The Death of Stars

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I: Stellar Evolution

[Diagram of the Hertzsprung-Russell diagram showing different stages of stellar evolution, including main sequence, giants, supergiants, and white dwarfs.]
# Burning stages of a 25 M\(\odot\) star

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Product(s)</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>100 Myr</td>
</tr>
<tr>
<td>He</td>
<td>C, O</td>
<td>1 Myr</td>
</tr>
<tr>
<td>C</td>
<td>Ne, Na, Mg, Al</td>
<td>1000 yr</td>
</tr>
<tr>
<td>Ne</td>
<td>O, Mg</td>
<td>3 yr</td>
</tr>
<tr>
<td>O</td>
<td>Si, S, Ar, Ca</td>
<td>180 days</td>
</tr>
<tr>
<td>Si</td>
<td>Ni</td>
<td>1-5 days</td>
</tr>
</tbody>
</table>
Triple-alpha process

\[ ^4\text{He} \rightarrow ^8\text{Be} \rightarrow ^4\text{He} + ^{12}\text{C} \]

- Proton
- Neutron
- Gamma Ray
‘Onion skin’ fusion layers

- Hydrogen fusion
- Nonburning envelope (hydrogen)
- Helium fusion
- Carbon fusion
- Oxygen fusion
- Neon fusion
- Magnesium fusion
- Silicon fusion
- Iron ash
Nucleon binding energies

![Graph showing nucleon binding energies](image-url)
Electron degeneracy pressure: Chandrasekhar limit

- Pauli Exclusion Principle – e\(^-\) are fermions
- Form Fermi-Dirac gas
- Solve hydrostatic equation

\[ M_{\text{Chandra}} = \left( \frac{\omega_3^0 \sqrt{3\pi}}{2} \right) \left( \frac{\hbar c}{G} \right)^{\frac{3}{2}} \left( \frac{1}{\mu_e m_H} \right)^2 \sim 1.39 \, M_{\text{Sun}} \]
Core collapse

$s27f_{\text{heat}}1.15$

II: Supernovae

- Electron degeneracy pressure can’t keep Fe core from collapsing (core-collapse supernova)
- Neutron formation is energetically preferred ($e^{-}$ capture)
- Massive neutrino flux
- Huge gravitational potential energy released: $\sim 10^{46} \text{ J}$
III: Supernova remnants

• Some supernovae leave behind material (gas and/or dust) expelled from supernova

• Three expansion phases:
  1. Free expansion (up to few hundred yr)
  2. Adiabatic expansion (kyr)
  3. ‘Snow-plow’ (Myr)
Famous supernova remnants (SNRs)

SN1987A

- Closest SN in 400 yr
- Enabled observation of radionucleides
- Neutrinos detected
- Blue supergiant progenitor

ALMA (ESO/NAOJ/NRAO)/A. Angelich.
Visible: Hubble Space Telescope
X-Ray: Chandra
SN 1054: the Crab Nebula

- Best known SNR
- Seen by Chinese and Arab astronomers
- Most luminous nebula
- Most luminous pulsar
Cassiopeia A

- Young (300 yr)
- One of first radio sources
- Brightest radio source (>1GHz)
- Carbon atmosphere
Sedov-Taylor expansion

\[ t^2 = \left( \frac{\rho}{E} \right) \left( \frac{r}{C} \right)^5 \]
Vela Jr.

- Only seen in x-ray or higher
- Possibly only 200pc away
- Possibly only 780 yr old
  \( \tau_{1/2}(^{44}\text{Ti}) = 60 \text{ yr} \)
The cosmic ray mystery

- Ice cores
- $^{60}$Fe in the sea floor
- Periodic global ice ages/warming
- Tree rings?
IV: Neutron Stars

Tolman-Oppenheimer-Volkoff limit
(neutron degenerate analogy to Chandrasekhar limit)

\[ M_{TOV} \sim 1.5 - 3.0 M_{\odot} \]

- Assume neutrons form degenerate cold Fermi gas
- Strong nuclear force much shorter range
- Equation of state highly uncertain
- We’ve observed \( \sim 2M_{\odot} \) neutron stars
Neutron degeneracy

- Exclusion principle
- Degenerate electrons
- Inverse beta decay (creates neutron ‘soup’)
Properties of neutron star (NS)

- Hot (but ‘cold’)
- **Huge** magnetic fields
- Strongest material known
- Exotic core?
Material properties of NS crust (BCC phase):


\( F_{\text{Gravity}} > F_{\text{Coulomb}} \), and electron degeneracy
So local defects not supported!
Magnetic field

Field strengths $\sim 10^{4} - 10^{11}$ T
(Earth: $\sim 30 \mu$T)
Gravitational waves: travelling perturbations in space-time

Produced by (non-axisymmetric) acceleration of mass/energy

Perturbation seen as a strain \( (\delta L/L) \)

Tiny amplitudes:

\[
\bar{h}_{ij} = \frac{2G}{c^4 D} \ddot{I}_{ij}
\]
Triaxial model

• Rotating, non-axisymmetric neutron stars (and possibly axions...)

