Astro 210

Lecture 34

April 16, 2018

Announcements:

- **HW10 due Friday 5:00 pm online**

- **Solar Observing** **Last Chance**
  first clear day this week – *likely tomorrow!*
  11:15 am to 2:45 pm Campus Observatory
  allow 20-30 min. bring **worksheet**. take **selfie**

- Hour Exam 2 grades posted. Most did well. Bravo!

Last Time: The Deaths of Massive Stars

Q: what is "massive" in this context?

Q: how is the life of a massive star similar to a lower mass star's life?

Q: how is a massive star's life different?

Q: evolution on HR diagram?

Q: final stages? observational evidence?

Q: what remains are left after the end?

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., oxygen, silicon, iron)

`www: Cas A Chandra image`

Origin of the Elements

most of the elements in the periodic table
(i.e., most of the diversity of the elements)
originate in supernova explosions

supernovae are element factories

ejected into space as gas and dust
enrich heavy element content of interstellar clouds
eventually part of new stars and planets

Q: other cosmic element factories?

Nucleosynthesis: The Synthesis of Atomic Nuclei

cosmic production of elements combines all events and sources
where nuclear reactions occur
and the results are ejected into space

element origins: the story thus far:

- *intermediate-mass stars:* $0.9 M_\odot \lesssim M \lesssim 8 M_\odot$
  sources of carbon (C)
  ejected in planetary nebulae
- *high mass stars*: $M \gtrsim 8 M_\odot$
  sources of O, Si, Fe ...
  ejected in supernova explosions

`www: circle of life cartoon`

we are made of star-stuff –Carl Sagan

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
$\longrightarrow$ also huge temperature: $> 10^9$ K!

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

in this energetic environment, *neutrinos produced abundantly*
in late evolution phases, star loses most energy via neutrinos!
already a "neutrino star" before explosion!
also: post-collapse core so dense 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!*
- singal from escaping *neutrinos 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 lucky "experiment" to test our ideas about supernovae

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

observationally confirms:
- *most ($>$ 99%!) of explosion energy carried by ν's*
- *post-collapse core dense enough to trap neutrinos!*

Neutron Stars

In supernova core, when collapse begins

e degeneracy pressure overcome by removing electrons!

electrons and protons crushed together

to form forming neutrons and neutrinos: $p^+ + e^- \rightarrow n + \nu$

- *neutrinos escape: star cools by ν emission!*
- *core reaches nuclear density:*

$\rho_{\text{nuc}} \sim 10^{18}$ kg/m^3 !!

neutron star

radius? set by density and mass

$\rho \sim \rho_{\text{nuc}} \sim M/R^3$, typically, $M_{\text{NS}} \simeq 1.5 M_\odot$

infer: $R \sim (M/\rho_{\text{nuc}})^{1/3} \sim 15 - 20$ 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
$\longrightarrow$ neutron star supported by degenerate neutrons!
$\longrightarrow$ 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: graduate student 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 $> v_{\rm esc} \rightarrow$ unbound!
equatorial material flung away!

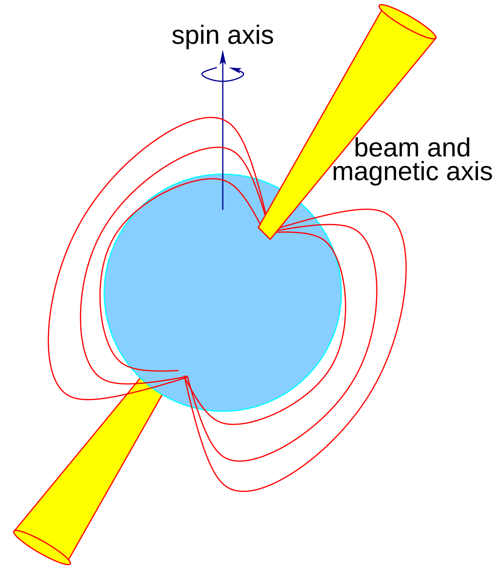
maximum possible rotation rate at equator:
when gravity balances centripetal acc.
$v_c = \sqrt{GM/R}$; but *at equator* $v_c = 2\pi R/P$
$\rightarrow 2\pi R/P = \sqrt{GM/R}$, so

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

shortest possible period!

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

Lighthouse Model for Pulsars:
spinning, magnetized NS $\rightarrow$ beam of radiation (radio, X-ray, ...)



www: Chandra Crab

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

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

www: Big Al