(Potentially) Unifying Themes

and

Astrophysical Outputs

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Exploring Nuclear Matter - Quarks to Stars

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ACT I

Some unifying themes (existing efforts or expertise, grouped by science topic)

PHY,HEP,MSD, * has U of C component

SUPERNOVAE & MASSIVE STARS
VERITAS (mass loss)*
PopIII nuc rates
half-lives
quark stars (as end state)
ocean floor (recent Pu)
CPT masses (r-process)
Si burning rates
r-proc seeding (low-A rxn theory)
presolar grains
r-process kinetic theory*
ADONIS

COSMOLOGY+
BBN rates & theory
buy-in for dark matter/energy?
PopIII nuc rates
strangelets
Auger*
ν mass (e.g. $\beta\beta$)
VERITAS DM*
VERITAS γ background*
any useful nuc info for DM?
new large telescope?*

S-PROCESS

presolar grains

n rates at branch pts

ACCRETING SYSTEMS

experimental nuc rates

nuc masses from trap

models of novae/XRB*

nova grains?

quark stars

COSMOCHEMISTRY

presolar grains

meteorite inclusions

half-lives

atom trap trace analysis*

COSMIC RAYS

Auger*

VERITAS*

grain lifetimes?

early solar/meteorites

UHE propagation code

hadron cross sections

radar detection

CHEMICAL EVOLUTION

misc nuc rates

theory treatment*

presolar grains

solar composition*

ACT II

A lot of the effort in PHY focuses on measurable INPUTS to astrophysical theory; question arose last time as to what the measurable OUTPUTS are

I wanted to put together a quick “tour” of outputs for general information

1. Massive stars and core collapse supernovae
2. Thermonuclear (Type Ia) supernovae
3. X-ray bursts and novae
4. heavy-element (s- and r-process) nucleosynthesis
5. Chemical evolution of the Galaxy and cosmochemistry

Stars of more than 8–11 $M_\odot$ initial mass eventually become **core-collapse supernovae**

These stars undergo nuclear burning in their interiors until there is a degenerate core of Fe, and (roughly) when it exceeds its Chandresekhar mass, the core collapses to nuclear density

The collapse to a small object (neutron star or black hole) releases 10^{53} erg of gravitational binding energy, emitted as thermal neutrinos

As the outer parts of the star fall on top, 10^{51} erg is transferred (somehow) to the outer material, disrupting the star, explosive nucleosynthesis occurs at shock front as it propagates out through shell-burning layers

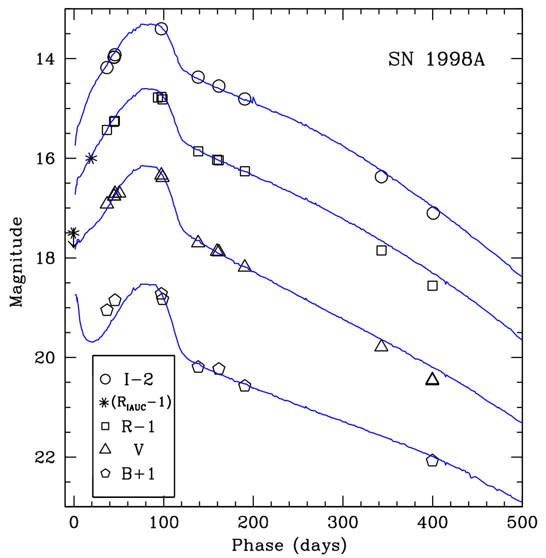
The heated and ejected material shines brightly for a few months

Longer-term luminosity fueled by radioactive decay, e.g. $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$

Over many hundreds of years, ejected material plows into interstellar medium (ISM) – emission occurs at the shock front where ISM piles up in “snow plow” – reverse shock propagates in and supernova material eventually produces nebular emission

