Soft Gamma-Ray Repeaters

$E_{iso} \sim \text{a few } 10^{44} \text{ erg in gamma-rays}$

Where does this energy come from?

- Accretion? No sign of a disk
- Rotation? Not enough energy available
- Magnetic fields? Yes
Growth of the Radio Afterglow

Size at $t+7$ days
$10^{16}$ cm
(1000 AU)

Velocity to $t + 30$ days
$\sim 0.8 \, c$

Decrease in $V_{\text{exp}}$

Taylor et al 2005
Magnetar burst sequence

Adapted from Duncan and Thompson 1992
Image Evolution

VLA 8.5 GHz

$E \sim 10^{45}$ ergs

One-sided
(anisotropic)
outflow

Taylor et al 2005
Radio Light Curves

(Gaensler et al. 2005; Gelfand et al. 2005)
Degenerates

White dwarf: Electrons run out of room to move around, but protons and neutrons are free to move. The electrons create the pressure, and in a WD this balances gravity, keeping the WD from collapsing.

Neutron star: Electrons and protons combine to form neutrons. Neutrons run out of room to move, and prevent further collapse.

Black hole: Gravity wins, nothing prevents collapse.
Neutron star structure

- Surface is cooler, probably forming a solid crystalline crust (cf WD).
- Inside is exotic matter.
• Implies enormous magnetic fields. Why?

• The B-field of the star becomes concentrated as star collapses: 
(\textit{Magnetic field strength at surface}) \times (\textit{surface area}) is conserved as star shrinks.

\[
(B_{ms})(4\pi R_{ms}^2) = (B_{ns})(4\pi R_{ns}^2)
\]

• The surface area drops by factor of \(\sim 10^{10}\) as it shrinks to neutron star size, so magnetic field strength increases by factor of \(10^{10}\)!
• What makes the neutron star shine?

• Where would the neutron stars be on the HR diagram? Why?
• Very dim, thus difficult to detect. Only a few isolated neutron stars have been imaged.

• About $10^8$ estimated to exist in our galaxy, and we have detected around 2000 (the active pulsars)
Evidence of atmosphere outside crust comes from X-ray observations.
Pulse rate speed up

• Some pulsars have been observed to have *glitches* – sudden changes in period. This is now interpreted to be the stretching and breaking of superfluid neutron whirlpools: interior is moving around frictionless, and when surface slows down, it may try to drag the surface along.
Mass limit to neutron stars

- Like white dwarfs and electron degenerate matter, neutron stars and neutron degenerate matter has an upper mass limit (~ 3 M\(_\bigodot\)). Most massive pulsar is J0740+6620 at 2.17 M\(_\bigodot\).

- When this is exceeded, the star collapses all the way to a black hole.

- This limit is not as well understood as the Chandrasekhar limit, since the pressure has two sources: degeneracy and the strong nuclear force.
Pulsating X-ray sources

- ns pulses in close binary systems with evolving star.
X-ray bursters

Explosive helium fusion near surface of neutron star

Thin hydrogen surface layer accumulated on neutron star through accretion ring

Surface Layer

Ignition of surface layer under degenerate conditions

Thermonuclear runaway until degeneracy lifted

Explosive helium fusion near surface of neutron star
Caused by (sometimes repeating) nuclear explosions on or near the surfaces of neutron stars.

1. Material from a star accretes onto a companion neutron star.

2. When enough accreted material builds up, thermonuclear reactions occur on the neutron star’s surface, creating a burst of X rays.

3. The X-ray burster fades within seconds.
Novae

- Novae are similar to X-ray bursters, but occur in a close binary system with a White Dwarf instead of a neutron star.
- Accretion is weaker and will cause a hydrogen fusion outburst.
- Lower energy, so will emit in the visible, but sometimes up to gamma-rays.
Novae ≠ supernovae!

- Both are thermonuclear detonations, but novae occur at or near the surface while supernovae occur in the core, and destroy star.

- At maximum, novae are around $M = -9$. Supernovae can be $10^4$ times brighter, $M = -19$.

- A nova might repeat, but a supernova can’t.
Recurring Nova T Pyxidis
PRC97-29 • ST ScI OPO • September 18, 1997
M. Shara and R. Williams (ST ScI), R. Gilmozzi (ESO) and NASA
Classical Relativity

How fast is Spaceship A approaching Spaceship B?

Both Spaceships see the other approaching at 2,000,000 m/s.

This is Classical Relativity.

Animated cartoons by Adam Auton
Einstein’s Special Relativity

Both spacemen measure the speed of the approaching ray of light.
How fast do they measure the speed of light to be?

