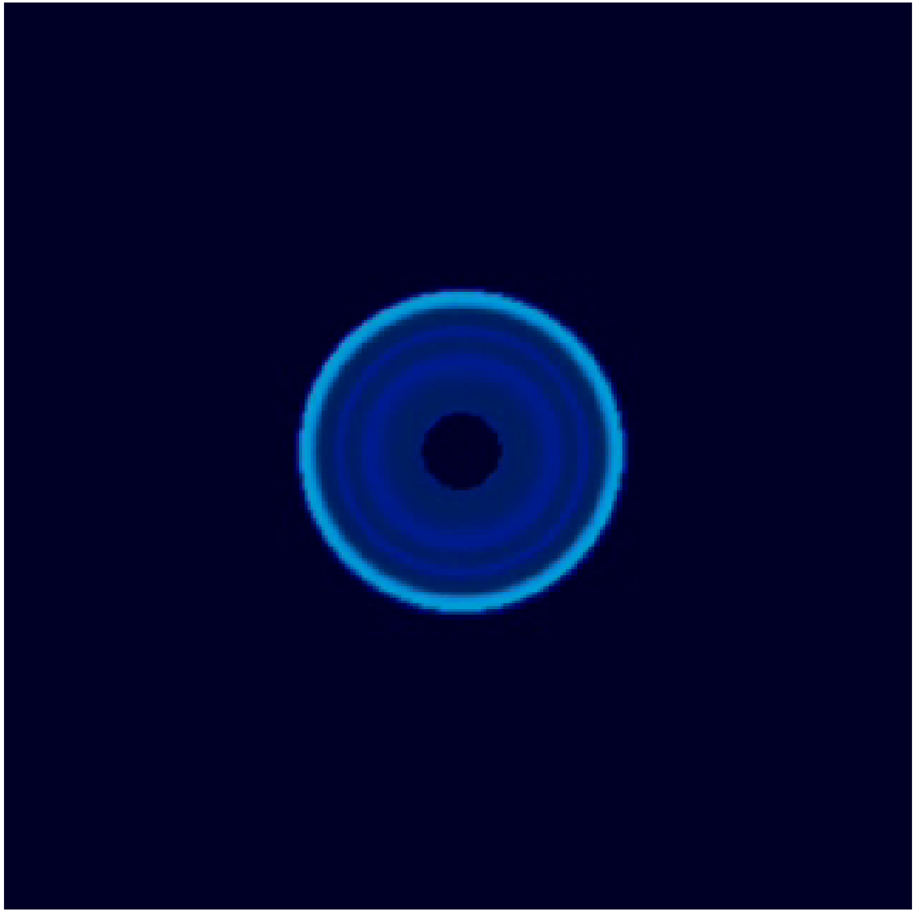
Neutrino Transport

- The transport of the neutrinos is described similarly to radiation
  - 7-dimensional (position + 2 directional angles + energy and time evol.)
  - Computational expensive—this is where most approximations are made
- Microphysics requirements are opacity and scattering cross-sections for neutrino interactions

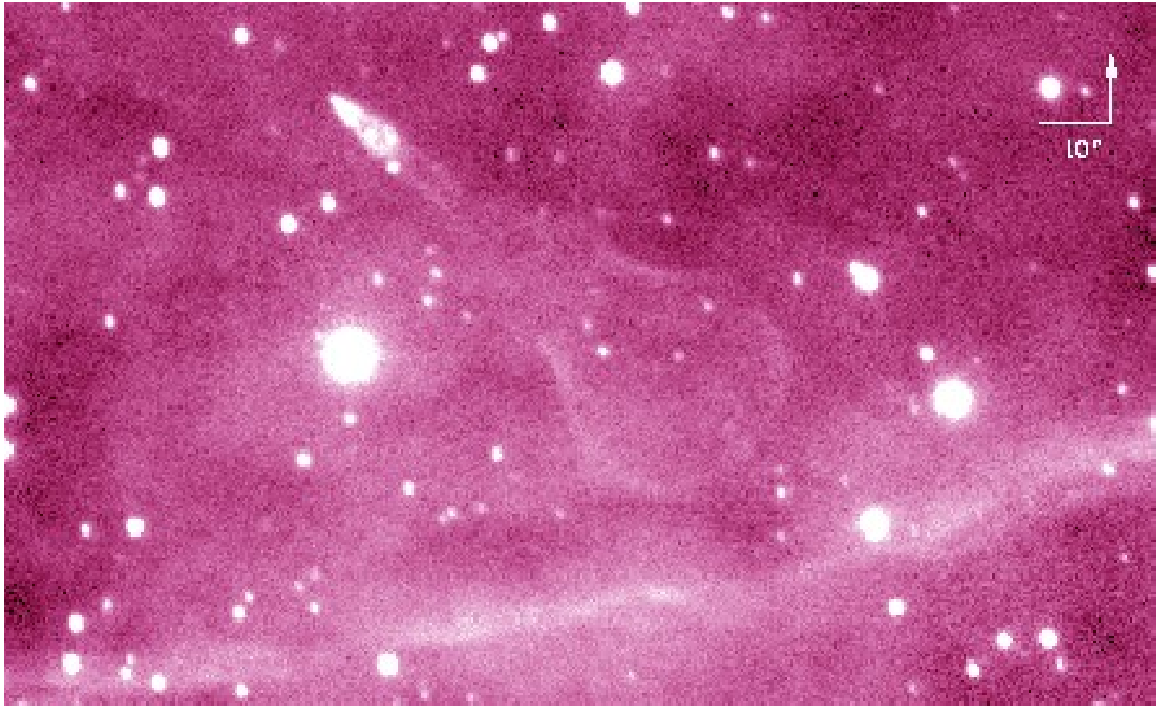
Modeling Core-Collapse Supernovae

- Many physical effects also involved:
  - General Relativity
  - Turbulence
  - Convection
  - Shock instabilities
  - EOS of dense matter
  - Rotation
  - Magnetic fields

