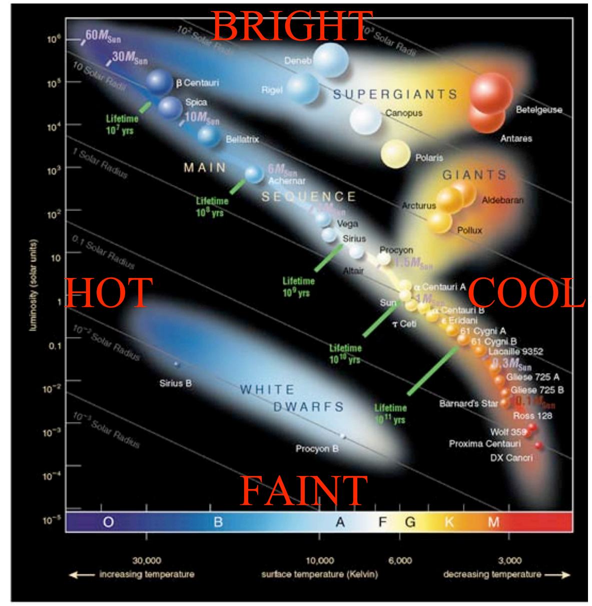
Announcements

- Homework#3 will be handed out at the end of this lecture.
  - Due October 14 (next Thursday)
- Review of Mid-term exam will be handed out Tuesday.
  - Mid-term exam will be variants (if not identical) of some of the problems in the review.
  - Study it to prepare well for mid-term!



We use binary stars to measure directly the masses of stars of every type. This leads to the:

Mass-Luminosity Relation

$$L \propto m^{3.5}$$

for main sequence stars only

- As one moves to the upper-left of the main sequence:
  - stars become more massive
  - stars become even much more luminous
  - stars become fewer in number

Mass–Luminosity Relation: Why?

- All main sequence stars fuse H into He in their cores.
- Luminosity depends directly on mass because:
  - more mass means more weight from the star's outer layers
  - more gravitational force --> contraction!
  - nuclear fusion rates must be higher in order to maintain gravitational equilibrium

Lifetime on the Main Sequence

How long will it be before MS stars run out of fuel? *i.e. Hydrogen?*

How much fuel is there? M

How fast is it consumed? $L \propto M^{3.5}$

How long before it is used up?

$$M/L = M/M^{3.5} = M^{-2.5}$$

Lifetime on the Main Sequence

- O & B Dwarfs burn fuel like a bus!
- M Dwarfs burn fuel like a compact car!

- Our Sun will last 10 billion years on the Main Sequence
  - MS Lifetime τ = 10 billion yrs / $M^{2.5}$

Lifetime on the Main Sequence

So for example:

B2 dwarf (10 $M_\odot$) lasts 32 million yr

F0 dwarf (2 $M_\odot$) lasts 1.8 billion yr

M0 dwarf (.5 $M_\odot$) lasts 56 billion yr

But the Universe is 13.7 billion yr old!

Every M dwarf that was ever created is *still* on the main sequence!!

Star Clusters I: Open Clusters

- 100's of stars
- million to billion years old
- irregular shapes
- gas or nebulosity is sometimes seen

SUBARU

Pleaides (80 million yrs)

Star Clusters II: Globular Clusters

- 100,000 stars
- 8 to 15 billion years old
- spherical shape
- NO gas or nebulosity

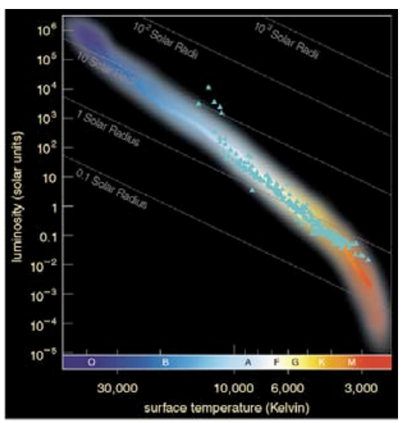
M 80 (12 billion yrs)

Clusters are useful for studying stellar evolution!

