Astro 596/496 NPA
Lecture 30
Nov. 2, 2009

Announcements:

- **No class meeting Wednesday!**
- Problem Set 5 due Friday ... but next Monday okay too
- Astro Colloquium here, tomorrow, **3:30pm**
  George Sonneborn (NASA) on *James Webb Space Telescope*
- Physics Colloquium Thursday, 4pm, 141 Loomis
  Matthew Strassler (Rutgers) on the *Large Hadronic Collider*

Supernova Energetics:

- mechanical (kinetic) energy in visible (bayonic) explosion
  $E_{\rm ejecta} \sim M_{\rm ej} v^2 \sim 10^{51}$ erg $\equiv 1$ foe
- explosion energy release: grav binding of proto-neutron star
  $\Delta E \sim G M_{\rm NS}^2 / R_{\rm NS} \sim 3 \times 10^{53}$ erg $= 300$ foe

Q: Where does the rest go?

Q: Implications for models of baryonic explosion?

Supernova Neutrinos

two phases of neutrino emission:
1. **neutronization**
2. **thermal emission**

neutronization neutrinos produced before collapse
emitted over < 1 sec, leave freely

during collapse: thermal νs still produced, initially leave freely
but core $\rightarrow$ nuke density:
- very high $T \sim 4 - 8$ MeV $\sim 10^{10}$ K
- very high $n_\nu \sim T^3$

neutrino mean free path $\ell_\nu = 1/(n_{\rm nuc}\sigma_\nu)$ becomes small
i.e.: $\ell_\nu \lesssim R_{\rm NS}$

Q: what happens to these thermal neutrinos?
Q: will they ever escape? if so, how?
Q: neutrino telescope time signature? flavors? anti-ν?

Supernova Neutrinos

when dese core has $\ell_\nu \lesssim R_{\rm NS}$: neutrinos trapped
proto-neutron star develops "neutrinosphere"
size set by radius where ~ 1 scattering to go: $r \sim \ell_\nu(r)$

inside r_ν: weak equilibrium $\rightarrow$ "neutrino star"

- all species ν_e, ν_μ, ν_τ and $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \approx$ equally populated
- ν_e have extra charged-current interactions
  slightly different T_ν and r_ν

neutrinos still leave, but must diffuse
emit neutrinos & energy (cool) over diffusion time
$\tau_{\rm diff} = 3r^2/\ell_\nu \sim 10$ s

Q: how to test this? Two ways! ...only one worked so far...

Supernova 1987A

explosion: Feb 23, 1987, in Large Magellanic Clous (LMC)
$d_{\rm LMC} \sim 50$ kpc – nearest (known) event in centuries spectrum:
shows H: Type II event $\rightarrow$ core collapse pre-explosion images:
progenitor $M \sim 20 M_\odot$ blue supergiant

(baryonic) explosion energy 1.4 ± 0.6 foe
no pulsar seen (yet) $\rightarrow$ could there be a black hole instead?

ejecta: $M({\rm O}) \sim 2 M_\odot$ observed
also N, Ne, Mg, Ni ...

light echoes: outburst reflections off surrounding material
allow for 3-D reconstruction of pre-explosion environment!

SN1987A: Light Curve

light curve: luminosity L vs t

`www: 1987A bolometric (all-wavelength) light curve`

- initially, powered by thermal energy, then adiabatically cool

- after ~ 1 month: powered by ^{56}Ni decay:
$^{56}\text{Ni} \rightarrow {}^{56}\text{Co}\ e^+\ \nu_e \rightarrow {}^{56}\text{Fe}\ e^+\ \nu_e$ (PS5)
Q: how can you test that this is the power source?

- really: decay to excited state $^{56}\text{Ni} \rightarrow {}^{56}\text{Co}^* \rightarrow {}^{56}\text{Co}^{gs} + \gamma$
^{56}Co de-excitation γs seen at 0.847 MeV and 1.238 MeV
but: seen earlier than expected for onion-skin star
Q: what does this mean?

SN 1987A Neutrino Signal

SN 1987A detected in neutrinos

first extrasolar (in fact, extragalactic!) νs

birth of neutrino astrophysics

Reliable detections: water Čerenkov

- Kamiokande, Japan
- IMB, Ohio, USA

observed $\sim$ 19 neutrinos (mostly $\bar{\nu}_e$) in 12 sec

`www: ‘‘neutrino curve’’`

detected $\sim$ *few* hrs before optical signal

Q: Why?

Q: what info–qualitative and quantitative–do the νs give?

Qualitatively

neutrino detection demonstrates basic correctness of core-collapse picture

Quantitatively

ν time spread: probes diffusion from protoneutron star

ν flux, energies: $\langle E_\nu \rangle^{\rm obs} \sim 15$ MeV

$\Rightarrow$ -neutrino energy release $\mathcal{E}_{\bar{\nu}_e} \sim \mathcal{E}_\nu/6 \sim 8 \times 10^{52}$ erg

Q: why divide by 6?

$\Rightarrow$ $\mathcal{E}_\nu \sim 4 \times 10^{53}$ erg

$\Rightarrow$ observational confirmation:
by far, most ΔE released in νs

$\Rightarrow$ basic core collapse picture on firm ground!

Also: signal probes ν & particle physics

`www: 2002 Nobel Prize in Physics: Masatoshi Koshiba`

Nearby Supernovae: May We Have Another?

Today: ready for another SN!

for event at 10 kpc, Super-K will see ~ 5000 events
gravity waves?

candidates: Betelgeuse? Eta Carinae?

But don't get too close!

- minimum safe distance: ~ 8 pc
  Q: why would this ruin your whole day?
  Q: should we alert Homeland Security today?