Average score on midterm 1 was 23 out of 30, with a standard deviation of 3 points. Passing score was 18. Everyone did very well, but if you barely missed the passing score, please speak to me after class.

New reading/homework set will be posted later today. This will include a solar observational project.

Update on Santa Barbara Kavli Institute Supernova Meeting press coverage from last year.
For years astronomers have tried in vain to blow up an Earth-size star using strings of computer code. Finally, mission accomplished. And the resulting 3-D simulation has revealed the step-by-step process that fuels such an explosion.

Dubbed white dwarfs, stars about the size of Earth and weighing as much as the Sun end their lives with quite a show. When their core furnace begins to burn out, white dwarfs explode in so-called type-1a supernovas that astronomers say could be responsible for producing most of the iron in the universe.

These type-1a supernovas seem to explode with about the same intensity, and astrophysicists have taken advantage of this uniformity. By calibrating the distance to each explosion, they can refine calculations of how fast the universe has been expanding throughout its lengthy history.

They used this method to come to the conclusion in the late 1990s that the expansion of the universe is accelerating. The finding left a looming question: What force could be pushing against gravity to cause the mushrooming? Astronomers dubbed the gravity challenger “dark energy.”

The new simulations could help scientists tweak their calibrations to account for the minor variations in intensity from one supernova to another.

Flash team member Robert Fisher said, “To make extremely precise statements about the nature of dark energy and cosmological expansion, you have to be able to understand the nature of that variation.”
Review of Two Weeks Ago

- Extrasolar planets
- 51b Peg
- HD209458b
Review of Last Week

- Interstellar Medium and Star Formation
  - Hydrostatic Balance
  - Role of dust
Today -- Stellar Structure and Stellar Evolution

- Stellar Structure
- Stellar Evolution
  - Evolution of a low-mass star
  - Evolution of a high-mass star
- Supernovae
Binary Stars
Binary Stars

- The majority of stars (unlike our sun) exist in bound systems of two stars orbiting about one another.

Artist’s Conception of a Red Giant Orbiting a Black Hole
Binary Stars

- Binary stars are significant because they allow the masses, periods, and separations of each star to be accurately determined.

- The orbits remain relatively fixed over time, so knowing the amount of angular momentum in the system gives us an additional clue about how the stars formed.
Visual Binaries

- Some binaries have wide enough orbits that the stellar components can be resolved in a telescopic image.

- In these cases, the binary period, orbital separation, and masses can all be determined directly.
In some cases, the two binary stars are close enough that they cannot be resolved in a telescopic image.

The Doppler technique can be used to detect many binaries spectroscopically that could not have been detected visually.
Observations of the stellar spectra over time reveal the period of the binary system as well as the separation, and hence the masses.
Eclipsing Binaries

- Some binaries, like planetary transits, eclipse one another along our line of sight to them.

- Measuring the light curve from the system gives us both stellar radii in addition to the stellar masses and orbital separation.
Alvan Clark (1804 - 1887) and the Discovery of Sirius B

- Alvan Clark was the foremost telescopic lens manufacturer of his time.

- Manufactured lenses for Naval Observatory (where Pluto’s moon Charon was discovered) and the University of Chicago Yerkes Observatory (which just shut down research very recently).

- In 1862, when testing a new 18 inch telescope at the Dearborn observatory at Northwestern University in Evanston, he discovered a companion to Sirius -- Sirius B.
Sirius B turns out to be an eclipsing binary, so that its radius can also be determined from the eclipse measurements.

These observations revealed a highly unusual structure -- a mass about that of the sun, and a radius about that of the Earth.

Sirius B became the first-known white dwarf star. How it managed to support itself against gravity would require entirely new physics.
Demographics of Young Binaries

Period distribution of binaries informs our understanding of star formation.
Stellar Clusters
Stellar Clusters

- Stars rarely form in isolation. Most stars form in giant molecular clouds with enough material to form tens of thousands to hundreds of thousands of stars.

- These stellar clusters are gravitationally bound to one another.

- Two major types of stellar clusters can be distinguished on the sky.

