X Stellar Evolution

1. Star formation.

The interstellar material is the cradle of the stars. This material is the stuff the stars are made of.

- How do stars form from this dilute gas (less than 1 particle/cm^3 as compared to more than 10^{19} particles/cm^3 in our atmosphere)?
- And where to look for forming stars in these gas clouds?

The darkest sections of the gas nebulae are the most promising sites for star formation.

Slide X.1

Such nebulae are up to several 100 light-years large (light needs 100 years to cross the cloud) and contain 1000 solar masses. The composition is with 75% H, 23% He and 2% heavy elements about the same as in the sun.

a) Conditions for star formation:

To form a star the cloud has to contract, i.e., the gravitation of the cloud material has to overcome motion of the atoms in the gas. (This condition is a similar to the one needed for an atmosphere to stay with a planet: the planet's gravity has to be strong enough to bind the randomly moving atoms to its environment.) Thus a star forming region has to be

Cool □ **motion of the atoms is slow**.
Dense □ **more mass in the volume, i.e. more gravity**.

Cool clouds are accompanied by molecules and dust, since cool and dense are also conditions for molecule and dust formation.

Molecules:

Cool clouds □ **molecules don't break** apart when they collide.
Dense clouds □ more chance for **atoms to come together** to make molecules.

Dust:

Cool clouds □ **molecules are not evaporated from dust**.
Dense clouds □ more chance for **molecules to form larger clusters**

"Stellar Nurseries": cool dense clouds of gas and dust.

We need IR or radio to see through dust into star-forming regions. A lot of information has been provided by the infrared satellite IRAS. **Slide X.2, 2a**

b) Start of the collapse

Slide X.3

If we see these gas clouds in the sky, they seem pretty stable. How do they start to collapse eventually? This is another place where shock waves become important. For example the shock wave (or blast wave) from a supernova or from a star with a strong stellar wind in the vicinity will compress the cloud, while passing over it. In response, the cloud becomes denser so that it now starts to contract under its own gravity.

View X.1

In this process the cloud may also break off into smaller pieces, and several stars can form simultaneously. **Slide X.4**

This fragmentation of a cloud can be seen clearly in the “pillars” of M16 as beautifully demonstrated in this picture taken by the Hubble Space Telescope **View X.1a**

c) Role of dust in star formation:

Earlier we have learned that compression will heat a gas. Therefore, it tends to resist any further collapse. Here the dust in these dense clouds comes to rescue:

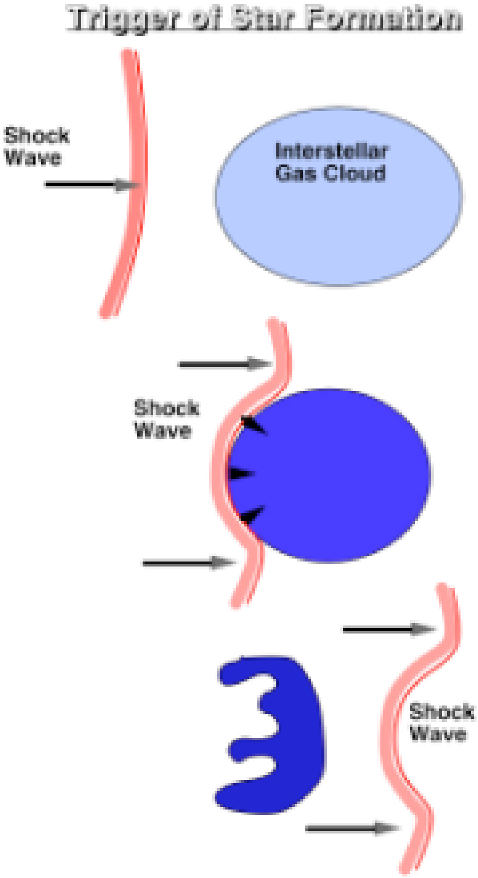
The dust can radiate heat efficiently and thus can keep the cloud cool enough so that the cloud will continue to collapse. Later on the gravity is already so strong that the hot gas can't come apart any more. The gas cloud now radiates like a blackbody: getting hotter, the radiation increases with T^4 (i.e., doubling the temperature the radiation will go up by a factor of 16). Thus gravity will force more and more energy out of this star embryo. At this time the energy source suggested by *Kelvin* and *Helmholtz* for the sun really works!!

Unfortunately, we cannot see directly into a star nursery. New stars are imbedded in a cocoon of gas and dust, which is heated by the light from the new stars. We mainly see the infrared light from the heated cocoon.

Almost all the stars are formed in clusters of stars

Slide X.5

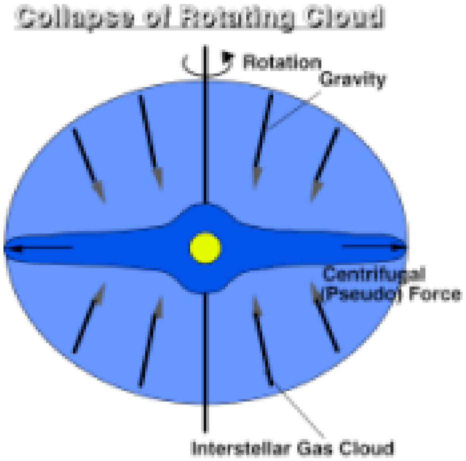
as seen here for the Jewel Box. A larger cloud is fragmented during the collapse and several stars form at the same time.



View X.1

2. Planet Formation

A) The Solar System



View X.2

Let us finish the section on star formation with one important obstacle: **angular momentum**. Its role in star formation will give us a clue to understanding the evolution of the solar system with all its planets. The gas cloud, which starts to collapse, is slowly rotating, because (as we will see later) our Milky Way galaxy is rotating as a whole. However, contracting a rotating body speeds up the rotation, because **angular momentum is conserved**.

Demo Funnel

In this demonstration the ball is pulled inward by gravity through the slope of the funnel (we simulate the gravity trough of the cloud) and the ball orbits faster and faster. This is the same effect, which speeds up the ice skater in a pirouette when she or he pulls the arms in. Now the centrifugal force wants to balance gravitation, as a result the cloud becomes disk shaped

View X.2

The collapse in the direction perpendicular to the rotation plane is not impeded. If we think of the star (or sun) forming in the center, this starts to look familiar, and it makes sense. The solar system shows this shape, and the planets carry more angular momentum than the sun, although they only have little mass. In fact, all planets carry 98% of the angular momentum of the solar system, while they account only for 1% of the entire mass. *Descartes* and *Kant* developed an **evolutionary model,** which described the **formation of the solar system** in this way. Although we have not yet observed planets orbiting other stars directly, a disc of material has been observed around β Pictoris, which resembles closely the early solar system. Slide X.5

However, there was the **problem** how the small mass of the planets could carry the large **angular momentum** away from the large center mass. But there are 3 additional effects, which allow passing angular momentum from a central body into the surrounding medium:
1) *Weizsäcker* found that when the cloud was still interacting as a whole **eddies** were formed in the gas with increasing sizes further out. These could have been the seeds for the later planets at growing distances.
2) The early solar nebula must have already had a **magnetic field**. Via magnetic forces the increasingly faster rotating central body would have spread up the clouds further out.
3) **Solar wind carries away angular momentum**, and young stars show a tremendous stellar wind, much stronger than the current solar wind.
Laserdisc Astro, p.2, Ch.36

Just over the last few years stars with a slight periodic motion have been found as an indicator that some massive planets (like Jupiter) orbit these stars. In addition, modern electronic cameras have provided us with a picture of one star (β Pictoris, 2nd star in the constellation painter) with an obvious disk of dust around it like is expected as the progenitor of the planets in the early solar system. These clues suggest that indeed many stars may have planets, and that the development of a planetary system is quite common in star formation. Therefore, we can take this scenario as a fairly good description of star and planetary system formation.

