High-Energy Neutrinos from Supernovae

Kohta Murase (Penn State)
SNEWS20 workshop @ Sudbury
Neutrinos: Unique Probe of Cosmic Explosions

~10 MeV neutrinos from supernova thermal: core’s grav. binding energy
- supernova explosion mechanism
- progenitor
- neutrino properties, new physics
Super-K detect ~8,000 $\nu$ at ~10 MeV (at 8.5 kpc)

GeV-PeV neutrinos from supernova? non-thermal: shock dissipation
- physics of cosmic-ray acceleration
- progenitor & mass-loss mechanism
- neutrino properties, new physics
IceCube/KM3Net detect ??? $\nu$ at TeV
Neutrinos: Unique Probe of Cosmic Explosions

- ~10 MeV neutrinos from supernova thermal: core’s grav. binding energy
  - supernova explosion mechanism
  - progenitor
  - neutrino properties, new physics
  Super-K detect ~8,000 $\nu$ at ~10 MeV (at 8.5 kpc)

- GeV-PeV neutrinos from supernova?
  non-thermal: shock dissipation
  - physics of cosmic-ray acceleration
  - progenitor & mass-loss mechanism
  - neutrino properties, new physics
  IceCube/KM3Net detect ~100-1000 $\nu$ at TeV
Young supernova “remnants”: responsible for CRs up to the knee and second (iron) knee diffusive shock (Fermi) acceleration: supported by simulations

Naively, early CR and HE neutrino production is negligible most of energy is in a kinetic form until the Sedov time

But situations are different when circumstellar material (CSM) exists

$$\mathcal{E}_d = \frac{M_{cs}}{M_{ej} + M_{cs}} \mathcal{E}_{ej}$$
Evidence of Strong Interactions w. Dense CSM

SN 2010jl (IIln)

Fransson+14 ApJ

Ofek+14 ApJ

SN 2014C (Ib->IIln) Margutti et al. 16

SN 2010jl (IIln)

SN 2014C (Ib->IIln) Margutti et al. 16

examples of strong interactions w. dense wind or CSM (IIln, SLSN-II)
Evidence for Dense Material around Progenitor

- Known to exist for Type IIb SNe ($M_{cs} \sim 0.1-10 \, M_{\odot}$)
- May be common even for Type II-P SNe
  \[ \frac{dM_{cs}}{dt} \sim 10^{-3} - 10^{-1} \, M_{\odot} \, yr^{-1} \]  (>> $3 \times 10^{-6} \, M_{\odot} \, yr^{-1}$ for RSG)

---

early spectroscopy
(Yaron+ 16 Nature Phys.)

SN 2013fs

light curve modeling
Forster+ 18 Nature Astronomy
see also Morozova+ 17 ApJ

---

r\textsuperscript{2} wind density profiles

- Dense nearby CSM
- Type IIb phase space
- Early spectra modelling
- Hα luminosity lower limit
- Possible underlying extended wind

---

CSM
no CSM

---

early spectroscopy
(Yaron+ 16 Nature Phys.)
Supernovae with Interactions with CSM

wind/shell

wind/shell

wind/shell

SN

ejecta

shocks

kinetic energy $\rightarrow$ thermal + non-thermal via shock

$p + p \rightarrow N\pi + X$

$\pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e (\bar{\nu}_e) + e^\pm$

$\pi^0 \rightarrow \gamma + \gamma$

dense environments = efficient $\nu$ emitters (calorimeters)
**Shock Dynamics -> Time-Dependent Model**

Equation of motion

\[ M_{sh} \frac{dV_s}{dt} = 4\pi R_s^2 \left[ \rho_{ej}(V_{ej} - V_s)^2 - \rho_{cs}(V_s - V_w)^2 \right] \]

Self-similar solution (Chevalier 82)

shock radius

\[ R_s = X(w, \delta) D^{-\frac{1}{\delta-w}} \mathcal{E}_{ej}^{\frac{\delta-3}{2(\delta-w)}} M_{ej}^{-\frac{\delta-5}{2(\delta-w)}} t^{\frac{\delta-3}{\delta-w}} \]

CSM parameter

\[ D = \frac{\dot{M}_w}{4\pi V_w} \]

\[ E_{ej} \sim 10^{51} \text{ erg}, \ M_{ej} \sim 10 \ M_{\odot} \]

\( w=2 \) for a wind CSM \quad \delta \sim 10-12 \text{ for typical progenitors}

Kinetic luminosity

\[ L_d = 2\pi \rho_{cs} V_s^3 R_s^2 \propto t^{\frac{6w-15+2\delta-\delta w}{\delta-w}} \]

parameters for dynamics: determined by photon (opt, X, radio) observations

※ Detailed model gives \( L_d t \sim E_{ej}(>V_s) \), larger than \( L_d t \sim (M_{cs}/ M_{ej} + M_{cs})E_{ej} \)
on neutrino spectra and detection prospects. For SNe IIn, we find that in most cases including Type II-P SNe, energy losses due to inelastic interactions, i.e., CRs and dust obscuration may introduce statistical problems (where dust obscuration may introduce statistical problems (Young et al. 2008). If unusually luminous SNe IIn and II-L are taken from the volume-limited fractions of all SN studies (Cappellaro et al. 1999; Smartt 2009). The criterion for the shock to be radiation unmediated is given by CR acceleration time is given by Page 7