- These two types of clusters are thought to have very different formation mechanisms -- in particular, globulars are known to be ancient, dating to the formation of the galaxy, whereas open clusters are much younger.
The most famous open cluster of stars is the Pleaides cluster.
Pleiades in the X-ray Band

- The brightest stars of the Pleiades are actually only the tip of the iceberg -- many more stars are members of the cluster, as is evident in this X-ray image.
The Bronze Age Nebra sky disk is one of the oldest known representations of the night sky -- dating from c. 1600 BC in Germany. It is believed that the Pleiades is represented in the upper right of the image.
Globular clusters are some of the most magnificent sights in the night sky, containing hundreds of thousands of stars in a relatively compact space of a few tens of thousands of light years in diameter.

- The central densities of the cluster become high enough that stellar collisions can occur.

- There is some evidence for these stellar collisions in “blue stragglers”.

- There is also long-standing speculation, and some evidence that continued stellar collisions may lead to massive black holes of thousands of solar masses at the center of the globular.
The Globular Cluster M80
Galactic Distribution of Globular Clusters

- Globular clusters are distributed in a sphere around the galaxy.

- Other disk galaxies have been observed to have their own system of globular clusters surrounding them.

- Some globulars may pass through the plane of the galactic disk from time to time, stripping away some stars in a “disk shocking”.
Stellar Associations

- Open clusters eventually become less dense over time, and form a loosely-packed, unbound stellar association that will eventually break apart.

- Membership in the association can only be confirmed by inspecting the motions of the stars on the sky -- their proper motions -- carefully.
One example of an association is the Christmas Tree cluster.

Like all other associations, it is unbound and will eventually move apart.
M51 “Whirlpool Galaxy” in Optical
Collision of M51 with NGC 5195

A. Toomre, 1978

Time
Atomic and Molecular Gas

**Atomic or Ionized**

- Single Atom (e.g., H, C, O) or Ion (H II, O VI)
  - Trace warm (~ 1000 - 10^4 K) gas in *visible* range of spectrum

**Molecular**

- Two or more Atoms (e.g., CO, NH₃)
  - Trace cold (~ 10 - 100 K) gas in *radio - infrared* range of spectrum
Whirlpool Galaxy M51 in Optical and Submm

HST + OVRO (Scoville et al, 2004)
Astronomers have historically characterized stars by their color. From our knowledge of the blackbody radiation emitted by all bodies, we know this stellar color translates directly into surface temperature.

<table>
<thead>
<tr>
<th>Spectral Class</th>
<th>Effective Temperature (K)</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>28,000 - 50,000</td>
<td>Blue</td>
</tr>
<tr>
<td>B</td>
<td>10,000 - 28,000</td>
<td>Blue-white</td>
</tr>
<tr>
<td>A</td>
<td>7,500 - 10,000</td>
<td>White</td>
</tr>
<tr>
<td>F</td>
<td>6,000 - 7,500</td>
<td>White-yellow</td>
</tr>
<tr>
<td>G</td>
<td>4,900 - 6,000</td>
<td>Yellow</td>
</tr>
<tr>
<td>K</td>
<td>3,500 - 4,900</td>
<td>Orange</td>
</tr>
<tr>
<td>M</td>
<td>2,000 - 3,500</td>
<td>Red</td>
</tr>
</tbody>
</table>
The spectral classes can be easily remembered by

- Oh Be A Fine Girl/Guy Kiss Me

Many other mnemonics have been created -- or make up your own!

- Oh Boy, Astronomy Final's Gonna Kill Me
- Out Back A Friend Grows Killer Marijuana
- Oven Baked Ants Fried Gently Keep Moist
- Only Boring Astronomers Find Gratification Knowing Mnemonics
Astronomers will often classify the brightness of stars by their magnitude. The original classification was meant to agree loosely with an ancient system due to Ptolemy -- magnitude 1 stars are among the brightest on the sky, and magnitude 6 stars are among the faintest visible to the naked eye.

Each increment on the magnitude scale represents not a linear increment, but a multiplicative factor. Every five increments represents a factor of 100.

Each increment turns out to be an equal multiplicative spacing, so a magnitude 2 star is 2.5 times fainter than a magnitude 1 star, and so on.

This is referred to as a logarithmic scale and is similar to how the notes of a musical scale, or the familiar Richter scales of earthquakes are constructed.
Stellar Magnitudes

- It is important to realize that these magnitude ratings reflect the *apparent* brightness of a star. Two stars of the same intrinsic brightness at two different distances will have two different magnitudes.