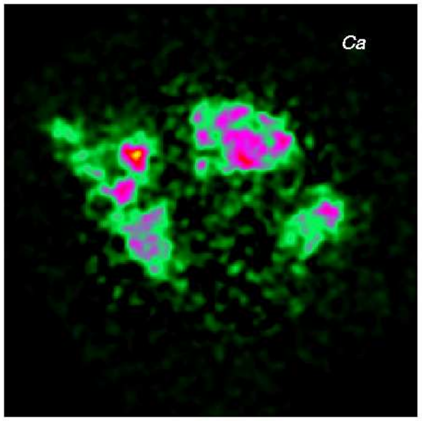
Initial observables:

- $\sim$ 10-second neutrino burst
- optical light curve, luminosity, optical spectral lines that mainly diagnose progenitor (Type II has H envelope, Ib & Ic have ejected their hydrogen)
- the most massive Ib & Ic events produce γ-ray bursts and may eventually provide standard candles



Later on:

- X-ray lines observed in remnant (satellite)
- X- and $\gamma-$rays at edge of remnant tell about surrounding material as it plows onto shock front (e.g. is it ISM, or wind material previously shed from star?)
- One case so far of ^{44}Ti γ-ray lines ($\tau_{1/2} =$ 60 yr) observed in a supernova remnant

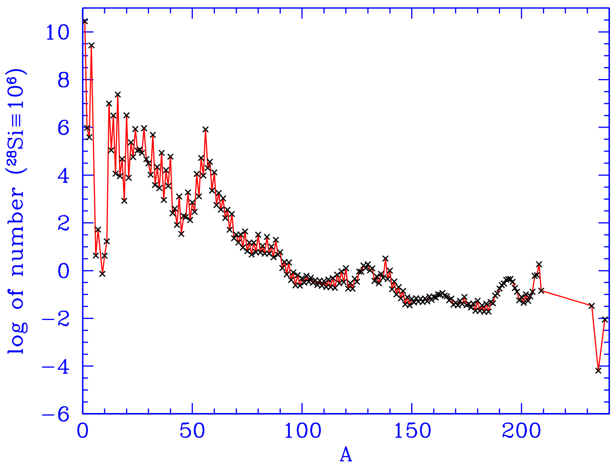


Much later on:

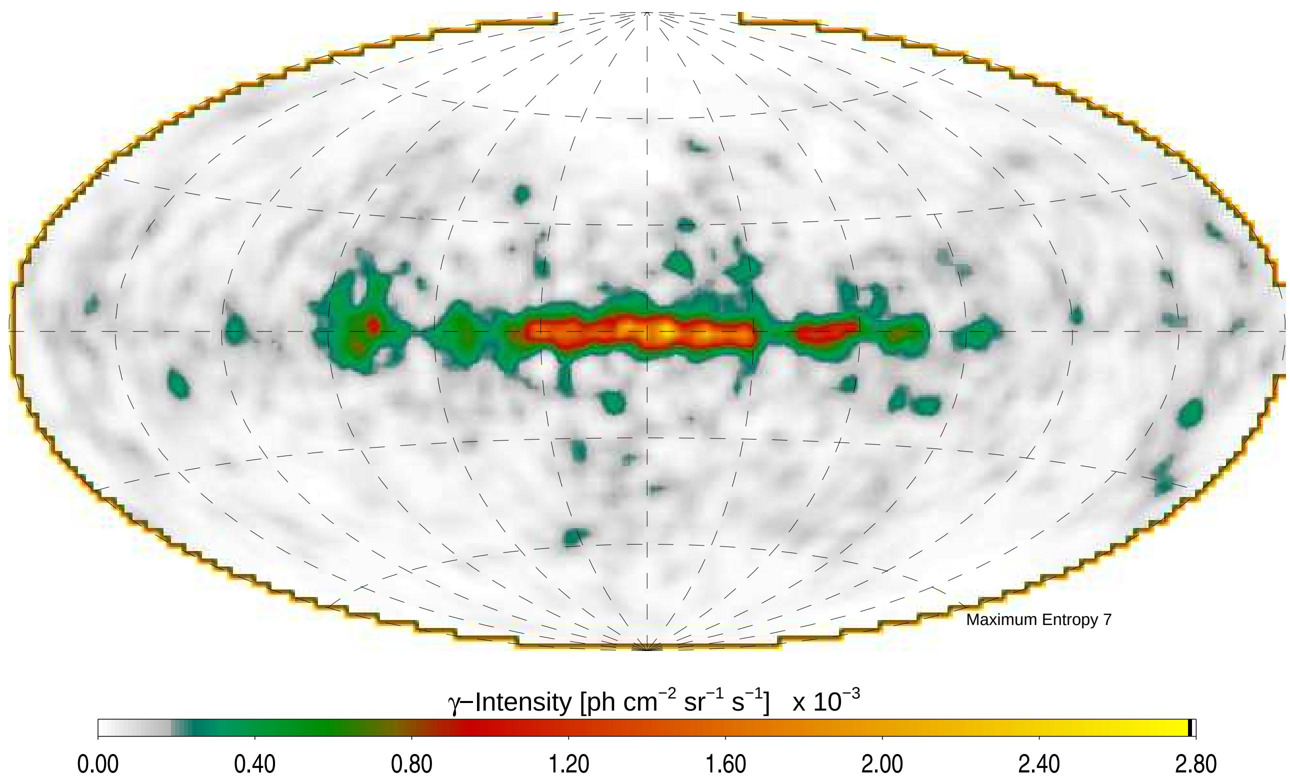
- Optical lines observed in an old star in our Galaxy may contain ejecta from only one or two supernovae, so there's a "fossil" record

- Local abundances reflect integration over Galactic history, much but not all of which was produced by supernovae

- Some pre-solar grains originate in supernovae



Gamma-ray lines of ^{26}Al and ^{60}Fe are also observed by satellites in diffuse emission in the Galaxy – probably linked mostly to massive stars, if not actually supernovae – the maps shows the $\sim 3M_{\odot}$ of ^{26}Al in the Galaxy



Type Ia supernovae

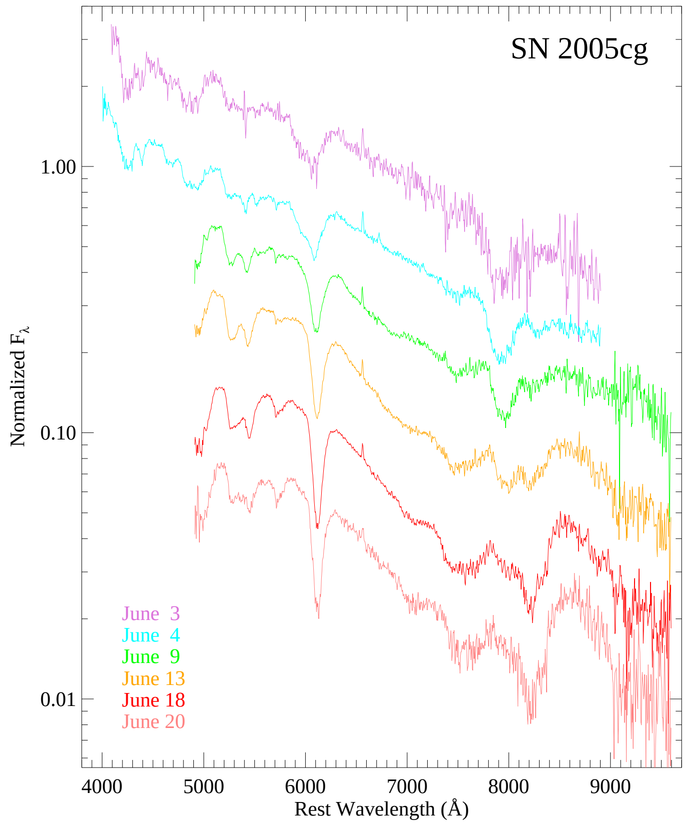
A carbon/oxygen white dwarf accreting material from a binary companion star can eventually exceed its Chandrasekhar mass