See also: **Chapter VI.10 (Planets around other Stars)**. Until about 12 years ago we only had one single planetary system to work with, our own solar system, and this has shaped our view on planets. Only recently have we started to see the variety that is possible.

B) Planets around other stars

With our solar system we have one basic scientific problem: in science we are usually not satisfied, if we can support a model or a theory only with one example. If we present a model of the formation of the solar system, we are just in that situation. There is only one solar system, i.e. the one that we live in. So using the general features that we just listed as the criteria for a scientific model may lead to a wrong result. Our solar system may not be a good example for systems with planets in general. One example may not be typical, and the model may be built on a very special case. More than one example is needed to validate a model. However, until 1995 we had only data about our solar system. Only then did we start to gain information about planets in other star systems. Therefore, the recent confirmation of planets in other star systems is a big leap forward.

Also, as mentioned already in VI.6, as humans we are pondering the question whether we are alone and special in the universe or only one out of many examples of intelligent beings. With confirming the first planets outside our solar system we have made a giant step towards potential clues on life in outer space. Together with
- potential life on ancient Mars and
- life found under very rough conditions on Earth

this increases the chances that there is more intelligent life out there. However, that does not necessarily mean that we may connect with them. The distances may still be much too large.

a) Planet Detection Techniques

Still, we have not seen these planets directly yet. The telltale is the periodic motion of the center star in response to the gravitational pull of its planets. View X.3
The motion is detected through a variable Doppler shift of spectral lines (the finger-print of the elements) from the star. The wavelength of light becomes longer (red-shifted), when the star is moving away from us, and shorter (blue shifted), when the star is moving towards us. Because a larger planet moves the star more effectively, it is no wonder that so far only heavy planets, with a mass ≥ that of Jupiter have been found.

The ultimate goal will of course be the direct detection of planets, and even better to see some structures on them. We know that we need a large objective diameter for a telescope to improve its resolution. How large must the telescope be to see a crude resolution for a planet of the size of Earth in the orbit around Alpha Centauri, the nearest neighbor star? We would need a diameter of 10 km. This sounds extremely ambitious, but it could be done with several small telescopes working together in orbit or with an array of telescopes on Earth. This is similar to the radio interferometers. View X.3a

b) Other Planetary Systems

It is interesting to see that new planets have been found around G-type stars, the star type of our sun. Yet they are relatively strange systems. View X.3b
In one case the planet orbits much closer than Mercury and is much heavier than Jupiter. In another case the "planet" is 8 times as heavy as Jupiter and in a highly elliptical orbit. These are signs of so-called **Brown Dwarfs**, objects too heavy for a planet, but that missed to become stars because of too little mass. This will be picked up a little later. It is interesting to see that these new planetary systems have Jupiter-like planets where the rocky planets are in our system. Our favorite models explain the rocky planets as the remainder of material after the volatile elements got blown or evaporated away close to the sun. These models may need revision due to the new information, but this is not yet conclusive.

Some of the planets are in the "Goldilock region" as far as their distance from the central star is concerned, meaning that they are where moderate temperatures can be achieved on the planets' surface. They are in the region where life could evolve, not necessarily on the Jupiter-like planets, but there may be moons around as in the Jovian system.

Will it ever be possible to detect signs of life on such planets?

3. Mature stars

After overcoming all these obstacles and together with the planetary system, the sun (or another star) has formed now. The star has shrunk so much that its interior is hot enough to enable nuclear fusion of H. The normal life of a star has begun.

A) Range of stars

From the observational results about stars we now know that there is a wide variety of stars with

View X.4

Masses from < 0.1 to ≈ 60 solar masses

and

Luminosity from $< 10^{-3}$ to 10^6 L_s (L_s = solar luminosity)

This information begs two questions:

1. What about masses beyond this range, i.e., masses smaller and larger than this range?
2. What does a complete star life look like? We know that they will exhaust their fuel at some point.

a) Upper and lower bound of star masses

We indeed do not find any stars below 0.08 solar masses. Talking about the energy source of the sun, we have noted that the temperature has to be high enough in the core that the H nuclei can overcome the electric repulsion. I.e., the pressure in the center must get high enough to ignite the nuclear fusion. Bodies with masses too low fall short of this condition. The planet Jupiter is such a case: If it had gained somewhat higher mass, it might have been a second star in our solar system. We call such objects **Brown Dwarfs**. Dwarfs, since they are tiny, and brown, since they don't shine. You can imagine that it is hard to find them in the sky, because they are dark, but astronomers suspect that there are many of such objects which could then contribute to the mass of the galaxies and the universe, but not to the luminosity.

-> *Missing Mass Problem*

Recently the indication was found that such objects indeed exist. Several objects have been classified as Brown Dwarfs.

HST Computer Views

On the high mass end another problem arises for a star: The luminosity is enormous and so is the energy flux. Since it is radiation in the interior, there is also a tremendous **radiation pressure**. We know the luminosity and thus the radiation pressure increases like:

$$P_{radiation} = \text{constant} * M^{3.5}$$

while the gravitational pressure (the lid on the nuclear oven) only varies like:

$$P_{gravitation} = \text{constant} * M^{2}$$

For masses > 60 M_S therefore the radiation pressure exceeds the gravitational pull, and the star would simply fly apart. This is the **Eddington limit** for stars.

b) Variation of energy output and lifespan of stars

We see immediately that the **lifetime of the stars** must be different for different masses. We know that the sun will live altogether for ≈ 10 Billion years. And this is determined by how fast it burns its fuel, the hydrogen in the core. A heavier star has more fuel. Will it then live longer than the sun? Looking at the Mass Luminosity diagram we find that a star

10 times as heavy as the sun

is

≈ 3000 times as luminous as the sun

Thus it burns its fuel 3000 times as fast, i.e., in one second it loses 12 Billion tons of mass instead of the 4 Million tons of the sun. Therefore, the lifetime will be

$$\frac{\text{10 times more mass}}{\text{3000 times faster}} = \text{1/300 of the life of the sun}$$

As usual in our society:

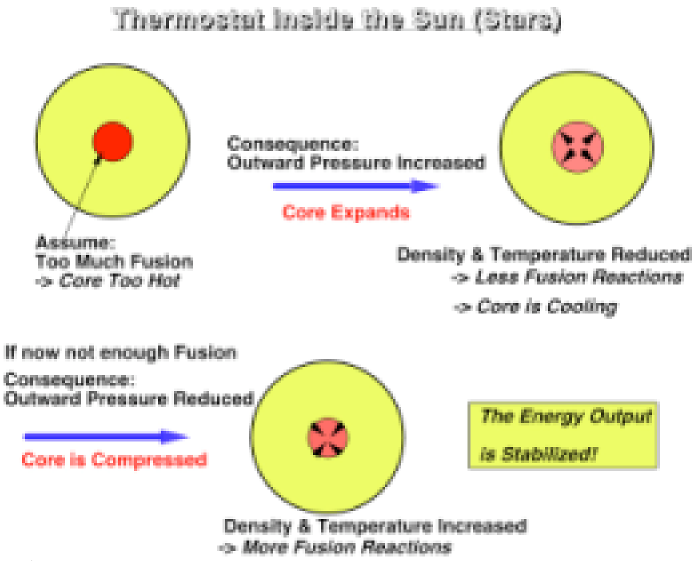
the rich are squandering their resources
whereas
the poor struggle to keep their stuff together to make ends meet.

