High-Energy Neutrinos from Supernovae: New Prospects for the Next Galactic Supernova

arXiv:1705.04750

Kohta Murase (Penn State)
TeVPA 2017 @ Columbus, Ohio
Neutrinos: Unique Probe of Cosmic Explosions

Super-K

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

IceCube

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

Super-K

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

IceCube

GeV-PeV neutrinos from supernova? non-thermal: shock dissipation
- physics of cosmic-ray acceleration
- progenitor & mass-loss mechanism
- neutrino properties, new physics
IceCube/KM3Net can detect ~1000 $\nu$ at TeV
Early Diffusive Shock Acceleration in Supernovae?

- CR and high-energy neutrino production is initially negligible. Most of the energy is in a kinetic form until the Sedov time. Uniform ISM: CR energy $\propto$ dissipation energy $\propto t^3$

- But situations are different when circumstellar material (CSM) exists. Many observational evidences in the recent several years.

(Raffaella Margutti’s talk)
Evidence of Strong Interactions w. Dense CSM

**SN 2010jl (IIn)**

*Fransson+14 ApJ*

**SN 2014C (Ib->IIn)**

*Margutti et al. 16*

**Examples:**

- **SN 2010jl (IIn):**
  - L = t^{-3(n-2)}, n = 7.6
  - Fransson+14 ApJ

- **SN 2014C (Ib->IIn):**
  - Log L (erg s^-1)
  - Time (days)

**Graphs and Figures:**

- Flux [erg cm^-2 s^-1 Å^-1]
- Log(Lbol) [erg s^-1]
- Time (days)
- Continuum Normalized Flux
- Velocity (1000 km s^-1)

**Notes:**

- We note that the total radiated energy is a large fraction of the initial gravitational energy.
- There is a significant IR excess due to warm dust, but the exact temperature is difficult to determine.
- The bolometric light curve for the SN ejecta, excluding the dust echo, shows a break in the power-law decay from the ejecta can be accurately characterized by a power-law index.
- Using the SED fitting, we can improve on the bolometric luminosity before our first epoch at 26 days, assuming a constant bolometric correction of 20 to 320 days, given by log L (erg s^-1) ∝ t / (t - 100 days) with a slope of 4 at t = 100 days.
- The main difference is that the continuum is getting substantially weaker in the later bands (H, OI, OII, HeI).
- For comparison, we fitted a blackbody spectrum to the UVOT measurements and are shown in Figure 8.
- There is a clear asymmetry in the Hα profile, indicating that the SN ejecta is interacting with a dense wind or CSM.
Evidence for Dense Material in “Ordinary” SNe II

Extended material is common even for Type II-P SNe
→ $\dot{M} \sim 10^{-3} - 10^{-1} \, M_{\text{sun}} \, \text{yr}^{-1}$ ($>> 3 \times 10^{-6} \, M_{\text{sun}} \, \text{yr}^{-1}$ for RSG)

early spectroscopy
(Yaron+ 16 Nat. Phys.)

see also
light curve modeling
Morozova+ 17 ApJ

SN 2013fs

Days since explosion

$\rho (g/cm^3)$

$\dot{M} = 10^{-7}$
$\dot{M} = 10^{-6}$
$\dot{M} = 10^{-5}$
$\dot{M} = 10^{-4}$
$\dot{M} = 10^{-3}$
$\dot{M} = 10^{-2}$
$\dot{M} = 10^{-1}$

$r^2$ wind density profiles

Type II in phase space

Dense nearby CSM

Early spectra modeling

$\text{H}_\alpha$ luminosity lower limit

Possibly underlying extended wind

Excluded region from radio obs.
Supernovae with Interactions with CSM

Star

wind/shell

wind/shell

ejecta

shocks

SN

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)
equation of motion of the shocked ejecta

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

self-similar solution (Chevalier 82)

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

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

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

\( w=2 \) for a wind CSM \[ \delta \sim 10-12 \] for typical progenitors

dissipation 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 can be determined by photon (opt, X, radio) observations!
\[ E_d \sim E_{ej}(>V_s) \] in the detailed model, larger than \( E_d \sim (M_{cs}/M_{ej})E_{ej} \) by KM+11
and the corresponding shock velocity as a reference. The shock radius is estimated to be on neutrino spectra and detection prospects.

For SNe IIn, we consider different types of CCSNe derived from LOSS. These values suggest that the CSM is not too dense (except for SNe IIn) where the stellar wind only boundary is comparable to the system size (see Refs. [36]).