Early (failed) explosion w/ convection



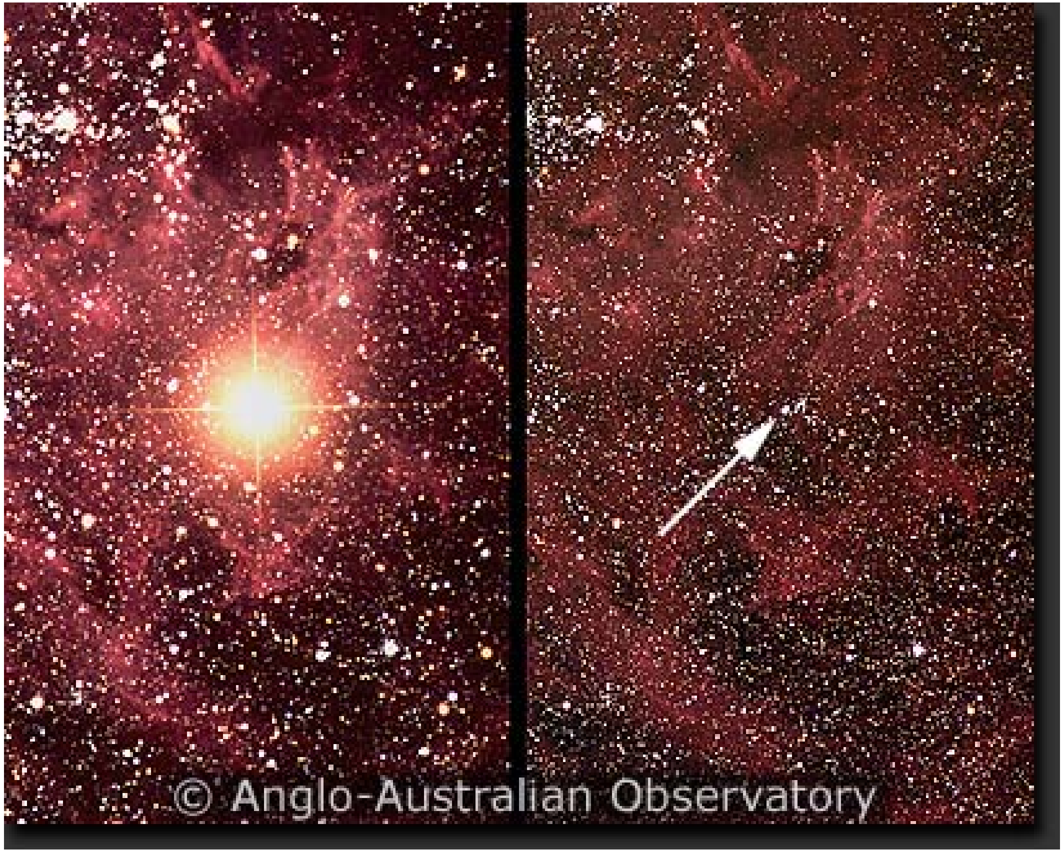
Neutron Star Kick



The guitar nebula—a bow shock from a 1600 km/s neutron star moving through the interstellar medium. http://www.astro.cornell.edu/~shami/guitar/

SN 1987A

- One of the most famous core-collapse supernovae is 1987A
  - Exploded in the Large Magellanic Cloud—a satellite galaxy of ours.
  - Closest supernova (only 51.4 kpc away) since Kepler's (1604) in our galaxy.
- 1987A was so close that we detected 24 neutrinos coming from the event.

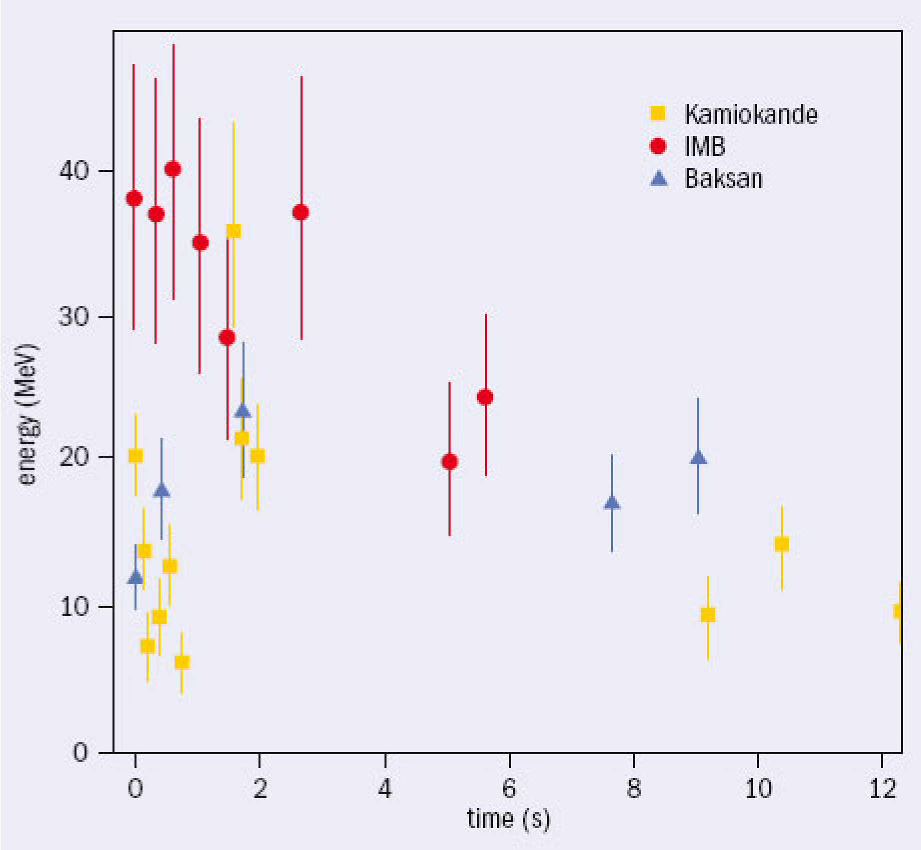


(Anglo-Australian Telescope)

The left image shows the supernova about 10 days after explosion and the right image shows the blue giant star before exploding.

SN 1987A Neutrinos

- Neutrinos preceding the visible light to Earth
  - Photon emission awaits the shock breaking out of the surface of the star
  - Direct confirmation of our physical model for CCSNe.



(CERN Courier)

Core Collapse SNe and Neutron Stars

- Proposed at an APS meeting in 1933 by Walter Badde and Fritz Zwicky and published in 1934.
- Note that the neutron was discovered by Chadwick in 1932
- Pulsars observed by Burnell and Hewish 1967
- Supernova 1987a observed in LMC
- 11 neutrino detections at Kamiokande detector, 8 at IMB (Irivine-Michigan-Brookhaven) detector, and 5 by the Baksan detector, respectively.
- Neutrinos were observed 2-3 hours before the visible outburst
- First Multi-messenger observation of an event!
- Validated the Core Collapse paradigm (54 years later!)

