Astro 210
Lecture 35
November 17, 2010

Announcements

- this week's homework computer-based
  pick one of two:
  for the theory-inclined: simulate a star
  for the observation-inclined: cosmology data analysis
  policy: comp project is like HW, so will take best 10 HW + comp scores

Last time: star masses and life cycles
Q: what is like for stars with $M < 0.9 M_{\odot}$*?*
Q: what about $0.9 M_{\odot} < M < 8 M_{\odot}$*? what's left at the end?*
Q: what about $M > 8 M_{\odot}$*? what's left at the end?*

Lives and Deaths of Stars

a star's life history, death controlled by it **mass**

$\boxed{M < 0.9 M_\odot}$ history like that of the Sun *so far*:
burn H $\rightarrow$ He ("main sequence" phase)
lifetime $>$ age of universe: live "forever"–none have yet died

$\boxed{0.9 M_\odot < M < 8 M_\odot}$ life cycle like the Sun's:
life: burn H $\rightarrow$ He, then "giant" phase burning He $\rightarrow$ C
death: eject $>$ 50% of mass as enriched gas–"planetary nebula"
leave behind compact object: white dwarf

$\boxed{M > 8 M_\odot}$
begins burning H $\rightarrow$ He, but continues:
core burning He $\rightarrow$ C, C $\rightarrow$ O, ..., up to Fe
then iron core forms white dwarf, until exceeding M_{Chandra}
$\rightarrow$ supernova explosion

Supernova Debris

supernova ejects $> 90\%$ of star's initial mass

Ejecta are:

1. hot
2. fast–up to $10\% c$
3. enriched with products of nuclear burning
   heavy elements (e.g., O, iron)

`www: Cas A Chandra image`

most of the elements in the periodic table
(i.e., most of the diversity of the elements) originate in supernova explosions
we are made atoms once in exploding stars!

Nucleosynthesis
cosmic production of elements
low-mass stars are source of C
Supernovae are source of O, Si, Fe ...

`www: circle of life cartoon`

iClicker Poll: Supernova Neutrinos

We saw that the Sun is a confirmed source of neutrinos
in fact: a few percent of the Sun's luminosity (energy release)
is in neutrinos rather than light

Now consider a massive star, exploding as a supernova
and vote your conscience:
Which best describes a supernova's energy release?

A $< 1\%$ of energy released in neutrinos, $> 99\%$ in photons

B $\approx 50\%$ of energy released in neutrinos, $\approx 50\%$ in photons

C $> 99\%$ of energy released in neutrinos, $< 1\%$ in photons

Supernova Neutrinos

In supernova explosion, core compressed to huge density
$\rightarrow$ also huge temperature: $> 10^9$ K!

particles in core have huge energies: $kT > 10^6$ eV $\approx m_e c^2$!

in this energetic environment, neutrinos produced abdunantly
much moreso than in the Sun
also: supernova core so dense that even neutrinos interact in it
  scatter repeatedly before leaving core

theoretical predictions:
- huge burst of neutrinos created in explosion
- $> 99\%$ of supernova energy release is in neutrinos!
- scatterings in dense core $\rightarrow$ signal spread over several seconds

Q: how to test this?

Historical Supernovae

supernovae rare: only ~ 3/century in our Galaxy

Supernova 1054 "guest star" in Taurus
no record in Europe, but noted by Chinese, Anasazi (Pueblos)
`www: Anasazi drawing`, `Y1K`, `www: present-day view: Y2K`

Supernova 1572 Tycho `www: sketch`
On the 11th day of November in the evening after sunset ... I noticed that a new and unusual star, surpassing the other stars in brilliancy, was shining ... and since I had, from boyhood, known all the stars of the heavens perfectly, it was quite evident to me that there had never been any star in that place of the sky ...

I was so astonished of this sight ... A miracle indeed, one that has never been previously seen before our time, in any age since the beginning of the world.

– Tycho Brahe

Q: What did Tycho get right? Where was he wrong?

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SN 1987A

most recent "nearby" supernova:
Jan. 1987: SN in nearby galaxy (LMC)
`www: discovery image`

a great "experiment" to test our ideas about supernovae
crown jewel:

⋆ supernova neutrinos detected on Earth
`www: SuperK`
signal as about 20 νs, spread over about 10 sec
but came from exploding star 50 kpc = 150,000 lyr away!
`www: 2002 Nobel Prize: Masatoshi Koshiba and SuperK`
confirms:

- most of explosion energy carried by ν's
- visible energy only 1% of total!

Neutron Stars

Most of massive star matter ejected
but what about the stuff left behind?

In core, when collapse begins
e degeneracy pressure overcome by removing electrons!
$p^{+} + e^{-} \rightarrow n + \nu$ "inverse beta decay"
crushes electrons and protons together, forming neutrons and neutrinos

- neutrinos escape: star cools by ν emission!
- core reaches nuclear density: $\rho_{\text{nuc}} \sim 10^{18}$ kg/m^3

$\boxed{\text{neutron star}}$

radius? set by densitiy and mass
$\rho \sim \rho_{\text{nuc}} \sim M/R^3$, typically, $M_{\text{NS}} \simeq 1.5 M_{\odot}$

$\rightarrow R \sim (M/\rho_{\text{nuc}})^{1/3} \sim 15 - 20$ km
tiny! size of Champaign-Urbana!

Q: but why doesn't the neutron star itself collapse?

neutrons, like electrons, are fermions
i.e., obey Pauli principle
$\rightarrow$ neutron star supported by degerate neutrons!
$\rightarrow$ a "neutron solid"

...or so theorist imagined

neutron stars originally predicted in mid 1960's
but thought to be so compact that unobservably small

Pulsars

sources that emit periodic, pulsed radio signals
discovered accidentally: Jocelyn Bell
`www: Princeton pulsar group: audio pulsar`
`www: 1974 Nobel Prize: Anthony Hewish`

Pulsar signals

- periods very regular–better than atomic clocks!
- very fast! P range 1 s down to < 1 ms!

A Rotating Star?

Q: what would happen if Earth spun that fast?

Warning! If spin too fast
equator speed $> v_{\text{esc}} \rightarrow$ unbound!
equatorial material flung away!

max possible rotation rate at equator:
when gravity balances centripetal acc.
$v_c = \sqrt{GM/R}$; but at equator $v_c = 2\pi R/P$
$\rightarrow 2\pi R/P = \sqrt{GM/R}$

$$\text{or } P = 2\pi\sqrt{\frac{R^3}{GM}} = \sqrt{\frac{3\pi}{G\rho}} = \frac{4\times 10^5 \text{ s}}{\sqrt{\rho}} \quad (\rho \text{ in kg/m}^3) \qquad (1)$$

shortest possible period!

density to explain 1ms?
$\rho_{\text{min}} \geq (4\times 10^5/P)^2 \sim 10^{17}\ \text{kg/m}^3$
$\rightarrow$ must be NS!

Lighthouse Model for Pulsars:
spinning, magnetized NS $\rightarrow$ beam of radio waves
diagram: Pulsar spin and off-axis radio beam

www: Chandra Crab

Note: NS extremely dense $\rightarrow$ strong gravity
escape speed $v_{\text{esc}} \sim 1/3\ c$!

Newtonian dynamics, gravity:
ok if $v \ll c$ won't do! need...

www: Big Al