B) Basic model of stars (like sun)

The compilation the observations about stars with their distribution in the *Hertzsprung-Russell* Diagram and their relationship between luminosity and mass provides us with a handle on how the stars function.

a) Life on the Main Sequence

How does this work? How does the stars manage to set their luminosity in relationship to their mass? The answer is:



View X.5

The Stars' Thermostat

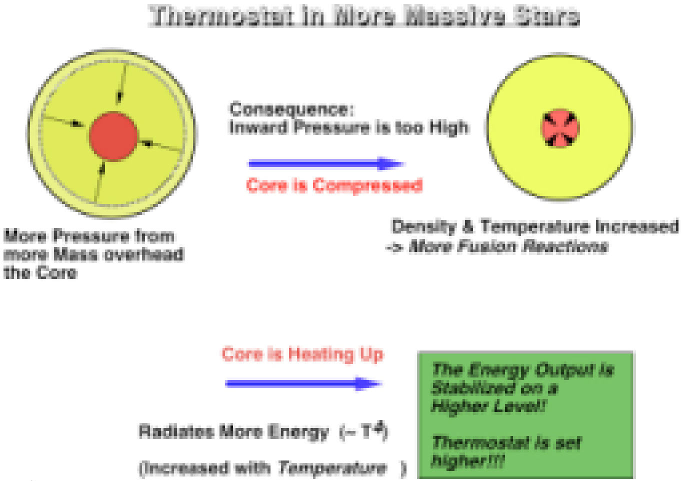
We have learned, while studying the sun, that in its interior the pressure, the density, and temperature increase inwards. And finally in the center the temperature and density are high enough that nuclear fusion goes on at a high enough rate. This energy source keeps the temperature and pressure high enough that all the sun's (star's) material is supported by **hydrostatic equilibrium**. But why so stable and just right for any star no matter what its size? There is a sensitive **thermostat** in the interior of our stars, in analogy to our thermostat in the living room: We set a comfortable temperature. If the thermostat finds the room temperature is too low, it turns up the furnace. If the temperature is too low, it turns down the furnace. Thus the temperature remains stable in the room. We need a specific technical device to achieve this. The stars have natural built in mechanism: View X.5

Assume it gets too hot in the core, i.e., the hydrogen furnace burns too strong
-> now the **pressure is increased**, and the **core expands**
-> this **decreases** the **density** of hydrogen
-> now less H nuclei meet and the **fusion winds down**
-> the **temperature decreases**
-> the **pressure decreases**, and the **core shrinks**
-> this **increases** the **density** of hydrogen
-> more H nuclei meet and **fusion is enhanced**
Thus the star just knows how to counteract any deviation from its equilibrium and remains stable for a long time.

b) Core compression:

The thermostat of a more massive star is set higher than that of a low mass star.
More massive star → higher central pressure → **hotter, denser** →
more fusion → more luminosity → **fuel used faster** → *shorter* life.
as can be easily seen from the way the thermostat functions. View X.6a

All the stars, which **burn H** in their core, are found on the **Main Sequence** in the H-R Diagram. As a consequence of the above relation their position is only determined by their mass! A star stays on the main sequence for a long time, since it contains lots of hydrogen.



View X.6a

However, this relation, i.e. that a more massive star has a hotter core and therefore burns fuel faster provides a surprising hint on, what happens in an aging star. Hydrogen in the core is used during the life of the star. Thus the "ash" of the fusion process, He, replaces part of the fuel in the core. Now less H nuclei are in the same volume. In struggling with this loss of efficiency the core shrinks and thus **gets hotter** due to gravitational compression. Now both

Temperature and density get **higher** in the core

Slide X.6

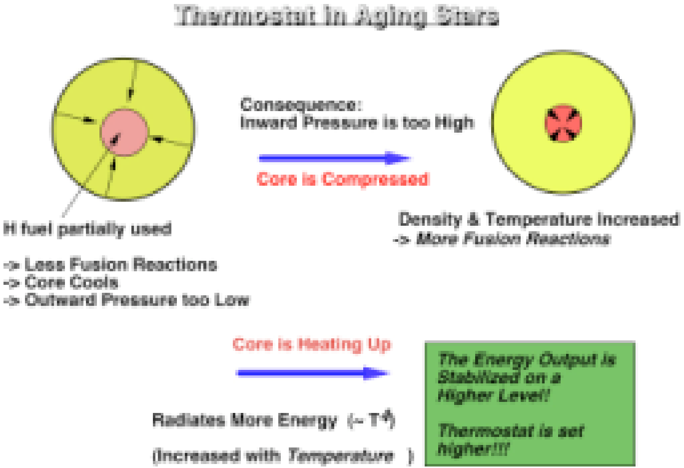
As a result the fusion rate in the star increases slightly with time.

View X.6b

Therefore, also the luminosity of the star increases. This is why the Main Sequence in the H-R Diagram has a significant width.

Computer View (H-R)

This leads us to an amazing conclusion: the sun was much dimmer in the early history of the solar system, i.e. also when life on Earth began. This strange puzzle is called the *"Early Sun Paradox"*: The sun was **about 25% less luminous** at that time. This has to be taken as a solid fact from star models.



View X.6b

But then how could life start under such cold conditions?
A possible answer is that **more carbon dioxide** may have been in the Earth's atmosphere (maybe due to more volcanoes at that time?) which presumably led to a **stronger greenhouse effect** and helped to keep the early Earth warm. Scientists are still struggling with some puzzling details: If the Earth's atmosphere would have become too cold at any time in the past (by creating CO_2 (dry) ice crystal clouds), the Earth would never have become warm. However, that life exists on Earth tells us that this never happened. We don't know for sure why yet.

4. Aging of stars

What happens, when there is not enough H in the core any more, i.e. the star runs out of fuel? As stated before, this happens to the most massive stars first. The star now alters its characteristics significantly. The star will leave the Main Sequence. Evidence for this behavior can be drawn from H-R Diagrams of star clusters. All stars in a Cluster were born at the same time, i.e., it provides a snapshot with stars at the same age, but in different stages of their life. View X.7

In a young cluster like the Pleiades the most massive stars lust start to leave the main sequence. In an older cluster this turn-off point is found already for stars with about 10 times the solar mass. as can be seen the stars become

brighter and **colder**

This means, they grow in size. They become **Red Giants**.

