Super-Eddington Accretion Onto Neutron Stars

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What is super-Eddington Accretion
Sites of super-Eddington Accretion
Accretion Atmospheres
Eddington Accretion

• Photons from a source deposit momentum (exerting a pressure) on any infalling material.
• The Eddington Rate is determined by the rate where the photons from the accretion exert enough pressure to halt further inflow.
• This limit is not valid if:
  ➢ The situation is non-steady state
  ➢ The photon flow is not symmetric
  ➢ Photons are trapped in the flow
Sites of Hyper-Accretion on Neutron Stars

• Fallback in Core-Collapse Supernovae
• Common Envelope Evolution
• Induce Gravitational Collapse (accretion as the supernova sweeps past a neutron star companion)
Binding Energy Of the Outer Layers Of the Star ($M_{\text{star}}$ -3 solar Masses)
Anatomy of Fallback

Fallback Mechanism

- Rarefaction wave: As the neutron star cools, it accretes, producing a rarefaction wave that catches the shock and decelerates it (Colgate 1971): Accretion happens quickly (first 100s)
- PdV work: The initial ejecta decelerates as it drives an explosion through the star. If the velocity decelerates below the escape velocity, it falls back (Fryer 1999): Accretion happens quickly (first 100s)
- Reverse shock: The shock decelerates in the flat density gradient of the envelope, driving a reverse shock. This decelerates the material behind the shock sufficiently to fall back (Nomoto 1988, Woosley 1988): Accretion takes 1000-10,000s.
Fallback rates

It is difficult to avoid fallback. Most happens at early times, but at the level of $10^{-4}$ Msun, this can happen even a year after the explosion.
Common Envelope Evolution

Many compact binary systems require that the binary go through a phase where a neutron star enters a common envelope with its companion.

During this phase, the binary tightens and matter accretes onto the neutron star.

Common Envelope by Passy et al. (2012)
Bondi-Hoyle-Littleton Accretion

- Bondi Radius
  \[ r_B = \frac{G M_{NS}}{v^2 + c_s^2} \]

- Bondi Accretion
  \[ \dot{M}_B \approx 4\pi r_B^2 \rho (v^2 + c_s^2)^{1/2} \]

- Ruffert studied this accretion in a series of papers and found that these formulae are fairly accurate for many situations.

- Angular momentum is likely also accreted and the matter may form a disk (and jet outflow).
Trapping Radius

The radiation is said to be trapped if the material flows downward faster than the radiation diffuses outward. Near the neutron star surface, the infall velocity is high and the high densities mean that the diffusion velocity is low (radiation is trapped in the flow. But the inflow velocity decreases with increasing radius, the density (and hence diffusion velocity increases with increasing radius) and radius where these two cross

\[ r_{tr} = \min \left( \frac{\dot{M} \kappa}{4\pi c}, r_B \right) \]
# Rates for Common Envelope Accretion

<table>
<thead>
<tr>
<th>Stellar Type</th>
<th>$r_{NS} - r_{SC}$ (10$^{11}$ cm)</th>
<th>Density (g cm$^{-3}$)</th>
<th>Entropy ($k_B$ nucleon$^{-1}$)</th>
<th>Velocity (km s$^{-1}$)</th>
<th>$c_s$ (km s$^{-1}$)</th>
<th>Bondi Radius (10$^{11}$ cm)</th>
<th>$\dot{M}$ ($M_\odot$ yr$^{-1}$)</th>
<th>Inhom. Factor $\epsilon_{\rho_c}$</th>
<th>$R_{\text{ang}}$ (10$^8$ cm)</th>
<th>Trap. Radius (10$^{11}$ cm)</th>
<th>Result$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $M_\odot$ MS</td>
<td>0.4</td>
<td>0.4</td>
<td>15</td>
<td>300</td>
<td>300</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>10 $M_\odot$ MS</td>
<td>1.0</td>
<td>0.25</td>
<td>17</td>
<td>300</td>
<td>400</td>
<td>0.75</td>
<td>1.4 x 10$^4$</td>
<td>3.4, -0.004</td>
<td>200</td>
<td>0.75</td>
<td>IC</td>
</tr>
<tr>
<td>1 $M_\odot$ Giant</td>
<td>250</td>
<td>5 x 10$^{-8}$</td>
<td>26</td>
<td>300</td>
<td>40</td>
<td>2.0</td>
<td>0.01</td>
<td>0.024, ~0</td>
<td>0.07</td>
<td>2.0</td>
<td>DC</td>
</tr>
<tr>
<td>1.0</td>
<td>0.08</td>
<td>10</td>
<td>70</td>
<td>300</td>
<td>300</td>
<td>0.6</td>
<td>3700</td>
<td>0.38, -0.15</td>
<td>1.7</td>
<td>0.74</td>
<td>IC</td>
</tr>
<tr>
<td>10 $M_\odot$ Giant</td>
<td>10</td>
<td>10$^{-3}$</td>
<td>29</td>
<td>300</td>
<td>250</td>
<td>1.2</td>
<td>100</td>
<td>0.42, 0.07</td>
<td>31</td>
<td>1.2</td>
<td>EX</td>
</tr>
<tr>
<td>0.5</td>
<td>250</td>
<td>10</td>
<td>300</td>
<td>1000</td>
<td>0.17</td>
<td>1.5 x 10$^6$</td>
<td>0.21, -0.07</td>
<td>$5 \times 10^{-3}$</td>
<td>0.18</td>
<td>IC</td>
<td></td>
</tr>
<tr>
<td>GMC</td>
<td>N/A</td>
<td>10$^{-11}$</td>
<td>45</td>
<td>1000</td>
<td>10</td>
<td>0.2</td>
<td>$8 \times 10^{-8}$</td>
<td>?</td>
<td>?</td>
<td>3 x 10$^{-5}$</td>
<td>?</td>
</tr>
</tbody>
</table>

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$^a$ This is the distance the neutron star is from the center of its companion.