Gamma-Ray Bursts

- 1960s spy satellites saw bursts of gamma-rays coming from space (not terrestrial thermonuclear explosions)
  - announcement of discovery waited until 1973 (Klebesadel et al.)
- Lots of initial ideas

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap & SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap & SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap & SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot sync e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap & SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
60.	Schlovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap & SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap & SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap & SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e- e+ opt thk plasma outflow indicated
69.	Bisnovatyi- et al	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Vahia et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare
72.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic

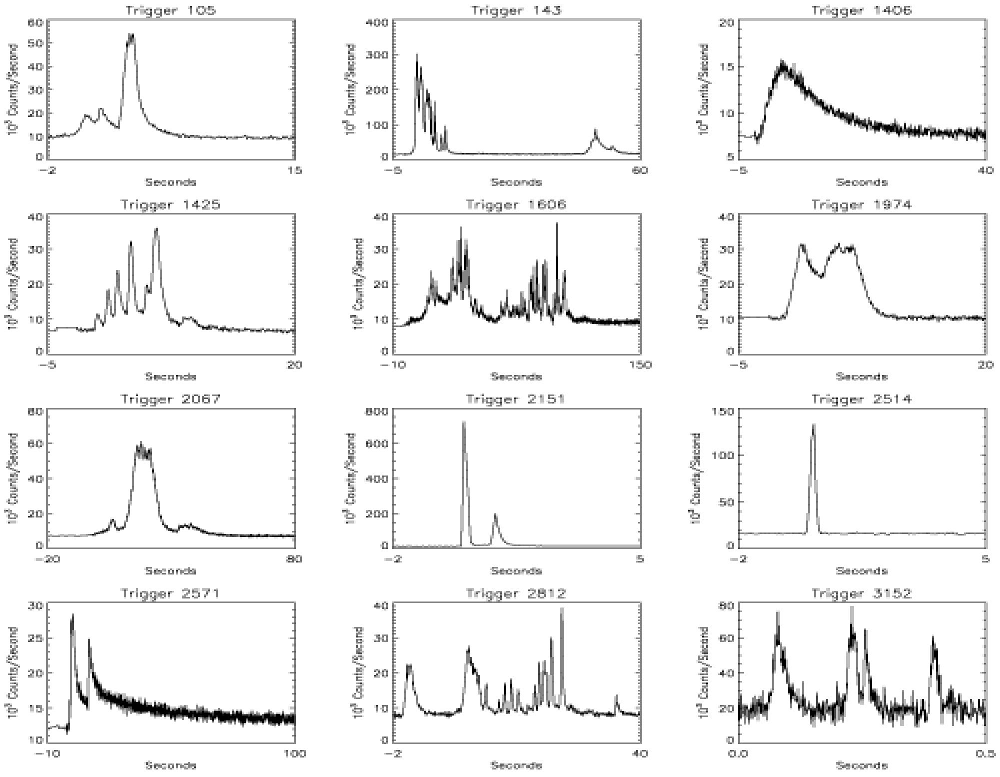
Gamma-Ray Bursts

75.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable particles
76.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion GRB with recurrence
77.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+ e- cascades by aligned pulsar outer-mag-sphere reignition
78.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revised)
79.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder region near NS
80.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spectra
81.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfen waves
82.	Trofimenko et al.	1989	Ap & SS, 152, 105	WH		COS	Kerr-Newman white holes
83.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E-field accelerates electrons which then pair cascade
84.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold area on NS
85.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hits primary
86.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS wanders though Oort clouds, fast WD bursts only optical
87.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from rot high-B NS
88.	Trofimenko	1989	Ap & SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GRBs
89.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
90.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
91.	Alexander et al.	1989	ApJ, 344, L1	NS		DISK	QED mag resonant opacity in NS atmosphere
92.	Melia	1990	ApJ, 351, 601	NS		DISK	NS magnetospheric plasma oscillations
93.	Ho et al.	1990	ApJ, 348, L25	NS		DISK	Beaming of radiation necessary from magnetized neutron stars
94.	Mitrofanov et al.	1990	Ap & SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's magnetosphere
95.	Dermer	1990	ApJ, 360, 197	NS		DISK	Compton scattering in strong NS magnetic field
96.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	DISK	Old NS accretes from ISM, surface goes nuclear
97.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes neutrino collisions, drives super-Ed wind
98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s
99.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
100.	Trofimenko et al.	1991	Ap & SS, 178, 217	WH		HALO	White hole supernova gave simultaneous burst of g-waves from 1987A
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B-field undergoes resistive tearing, accelerates plasma
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav rad and collide
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result
105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolve into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapsed to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRB, cosmic rays
108.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
109.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
111.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
113.	Narayan et al.	1992	ApJ, 395, L83	BH	NS	COS	BH - NS merger gives optically thick fireball
114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have neutrinos collide to gammas in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have neutrinos collide to gammas in clean fireball
117.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM

Table from: Nemiroff, R. J. 1993, Comments on Astrophysics, 17, No. 4, in press

Gamma-Ray Bursts

- Lightcurves:



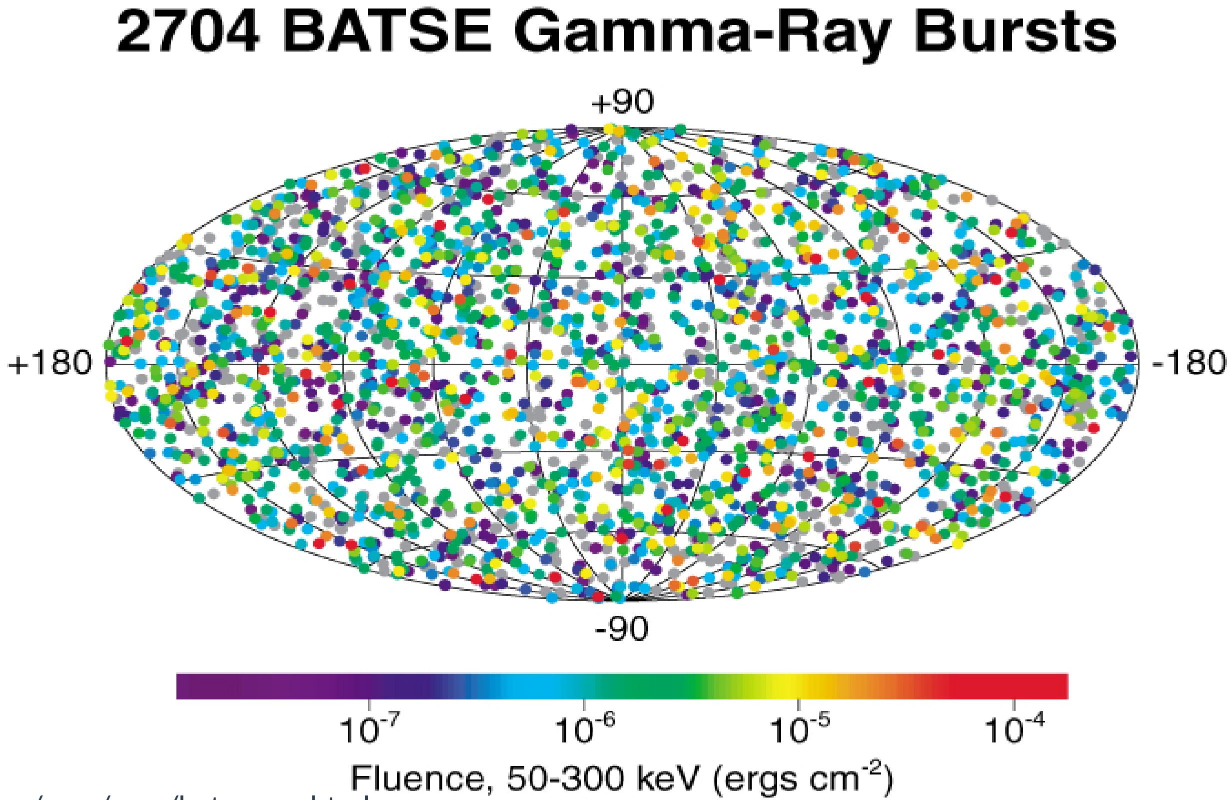
(Credit: J.T. Bonnell (NASA/GSFC))