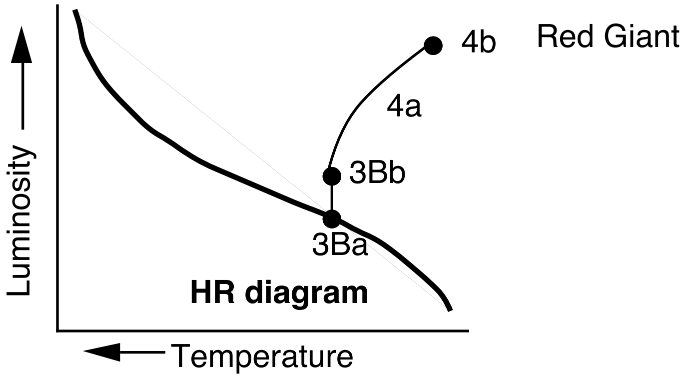
Computer View (H-R)

a) Burnt Out Core and Shell Burning

Almost no H is left in the very core. It consists of He and no fusion is possible any more. Since there is not enough pressure to withstand the weight of the material above, the He core shrinks to maintain pressure and drags down overlying H.

Slide X.7

Now there is a hot core underneath a **H shell**. Like on a hot oven plate the overlying H starts **"burning"**. Since it burns at a higher temperature the luminosity increases. The surface expands and cools, and thus becomes red. The result is a **Red Giant**. Slide X.8

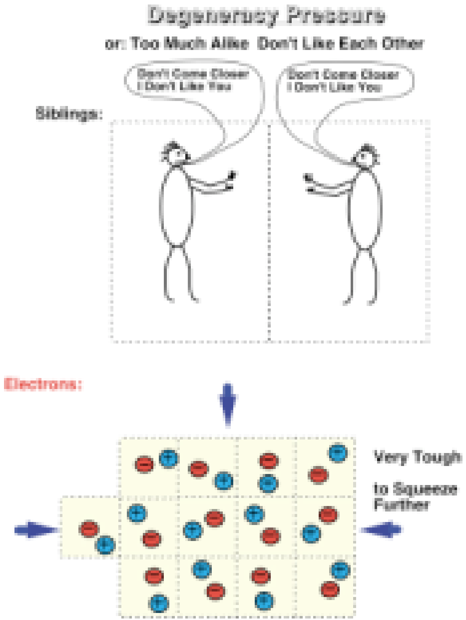


b) Degenerate He Core

Now something strange happens to the star's core:
The material is compressed more and more. So far the pressure has increased due to the increasing energy or increasing velocity of the particles. The core consists of He nuclei and electrons now, and the particles have come so close to each other the sheer proximity poses an obstacle to further shrinkage. Beyond a certain density the electrons themselves start to resist being squeezed further. View X.8

Electrons don't like to meet too closely their identical counterparts. As an analogy, sometimes two siblings don't like to be too close together and rather move apart. This property of the electrons is called **Degeneracy**.

Electrons can't be packed too close together, because this causes a huge pressure. The closer the electrons come to each other, the higher the pressure.



View X.8

Now the core can continue to be heated, but the **rising temperature does not increase the pressure** any more. However, at a temperature of about 100 Million K He nuclei start to fuse. Since the **core does not expand** as a reaction to **heating** a lot of the He burns in huge **He flash**. The star's **thermostat** simply **does not work** under these conditions. For a brief moment the star’s core is a giant nuclear fusion bomb.

c) He Burning

After the flash the He burning and related temperature increase destroys the degeneracy pressure condition. For some time the star has regained its thermostat again. The He core fusion now produces C and O. During this phase the luminosity decreases, the surface shrinks and warms up. The star is now building up a **C and O core**, where again the fusion ceases after some time. A **He-"burning" shell** develops with an overlying H-"burning" shell **Slide X.9**

The evolution is similar to the burnout of H.

d) Formation of Heavier Elements

The core shrinks further and becomes hotter. The conditions are met to fuse even heavier elements. By adding more He nuclei Ne, Si, S are formed. Finally, elements are made up to Fe *(Fowler*: Nobel Prize) in the innermost shells. The star looks like a huge onion now with its many different layers. **Slide X.10**

Now the star faces an enormous **energy crisis**. It runs out of fuel. To create elements **heavier than Fe *requires* energy**, rather than providing energy.

Fe nucleus + (something) → *more* mass than sum of parts. All nuclei heavier than Fe weigh more than Fe plus some H or He nuclei.

To produce anything beyond Fe requires **energy** to be **converted into mass**. The only thinkable energy must come from ***gravity***. This requires further shrinkage. At this point we should bear in mind that each of the additional fusion steps requires a higher temperature, thus a higher pressure, and consequently a larger star mass. Depending on the mass, the path of the star may stop at any of the steps in between. But what is the final step after all possible fuel is expended?

Before we move on to the last chapter of the stars’ life, let us briefly review what we achieved up to here.

Tests of Star Models

Can we believe this elaborate picture? We have indeed ample evidence for the model as presented.

It fits the
- **Temperature - luminosity relation** (in the HR diagram) and the
- **Mass-luminosity relation**.

It explains the
- **Abundance of heavy elements** at least up to Fe

  and the
- **Star Tracks**

in H-R Diagrams of clusters of stars with the same age.

We yet have to explain:
- Why the elements leave the stars again?
- Why are there at all elements heavier than Fe?

That has to do with the very final stages of the very heavy stars’ life.

5. Star deaths

How do the stars end their life? In the picture drawn so far, I have pretended that all stars follow the same path. This is true for the first step, but when it comes to the burning of He the paths split, depending on how much mass a star has. With not enough mass the star will never manage to ignite the furnace again after its H fuel has burnt out. Thus we have to differentiate between stars according to their mass.

Laserdisc Life Cycle of the Sun
Astronomy, Side 1, Chap. 37

We will see that stars will die in a dramatically different way depending on their mass. Low mass stars die slowly whereas heavier stars come up with quite spectacular events towards the end of their life. **Computer, H-R Diagram**

A) Low mass stars

a) Mass loss via winds and/or pulsed ejection

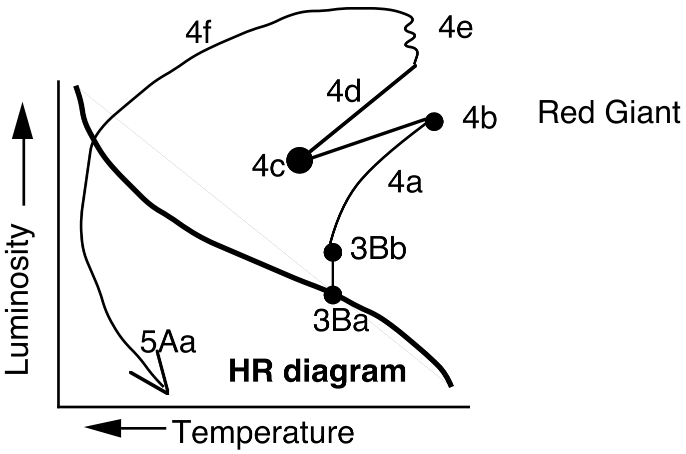
Red Giants burn in an unstable way. This can go as far as ejecting some material of the outer layers of the star. Finally, almost all of the outer shell gets ejected.