Carbon burning begins somewhere inside the white dwarf and engulfs the whole star, yielding $\sim 10^{51}$ erg of energy as C and O are fused into Si- and Fe-group elements

The original object is completely disrupted, leaving no compact remnant; remnant remains bright for a few months, powered mostly by ^{56}Ni decay

Important observables:

- Relation between peak brightness and width of optical light curve – useful as cosmological standard candle
- Optical emission lines that probe further into the star as the remnant evolves (composition vs position & vs velocity) give important constrains for models of the explosion
- At much later times, remnant plows into ISM much as for core collapse, maybe less informative than that case



Explosive proton burning: classical novae and X-ray bursts

In **nova** outbursts, a white dwarf accretes hydrogen from the surface of a binary companion until a critical amount builds up

There follows a burst of energy generation followed by steadier H burning, $10^{46} - 10^{47}$ erg

Object shines brightly for a roughly a month

Observables:

- energy output and spectral features (nucleosynthesis?) primarily from IR and optical (UV at peak luminosity)

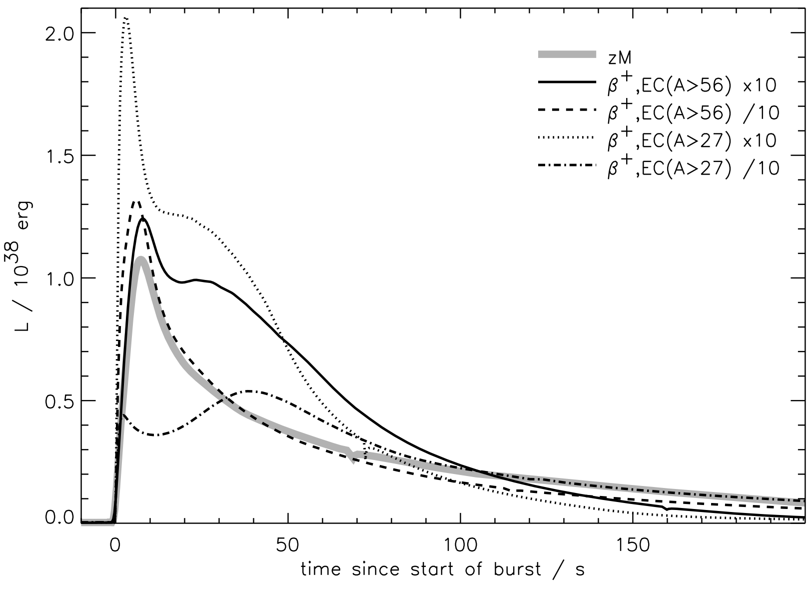
- possible signatures in presolar grain compositions?

X-ray bursts are analogous events, but on the surface of a neutron star rather than a white dwarf

These tell us a lot about neutron stars, or at least their surfaces

Observables are essentially entirely X-ray light curves (luminosity vs time, observed by satellite), and these can contain features that depend crucially on nuclear properties

Gravitational potential well is probably too deep for synthesized nuclei to get out