- all stars are the same distance
  - use apparent magnitudes
- all stars formed at about the same time
  - they are the same age

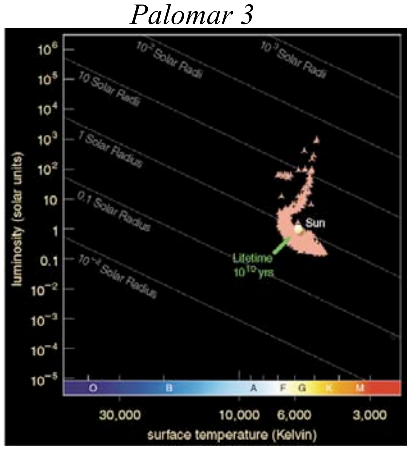
Plot an H-R Diagram!

Pleiades H-R Diagram

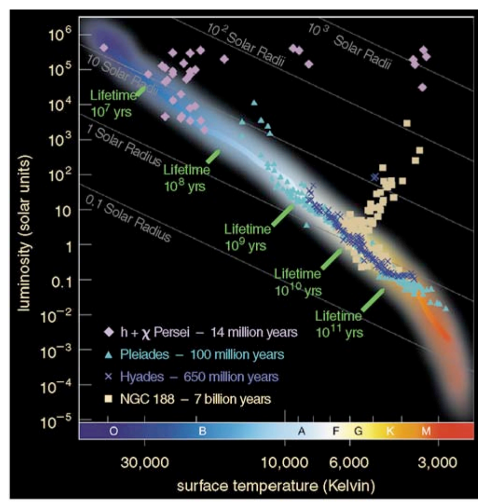


Globular Cluster H-R Diagram

Palomar 3



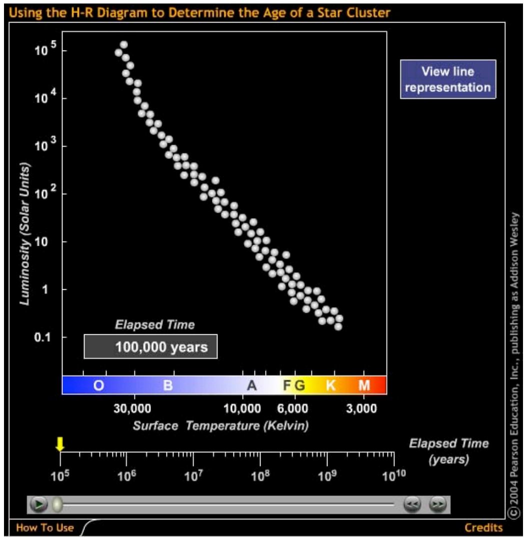
Cluster H-R Diagrams Indicate Age



- All stars arrived on the MS at about the same time.
- The cluster is as old as the most luminous (massive) star left on the MS.
- All MS stars to the left have already used up their H fuel and are gone.
- The position of the hottest, brightest star on a cluster's main sequence is called the

  main sequence turnoff point.

Older Clusters have Shorter Main Sequences



Lecture 12
Star Stuff

Reading: 17

Stellar Evolution

- Stars are like people in that they are born, grow up, mature, and die.
- A star's **mass** determines what life path it will take.
- We will divide all stars into three groups:
  - **Low Mass** ($0.08\ M_{sun} < M < 2\ M_{sun}$)
  - **Intermediate Mass** ($2\ M_{sun} < M < 8\ M_{sun}$)
  - **High Mass** ($M > 8\ M_{sun}$)
- Remember, our Sun is a low-mass star!!
- The H-R Diagram makes a useful roadmap for following stellar evolution.

Stellar Evolution

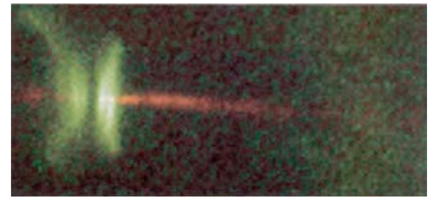
- The life of any star can be described as a battle between two forces:
  - Gravity vs. Pressure
- Gravity always wants to collapse the star.
- Pressure holds up the star.
  - the type of star is defined by what provides the pressure
- Remember Newton's Law of Gravity
  - the amount of gravitational force depends on the mass
  - gravitational potential energy is turned into heat as a star collapses