- If one also knows the distance to the star (not always the case!), then one can correct for the distance and obtain an *intrinsic magnitude*. By convention this is chosen to be a distance of 10 pc, or 32 LY.

- Examples of apparent magnitudes
  - Sun       -26.3 (intrinsic 4.8)
  - Vega      0
  - Uranus    5.5
  - Pluto     13
  - HST Limit 30
Around the beginning of the 20th century, two astrophysicists noticed something fundamental about the properties of stars. They compared stellar properties by displaying *intrinsic* stellar luminosity along one axis and temperature along the second axis.
When displayed in this fashion, definite patterns popped out immediately.
Which star is larger, A or B?
This classification system helped identify the major classes of stars:

- **Main Sequence.** This is where all stars begin their lifespans burning hydrogen, and where they spent most of their life. (Example: our sun.)

- **Giant Branch.** After stars deplete their supply of hydrogen they swell up to an enormous radius and begin burning helium and heavier elements on this branch. (Example: Aldebaran.)

- **Supergiants.** Among the brightest stars in the universe, shortly before the end of their lifespan. (Example: Rigel.)

- **White Dwarfs.** Stars similar in mass to our sun will wind up as white dwarfs -- extremely dense, hot stellar remnants. (Example: Sirius B.)
Question

☑ Which star is more evolved, A or B?
The Source of Stellar Energy

- Every star radiates away energy as visible light, and other parts of the electromagnetic spectrum.

- By conservation of energy, this energy must be produced at the same rate as it is radiated away if the star is to remain in equilibrium.

- But what is the source of stellar energy??
Hydrogen Combustion?
The total lifetime of the sun is determined by the total energy contained in the sun, and its luminosity -- the rate at which it radiates away energy.

The larger the energy content of the sun, the longer its lifetime.

A simple estimate of the lifetime of the sun assuming the source of its energy is due to chemical reactions (reactions involving rearrangement of electrons of atoms) -- while absolutely enormous by terrestrial standards -- yields a solar lifetime of only about 100,000 years.

100,000 years is a very long time -- but how old is the sun?
In 1869, John Wesley Powell, who grew up in Illinois and attended Wheaton College and later headed the US Geological Survey, led an expedition through the Grand Canyon and estimated its age -- today known to be nearly 2 billion years old.

Today we know from crater records of the moon and radioactive dating of meteorites that the solar system is about 4.6 billion years old.
A more reasonable candidate for the source of stellar energy was gravity itself.

Kelvin and Helmholtz proposed gravity as a source of stellar energy in the 1860s.

In this model, as stars like our sun radiate away energy, they contract under the influence of gravity and heat up in their interiors.

In the gravitational contraction scenario, the lifetime of the sun is therefore set by the total gravitational potential energy within the sun.

There is much more energy stored in gravitational potential than in chemical reactions, but even still, the estimated lifetime is about 100 million years -- far too short.
The actual source of stellar energy took several decades of work, and a fundamentally new discovery in physics.

In 1905, as part of his Theory of Special Relativity, Einstein discovered that energy and mass are equivalent -- $E = mc^2$.

According to Einstein’s formula, a small amount of mass can be converted into a large amount of pure energy.
One hundred years ago, no one had ever imagined that every piece of matter is equivalent to an enormous quantity of energy. Today this idea is put to practical use every day, for instance at the Fermi National Laboratory just west of Chicago.
Hans Bethe (1906-2005) was a monumental figure in 20th-century physics, with a career spanning seven decades.

Bethe won the Nobel prize in 1967 for “his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars” -- completed in the 1930s. This was the first Nobel to be awarded to an astronomical topic.

Head of the theory division during the Manhattan Project, he later became an outspoken critic of nuclear weapons and the arms race. “The true extent of his moral strength would only emerge when his role in the birth of the nuclear age posed a host of ethical choices,” read his obituary in Nature.
The culture of postwar physics split into two camps, generally either in support of nuclear weapons development, and opposed to it on moral grounds.

After the war, J. Robert Oppenheimer, former head of the Manhattan project, was brought before a committee to determine whether he should retain his security clearance.