There was an old lady called Wright who could travel much faster than light.
She departed one day in a relative way and returned on the previous night.
Special Relativity

- Stationary man measures 300,000,000 m/s
- Man traveling at 1,000,000 m/s
  - Moving at 300,000,000 m/s? - A
  - Moving at 301,000,000 m/s? - B

All observers measure the SAME speed for light.
Postulates of Special Relativity

- **1st Postulate**
  - The laws of nature are the same in all uniformly moving frames of reference.
    - Uniform motion – in a straight line at a constant speed
  - **Ex.** Passenger on a perfectly smooth train
    - Sees a train on the next track moving by the window
      - Cannot tell which train is moving
    - If there are no windows on the train
      - No experiment can determine if you are moving with uniform velocity or are at rest in the station!
  - **Ex.** Coffee pours the same on an airplane in flight or on the ground.
Combining “Everyday” Velocities

- Imagine that you are firing a gun. How do the speeds of the bullet compare if you are:
  - At rest with respect to the target?
  - Running towards the target?
  - Running away from the target?
The Speed of Light

- How does the measured speed of light vary in each example to the right?
The Speed of Light

- How does the measured speed of light vary in each example to the right?
  - In each case the measured speed is the same!

- 2nd Postulate of Special Relativity
  - The speed of light is the same for all observers!
Postulates (cont.)

- **1\text{st} Postulate**
  - It impossible for two observers in relative motion to determine who is moving and who is at rest!

- **2\text{nd} Postulate**
  - The speed of light is the same for all observers!

Observers on the ground and in the rocket both measure $c$!
Relativistic Velocity Addition

- Classically: \( V = v_1 + v_2 \)

- Relativistically:

\[
V = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}}
\]

- Ship moves away from you at 0.5\(c\) and fires a rocket with velocity (relative to ship) of 0.5\(c\)
  
  - How fast (compared to the speed of light) does the rocket move relative to you?
Relativistic Velocity Addition

- Classically: \( V = v_1 + v_2 \)
- Relativistically:
  \[
  V = \frac{v_1 + v_2}{1 + \frac{v_1 v_2}{c^2}}
  \]
- Ship moves away from you at 0.5\(c\) and fires a rocket with velocity (relative to ship) of 0.5\(c\)
  - You see rocket move at 0.8\(c\)
    - No massize object can be accelerated to the speed of light!
- If instead the ship fires a laser at speed \(c\), what speed do you measure for the light?
Relativistic Velocity Addition

- Classically: $V = v_1 + v_2$
- Relativistically:
  \[
  V = \frac{v_1 + v_2}{1 + \frac{v_1v_2}{c^2}}
  \]

- Ship moves away from you at 0.5$c$ and fires a rocket with velocity (relative to ship) of 0.5$c$
  - You see rocket move at 0.8$c$
    - No massize object can be accelerated to the speed of light!

- If instead the ship fires a laser at speed $c$
  - You would measure $c$ for the speed of light
Question:

If you have a time machine and can go backwards in time, what is the maximum velocity can you achieve:

A: the speed of light
B: close to the speed of light, but not equal to it
C: infinitely large velocity
Simultaneity

- Two events that happen at the same time in one frame of reference may or may not be simultaneous in a frame moving relative to the first.
  - Result of constancy of speed of light
  - How do the observations of the internal and external observers differ?
    - Who is right?
Spacetime

- 3-D space
  - Three numbers to locate any point
  - Objects with size: Length, width, height
- Time (fourth dimension)
  - Intimately tied to space
    - Most distant galaxies are also the youngest!
    - Seen as they were billions of years ago!
Spacetime (cont.)

- Two side-by-side observers agree on all space and time measurements
  - Share same spacetime
- Two observers in relative motion disagree on space and time measurements
  - But always same ratio!
    - Differences imperceptible at low speeds
    - Important at speeds near \( c \) (relativistic speeds)

Observers in relative motion experience space and time differently, but speed of light is always constant!
Time Dilation Worksheet

How long does it take an observer to travel 1 light-hour and back at the speed of light?
Time Dilation Worksheet

How long does it take Alex to travel 1 light-hour and back at the speed of light?

If clock reads 12pm, an observer 1 light hour away (Juan) reads 11am!