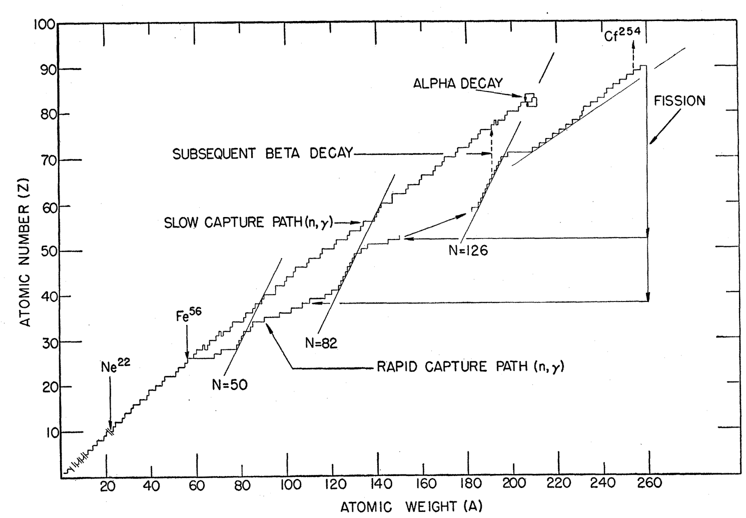


s-process

The s-process is buildup of nuclei larger than Fe by gradual neutron capture, so the neutron capture rate is slow relative to beta decay and nothing very unstable is produced (s = slow)

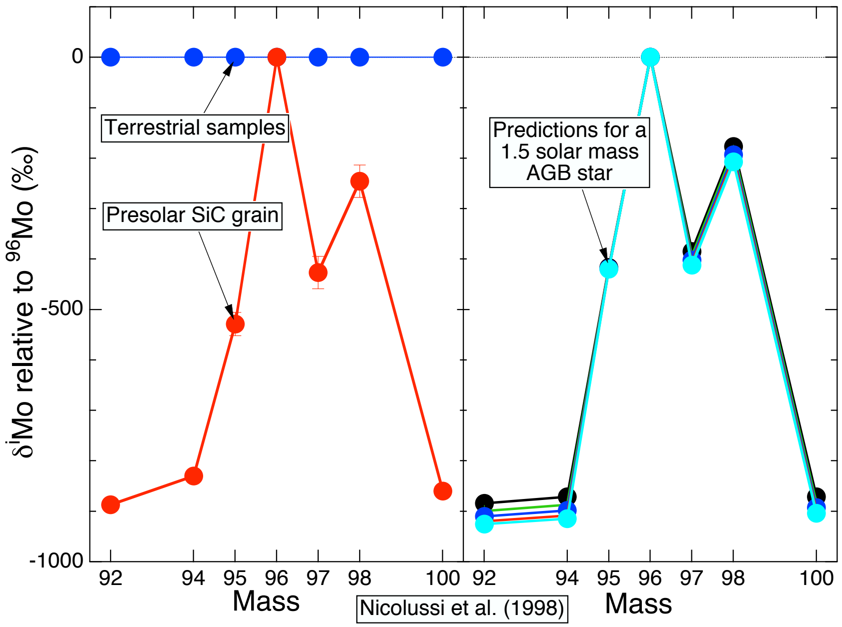
This happens during the He-burning phase in massive stars, producing nuclei up to $A \sim 90$

The "main" s-process making nuclei from Fe to Pb occurs in low-mass stars during the asymptotic giant branch phase, with neutrons produced in a He-burning shell via ^{13}C$(\alpha, n)^{16}$O or ^{22}Ne$(\alpha, n)^{25}$Mg



Observables:

- optical lines of newly-minted nuclei in S-type AGB stars – abundance by Z only
- pre-solar grain compositions – relative amount by A for given Z
- solar system bulk composition as integral over Galactic history
- surfaces of some old stars as “fossils” that separate s from r (optical & UV spectroscopy)



r-process

This is rapid neutron capture in some neutron-rich, explosive environment, forming nuclei from Fe to actinides