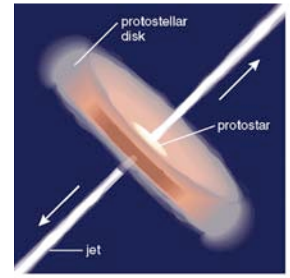
Star Formation

- As the protostar collapses, angular momentum is conserved
  - the protostar rotates faster
  - matter falling in to the protostar flattens into a (protostellar) disk
  - a planetary system could form from this disk

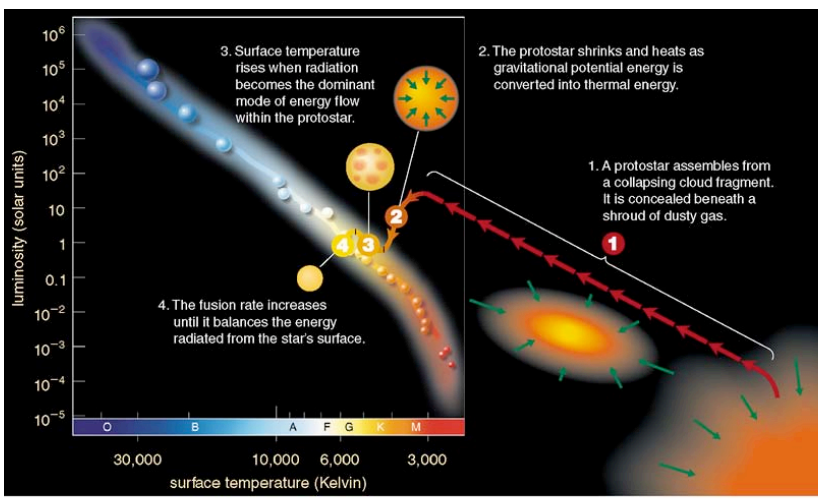
Direct Evidence of Disks & Jets

a disk forms

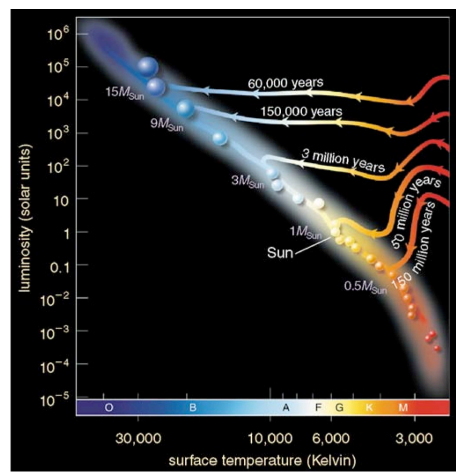




Stages of Star Formation on the H-R Diagram



Arrival on the Main Sequence

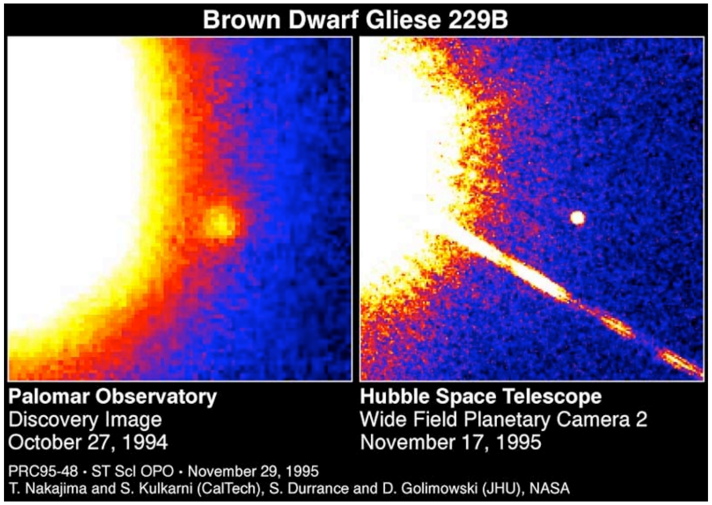


- The mass of the protostar determines:
  - how long the protostar phase will last
  - where the new-born star will land on the MS
  - i.e., what spectral type the star will have while on the main sequence

Missing the Main Sequence

- If the protostar has a mass < 0.08 M_{sun}:
  - It does not contain enough gravitational energy to reach a core temperature of 10^7 K
  - No fusion reactions occur
  - The star is **stillborn**!
- We call these objects Brown Dwarfs.
- They are very faint, emit infrared, and have cores made of Hydrogen
  - degenerate cores