• Low $h_0(t)$ ... but can average
Divergence from axisymmetry: ellipticity

\[ \varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}} \quad \varepsilon_{\text{max.}} \sim 5 \times 10^{-6} \times \left( \frac{\xi_{\text{max.}}}{10^{-1}} \right) \]

Determines maximum height of ‘hills’ supported within NS crust ( \( O(\text{few mm}) \) )

Expected strain amplitude:

\[ h_0 = \frac{4 \pi^2 G}{c^4} \cdot \frac{I_{zz} f_{GW}^2}{D} \cdot \varepsilon \]
Cassiopeia A

• Young (~300 yr) compact object
• Position is well known
• Unknown spin-down parameters

Manifold parameters for Cas A

• $f_0$ in LIGO band (~10% of pulsars)
• Braking index, $n = 5 \rightarrow$ quadrupole radiation (but $n_{\text{obs.}} \sim 3$ ...)

\[
n = \frac{f \ddot{f}}{\dot{f}^2}
\]

Cas A very young $\rightarrow$ second spin-down required

Spin-down parameters: $f, \dot{f}$ and $\ddot{f}$

Manifold parameters: $\lambda_1 = f_0, \lambda_2 = \dot{f}, \lambda_3 = \ddot{f}$
Age-based Upper Limit

\[ h_{\text{age}} \leq \sqrt{\frac{5GI_{zz}}{8c^3 \tau}} = 1.2 \times 10^{-24} \times \frac{3.4 \text{ kpc}}{D} \times \sqrt{\frac{I_{zz}}{10^{38} \text{ kg m}^2}} \times \frac{300 \text{ yr}}{\tau} \]
How GWs are detected
The LIGO Network

Hanford, WA

Livingston, LA

4 km baseline, seismic isolation
The LIGO-Virgo Network

3,030 km

8,900 km

8,700 km
Computational bound

All this averaging means CW searches are computationally limited.

*Cas A* search took 420,000 CPU hrs on Albert Einstein Institute’s Atlas supercomputer.

We used this bound explicitly to determine a figure of merit for other targets.
What targets we look at

## Young compact objects in SNRs

<table>
<thead>
<tr>
<th>SNR (G name)</th>
<th>Other name</th>
<th>RA+dec (J2000)</th>
<th>D (kpc)</th>
<th>τ (kyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9+0.3</td>
<td></td>
<td>174846.9-271016</td>
<td>8.5</td>
<td>0.1</td>
</tr>
<tr>
<td>18.9-1.1</td>
<td></td>
<td>182913.1-125113</td>
<td>2</td>
<td>4.4</td>
</tr>
<tr>
<td>93.3+6.9</td>
<td>DA 530</td>
<td>205214.0+551722</td>
<td>1.7</td>
<td>5</td>
</tr>
<tr>
<td>111.7-2.1</td>
<td>Cas A</td>
<td>232327.9+584842</td>
<td>3.3</td>
<td>0.3</td>
</tr>
<tr>
<td>189.1+3.0</td>
<td>IC 443</td>
<td>061705.3+222127</td>
<td>1.5</td>
<td>3</td>
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<tr>
<td>266.2-1.2</td>
<td>Vela Jr. (I)</td>
<td>085201.4-461753</td>
<td>0.2</td>
<td>0.69</td>
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<tr>
<td>266.2-1.2</td>
<td>Vela Jr. (II)</td>
<td>085201.4-461753</td>
<td>0.75</td>
<td>4.3</td>
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<tr>
<td>291.0-0.1</td>
<td>MSH 11-62</td>
<td>111148.6-603926</td>
<td>3.5</td>
<td>1.2</td>
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<tr>
<td>347.3-0.5</td>
<td></td>
<td>171328.3-394953</td>
<td>0.9</td>
<td>1.6</td>
</tr>
<tr>
<td>350.1-0.3</td>
<td></td>
<td>172054.5-372652</td>
<td>4.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Upper limit plots

G111.7-2.1 (Cas A)

Intrinsic strain $h_0$

Frequency (Hz)

G266.2-1.2 (Vela Jr.) wide

Intrinsic strain $h_0$

Frequency (Hz)