Formation of stellar mass black holes from core collapse

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Outline

- Background
- Basic ideas in BH formation
- Observations and modeling
  - Faint SN
  - Hypernovae
  - BH in Nova Scorpii
- Summary and Conclusions
History

- 1915: Einstein finds gravitational field equations (GR)
- 1916: Schwarszchild solves equations for uncharged, spherically-symmetric, non-rotating systems
- 1939: Oppenheimer & Snyder studies gravitational collapse of a star in GR
- 1960’s-present: neutrino-driven SN mechanism
Evidence for black holes

- Masses greater than the maximum NS mass: $1.5-2.5 \, \text{M}_{\odot}$ (from detailed EOS calculations); $3.2 \, \text{M}_{\odot}$ (upper limit from causality; Lattimer & Prakash)
- $\sim 10^9$ SMBHs in the Galaxy, from stellar popn modeling (Brown & Bethe 1994)
- 20 confirmed black holes in X-ray binaries, with secure masses (as of 2006)
- mass gap between NS and BHs? characteristic or range of masses?
BH formation via core collapse

- A black hole forms:
- IF ram pressure from infall overcomes shock pressure from neutrino heating
- IF binding energy is larger than explosion energy → matter falls back and accretes to compact object

→ A star that is sufficiently massive will form a black hole, but how massive?
BH formation via core collapse

- **NS-BH transition mass**: where binding energy \(\sim\) explosion energy
- Fryer 1999 models found transition mass \(\sim 18-25 \, M_{\odot}\)
- An adiabatic shock slows down where \(\rho \sim r^{-n}, \, n<3\): mantles of larger mass progenitors (WW95)
BH formation via core collapse

- **approximate** map of outcomes (no rotation, no companions)
- crude prescription for mass loss rate $\sim Z^{0.5}$ (largest uncertainty)
- $\sim 75\%$ NS, $20\%$ BH; easier to form BH at low metallicities

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Heger et al. 03
Observational signatures

- increasing mass of H envelope: Type I, Type III, Type IIp
- effect of rotation: faint SN, hypernovae, GRBs (extremes?)
- future: vanishing supergiants, gravitational waves
SN1997D: faint SN light curve

- Type IIp
- $M_V(\text{max}) \sim -14.65$
- $M(^{56}\text{Ni}) = 0.001$ to $0.004 \ M_{\odot}$
- $V_{\text{expansion}} \sim 1200 \ \text{km/s}$
- decline rate $\sim ^{56}\text{Co}$ powered tail

- progenitor mass $\sim 26 \ M_{\odot}$
- progenitor radius $\sim 300 \ R_{\odot}$
- mass of ejecta $\sim 24 \ M_{\odot}$
- kinetic energy $\sim 4 \times 10^{50} \ \text{erg}$
- $M(^{56}\text{Ni}) \sim 0.002 \ M_{\odot}$
- remnant mass $\sim 1.8 \ M_{\odot}$
Faint SN: simulations

- 2D core collapse simulations by Fryer 1999
- “fallback” from energy accounting (not hydro)
- massive remnants, low kinetic energies, low masses of neutron-rich ejecta
- results sensitive to model input physics (neutrino heating, EOS) and progenitor model (mass loss, opacity, convection)

<table>
<thead>
<tr>
<th>MODEL</th>
<th>$M_{\text{Core}}$ ($M_\odot$)</th>
<th>$M_{\text{Remnant}}$ ($M_\odot$)</th>
<th>ENERGY (10$^{51}$ ergs)</th>
<th>$Y_\epsilon &lt; 0.4$</th>
<th>$Y_\epsilon &lt; 0.45$</th>
<th>$Y_\epsilon &lt; 0.49$</th>
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- results do not match with SN1997D model:

$K_{E_{\infty}} = 4 \times 10^{50}$ erg $\rightarrow E_{\text{expl}} = 1.4 \times 10^{50}$ erg

---> twice as large as in 25 $M_{\odot}$ simulation
Faint SN and EMP stars?