The First Brown Dwarf Discovery



Life on the Main Sequence

- Where a star lands on the MS depends on its **mass**
  - O stars (O V) are most massive
  - M stars (M V) are least massive
- MS stars convert H to He in their cores
- The star is stable, in balance
  - Gravity vs. pressure from H fusion reactions

Life on the Main Sequence

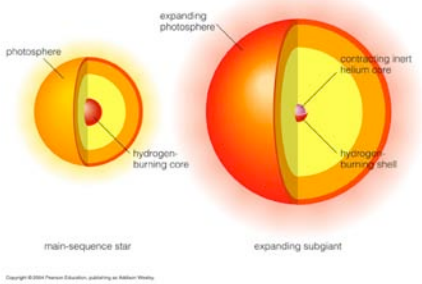
How long do these stars stay on the MS?

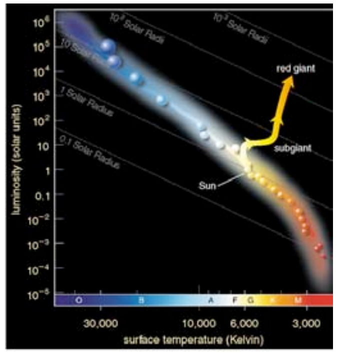
Until they burn up their fuel (H)!!

Massive stars have more fuel, but they are also brighter, so they use it up faster.

Leaving the Main Sequence

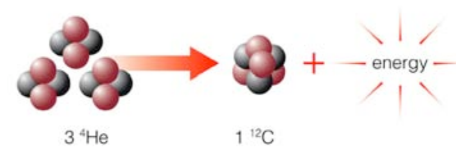
- The core begins to collapse
  - H shell heats up and H fusion begins there
  - there is less gravity from above to balance this pressure
  - so the outer layers of the star expand
  - the star is now in the **subgiant** phase of its life





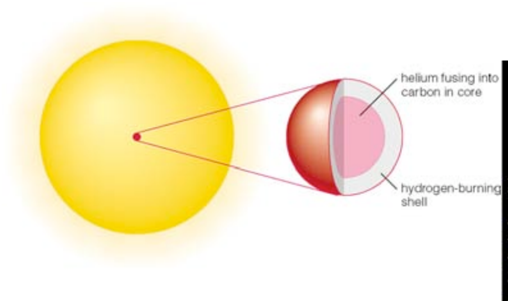
Red Giants: Burning Helium

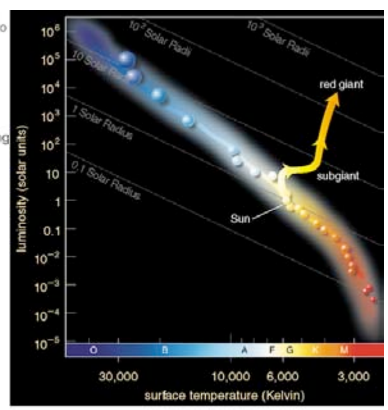
- The He core collapses until it heats to 10^8 K
  - He fusion begins (He α C)
  - sometimes called the "triple-α process"



- The star, called a Red Giant, is once again stable.
  - gravity vs. pressure from He fusion reactions
  - red giants create and release most of the Carbon from which organic molecules (and life) are made

Red Giants





The Sun as a red giant: luminosity is so high that temperature on Earth will rise up to more than 1,000K!!

•We should find other place to live…

Planetary Nebulae

- When the Red Giant exhausts its He fuel
  - the C core collapses
  - Low & intermediate-mass stars don't have enough gravitational energy to heat to 6 x 10^8 K (temperature where Carbon fuses)
- The He & H burning shells overcome gravity
  - the outer envelope of the star is gently blown away
  - this forms a planetary nebula

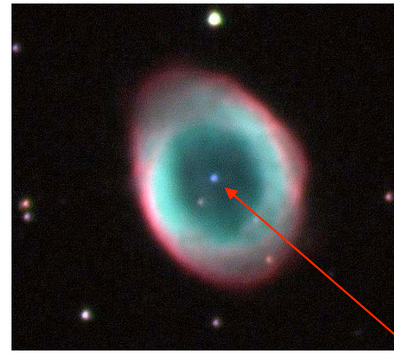
Movie. Click to play.

