Fast Luminous Blue Transients from Newborn Black Holes

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Reference: MNRAS, 451, 2656
The Diversity in Collapsars

- **Slow rotation**
  - Dim, but abundant
  - ~1/100 yr
- **Fast rotation**
  - Maybe bright, and not so rare
- **Extremely fast rotation (with strong B field)**
  - Very Bright, but very rare
  - ~1/10^5 yr
The polar regions are largely clear of matter by the time the disk formed.

The outermost layers have sufficient angular momentum to form a disk.

The Inner core is directly swallowed by the central black hole.
The PS1-MDS Transients

Pan-STARRS1 Medium Deep Survey (PS1-MDS) for Rapidly Evolving and Luminous Transients

- $t_{1/2} < 12\ \text{day}$ --- rapidly evolving than any SN type
- $L_{\text{peak}} \sim 10^{42-43}\ \text{erg s}^{-1}$ --- luminous as bright SNe
- $T_{\text{peak}} \sim \text{a few } 10^4\ \text{K}$ --- blue
- No line blanketing --- not powered by the radioactive decay
- Host Gal. = star forming Gal. --- related to massive stars
- Event rate $\sim 4-7\ %$ of core-collapse SN --- not rare
Fast & Luminous & Blue = Difficult?

Optically-thick hot ejecta → Adiabatic (homologous) expansion → Diffuse thermal emission

\[ \tau \propto t^{-2}, E_{\text{int}} \propto t^{-1}, T \propto t^{-1} \quad c/v_{\text{out}} \approx \tau \]

\[ t_p \approx \left( \frac{3 \kappa M_{\text{ej}}}{4\pi v_{\text{out}} c} \right)^{1/2} \sim 30 \text{ days} \left( \frac{M_{\text{ej}}}{M_{\odot}} \right)^{1/2} \left( \frac{v_{\text{out}}}{10^9 \text{ cm/s}} \right)^{-1/2} \left( \frac{\kappa}{0.4 \text{ cm}^2/\text{g}} \right) \]

\[ L_{\text{bol},p} \approx E_{\text{int},0} \frac{r_0}{v_{\text{out}} t_p} \frac{1}{t_p} \leftarrow E_{\text{int},0} \approx \frac{1}{2} M_{\text{ej}} v_{\text{out}}^2 \]

\[ \sim 10^{40} \text{ erg/s} \left( \frac{M_{\text{ej}}}{M_{\odot}} \right) \left( \frac{v_{\text{out}}}{10^9 \text{ cm/s}} \right)^2 \left( \frac{\kappa}{0.4 \text{ cm}^2/\text{g}} \right)^{-1} \left( \frac{r_0}{10^{11} \text{ cm}} \right) \]

\[ T_p \approx T_0 \frac{r_0}{v_{\text{out}} t_p} \sim 3800 \text{ K} \left( \frac{M_{\text{ej}}}{M_{\odot}} \right)^{-1/2} \left( \frac{v_{\text{out}}}{10^9 \text{ cm/s}} \right)^{-1/2} \left( \frac{\kappa}{0.4 \text{ cm}^2/\text{g}} \right)^{-1} \left( \frac{r_0}{10^{11} \text{ cm}} \right) \left( \frac{T_0}{10^9 \text{ K}} \right) \]

It requires \( M_{\text{ej}} \ll M_{\odot}, v_{\text{out}} \gg 10^9 \text{ cm/s} \), and somehow suppressed adiabatic cooling, but
The polar regions are largely clear of matter by the time the disk formed.

The outermost layers have sufficient angular momentum to form a disk.
Fall back disk may be ubiquitous!

e.g.,

BSG

WR
in binary

Outer layers of up to \( \sim \) a few \( M_\odot \) can “naturally” have sufficient
Then, what will happen?

\[ \dot{M}_d \approx \frac{M_d}{t_{\text{acc}}} \text{, or} \]

\[ \dot{M}_d \sim 3 \times 10^{-5} \, M_\odot \, s^{-1} \]

\[ \times \left( \frac{M_d}{1 \, M_\odot} \right) \left( \frac{R_*}{10^{12} \, \text{cm}} \right)^{-3/2} \left( \frac{M_{BH}}{10 \, M_\odot} \right)^{1/2} \]

where \( t_{\text{acc}} \approx \pi \left( \frac{R_*^3}{8G M_{BH}} \right)^{1/2} \), or

\[ t_{\text{acc}} \sim 3 \times 10^4 \, \text{s} \left( \frac{R_*}{10^{12} \, \text{cm}} \right)^{3/2} \left( \frac{M_{BH}}{10 \, M_\odot} \right)^{-1/2} \]

\[ \gg \dot{M}_{\text{Edd}} = \frac{4\pi G M_{BH}}{c \kappa} \]

\[ \sim 10^{-15} \, M_\odot \, s^{-1} \left( \frac{\kappa}{0.2 \, \text{cm}^2 \, \text{g}^{-1}} \right)^{-1} \left( \frac{M_{BH}}{10 M_\odot} \right) \]

Super-Eddington accretion!