Oppenheimer had previously opposed the development of the hydrogen bomb (the “Super”) on technical grounds.

Hans Bethe testified in support of Oppenheimer.

Edward Teller (the real life inspiration for Dr. Strangelove) favored building the Super at all costs, and presented a carefully-worded testimony bringing Oppenheimer’s judgement into question.

Oppenheimer’s security clearance was removed from him. By all accounts, this had a devastating impact on him, and created a divide in the postwar physics culture.
Oppenheimer and Teller at the time of Oppenheimer Receiving the Fermi Award
J. Robert Oppenheimer on the First Atomic Bomb Blast at Alamogordo New Mexico
Ironically, despite the high-profile attention paid to Oppenheimer, the largest security threat was a young German scientist participating as part of the British mission, named Klaus Fuchs.

The transferal of nuclear weapons technology to the Soviet Union arguably stabilized the immediate postwar era.

Perhaps most ironic of all is the fact that the Rosenbergs were both sentenced to death in the US for a relatively minor role as espionage agents, while Fuchs (as a British citizen) was given a relatively light sentence due to differences in British and American law.

After serving his sentence, Fuchs emigrated to East Germany, where he was a hero, and was appointed head of a physics institute.
Nuclear Energy

- Nuclear energy can be used for both peaceful purposes and for destructive ones.

- The Henry Moore statue "Nuclear Energy," stands at the precise spot where Fermi constructed the first nuclear reactor in 1942 at the University of Chicago, and is a reminder of this dual nature of nuclear energy.

- We now turn to understanding how nuclear energy is used in perhaps the most peaceful and environmentally-friendly ways -- in powering stars.
A Nuclear Primer

- Nuclear physics involves the interactions of several different types of particles.

- The particles in the following list are not necessarily fundamental -- some (like the proton) are believed to consist of several smaller, more fundamental particles (quarks).

- However, one can understand nuclear physics without probing the deep interior structure of the nucleons -- the protons and the neutrons -- themselves.

<table>
<thead>
<tr>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
</tr>
<tr>
<td>Neutron</td>
</tr>
<tr>
<td>Electron</td>
</tr>
<tr>
<td>Neutrino</td>
</tr>
<tr>
<td>Gamma Ray</td>
</tr>
</tbody>
</table>
Every nucleus is made up of one or more protons and neutrons -- nucleons, with electrons orbiting much further out.
The interior of the stars can reach millions or even billions of degrees.

When atoms are heated to very high temperatures, the electrons are “stripped” or ionized from their nuclei, forming a continuous soup of nuclei and unbound electrons -- a plasma.

The most familiar example of a plasma is the flame of a candle, where the energy released by combustion of the wick generates the hot plasma that we see as a flame.

The interior of the stars is in a plasma state, similar to the candle flame. However, the source of energy in a star is nuclear, whereas the source of energy of the candle is chemical.
The physics of nuclear burning in stellar interiors can be summarized by energy generation cycles.

The basic nuclear physics is very similar to basic chemistry -- there is both a product and reactants, and the product and the reactants must “balance”.

In the case of basic chemistry, each element maintains its own identity, so the number of atoms of each species must balance -- for instance, $2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O}$. 
In a nuclear reaction, nuclei can change identity from one element to another, so it is no longer true that their elemental composition remains fixed.

However, some other properties must remain fixed -- like the total number of nucleons (protons & neutrons), and the total number of leptons (electrons & neutrinos).

Example: \( n \rightarrow p + e^- + \text{anti-neutrino} \)
In order to keep track of various nuclear species, a convention is used to label nuclei.

The atomic element of a nucleus is determined *solely by the number of protons*.

Variants of an element with varying numbers of neutrons are referred to as *isotopes* of that element.

Example: a nucleus with 2 neutrons and 2 protons.

<table>
<thead>
<tr>
<th>Number of protons gives atomic element.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^4)He</td>
</tr>
</tbody>
</table>

Total number of protons + neutrons designates isotope.
Some nuclei are radioactively unstable, and will transition from one nuclear state to another.

In some cases, a nucleus is formed in an excited state, similar to an excited state of an atom.

In an excited atomic state, an electron will transition from one state to a lower state, emitting a particle of light (a photon) in the process.