We find that in most cases including Type II-P SNe, jump is smeared out by radiation from the downstream, which is relativistic whose normal is parallel to the magnetic field. Considering these conditions, the shock evolution is given by known self-similar solutions.

The CR acceleration time is given by

\[ t_{\text{acc}} = \frac{E}{h_{\text{BR}} V_{\text{max}}} \]

where \( E \) is the characteristic energy of the CRs, \( h_{\text{BR}} \) is the Sunyaev-Zel'dovich parameter, and \( V_{\text{max}} \) is the maximum velocity [32]).

The CR acceleration time is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain

\[ t_{\text{esc}} = \frac{1}{H_0} \approx 13 Gyr \]

We consider that the CSM is not too dense (except for SNe IIn) where the CSM mass loss rate is limited by the particle escape or dynamical time. For simplicity, assuming that the escape time is the Hubble time, we obtain
$t_{\text{onset}} \sim \text{time leaving the star (typical) or breakout time (IIIn)}$
slowly declining light curve while pion production efficiency $\sim 1$
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 Kashiyama, KM+ 13 ApJL)
Some Remarks

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

• Time window
  depends on SN types; guidelines are provided by the theory ($f_{pp} \sim t_{dyn}/t_{pp} \sim 1$)
  e.g., characteristic time window: $\sim 1-10$ day for SNe II

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

* Type II cases are different from the Type IIn case
  II-P/II-L/IIb/Ibc: shock in the CSM is collisionless & $M_{csm} \ll M_{ej}$
  IIn: shock can be radiation-mediated & $M_{csm}$ could be larger than $M_{ej}$
  limitation of self-similar, $t_{onset}$ determined by breakout, ejecta deceleration, radiative shock, other relevant CR cooling processes (pp, Coulomb etc.)…
  (for work on SNe IIn, see KM, Thompson, Lacki & Beacom 11 and Petropoulou’s talk)
**Implications**

- **Astrophysical implications**
  a. pre-explosion mass-loss mechanisms
     - how does a dense wind/shell form around the star?
  b. PeVatrons
     - can CRs be accelerated up to the knee energy at $10^{15.5}$ eV?
  c. real-time observation of ion acceleration for the first time
     - is it consistent with the diffusive shock acceleration?
  d. promising targets of multi-messenger astrophysics
     - MeV vs & possibly gravitational waves
     - optical, X-rays, radio waves, and gamma rays (up to ~Mpc by Fermi)

- **Particle physics implications** – large statistics change the world
  - neutrino flavors (matter effect is not relevant), neutrino decay,
  - neutrino self-interactions, oscillation into other sterile states etc.
  
  cf. more lucky examples?
  - Betelgeuse: $\sim 10^3$-$3 \times 10^6$ events
  - Eta Carinae: $\sim 10^5$-$3 \times 10^6$ 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
Shock Breakout Emission from Type Iln SNe

SNe Iln radiation comes from shock interactions with dense CSM (different from ordinary SNe IIP & I: cooling envelope & radioactive nuclei)

Photon diffusion time:
\[ t_{\text{diff}} \sim \frac{R^2}{\kappa_{\text{rad}}} \sim n\sigma_T R^2/c \]

Dynamical time:
\[ t_{\text{dyn}} \sim \frac{R}{\beta c}, \beta = \frac{V}{c} \]

Shock breakout:
\[ t_{\text{rise}} = t_{\text{diff}} = t_{\text{dyn}} \iff \tau_T = \frac{1}{\beta} = \frac{c}{V} \]

CSM mass:
\[ M_{\text{cs}} \sim \left( \frac{4\pi R^2}{3\sigma_T} \right) m_p \tau_T \]

Dissipation energy:
\[ E_{\text{rad}} \sim \frac{1}{2} M_{\text{cs}} V^2 \]

Ex. SN 2009ip
\[ t_{\text{rise}} = 10 \text{d}, R=0.5 \times 10^{15} \text{ cm} \]
\[ \rightarrow M_{\text{cs}} \sim 0.05 M_{\odot} \]
\[ \rightarrow E_{\text{rad}} \sim 2 \times 10^{49} \text{ erg} \]

Consistent w. obs.!
Neutrinos from Type IIn SNe

- If CRs carry ~10% of $E_{ej}$ → # of $\mu$s ~a few for SN@10Mpc
- Stacking analyses for nearby SNe (~O(100) needed)
- GeV $\gamma$ rays can be seen by Fermi up to $\sim 30$ Mpc
- TeV $\gamma$ rays are detectable by CTA up to $\sim 30-100$ Mpc