HST JPEG Death of Star
HST Hourglass nebula
HST Cat's eye nebula

(Planetary Nebula) **Slide X.13**

They eject material in bursts. It can even be the complete outer shell of a red giant. The result in the sky is a nebula around the star, which looks ring-like, because more light comes from the edge of the sphere. **View X.12**

These nebulae are called planetary nebulae (since at first they were compared with the disc shape the planets are seen in a telescope). These nebulae contain the excess material of the star, which brings it into the limit to become a white dwarf. This is also the first sign of recycling of star material. It ends up again in the interstellar matter and may be built into new stars. **View H-R Diagram**



In connection with the burnout of the H fuel we have seen that the core contracts, until the degeneracy pressure of the electrons stops further compression. The star's energy radiation is now balanced again by loss of gravitational energy (as during the formation of the star). The contraction due to gravity makes the core hotter and more compact. Finally, the electrons can't be packed closer together and the **"electron degeneracy"** supports a **huge pressure.** If the mass of the star is less than 0.4 of the sun's mass, the core will never get hot enough to start the He burning. Therefore, this is the end of the energy production of such a star. If the star is heavy, this goes on to C, O and even further, but at a certain point no new reaction can be started.

a) White Dwarf

The result is a **White Dwarf,** which is the star's corpse. At this point all the remaining star matter has been attracted into the core. The White Dwarf is completely supported by electron degeneracy pressure. Therefore, the White Dwarf will not shrink any further, since the electrons are already as close as they can get under the gravity of the star.

Such a star typically has a size close to the Earth. Imagine a star of the size of the Earth! The material is incredibly compressed:

1 cm^3 (about the size of a sugar cube) would weigh **1 Ton = 1000 kg on Earth**! The typical surface temperature at this point is ≈15,000 K. Now the star will only cool further, i.e. it will move to the lower right in the H-R diagram and will finally become dark and invisible.

Slide X.11

Slide X.12

Our galaxy contains billions of white dwarfs (actually 10% of the stars). The first one discovered was a companion of Sirius, the brightest of our stars. It was discovered by the motion of Sirius in the sky, as if there was another star orbiting, yet unseen.

View X.9

From its brightness (1/10000 of Sirius) and its temperature (≈15000 K) it was concluded that it indeed must have the size of the Earth.

View (WD Earth)

c) Age determination of stars through White Dwarfs

Through new observations by the Hubble Space Telescope a possible problem with the age of the universe has come up: the universe (as measured from its expansion starting from the beginning; we will talk about this later) seems to be younger than its oldest stars. Now there is the good possibility that our knowledge of the age of stars is not the best, since we have gained this from the complicated picture of the stars' life with all the steps. To base this on something simpler astronomers are looking for evidence in the White Dwarfs. Deducing their age is much simpler and therefore believed to be more precise.

White Dwarfs cool with age, and this depends only on their mass. A heavier White Dwarf cools slower. As an analogy: a larger cooking pot takes longer to cool than a smaller one! For the heaviest White Dwarfs this time span of cooling is much longer than the previous life of their stars. We know that all White Dwarfs start with about the same temperature

View WD Age a

Now we search for the dimmest White Dwarfs

View WD Age b

Because the luminosity of all the White Dwarfs is well known, we can exactly determine how much energy they lose and how fast they cool, and this leads to ages of the oldest White Dwarfs of 8 - 10 Billion years

The oldest stars in Globular Clusters were thought to be ≈ 14 Billion years.

So we have to find White Dwarfs in Globular Clusters? But because of their distance and the low luminosity of White Dwarfs this was hard to do. Again Hubble may come to rescue.
HST WD in M4

d) Mass of WD

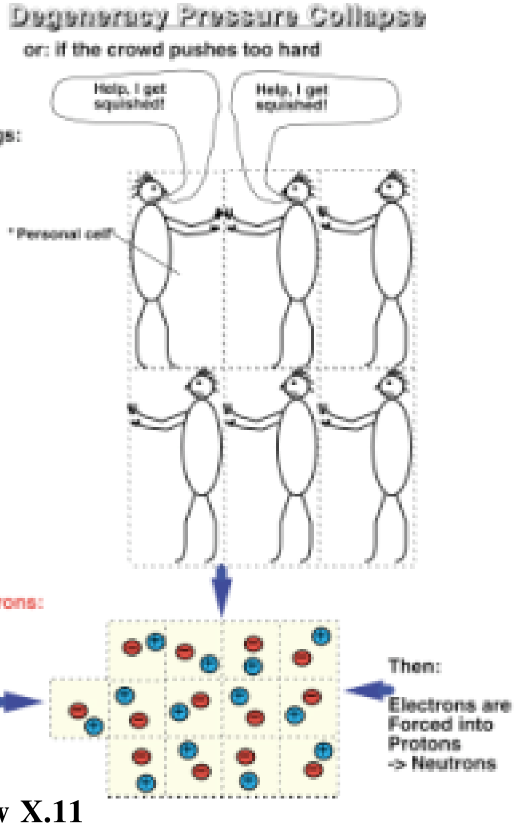
White dwarfs show another very strange property. Normal stars (during their life on the main sequence) with a higher mass also grow larger in size, as long as their interior is controlled by the thermostat. However, the heavier a white dwarf becomes the smaller it is.
View X.10

This makes us wonder when the star shrinks to nothing. Indeed *Chandrasekhar*. (He got the Nobel Prize for his discovery) found that the electron degeneracy cannot support more than a mass of 1.4 solar masses.

White Dwarf < 1.4 Solar Masses

A star with $M > 1.4\ M_{sun}$: will even collapse further. View X.11

This is as if I exert too much pressure on the chalk and it disintegrates into chalk dust. The internal forces of the chalk give up. In the case of the white dwarf the forces of the electrons give up. Demo Chalk



View X.11

B) Binary Stars

Up to here we have only talked about single stars. In principle the evolution of binary stars is similar, since they do not influence each other very much during the main phase of their life. However, in the later stages of their life these systems show a few interesting variations. Let us assume a system in which one of the components is already a dead white dwarf and the other one is just becoming a red giant. Now the red giant may grow into the gravitational sphere of the companion, and material will start to flow over to the companion.
View Binary with mass flow

a) Novae:

This is an example of mass transfer in a binary star system. The White Dwarf gains mass (mostly Hydrogen) from the other star. When more and more H builds up, it is under pressure and high temperature.
HST Nova Cygni

 An explosive (degeneracy) fusion starts on the surface.

Such stars repetitively become very bright. Slide X.15
and throw material into the neighborhood, as seen on this photo 40 years after the explosion of Nova Herculis. Slide X.16
This is another, more dramatic, example of recycling of material in the universe.

b) Type Ia Supernova

A yet more dramatic example of mass transfer in a binary star system and of recycling is the first type of a Supernova. Again we start from a binary system with a White Dwarf and a Red Giant. This time the mass of the White Dwarf is almost the limiting mass of White Dwarves (just somewhat less than 1.4 M_S).
A star with M > 1.4 M_{sun}: will even collapse further. **View X.11**
This is as if I exert too much pressure on the chalk and it disintegrates into chalk dust. The internal forces of the chalk give up. In the case of the white dwarf the forces of the electrons give up. **Demo Chalk**

Adding more mass to the White Dwarf ⇒ shrinks ⇒ hotter interior

View X.12
Finally, it leads to a **collapse when M > 1.4 M_S**, since the mass cannot be supported any more. However, the sudden compression leads to a sudden flash of fusion of all the elements that were already built up (from H to C) (very rapid due to degeneracy). As a consequence the White Dwarf explodes. In the process of the explosion this supernova sets free all the material in its interior and again recycles the material into the interstellar medium.
Since such stars collapse and explode with exactly the same mass (1.4 M_S) Type Ia Supernovae have all the **same luminosity!!** Therefore, they form excellent bright **Standard Candles.** Since they are bright, they can be used to determine distances even farther out than with Cepheid Variable stars. (We will come back to this issue in Chapter XIII.)