In an excited nuclear state, a nucleus will transition from an excited state to a lower state, emitting a particle of light (a photon) in the process.

Because the nuclear energies are much greater than atomic energies, the photon emitted in a nuclear decay is thousands to millions of times greater than those emitted by atoms -- generally in the X-ray to gamma ray portion of the electromagnetic spectrum.
In other radioactive nuclei, a neutron inside the nucleus is converted into a proton of a beta particle (an electron).

The change of the number of protons alters the atomic element of the nucleus by increasing by one -- *nuclear alchemy*.

Similarly, other radioactive nuclei are unstable to the emission of an alpha particle (a helium nucleus). The atomic number of the nucleus is lowered by two.
When stars are first formed, their composition is primarily hydrogen, with a smaller fraction of helium, lithium, and other heavier elements.

During the first phase of its lifespan, the star burns hydrogen to power its luminosity and support itself in hydrostatic balance against gravity.

This hydrogen-burning portion of a star’s lifespan is referred to as the main sequence -- a historical term dating from the arrangement of these stars on the HR diagram.

Most of a star’s lifespan is spent on the main sequence burning hydrogen. The later phases of its lifespan occur progressively quicker and account for a shorter portion of its lifespan.
The proton-proton cycle uses four protons to build up one helium nucleus.
At stellar masses much larger than the sun, the CNO cycle is the dominant source of nuclear energy.
Although C is a key element of the CNO cycle, and carbon, nitrogen, and oxygen isotopes take part of the process, they are catalysts and are not used up in the reaction.

Counting up all of the participants of the CNO cycle, we see that four protons are used in the process, and one helium nucleus (as well as some neutrinos, gamma rays, and positrons) is produced.

Remarkably, the net result of the CNO cycle is essentially the same as the p-p cycle -- converting protons into helium.
Energy Transport Within the Sun

- The interior of the sun is millions of degrees, whereas the surface is only about 7 thousand degrees.

- Energy must be transported from the high temperature interior to the edge of the sun if it is to shine.

- In the interior of the sun, the radiation given off by the core transports the energy. At the edge of the core, convective motion of the gas itself transports the energy.
Stellar Life Cycles -- You’ll Take the Low (Mass) Road, I’ll take the High (Mass) Road… and I’ll Get to the Endpoint Before You

- Stars of different masses evolve at different rates on the main sequence and beyond.

- Higher mass stars have a higher central temperature, to support the greater overlying weight of their envelopes.

- Nuclear reactions are extremely sensitive to temperature, causing higher mass stars to consume fuel much more rapidly than lower mass stars.

- In addition, some nuclei only begin to ignite at the higher temperatures accessible to higher-mass stars.
The upshot is that a high mass star burns brilliantly, but shortly -- a lifetime of just a few million years for the most massive stars approaching 100 solar masses.

Stars like our sun have lifespans of about 10 billion years.

Stars of much smaller mass than our sun have lifespans vastly exceeding the current age of the universe and have hardly evolved at all.
As hydrogen becomes depleted in the core of the star, it contracts briefly until the outer layers heat up and undergo ignition.

The sudden input of energy in the outer layers of the star cause it to expand tremendously, producing a luminous *red giant star*.

The expansion of the outer layers of the star causes the outer layers to cool in the process, causing the redder appearance of the star.

The enormously-larger luminosity powers a powerful radiation pressure on the outermost layers, blowing much of this material away in winds.
Red Giant Phase of the Sun

- In five billion years, our sun will swell to an enormous size, nearly one hundred times its current size, and nearly half the size of the Earth’s orbit.

- Mercury and possibly Venus will become entirely engulfed in the sun, and the Earth will become a scorched and dry planet, similar to a large Mercury.
In a cluster, all stars were formed at roughly the same time.

Inspecting the HR diagram of a stellar cluster therefore reveals stellar structure of stars of different masses at the same age.

The turnoff point (TO) begins at the top of the main sequence (MS) for the most massive stars and moves downwards as the cluster ages.
Nuclear Catastrophe -- Helium Flash

- Once the hydrogen in the outer layers of the star has also been consumed, the star encounters a nuclear catastrophe -- it has depleted its primary source of nuclear energy, and is too cold to ignite helium.

- It contracts in radius, causing the helium there to ignite suddenly, in a matter of minutes or hours.