Planetary Nebulae

Cat's Eye Nebula

Twin Jet Nebula

Planetary Nebulae

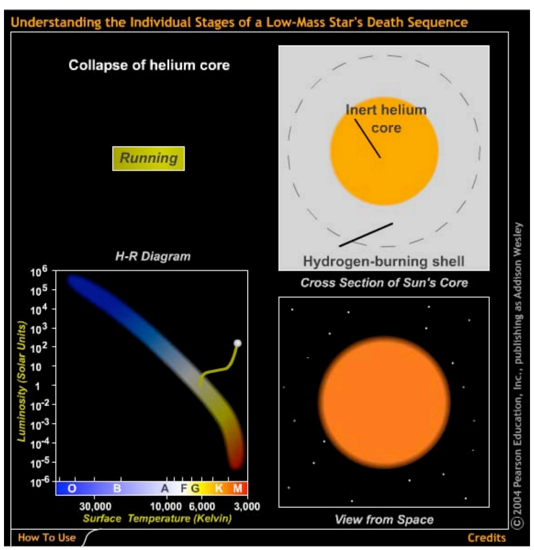


Ring Nebula

Hourglass Nebula

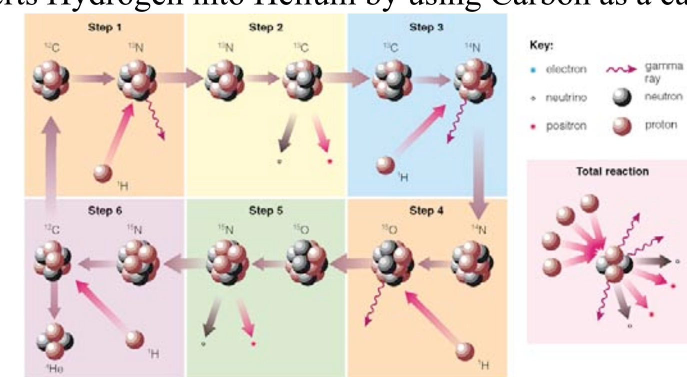
The collapsing Carbon core becomes a White Dwarf

Low-Mass Stellar Evolution Summary



High Mass Main Sequence Stars

The CNO cycle is another nuclear fusion reaction which converts Hydrogen into Helium by using Carbon as a catalyst.



Effectively 4 H nuclei go IN and 1 He nucleus comes OUT.

High Mass Main Sequence Stars

CNO cycle begins at 15 million degrees and becomes more dominant at higher temperatures.

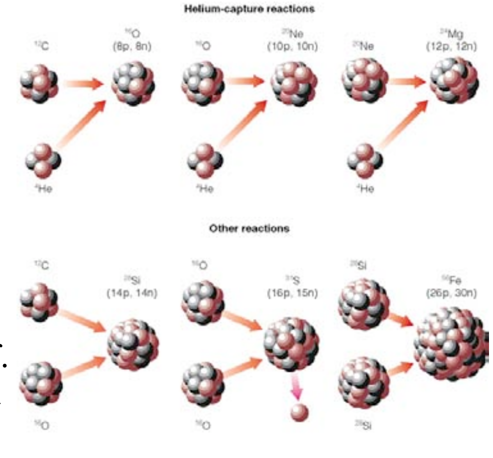
The C nucleus has a (+6) charge, so the incoming proton must be moving *even faster* to overcome the electromagnetic repulsion!!

The Sun (G2) -- CNO generates 10% of its energy
F0 dwarf -- CNO generates 50% of its energy
O & B dwarfs -- CNO generates most of the energy

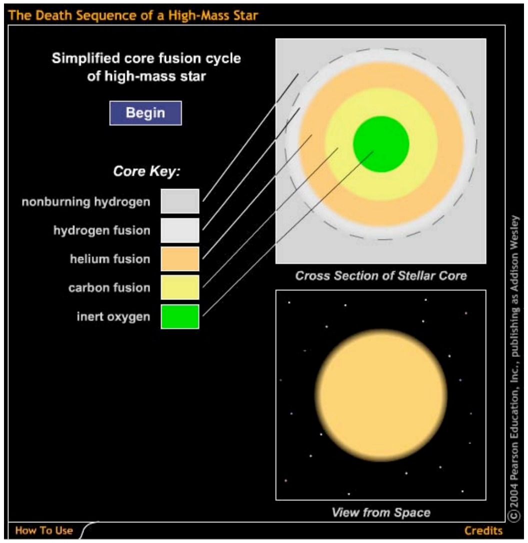
Supergiants

What happens to the high mass stars when they exhaust their He fuel?