\& Outflows!

\[ \sim 10\% \, \text{of the accreted mass} \]

\[ \bar{v}_{\text{out}} \approx (2G M_{BH}/r_0)^{1/2} \text{, or} \]

\[ \bar{v}_{\text{out}} \sim 1 \times 10^{10} \, \text{cm} \, \text{s}^{-1} \left( \frac{f_r}{10} \right)^{-1/2} \text{ Fast!} \]

\[ T_0 \approx \left( \frac{\dot{M}_{\text{out}} v_{\text{out}}}{8\pi \alpha r_0^2} \right)^{1/4} \text{, or} \]

\[ T_0 \sim 8 \times 10^8 \, \text{K} \left( \frac{f_r}{10} \right)^{-5/8} \left( \frac{f_M}{0.1} \right)^{1/4} \text{ Hot!} \]

\[ \times \left( \frac{M_d}{1 \, M_\odot} \right)^{1/4} \left( \frac{R_*}{10^{12} \, \text{cm}} \right)^{-3/8} \left( \frac{M_{BH}}{10 \, M_\odot} \right)^{-3/8} \]
Fast Luminous Blue Transients

Optically-thick hot wind $\rightarrow$ Adiabatic wind + homologous expansion $\rightarrow$ Diffuse thermal emission

$$t_p \approx \left( \frac{3\kappa M_{ej}}{4\pi \bar{v}_{out}} \right)^{1/2} \sim 3 \text{ days} \left( \frac{M_{ej}}{0.1 M_\odot} \right)^{1/2} \left( \frac{\bar{v}_{out}}{10^{10} \text{ cm/s}} \right)^{-1/2} \left( \frac{\kappa}{0.4 \text{ cm}^2/\text{g}} \right)$$

$$L_{bol,p} \approx C \times E_{int,0} \left( \frac{\bar{v}_{out} t_{acc}}{r_0} \right)^{-2/3} \left( \frac{t_p}{t_{acc}} \right)^{-1} \frac{1}{t_p}, \quad T_p \approx T_0 \left( \frac{\bar{v}_{out} t_{acc}}{r_0} \right)^{-2/3} \left( \frac{t_p}{t_{acc}} \right)^{-1}$$

✓ $L_{bol} \sim 10^{41-43} \text{ erg s}^{-1}$

✓ Blue continua with $T \sim 10^4 \text{ K}$

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Summary and Discussion

• Fast blue transients
  ✓ a day to 10 day depending on progenitor structure
  ✓ $L_{\text{bol}} \sim 10^{41-43}$ erg s$^{-1}$
  ✓ Blue continua with $T \sim 10^4$ K
  ✓ may not be rare (~5% of CCSNe).

• can be explained by the disk outflow from fast rotating collapsars, but not that fast as GRBs

• Multi-messenger approach
  ✓ (weak) jet?
  ✓ Radio?
  ✓ Gravitational wave?
Back up
Stellar-Mass Black Holes

\[ f(m_1) \equiv \frac{m_1 \sin^3 i}{(1 + q)^2} = \frac{P_{\text{orb}} V_2^2}{2\pi G} \]
Collapsars: BHs not NSs?

Supernova shock is stalled or not? How much material fallback on protoNS?

The key will be inner density structure within $r \sim 1000$ km, $M_r \sim 2-3 \, M_\odot$

Red supergiant (RSG)

Blue supergiant (BSG)

Walf-Rayet star (WR)

All types of massive star can form BHs.
Now is the good timing
Figure 1
Scale drawings of 16 black-hole binaries in the Milky Way (courtesy of J. Orosz). The Sun–Mercury distance (0.4 AU) is shown at the top. The estimated binary inclination is indicated by the tilt of the accretion disk. The color of the companion star roughly indicates its surface temperature.
Possible Outcomes in a BH Formation

Kochanek+08
Possible Outcomes in a BH Formation

Gamma-ray bursts?  
Hypernovae?  
Super-luminous supernovae?

luminous, but rare
Possible Outcomes in a BH Formation

Dimer class of SNe?  
(e.g., 1987A)

probably not rare
Possible Outcomes in a BH Formation

- Possible outcomes:
  - Core collapse
  - Explosion
  - No explosion

- Variations:
  - $^{56}\text{Ni}$
  - No $^{56}\text{Ni}$

- Further details:
  - BH in envelope
  - BH in disk
  - Isolated BH

- Annotation:
  - "Unnovae"
  - Probably not rare
Even if the SN shock is stalled, a weak shock can be driven by neutrino mass loss of the PNS.

A significant part of the energy comes from H recombination.

\[ E_{\text{sh}} \sim 10^{47-48} \text{ erg} \]

\[ \gtrsim \text{Bind. E of H envelope of RSG} \]

\[ T \sim 3000 \text{ K} \]
Searching for vanishing supergiants

- Monitoring \(\sim 10^6\) RSGs in \(\sim 25\) Gal. within \(\sim 10\) Mpc with \(\sim 0.5\) yr cadence for \(\sim 5\) yrs using the Large Binocular Telescope
- Examine sources with
  \[ \Delta (\nu L_\nu) \geq 10^4 L_\odot \]
- 3 core collapse supernovae
- 1 candidate of vanishing RSG
- Continuous obs. will give meaningful constraints on failed SN rate.

Kochanek+08, Gerke+15
Possible Outcomes in a BH Formation

- BH + super Eddington disk
- maybe not rare

Diagram:
- Possible outcomes:
  - core collapse
  - explosion
    - 56Ni
    - no 56Ni
  - no explosion
    - stalled shock
    - direct collapse

- Possible states:
  - BH in envelope
  - BH in disk
  - isolated BH
Fall back disk may be ubiquitous
The PS1-MDS Transients
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Drout+14
The PS1-MDS Transients

Blue Continua
No Line Blanketing

Drout+14
The PS1-MDS Transients

Host Gal. = SF Gal.  

Drout+14
The PS1-MDS Transients

4%-7% of CCSN@z = 0.2

Drout+14