- Alex travels at speed of light for one hour towards Juan and stops
  - What does the clock tower read when Alex stops? Does Alex read the same time as the stationary observer?
Time Dilation

- If clock reads 12pm, Juan, 1 light hour away reads 11am!
  - Travel at speed of light for one hour towards observer and stop
    - What does Alex read at the end of his trip?
      - Both read 12pm
      - Time stood still for Alex!
    - So if Alex travelled at speed $< c$ what would he observe?
Time Dilation

- If clock reads 12pm, Juan, 1 light hour away reads 11am!
  - Travel at speed of light for one hour towards observer and stop
    - What does Alex read at the end of his trip?
      - Both read 12pm
      - Time stood still for Alex!
  - So if Alex travelled at speed $< c$
    what would he observe?
  - Now Alex travels at high speed back towards clock
    - Sees tower clock speed up!
    - Will the two effects cancel?
Time Dilation

- If clock reads 12pm, Juan, 1 light hour away reads 11am!
  - Travel at speed of light for one hour towards observer and stop
    - What do you read at the end of your trip?
      - Both read 12pm
      - Time stood still for Alex!
  - So if Alex travelled at speed $< c$ what would he observe?
  - Now Alex travels at high speed back towards clock
    - Sees tower clock speed up!
    - Will the two effects cancel?

Yes! But Alex’s wristwatch will disagree with town clock! How?
Time Dilation (cont.)

- Moving clocks run slow!
  - Light clock: time between mirrors = 1 tick
  - Observer moving with clock: no dilation!
  - External observer: Light travels longer path
    - But, speed of light constant => each tick takes longer!
- True for all clocks! Property of spacetime!
Time Dilation Animated

- Time between ‘ticks’ = distance / speed of light
- Light in the moving clock covers more distance…
  - …but the speed of light is constant…
  - …so the clock ticks slower!
- Moving clocks run more slowly!
Time Dilation (cont.)

- Experimentally confirmed
  - Particle accelerators
  - Atomic clocks: Jets & GPS

- Only relative velocity matters!
  - Observer moving with clock would see external clocks run slower! How can this be?
Twin Paradox

- Suppose there are two twins, Al and Bill age 10. Al goes to summer camp 25 light-years away. If he travels at 0.9999c then it takes 25 years each way and Bill is age 60 when Al gets back. But Al is only 10 and a half because time for him was moving slower. But from Al’s point-of-view Bill was the one moving so how did Bill get so old?
Truck and Garage Paradox

- Suppose you have a truck 20 ft long and you want to park it in a Garage that is only 10 ft deep. Is there a way to make it fit?

- Yes! If you move the truck in at 0.865c then it will be contracted in length to just 10 feet. At 0.99c it will measure just 2.8 feet and fit easily (until it hits the wall of the garage).
Relativistic Mass

- There is an increase in the effective mass of an object moving at relativistic speeds given by:

\[ m = \gamma m_0 \quad \text{where} \quad \gamma = \sqrt{\frac{1}{1 - \frac{v^2}{c^2}}} \]

- you have to reach 0.14c to change the mass by 1%
- at 0.99c the mass is 7.14 times greater than rest mass
- at 0.9999c the mass is 70 times greater than rest mass
Lorentz Transformations

- Light from the top of the bar has further to travel.
- It therefore takes longer to reach the eye.
- So, the bar appears bent.
- Weird!
Doppler Boosting

- Beam becomes focused.
- Same amount of light concentrated in a smaller area
- Flashlight appears brighter!
Relativistic Doppler Equation

\[ z = \frac{\Delta \lambda}{\lambda} \]

\[ 1 + z = \sqrt{\frac{1 + \beta}{1 - \beta}} \quad \text{or} \quad \beta = \frac{(1 + z)^2 - 1}{(1 + z)^2 + 1} \]

Where \( \beta = \frac{v}{c} \)
Question:

Photons (packets of light) move at the speed of light. Their rest mass is therefore:

A: the same as their relativistic mass
B: much greater than their relativistic mass
C: less than their relativistic mass
D: zero
Question:

The speed of protons in a big accelerator must be:

A: equal to the speed of light
B: greater than the speed of light
C: less than the speed of light
D: zero
Question:

Suppose a muon is created 5 km up in the atmosphere. If it is moving at 0.998c and has a lifetime of $2 \times 10^{-6}$ seconds, can it reach the ground?

A: No
B: Yes
C: can’t say
Relativistic Summary

- time dilation: \( t = t_0\gamma \)
- length contraction: \( L = L_0/\gamma \)
- mass increases: \( m = \gamma m_0 \)

where

\[
\gamma = \sqrt{1 - \frac{\nu^2}{c^2}}
\]

- 0.14c \( \rightarrow \gamma = 1.01 \)
- 0.99c \( \rightarrow \gamma = 7.14 \)
- 0.998c \( \rightarrow \gamma = 15 \)