$^b$ IC = immediate collapse, EX = explosion, DC = delayed collapse.
Binary Driven BH formation

- Neutron star accretes ejecta when its companion star explodes.
- Depending upon the orbital separation, this accretion can be substantial.
- Opacity is based on C/O material – higher than CE phase
Binary-driven Accretion

- Opacity dominated by heavy elements: the line opacity higher than electron scattering so the radiation is trapped further out.
ICG only works for CO cores

Hypercritical accretion does not occur for helium cores:
• Separation is wider, so accretion rate is lower
• Opacity is dominated by helium so it is more difficult to trap radiation.
Building a NS Atmosphere

Free-fall Conditions

\[ v_{ff} = \sqrt{\frac{2GM}{r}} \]

\[ \rho_{ff} = \frac{\dot{M}_B}{4\pi r^2 v_{ff}} \]

Gamma-law EOS

\[ P_{sh} = \frac{\gamma + 1}{2} \rho_{ff} v_{ff}^2 \]

\[ \rho_{sh} = \frac{\gamma + 1}{\gamma - 1} \rho_{ff} \]

Radiation dominated Gas

\[ S = 5.5 \times 10^3 \left[ \frac{\gamma + 1}{2} \right]^{3/4} \frac{\dot{M}_B^{-1/4} r_{6}^{-3/8}}{(\gamma + 1)/(\gamma - 1)} M_{NS}^{7/8} \]
NS Atmospheres: Structure of Atmosphere

The graph shows the relationship between log entropy (in units of $k_B$/nucleon) and log radius (in cm) for different mass loss rates $\dot{M}$:

- $\dot{M} = 1 \, M_\odot$/year
- $\dot{M} = 10 \, M_\odot$/year
- $\dot{M} = 10^2 \, M_\odot$/year
- $\dot{M} = 10^3 \, M_\odot$/year
- $\dot{M} = 10^4 \, M_\odot$/year

The graph illustrates the decrease in entropy as the radius increases for all mass loss rates.
Atmosphere Extent

The fallback atmosphere keeps expanding until neutrino cooling halts the expansion. This derivation assumes that the unstable entropy profile drives quick (and smooth) convection that equalizes the entropy.

\[ \frac{d\epsilon_{\text{tot}}}{dt} = \frac{GM_{\text{NS}} \dot{M}_B}{r_{\text{NS}}} \]

\[ \frac{d\epsilon_{\text{pp}}}{dt} = 9.2 \times 10^{16} \left( \frac{M}{1.4 \, M_\odot} \right)^{13/8} \left( \frac{\dot{M}_B}{M_\odot \, \text{yr}^{-1}} \right)^{5/4} \times \left( \frac{r_{\text{NS}}}{10 \, \text{km}} \right)^{-6} \left( \frac{r_{\text{sh}}}{100 \, \text{km}} \right)^{15/8} \text{ ergs g}^{-1} \text{ s}^{-1} \]

\[ r_{\text{sh}}^{4/3} = 6.7 \times 10^8 \dot{M}_B^{-10/27} \text{ cm} \]
Explosive Convection
Hyper-Accretion Diagnostics: Nucleosynthesis

- Nuclear yields pervade many of the diagnostics discussed here (initial models, conditions for remnants)
- Detailed yields can also be compared to grains, stellar abundances, ...
- r-process yields can also be used to constrain the conditions on the proto-neutron star (fallback, ...)
Bubbles in IGC Event
Neutrinos from Super-Eddington Accretion

Neutrinos from fallback are generally above 1 foe/s 5-10s after explosion with energies around 20 MeV – Fryer 2009

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>$L_{\nu_e}$ ($10^{51}$ ergs s$^{-1}$)</th>
<th>$T_{\nu_e}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>103.4</td>
<td>5.07</td>
</tr>
<tr>
<td>50</td>
<td>32.0</td>
<td>5.23</td>
</tr>
<tr>
<td>100</td>
<td>13.4</td>
<td>4.88</td>
</tr>
<tr>
<td>200</td>
<td>8.21</td>
<td>4.48</td>
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<tr>
<td>500</td>
<td>5.00</td>
<td>4.13</td>
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<td>1000</td>
<td>3.61</td>
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<td>2000</td>
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<td>1.80</td>
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<td>4000</td>
<td>1.43</td>
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<tr>
<td>8000</td>
<td>0.77</td>
<td>2.95</td>
</tr>
<tr>
<td>10000</td>
<td>0.60</td>
<td>2.79</td>
</tr>
<tr>
<td>12000</td>
<td>0.47</td>
<td>2.63</td>
</tr>
<tr>
<td>14000</td>
<td>0.37</td>
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<tr>
<td>16000</td>
<td>0.30</td>
<td>2.35</td>
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<tr>
<td>18000</td>
<td>0.22</td>
<td>2.19</td>
</tr>
<tr>
<td>20000</td>
<td>0.17</td>
<td>2.06</td>
</tr>
</tbody>
</table>

Total: $E_T$ ($10^{51}$ ergs) 151.7

KII .......................... 7.50
IMB .......................... 3.95

Neutrinos from cooling neutron stars emit below 1 foe/s at 10s with energies around 10MeV - Burrows 1988
Summary

• Super-Eddington accretion occurs in a variety of astrophysical settings.

• Whether photons are trapped depends on the accretion rate and the material composition, but if they are hypercritical accretion will occur.

• For binary-driven accretion, the accretion can be substantial, but to get rates, we need a lot more work.