Galactic or Cosmological

- Gamma-ray observations are hard, and tend to have poor pointing (at least for early instruments) making the identification of sources difficult
- What was know initially: short timescale of fluctuations implies that a compact object needed to be involved
- Main dilemma:
  - an enormous energy flux is recorded
  - galactic origin means that total energy release is a lot lower (and deemed more feasible initially)
- Compton Gamma-Ray Observatory launched in 1991 had 8 gamma-ray detectors (at corners)

Gamma-Ray Bursts

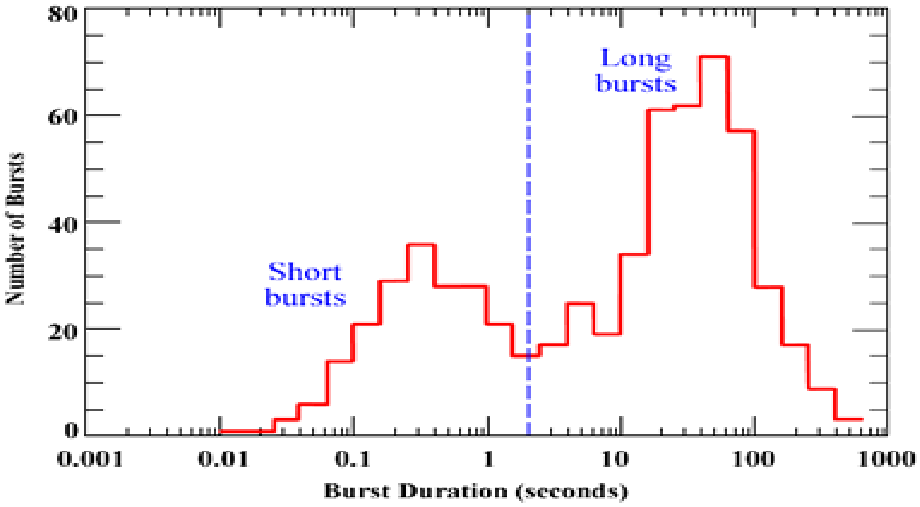
- Isotropic on the sky



http://heasarc.gsfc.nasa.gov/docs/cgro/cgro/batse_src.html

Gamma-Ray Bursts

- Two populations
  - Long and short based on duration
  - Short burst spectra are harder (emission at higher energy photons / lower energy is larger)
- Note that spectra are non-thermal
- Two models
  - Relativistic jets in core-collapse supernova (long)
  - Merging neutron stars (short)

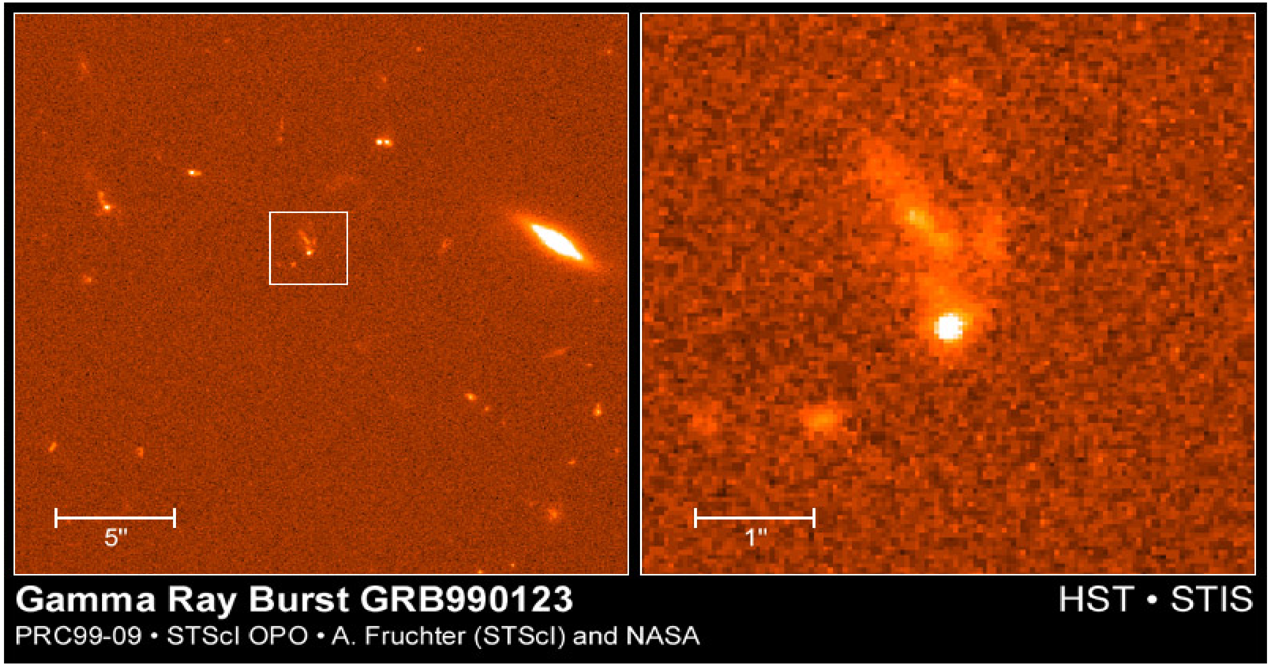


(Cosmos: SAO encyclopedia of Astronomy)