TABLE I: CSM parameters for various types of SNe considered based on the observations of SN 2013fs (II-P). A faster component of the SN ejecta is decelerated earlier, and the shock evolution is given by known self-similar solutions remain valid until the whole ejecta is expanded. The CR acceleration time is given by Page 7

$\begin{array}{|c|c|c|c|c|}
\hline
\text{Class} & \mathcal{D}_* & \mathcal{M}_w [M_\odot \text{ yr}^{-1}] & \mathcal{V}_w [\text{km s}^{-1}] & \mathcal{R}_* [\text{cm}] \\
\hline
\text{IIIn} & 1 & 10^{-1} & 100 & 10^{13} \\
\text{II-P}^a & 10^{-2} & 10^{-3} & 100 & 6 \times 10^{13} \\
\text{II-P}^b & 1.34 \times 10^{-4} & 2 \times 10^{-6} & 15 & 6 \times 10^{13} \\
\text{II-L/IIb} & 10^{-3} & 3 \times 10^{-5} & 30 & 6 \times 10^{12} \\
\text{Ibc} & 10^{-5} & 10^{-5} & 1000 & 3 \times 10^{11} \\
\hline
\end{array}$

Core-Collapse SN Fractions

- II-P 48.2%
- II-L 8.8%
- IIb 10.6%
- Ibc 7.1%
- Ibc-pec 4.0%
- Ic 14.9%
- IIn 6.4%

← Betelgeuse
Neutrino Light Curve

$t_{\text{onset}} \sim$ time leaving the star (typical) or breakout time (IIln) slowly declining light curve while pion production efficiency $\sim 1$
Neutrino Fluence

Fluence for an integration time at which $S/B^{1/2}$ is maximal (determined by the detailed time-dependent model)
Prospects for Neutrino Detection

~ 10-1000 events for Type II supernovae at 10 kpc
~ 0.01-0.1 events for Ibc (but see Kashiya, KM+ 13 ApJL)
Key Points

• Testable & clear predictions (no need for jets, winds, shocks in a star)
  free parameters: $\varepsilon_{\text{CR}}$ & $s$ (typical values: $\varepsilon_{\text{CR}} \sim 0.1$ & $s \sim 2.0$-$2.3$)

• Time window:
  provided by the theory ($f_{pp} \sim t_{\text{dyn}}/t_{pp} \sim 1$)
  e.g., $\sim$hours to days for SNe II (II-P/II-L/IIb), $\sim$hours (Ibc), $\sim$months (IIn)

• Energy range:
  IceCube/KM3Net: TeV-PeV (even Glashow resonance anti-$\nu_e$ & $\nu_\tau$ events)
  Hyper-K/PINGU/ORCA: GeV

* Type II cases: rather different from the Type IIn case
  II-P/II-L/IIb/Ibc: shock is collisionless & $M_{\text{csim}} \ll M_{\text{ej}}$
  IIn: shock can be radiation-mediated & $M_{\text{csim}}$ could be larger than $M_{\text{ej}}$
      → more complications (limitation of self-similar, ejecta deceleration,
          radiative shock, other relevant processes (Coulomb collisions etc.)…
  ※ vs from breakout from envelope (previously studied): largely suppressed (see KM+19 ApJ)
Implications

- **Astrophysical implications**
  a. Pre-explosion *mass-loss* mechanisms
     How does a dense wind/shell form around the star?
  b. *PeVatrons*
     Are supernovae the origin of CRs up to the knee energy at $10^{15.5}$ eV?
  c. **Real-time** observation of ion acceleration for the first time
     How are CR ions accelerated?
  d. Best targets for **multi-energy neutrino & multi-messenger** astrophysics
     MeV vs & possibly gravitational waves, followed by GeV-PeV vs
     optical, X-rays, radio waves, and gamma rays (up to ~Mpc by Fermi)

- **Particle physics implications** – *large statistics*
  flavor studies, BSM searches (neutrino self-interactions, neutrino decay, oscillation into other sterile states etc.

  cf. more lucky examples?
  Betelgeuse: $\sim 10^3$-3x$10^6$ events
  Eta Carinae: $\sim 10^5$-3x$10^6$ events
- We provided the new time-dependent model for high-energy neutrino/gamma-ray emission from different classes of SNe.
- Type II: \( \sim 1000 \) events of TeV \( \nu \) from the next Galactic SNe.
- SNe as “multi-messenger” & “multi-energy” neutrino source.