- puzzle of low mass (0.8 $M_{\text{sun}}$) EMP star HE0107-5240: [Fe/H]=-5.3, [C/Fe]=4, [N/Fe]=2.3.
- model: all material below 6 $M_{\text{sun}}$ fall back, M(Fe) ejected = $8 \times 10^{-6} M_{\text{sun}}$
- possible explanation: formed from gas enriched by supernova with small Fe injection, but enhanced in C and O (allowing gas to cool)
Hypernovae: introduction

- extraordinary class of Type II SN
- larger kinetic energies, ejected mass or, synthesized $^{56}$Ni mass
- progenitor masses $\geq 20 \, M_{\odot}$
- first connection with GRBs: SN1998bw/GRB980425, SN2003dh/GRB030329
- handful discovered: SN1997ef, SN1997dq, SN1999as, SN2002ap (Type Ic’s), SN1997cy, SN1999E (Type IIln’s)
- thought to be result of jet-driven explosion: collapsar model

SN1998bw
- Type Ic
- $E_{\text{Kin,51}} = 50$
- $M(^{56}\text{Ni}) = 0.4 \, M_{\odot}$
- $M_{\text{ejecta}} = 10 \, M_{\odot}$
Hypernova: simulations

- jet-induced explosion models
- jets injected with opening half-angle $\theta_{\text{jet}}$, jets inject energy proportional to accretion rate
- outcome: highly aspherical explosion, dense central core
- trends: more massive star makes a more energetic explosion (higher gravity $\rightarrow$ higher accretion rate)
- more massive star forms a more massive remnant

Maeda & Nomoto 03

<table>
<thead>
<tr>
<th>Model</th>
<th>$M_{\text{MS}}$</th>
<th>$M_{\text{REM0}}$</th>
<th>$\alpha$</th>
<th>$\theta_{\text{jet}}$</th>
<th>$E_{\text{total}}$</th>
<th>$M_{\text{REM}}$</th>
<th>$M^{(56}\text{Ni})$</th>
<th>[S/Fe]</th>
<th>[C/O]</th>
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<tr>
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<td>1.5</td>
<td>1.51E-1</td>
<td>-0.26</td>
<td>-0.82</td>
</tr>
</tbody>
</table>

$M_{\text{prog}} = 40 \text{ M}_{\odot}$
$\rightarrow M_{\text{rem}} > 5 \text{ M}_{\odot}$

$M_{\text{prog}} = 25 \text{ M}_{\odot}$
$\rightarrow M_{\text{rem}} \sim 2 \text{ M}_{\odot}$
Hypernova nucleosynthesis

- distinct regions of explosive nucleosynthesis: complete Si burning (Zn, Cr, Co, V) and incomplete Si burning (Mn, Cr)
- regions pushed outward in higher E explosion
- higher E -> lower [Fe/H] because $M_{\text{swept}} \sim E$
- higher E -> higher [Zn/Fe], lower [Mn/Fe]
BH in Nova Scorpii

- direct evidence of SN origin for a BH
- X-ray nova (1994), GRO J1655-40
- \( M_{BH} = 5.4 \pm 0.3 \, M_{\odot} \)
- \( M_{\text{secondary}} = 1.45 \pm 0.35 \, M_{\odot} \)
- secondary atmosphere enriched by factor of 6-10 in \( \alpha \)-process elements
- high space velocity > 106 km/s -> NS kick or asymmetric mass ejection
- Podsiadlowski et al. 02 modeled the pollution of the secondary
  - fallback material must reach secondary before falling back or mixed during the explosion with material that will escape
  - they found progenitor mass \( \sim 10^{-16} \, M_{\odot} \), range of \( E_{\text{kin}} = 1-10 \times 10^{51} \) erg are consistent with observations
  - hypernova models preferred: large \( M_{BH} \), S, Si produced farther out

<table>
<thead>
<tr>
<th>Parameter</th>
<th>N</th>
<th>O</th>
<th>Mg</th>
<th>Si</th>
<th>S</th>
<th>Ti</th>
<th>Fe</th>
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<tr>
<td>([X/_{\odot}])</td>
<td>0.45</td>
<td>1.00</td>
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<td>0.90</td>
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<td>(\Delta[X/_{\odot}])</td>
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<td>0.20</td>
<td>0.40</td>
<td>0.20</td>
</tr>
</tbody>
</table>

*Note — \([X/_{\odot}]\): logarithmic abundances relative to solar; \(\Delta[X/_{\odot}]\): observational uncertainties in \([X/_{\odot}]\). From Israeli et al. 1999.*
Summary and conclusions

- Stellar mass black holes exist, and their formation is accompanied by SNe at least in some cases.
- Two possible scenarios: faint SNe and hypernovae, hypernovae may be connected to GRBs
- BH-forming SNe may have made unique contributions to early chemical evolution
- Need more observations!
- Need better models!