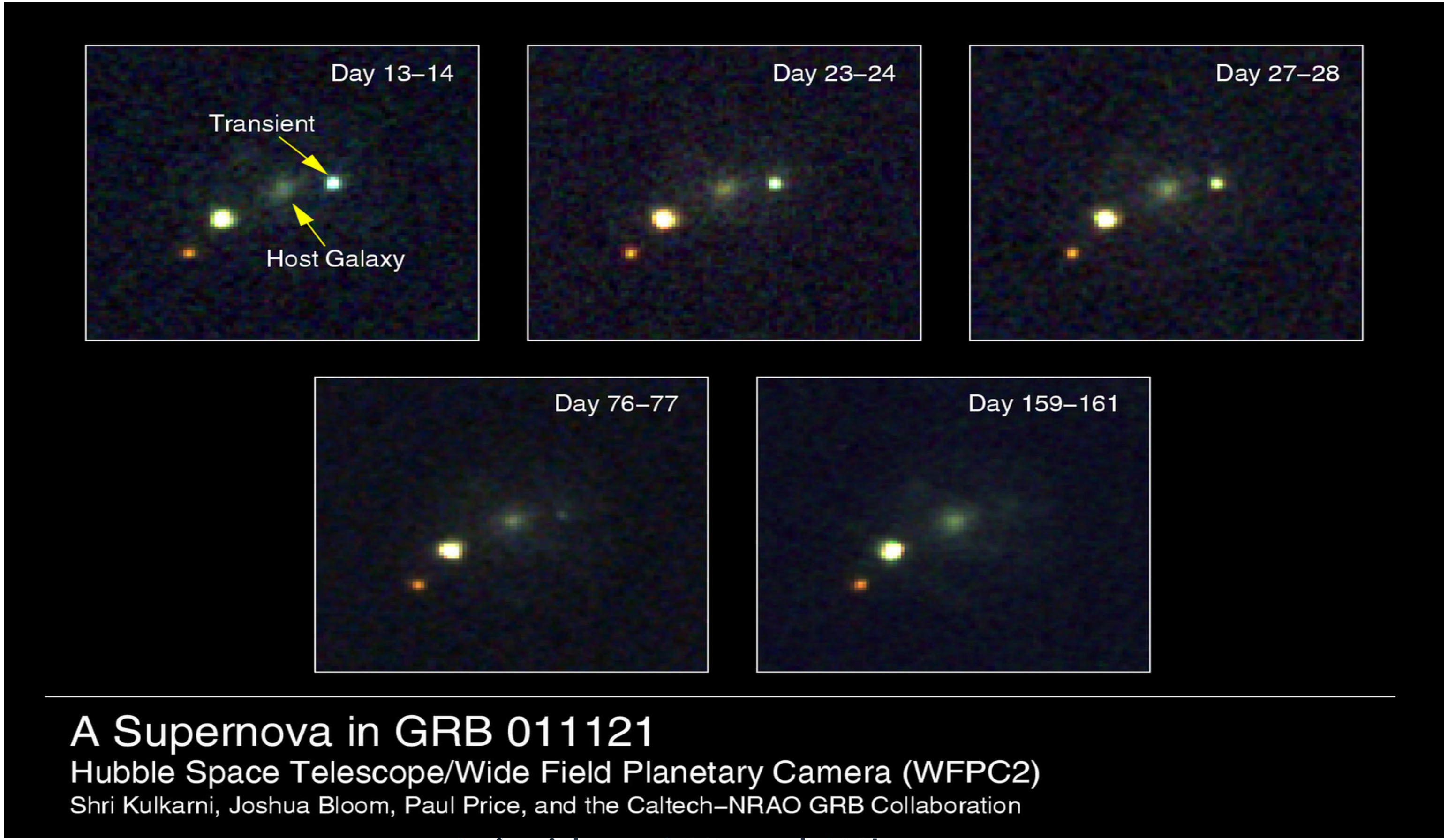
Gamma-Ray Bursts

- Debate for many years whether cosmological or galactic
  - An isotropic distribution could still be in the halo of our galaxy
- Energy budget for the two cases is vasty different
- Finally settled when an X-ray afterglow was detected
  - host galaxy could have redshift measured
  - At least long GRBs are cosmological

Gamma-Ray Bursts



Gamma-Ray Bursts



Coincident GRB and SN!

GRB Energy Budget

- Energy requirements can be dramatically lowered if the gamma-ray emission is collimated

$$E_{\text{true}} = E_{\text{isotropic}} \frac{\Delta\Omega}{4\pi}$$

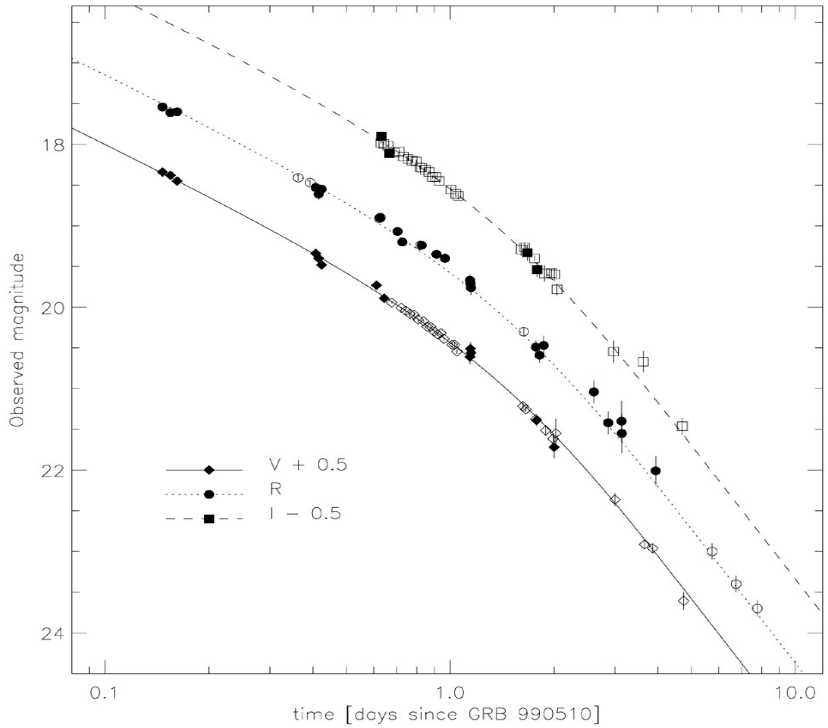
  - assuming a small angle:

$$\Delta\Omega \approx 4\pi \left(\frac{\theta_j^2}{2} \right)$$

- Beaming factor, $f \sim 4\pi/\Delta\Omega$, is small
  - burst only observed if we are looking down the beam
  - jet opening, $\theta_j \sim 1/\gamma$ (this is relativistic beaming, aka, "headlight effect")
  - relativistic beaming means that we can see more of the jet as the Lorentz factor drops
  - when we slow down enough, we can see more than the jet width—break in the lightcurve