- They have enough gravitational energy to heat up to 6 x 10^8 K.
  - C fuses into O
- C is exhausted, core collapses until O fuses.
- The cycle repeats itself.
  - O -> Ne -> Mg -> Si -> Fe



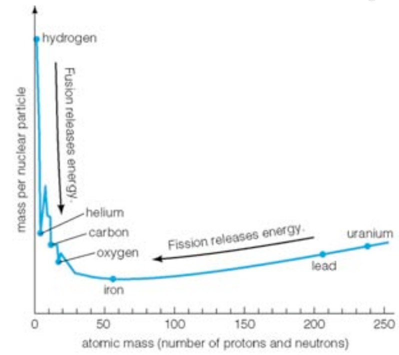
High-Mass Stellar Evolution Summary



The Iron (Fe) Problem

- The supergiant has an inert Fe core which collapses & heats
  - Fe can not fuse
  - It has the lowest mass per nuclear particle of any element
  - It can not fuse into another element without *creating* mass

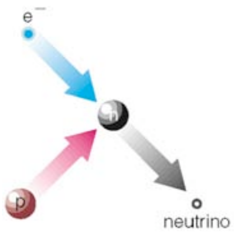
So the Fe core continues to collapse until it is stopped by electron degeneracy. (like a White Dwarf)



Supernova

- **BUT**… the force of gravity increases as the mass of the Fe core increases
  - Gravity overcomes electron degeneracy
  - Electrons are smashed into protons -> neutrons

- The neutron core collapses until abruptly stopped by neutron degeneracy
  - this takes only seconds
  - The core recoils and sends the rest of the star flying into space



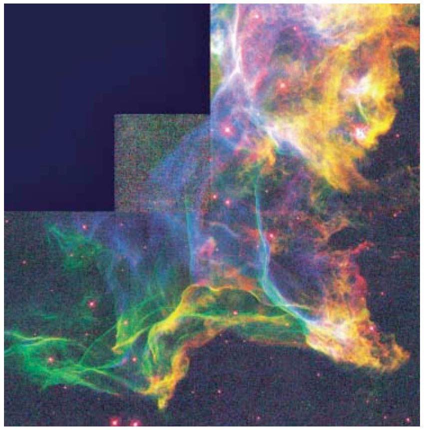
Supernova

Crab Nebula in *Taurus*
supernova exploded in 1054

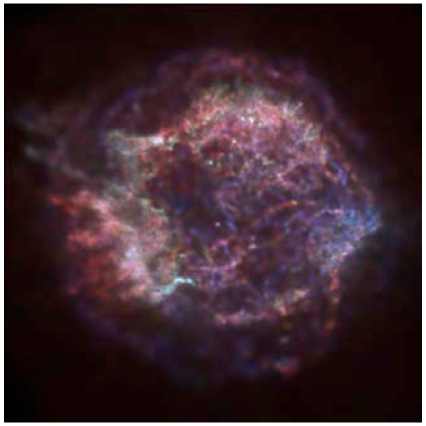
The amount of energy released is so great, that most of the elements **heavier** than Fe are instantly created

In the last millennium, four supernovae have been observed in our part of the Milky Way Galaxy: in 1006, 1054, 1572, & 1604

Supernovae



Veil Nebula



Tycho's Supernova (X-rays)
exploded in 1572

Summary of the Differences between High and Low Mass Stars

- Compared to low-mass stars, high-mass stars:
  - live much shorter lives
  - have a significant amount of pressure supplied by radiation
  - fuse Hydrogen via the CNO cycle instead of the p-p chain
  - die as a supernova; low-mass stars die as a planetary nebula
  - can fuse elements heavier than Carbon
  - may leave either a neutron star or black hole behind
    - low-mass stars leave a white dwarf behind
  - are far less numerous

Next Stop: “Einstein’s World”

- Lecture 13: Space, Time, and Gravity
  - Reading: S2, S3
- Lecture 14: The Bizzarre Stellar Graveyard
  - Reading: Chapter 18
- **Please pick up homework!!**
  - **Due October 14 (next Thursday)**