The categorization Type I Supernova suggests that there must also be Type II Supernovae. This is indeed the case, and we can distinguish them according to their light curves, i.e., the way, how the luminosity changes with time after the initial flash.
There is no remainder from a SN Type Ia!! But they have a very characteristic light curve!
View X.13
Type II Supernovae signal the death of stars with a very high mass, not necessarily in binary systems.

C) High mass stars

Stars with masses higher than 3-4 solar masses all die with a huge Bang! They have accumulated enough mass to increase the core temperature enough so that elements up to iron are produced.

The core shrinks further and becomes hotter. The conditions are met to fuse even heavier elements. By adding more He nuclei Ne, Si, S are formed. Finally, elements are made up to Fe (Fowler: Nobel Prize) in the innermost shells. The star looks like a huge onion now with its many different layers. **Slide X.10**

Now the star faces an enormous **energy crisis**. It runs out of fuel. To create elements **heavier than Fe *requires* energy**, rather than providing energy.
Fe nucleus + (something) ⇒ *more* mass than sum of parts. All nuclei heavier than Fe weigh more than Fe plus some H or He nuclei.

To produce anything beyond Fe requires **energy** to be **converted into mass**. The only thinkable energy must come from ***gravity***. This requires further shrinkage.

a) Explosive Processes

To see what happens, let us follow the evolution of the star (Sanduleak) Sk-69202 to its climax. (Anyone knows this star?) This was the famous supernova of 1987 (SN1987a) in the Large Magellanic Cloud, our neighbor galaxy, so that astronomers could watch this event as from the best seat in the theater. It was the first close SN after > 300 years.

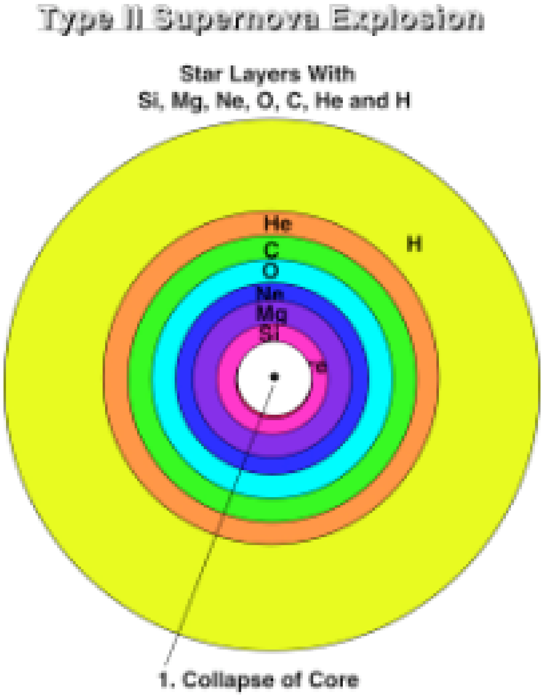
View X.14

Let us follow its complete history: Slide X.17, 17a

Once upon a time ≈**20 million years ago** a star was formed in the LMC with about 12 solar masses, i.e. during the Miocene epoch on Earth when ape-like animals developed on Earth. It burnt all its **H** in only ≈ **15 million years**, during the evolution to the great-great ancestors of Man on Earth. **Helium** burning started at the end of Pliocene ≈ **5 million years ago. Carbon** burning started during the dawn of human history (at the time of the cave paintings of Lascaux, of Stonehenge, **≈ 5000 years ago**) for several thousand years. There is a significant acceleration in the evolution! The available energy reservoir becomes smaller and smaller. By **1980 Oxygen** and **Neon** burning started. Slide X.18

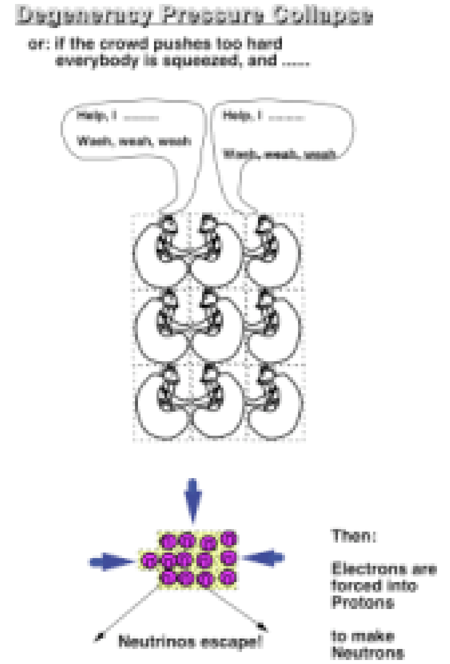
On about **February 20, 1987**, **Silicon** burning started to go via some other elements quickly to **iron**. The last nuclear burning stages lasted only minutes and seconds.

On **February 23, 1987, at 7:35 UT** (We have to see these times as 170,000 years in the past, since the star is 170,000 light years away.) the iron core was so heavy that the degeneracy pressure couldn't hold it any more. Fe core gains mass from the ongoing fusion in the overlying layers, the electron degeneracy fails. The result is a collapse into **neutron star** core or **black hole** core. View X.15



View X.15

First question:



View X.16

How did we learn about this time so exactly? Did someone happen to see the star flash up? No, of course not! This cannot be so fast! The information has to work its way up through the star.

As from the nuclear reactions in the sun's interior, the **Neutrino**s are the messengers. During the collapse the electrons are forced into the protons: View X.16

e + p + squeeze □ neutron + neutrino

This is where most of the SN energy goes. There is an incredible flash of Neutrinos: $1.6*10^{16}$ neutrinos/m^2 have passed the Earth and each of our bodies on Febr. 23, 1987, but nobody felt a thing, since they go through matter like through vacuum. They were measured with neutrino detectors that were used for the sun.

View X.17

This was an opening event for **Neutrino astronomy**.
The 1987 SN: neutrinos gave *proof* of the neutron star formation. The neutrinos arrived before the light, i.e. the action was in the core of the star! The light still needs to come out. It also helped in the determination of an **upper limit on the neutrino mass** (all neutrinos arrived at same time). Thus neutrinos will not contribute significantly to the *missing mass* in the galaxies.

Second Question:
I thought a supernova is an exploding star, but here everything collapsed. What is wrong?