GRB Jets

- Lightcurve breaks support jet model for long bursts
  - opening angles are ~4°
- Energy budget reduces to 10^{51} erg



(Harrison et al. 1999)

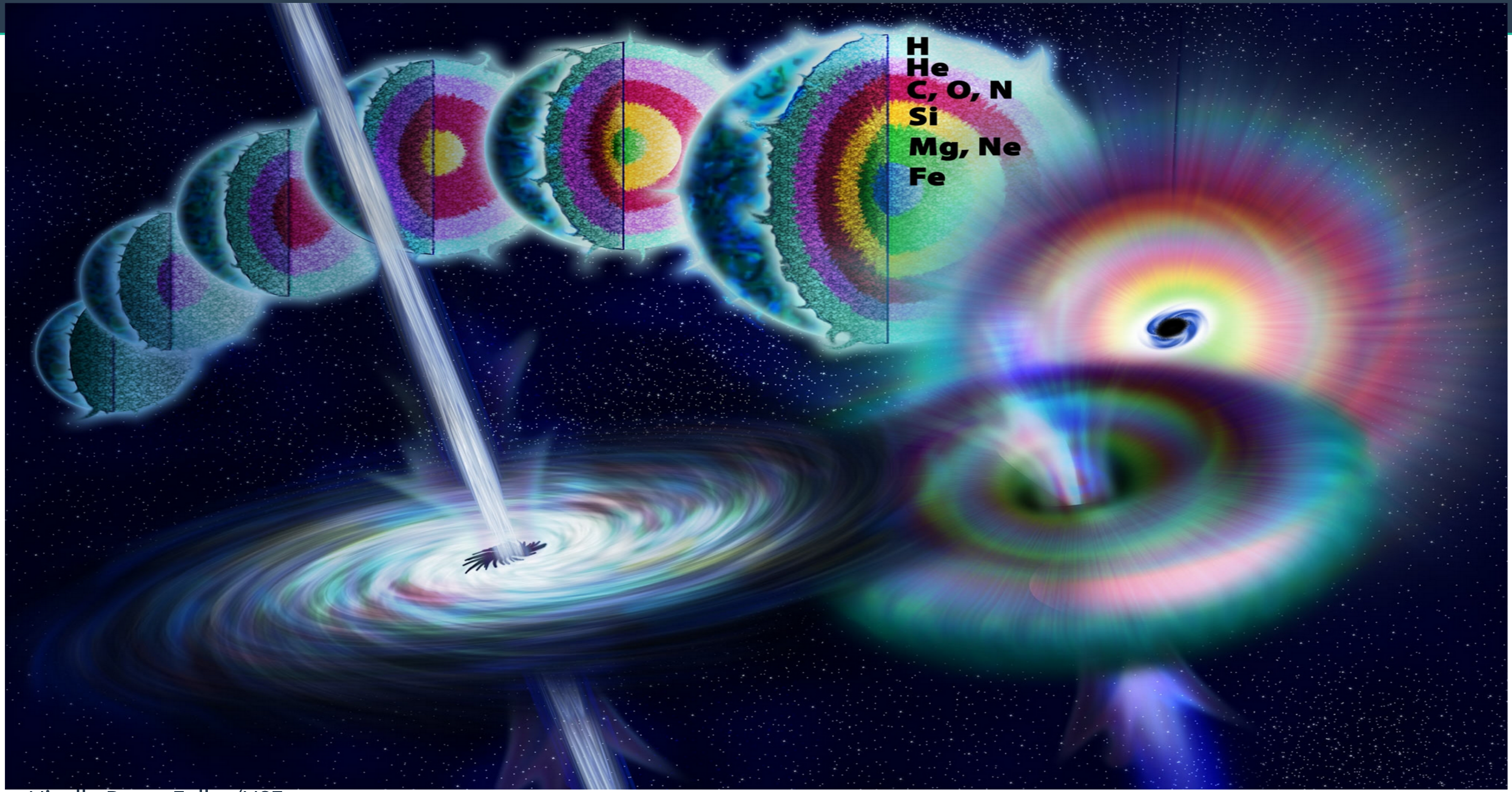
Short vs. Long

- Short bursts occur in all types of galaxies (even w/o star formation)
- Short have lower redshifts
- Short burst energies are several orders of magnitude smaller