- The helium burns to form C and O nuclei in the triple-alpha process. This is the main source of C and O in the universe, including every carbon atom in our bodies.
After helium flash, the star begins to burn helium in its core, and evolves at roughly constant luminosity, but with a hotter outer layer. It therefore contracts, and shifts over to the left on the HR diagram as a horizontal branch star.
Eventually the helium in the core is depleted. For stars of 8 solar masses and less, there is insufficient mass to ignite the carbon, so the star continues its lifespan by burning helium and hydrogen in shells -- **an asymptotic giant branch star**.

AGB stars lose their outer layers at a high mass loss rate and pulsate in radius and luminosity.
Out of the Frying Pan, Into the Fire -- The Ultimate Fate of the Earth and the Atoms of Our Bodies

- On the AGB, our own sun will swell beyond even its size as a red giant and consume the baked-out Earth. The Earth will be completely incinerated as it spirals into the enormously hot center of the sun.

- All hydrogen contained in the liquid water of the Earth will have long since evaporated and been lost to space, but remaining hydrogen in the Earth will be rapidly burnt in nuclear reactions.

- The AGB sun will be too cool to burn carbon, so the carbon and oxygen atoms in our bodies will pass unburned through the sun’s interior, and may leave the sun in a planetary nebula.
Planetary Nebulae

- The outer stellar layers blown off by AGB stars are visible to us on Earth as planetary nebula, and form some of the most fascinating objects on the sky.

Ring Nebula

Cat’s Eye Nebula
White Dwarf

- Eventually, once the outer layers of the AGB star are completely blown off, the star becomes a white dwarf like Sirius.

- White dwarfs are now known to be sustained by the extreme closeness of their electrons, which leads to a quantum-mechanical pressure known as degeneracy pressure.

- The white dwarf is a stable end-product of stellar evolution for masses less than about 1.4 times the mass of the sun.

- These dwarfs slowly cool in time, and form a sequence of cooling white dwarfs down and to the right on the HR diagram.
Cooling white dwarfs can be clearly seen on this modern HR diagram from the *Cambridge Encyclopedia of Stars*, at point D.
Question

- Which WD is hotter, A or B?
Question?

- Which WD has a larger radius, A or B?
The standard nuclear networks predict that in addition to producing helium, neutrinos and anti-neutrinos should be produced in the solar interior.

Neutrinos interact extremely weakly with ordinary matter -- only one in a trillion are stopped by the Earth. Detecting neutrinos became a challenging experimental problem -- one pioneered by Raymond Davis, Jr., who constructed enormous experiments far underground in deep mines, such as the Homestake Mine in South Dakota.

Early results indicated that the number of neutrinos detected fell below the number expected from the standard solar model -- a discrepancy which became one of the major riddles in modern astrophysics known as the solar neutrino problem.
In order to help resolve the discrepancy in the solar neutrinos predicted by the standard solar model and those measured, a large neutrino observatory was constructed in Canada, and another in Japan.

These observatories determined that the neutrinos changed into a variety not detectable in previous experiments in flight to the Earth. This “neutrino mixing” is the resolution to the solar neutrino problem.

In 2002, Raymond Davis, Jr. and Masatoshi Koshiba were awarded the Nobel Prize in physics for their experimental work in detecting neutrinos. Davis was 88 years old at the time he received the award, making him the oldest Nobel winner ever.
The evolution of massive stars (> 8 times mass sun) is similar to that of lower-mass stars through the beginning stages, except far more rapid due to its greater mass burning rate.

Where a 1 solar mass star spends 10 billion years reaching the red giant stage, a 10 solar mass star may reach the same evolutionary point in just 10 million years.

Once it begins to burn helium, a massive star will appear as a bright blue supergiant star like Rigel, among the most luminous stars on the sky.
In low mass stars, hydrogen and then helium is first ignited in the core, and then moves to shell burning. The burning stops at carbon, which cannot be burnt.

In stars above 8 solar masses, nuclear burning can proceed to higher and higher mass nuclei -- through carbon, oxygen, neon, magnesium, silicon, sulfur, and iron.

At each step in the process, the core temperature rises higher and higher, and the associated time to complete the burning cycle becomes shorter and shorter.