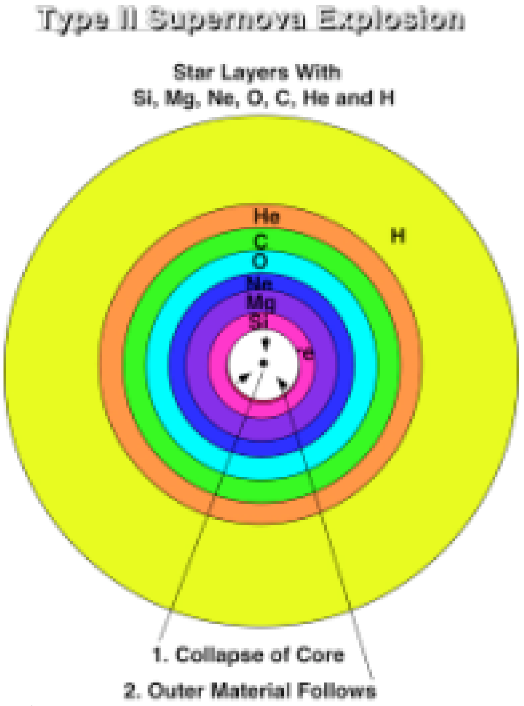
View X.15a

Demo Ball

Nothing is wrong. The rest of the star starts to fall on to this heavy core with an incredible speed and it bounces off the extremely "hard" core. This shock fuels all nuclear reactions and produces all other elements (heavier than iron). This 'Rebound' and the neutrinos from the core lead to expulsion of the outer ≈ 80% of the star.

View X.15b

And the **Energy source = gravity** for all this!
The incredible light emission comes from the expanding hulk of the star. It outshines a whole galaxy, i.e. it can become brighter than 10 billion suns.



View X.15a

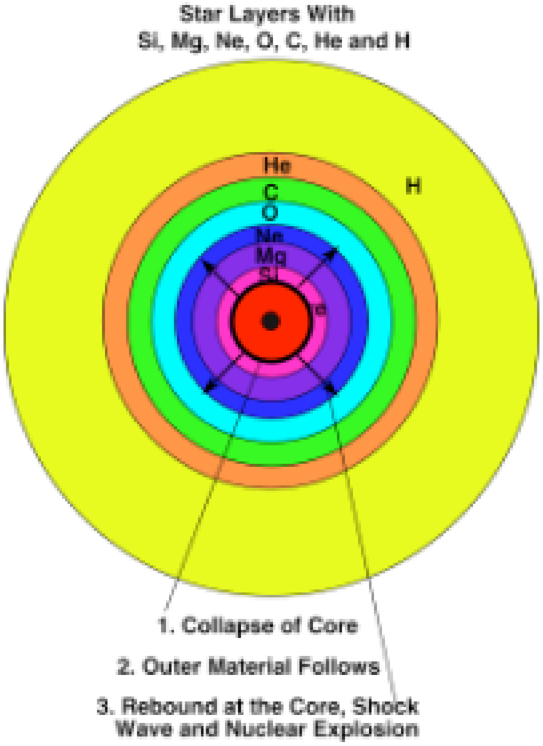
The 1987 event was a beautiful support for the theory that Type II SN's come from massive supergiants. SN 1987: a massive supergiant disappeared.

Slide X.19

We are talking about a Type II SN, which is the most important one for the understanding of the evolution of the universe. I will only mention for completeness that there is another Type (Type I) which is an exploding white dwarf after it has added too much mass from a companion star in a binary star system.

b) Consequences of SN

What are the **SN remnants**?
What do we see after in the sky after the event?
We are lucky that several SN have been observed in the galaxy and reported. The most spectacular event was the SN in the year 1054, reported by Chinese astronomers (as the guest



View X.15b

star) in the constellation of Taurus. 2 more were seen, one of them in 1572 by *Tycho Brahe*

Slide X.20

as seen here on this ancient picture, and another one in 1604 by *Kepler*. Now enough time went by to reveal what happened:
In 1731 an amateur observed a small nebula in Taurus, exactly where the SN in 1054 had been seen.

Slide X.21

It is now known as the Crab nebula. Doppler shift measurements show that it is still an expanding hot nebula (expanding with ≈ 1400 km/sec). Some of the nebulae are visible only with X-ray telescopes & are only now being discovered

Slide X.22, 23

And this is the material, which runs into the neighboring interstellar gas. This makes the SN so important

i. The SN material contains very important ingredients:

SN **produce elements heavier than Fe**: They are the only place in the universe where this can happen!

Fe nucleus + (something) *more* mass than sum of parts.

This *requires energy* to be converted into mass. Supernovae get it from *gravity*.
Again from the **SN 1987** this could be seen directly: **Gamma rays from radioactive cobalt** (which is heavier than iron) were observed:

 proof of heavy element formation in supernovae.

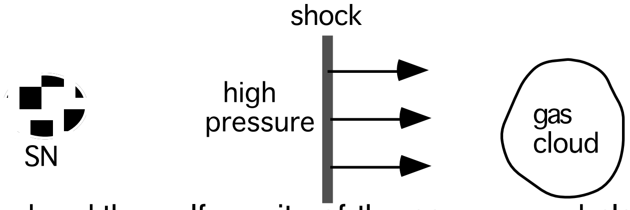
ii. Recycling (we are made of 'star stuff')

The expulsion of star material shows that material is recycled and that we are made of star material. Supernovae are the production sites of the heavier elements.

iii. Strong shocks

The blast wave of the SN produces a shock in the interstellar medium, i.e. a pressure jump after the passage. As we have discussed already, shocks initiate star formation. This leaves us with a nice closed cycle for current star formation.

View X.19



The density increases after the shock passed and the self-gravity of the compressed cloud is increased, it starts to collapse. It may have happened for the Solar system. Some special isotopes have been found in meteorites, which may pinpoint a nearby SN at the beginning of the solar system formation.

Shocks are also efficient particle accelerators. **View X.20**

Particles gain much energy after bouncing repeatedly at the shock. We have discussed this already in the solar system. This is the source of cosmic rays in our galaxy.

c) End Products of the Collapse

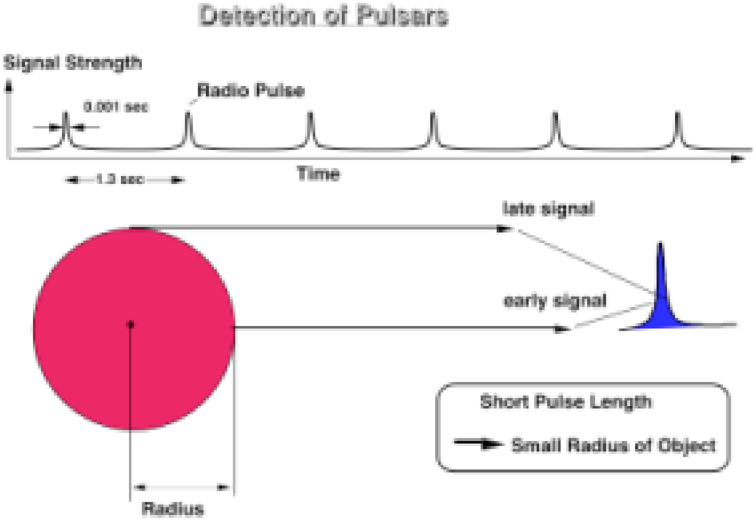
After the expulsion of the outer layers of the SN a **Neutron star** is left behind. As discussed earlier it is formed when $M > 1.4\ M_{sun}$. Otherwise it would have been a white dwarf without the spectacular interlude of the SN. Now the neutrons play the part of the electrons and hold up the

Neutron degeneracy pressure

They behave similar to electrons and cannot squeezed beyond a certain point, but their required volume is much smaller than that of electrons, because they are so much heavier than electrons. A typical neutron star has a diameter of 20 - 30 km (It would fit between here and Portsmouth). Imagine: more than 1.4 Suns in this small volume. If the white dwarf matter was incredibly heavy, this stuff is outrageous:
1 sugar cube of neutron star material would weigh **1 billion tons** on Earth. This object was first predicted around 1930, but could not be found until 1967. It seems ludicrous to look for such a tiny object among the stars. Thus astronomers didn't worry about it.