Engines

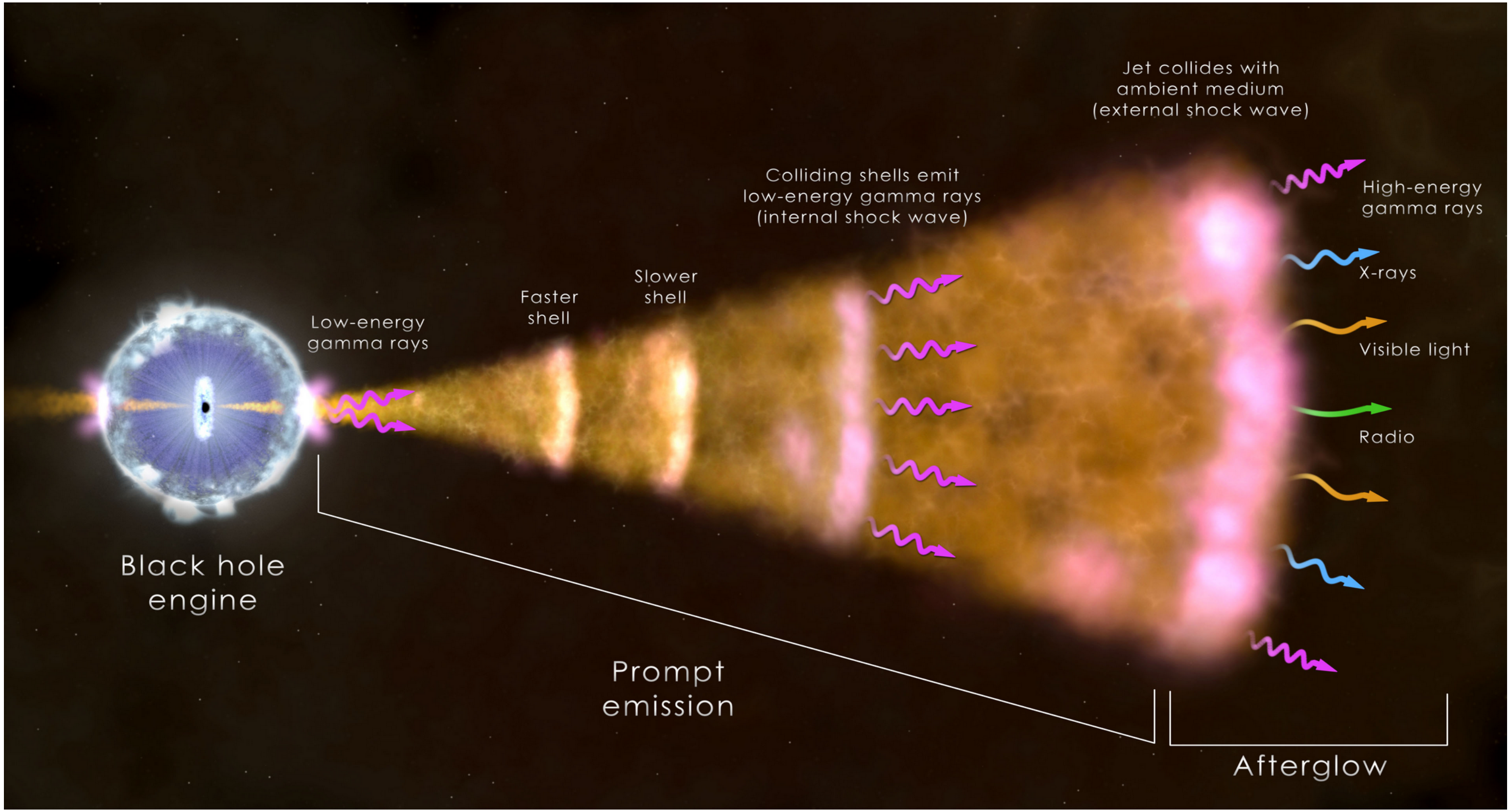
- The collapsar is the standard model for long bursts
  - Rapidly rotating, massive star core-collapse SNe
    - Wolf-Rayet: stripped H envelope
  - Black hole forms, fed by accretion disk
  - Jet formation from energy deposition along rotation axis
  - Collimated shock breakout at relativistic speeds—highly beamed emission
  - Afterglow produced as shock slows via interaction with ISM
- Neutron star merger for short bursts
  - jet production likely involved as well.

Gamma-Ray Bursts



Nicolle Rager Fuller/NSF

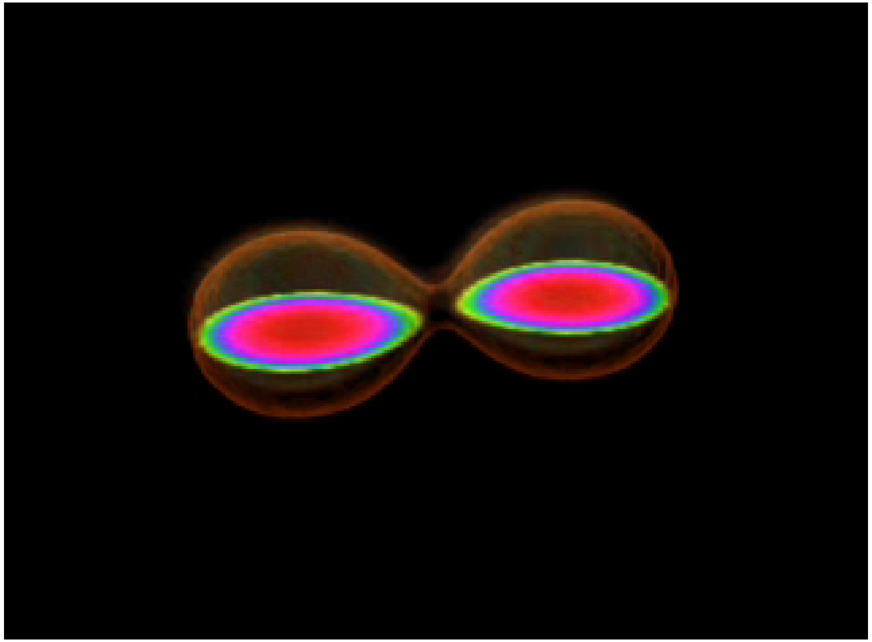
Emission Mechanism



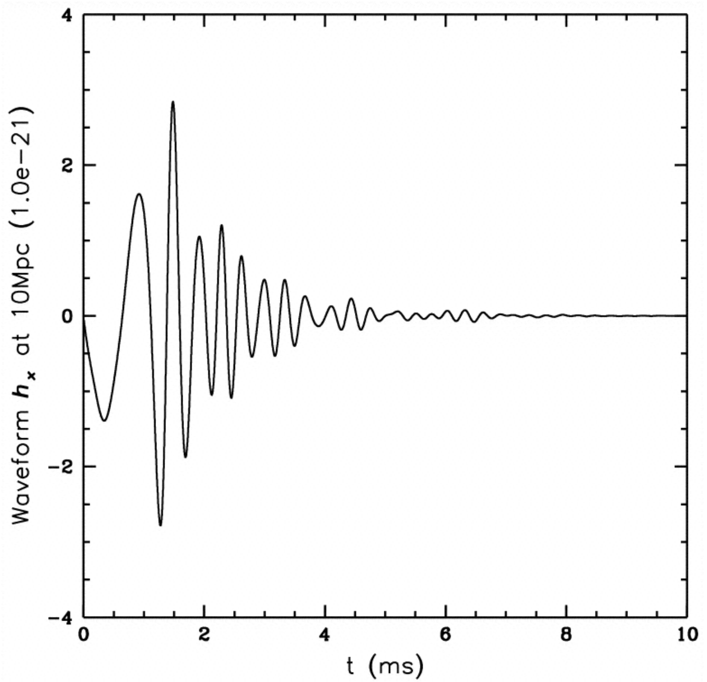
http://www.nasa.gov/feature/goddard/nasas-swift-spots-its-thousandth-gamma-ray-burst