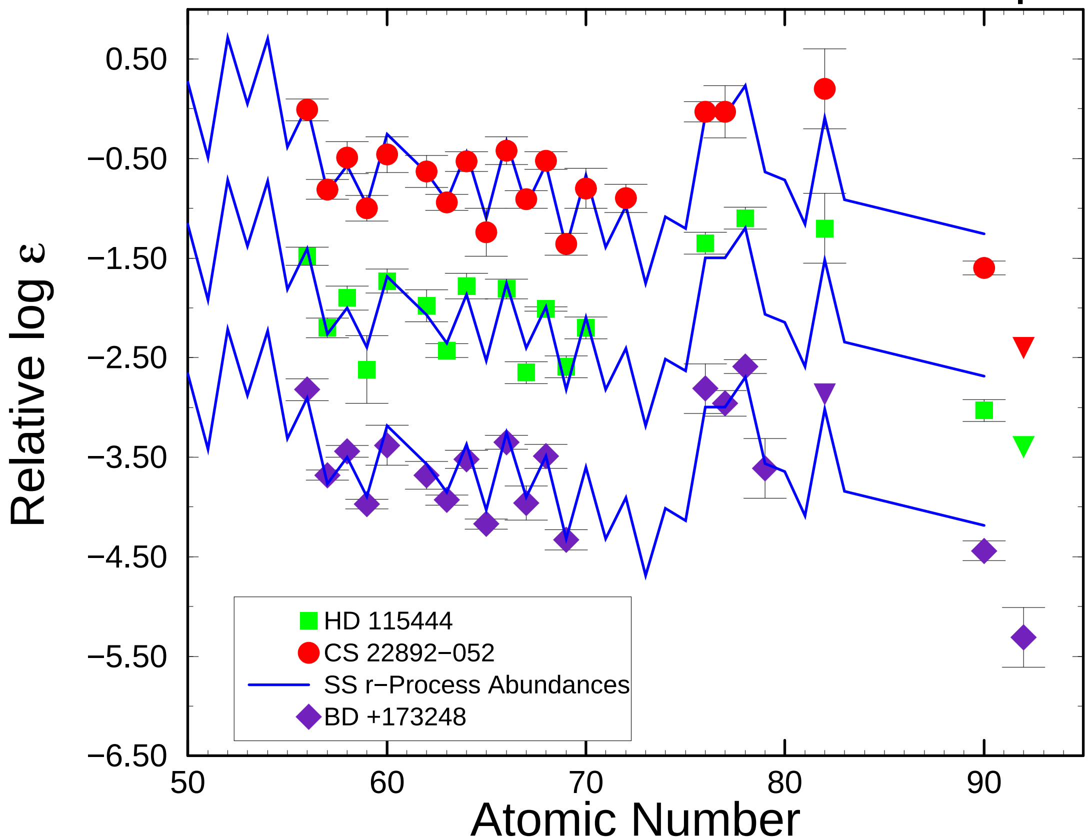
Leading candidate is core collapse supernovae, but the site is unknown, could be e.g. neutron star mergers or transition from neutron to quark star

We know about the r-process from solar system bulk composition, most information comes from subtracting the (modelled) s-process contribution from solar composition

Some very old stars show large enrichments of heavy elements in relative amounts characteristic of the r-process (optical and UV spectroscopy), presumably from earlier supernovae

Universality of the r-process is a big current puzzle – from mass Ba to Pt, the same r-process abundance pattern as in the solar system can be seen on the surfaces of some of the oldest stars in the Galaxy, presumably the product of the first generation of supernovae

The curve in blue shows the scaled solar system r-process abundances, with s-process subtracted out – each color of dots is a metal-poor star



Galactic chemical evolution and cosmochemistry

chemical evolution – history of nuclear enrichment in the Galaxy as stars contibute heavier nuclei to the initial H and He

cosmochemistry – same topic, viewed as an extension of geochemistry

Observables:

- composition of low-metallicity stars (optical & UV)
- solar system bulk composition – analytic chemistry of chondritic meteorites and optical/UV lines in the Sun
- meteorite inclusions from early in solar system formation
- pre-solar grains condensed at nucleosynthesis sites and embedded in meteorites (mass spectrometry)
- (relatively low-energy) cosmic-ray composition (space-based, e.g. Ulysses, ACE)