It was observed by chance by radio astronomers. *Hewish* got the Nobel Prize for it, but it was his graduate student *Jocelyn Bell* who found the strange signal first. It was a short radio pulse with a periodic repetition every ≈ 1.3 sec and was called a **Pulsar**. After checking and dismissing all possible human sources the scientists thought first that it might be signals by other intelligent beings. The pulsar was referred to as LGM source (Little Green Men). However, this was abandoned shortly, because there was no message in the signal, just a regular pulse. Also there were more such sources, and the search for a natural origin was more fruitful.

View X.21



View X.21

The source had to be very small: each pulse lasted only for 0.001 sec. A source cannot be larger than the distance that light would travel during the pulse duration. The first part of the signal comes from the closest point and the last part from the farthest point. 0.001 light seconds is just a few 100 km, i.e. even smaller than a white dwarf. This pointed to the hypothetical Neutron star.

But how do we get these regular pulses?
After the collapse the SN remnant must **rotate very fast**. It has to **conserve the angular momentum**, like the gas cloud when collapsing into the solar system or like our demonstration with the rotating chair. Indeed, if we would collapse a star somewhat bigger than the sun, but with the same rotation, we end up with a rotation period of the neutron star of less than 1 sec.

At the same time the star would get an extremely **strong magnetism** due to the **compression of magnetic field lines**.

The result is a rotating neutron star with strong magnetism.

Slide X.24

The analogy is a lighthouse. Take the time and look at the lighthouse in Portsmouth. There is a rotating light source in the lighthouse, like in our demonstration here.

Demo Lighthouse

Only when the light beam passes over you, you see the light for a brief instant.
Electrons in the strong magnetism produce synchrotron radiation. This is most intense over the magnetic poles of the neutron star, and a beam of radiation is sent along the magnetic

field lines. This is similar to the lighthouse beam. This radiation has been found also in the visible light, in X rays, and in gamma rays. Slide X.25

The energy output of pulsars is tremendous, much higher than that of the sun, but what can be the source? With its strong magnetic field the pulsar holds on to the neighboring material. Thus it can use the **rotational energy**. Prediction: the **rotation** should become **more slowly**. Indeed it is observed that the pulse rate **slows down just at the right rate**.

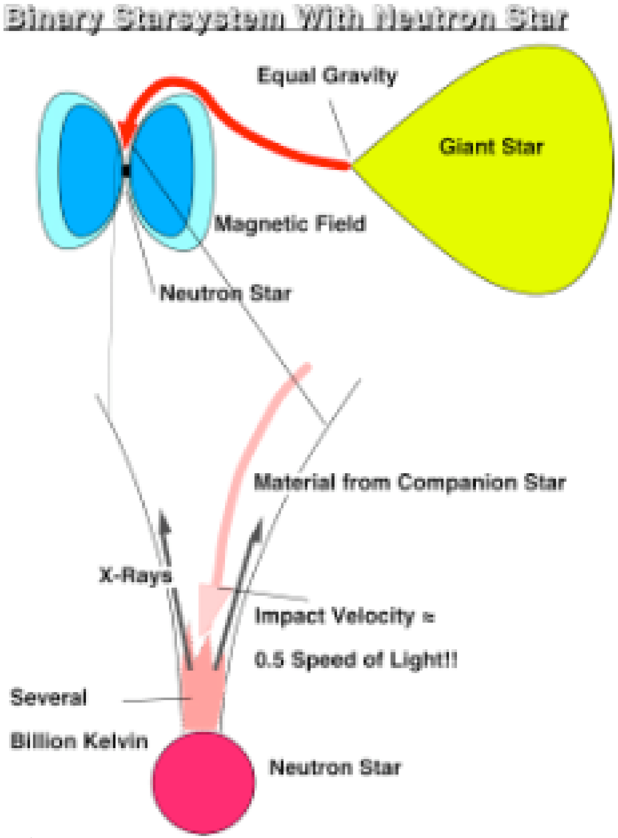
Importance of pulsars:
Pulsars have been used in a variety of fields now:

i. *Proves* that neutron stars exist.
ii. Found in SN remnants. *Proves* the Type II SN scenario.
iii. Energize SN remnants (e.g. synchrotron from Crab Nebula).
iv. Tell us where SN's have occurred. Globular clusters have had many SN's which may have ejected stars from the clusters.
v. Incredibly accurate Clocks in space:

The periodic change of the pulse rate by the Doppler effect is used to detect, e.g. the "new planet" around a pulsar. View X.22

Pulsars are also used to study the interstellar plasma between the pulsar and us.

d) Binary X-ray sources (Systems with Compact objects)



View X.23

Another very spectacular source of X-rays and gamma rays are Binary star systems with a neutron star and a giant star. Slide X.26

The giant star reaches out to the gravity sphere of its neighbor, and a lot of material is transferred.
Mass from the normal star finally falls onto the compact object, i.e. it **approaches the surface** with a **tremendous speed** (up to **half of the speed of light**) and is compressed in the process. As a consequence, it is heated to temperatures such that it emits **X-rays (and gamma rays).** View X.23

Using a Pulsar clock, we can easily determine the orbit of the objects and then get the **mass of the star** from *Kepler's* 3rd law. We can verify if the compact object has the 'right' mass to be a neutron star or not. This provides additional evidence for existence of neutron stars. This is also a test, whether there is the even more dramatic cousin of the neutron star in the system, i.e. a **Black Hole**.

This begs the question: What is the largest mass that can be supported by neutron degeneracy pressure? There is a similar limitation as for white dwarfs. However, before it runs into this trouble the star will simply disappear for us. Beyond this mass limit (of approx. 3 solar masses) a Black Hole will be formed. To decide which one is there, a neutron star or a black hole, a binary system provides us with the means to determine the mass of the stars. **Slide X.27**

We will not be able to see a Black hole, but its influence on the surroundings. Scientists believe that they have discovered a view into the abyss where material flows into a black hole with this picture from the Hubble Space Telescope. **Slide X.28**

Mac Gravitation

We can illustrate this limit, if we ask: What is the **velocity** a particle must have away from the star in order **to escape**? A **rocket launched from the Earth** must run at **11.2 km/sec** at shutdown of the motor, otherwise it will either return to the ground or stay in orbit. For an object as heavy as a star and then becoming smaller and smaller, this velocity becomes huge. For neutron stars it is 0.5 the speed of light. What if it is the speed of light? Well then even light will not escape the surface any more!! The object is invisible for us. However, here we have to talk about some phenomena, which happen at such high speeds. This brings us to Einstein's theory of relativity.