GW170817 and GRB 170817A

- Neutron Star Merger → GRB → kilonova



Visualization Jedi Master: Dave Bock



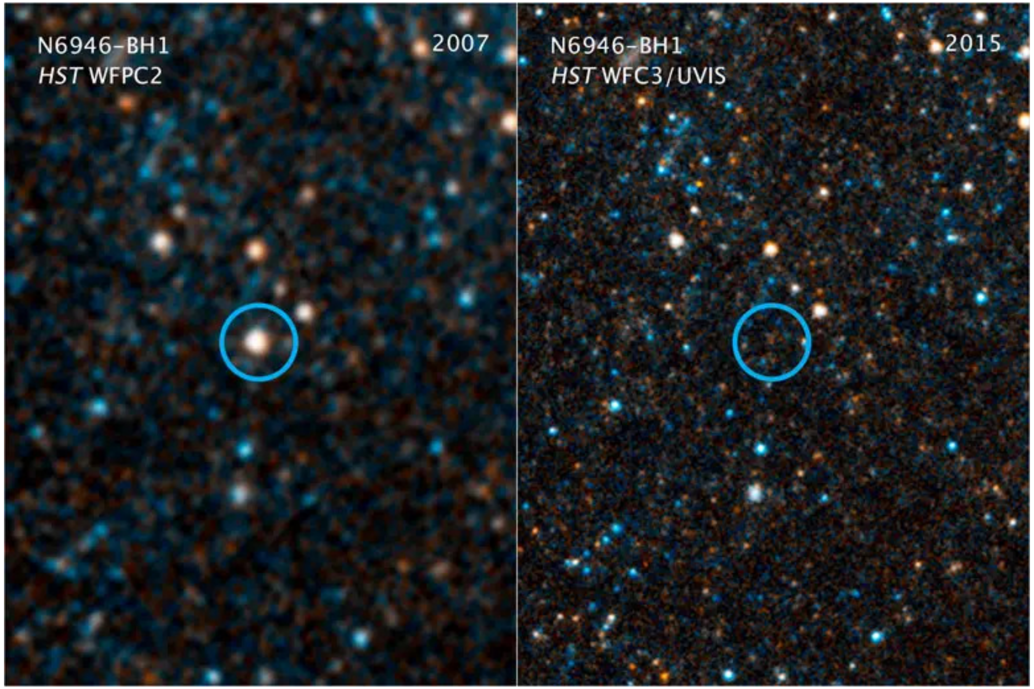
Calder & Wang ApJ 570, 303, 2002

Kilonovae

- Transient visible for weeks following a NS or NS/BH merger.
- ~ 1000 L_{nova}
- First observed following GW170817 (LIGO, 2017) and independent observation of GRB 170817A.
- Wikipedia: Observed by 70 observatories on 7 continents.
- NS mergers and Kilonovae are likely source of r-process elements!

Failed Supernovae

Observations of massive stars that just disappeared have been made, suggesting failed supernovae collapse to a black hole.



https://scitechdaily.com/astronomers-watch-as-collapsing-star-turns-into-a-black-hole/

Failed Supernovae

Observations of massive stars that just disappeared have been made, suggesting failed supernovae collapse to a black hole.

First observation:

https://www.pnas.org/doi/10.1073/pnas.1920319116

Recent preprint:

https://arxiv.org/abs/2201.12187

News article on first observation:

https://scitechdaily.com/astronomers-watch-as-collapsing-star-turns-into-a-black-hole/

Pair Instability Supernovae

- Really massive stars go unstable before the iron core forms
  - electron/positron pair production kicks
    - in our eos regime diagram, this is when $kT \sim 2\, m_e\, c^2$
      - $T \sim 10^9$ K
    - lowers adiabatic exponent to be < 4/3—dynamic instability kicks in
      - Similar to the effect that ionization has on the adiabatic index
  - core is massive and undergoes a runaway thermonuclear reaction
  - 40 $M_\odot$ of ^{56}Ni may be produced
- May especially be important for the first stars (pop III). Low metallicity is the key for making stars this massive (100+ $M_\odot$)

Pair Instability Supernovae

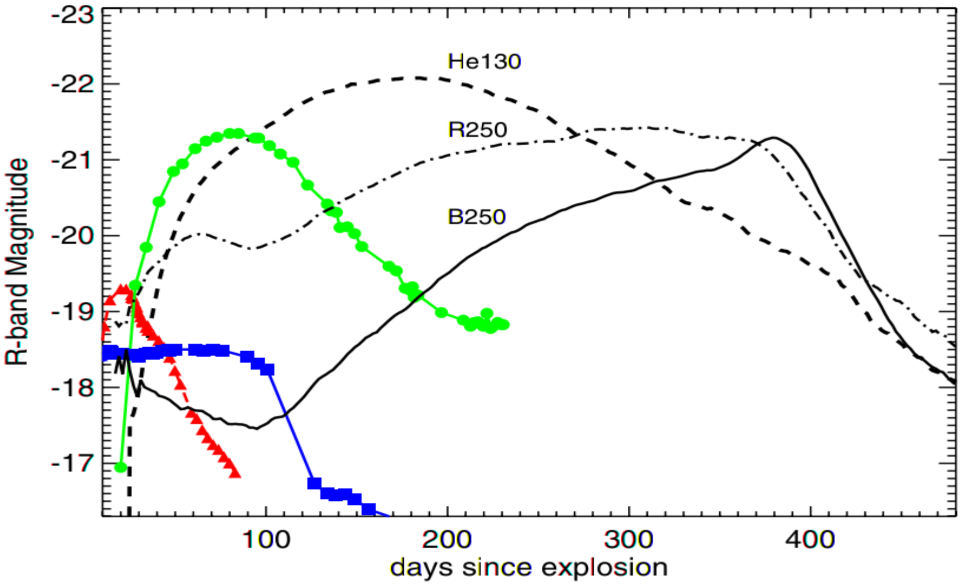


Figure 6. Synthetic *R*-band light curves (at $z = 0$) of bright PI SN models—R250 (dashed-dot), B250 (solid), and He130 (dashed)—compared to observations of a normal Type Ia supernova SN 2001el (red triangles; Krisciunas et al. 2003), a normal Type IIP supernova SN 1999em (blue squares; Leonard et al. 2002), and the overluminous core-collapse event SN 2006gy (green circles; Smith et al. 2007).

(Kasen, Woosley, & Heger, 2011)

Source Material

- *An Introduction to Modern Astrophysics*, 2nd ed. by Carroll and Ostlie
- *Stellar Interiors*, 2nd ed. by Hansen, Kawaler, and Trimble
- *Principals of Stellar Evolution and Nucleosynthesis* by Clayton
- *An Introduction to the Theory of Stellar Structure and Evolution* 2nd ed. by Prialnik
- José, J, 2024, EPJ Web of Conferences 297, 01006
- Notes kindly given by M. Zingale