By the end of this process, the core of a red supergiant is over 7 billion degrees, and one entire solar mass of iron is produced from silicon one day!
Iron is unique among all nuclei in that it has the highest binding energy per nucleon.

As a result, one cannot liberate any additional energy from iron -- any further nuclear reactions can only occur by adding energy.

Once one has formed iron in the core of a massive star, the star can no longer liberate nuclear energy in its core.

Once the core exceeds a certain mass, it becomes unstable, and begins to collapse inwards.
In the 1930s, while still a young man on a sea voyage from his native India to Cambridge, Subramanyan Chandrasekhar attempted to formulate an idealized model of a white dwarf star.

He discovered that when one models the white dwarf, the electrons inside it are moving a substantial fraction of the speed of light, and therefore one needs to account for the effects of relativity laid down by Einstein.

He demonstrated that by combining the quantum-mechanical effects of degeneracy pressure with the physics of relativity, there exists a maximum mass for a stable white dwarf -- approximately 1.4 times the mass of the sun.
The collapse of the core leads to the formation of an intense shock front moving at about 10% of the speed of light through the star, on a millisecond timescale.
A Neutron Star is Born

- At the center of the star, during the supernova, the densities become so high that electrons are squeezed back onto the protons to form neutrons -- through the inverse-beta reaction $\text{proton} + \text{electron} \rightarrow \text{neutron} + \text{neutrino}$.

- Remarkably, although they interact very weakly with matter, over 99% of the supernova energy is released through the neutrinos.

- This leads to the formation of a massive “neutron star” at the center of the supernova.

- Neutron stars, like white dwarfs, are supported by degeneracy pressure.

- Unlike white dwarfs, where the degeneracy is due to electrons, in neutron stars it is due to neutrons.

- One can show that there exists a maximum mass for neutron stars, analogously to the Chandreskhar limit for white dwarfs -- and that this mass is in the range of 2 - 5 solar masses.
This movie is taken from an older (c. 1995) 2-D simulation of a core collapse supernova by Adam Burrows and colleagues.
In 1987, the nearest supernova since the time of Kepler went off in the Large Magellenic Cloud (LMC), a satellite galaxy of the Milky Way.

This supernova was closely-watched by astronomers around the world in every part of the spectrum from gamma rays to radio, and even neutrinos (!), from the time of its discovery.
Three hours prior to the time that light from the supernova first became visible on the Earth, a total of 24 neutrinos at three neutrino experiments were detected.

Although 24 neutrinos seems like a very small number in comparison to the total estimated neutrino count of $10^{53}$, their detection was incredibly important, because

- A) It was the first direct confirmation that the nuclear reaction converting protons to neutrons was indeed occurring in a core collapse supernova.
- B) It confirmed that the bulk of the energy released in the supernova is carried away by the escaping neutrinos.
In addition to the core collapse supernovae, it is possible to take a white dwarf in a binary system, and pile mass onto it until it exceeds its Chandrasekhar mass and undergoes an explosion as well.

These *thermonuclear supernovae* are sometimes referred to as “type I” supernovae -- an observational designation that they lack hydrogen in their spectra.

Core collapse supernovae are generally “type II” supernovae -- a an observational designation that they have hydrogen in their spectra, though there are some notable exceptions.

Type I supernovae have recently become quite valuable as “standard candles” in very distant parts of the cosmos, since each one explodes with nearly the same energy.
We therefore have a cartoon schematic of both major types of supernovae.

However, despite this broad consensus, no one knows in detail how either type of supernova explodes.
The white dwarf accretes mass from its companion star, and eventually exceeds the Chandresekhar mass, becoming unstable.

Near the center of the white dwarf, increased pressure leads to the ignition of a nuclear flame bubble.
Possible Type Ia Mechanism

- As the flame bubble burns outwards, just like a terrestrial hot-air balloon, the hot ash is buoyant and begins to rise.

- The less dense material of the bubble is similar to the familiar case of water-on-oil, and becomes unstable and highly non-spherical.
Possible Type Ia Mechanism

- The buoyant bubble rises through the white dwarf and breaks out of the surface.

- Some ash material from the bubble moves over the surface of the star and builds up a jet on the opposite side from breakout, leading to a detonation there.
What happens when not even light can escape from a region of spacetime?