The Once and Future Sun

This is the hypertext version of a public lecture given on 1997 June 12 at the Perkins Observatory in Delaware, Ohio, as part of the 1997 *New Vistas inAstronomy* lecture series.

Introduction

The life cycle of a star, from birth in a dense interstellar cloud to its final end, is a process that lasts anywhere from a few Million years for the most massive stars to many Billions of years for stars like the Sun.

How, then, can we hope to understand a Billion-year process if we astronomers have only been studying the stars with modern techniques for the last 100 years?

A simple analogy illustrates how we do this. Suppose you are a biologist wanting to understand the life cycle of an oak tree. Oak trees can live to be a few hundred years old, yet on an afternoon hike in a forest, you can piece together the sequence in outline not just for oaks, but for all other species of trees in the forest. A little extra fieldwork visiting forests of different ages (old growth and young new growth near abandoned farms), and you should be able to work out all of the relevant timescales. After more advanced work on the detailed biology of individual trees would allow you to discern the basic principles that govern the growth and development, you could relate these to your observations of forests, and develop a comprehensive picture of the life cycle of oaks.

So too with the stars. We can observe clusters of stars all born at about the same time to get an idea of how stars of the same ages but different masses appear. By observing many different star clusters, each with a different age, we have pieced together how the clusters age and work out the timescales of "stellar evolution". By studying individual stars, and working out the detailed physics, we have been able to develop a comprehensive physical theory of the appearance and evolution of stars.

Coming to an understanding of the process of stellar evolution is one of the great triumphs of 20th century astrophysics. We are now sufficiently confident of our results that an apparent discrepancy between the ages of the oldest stars in the Galaxy and the estimated age of the Universe is thought by many to signal weaknesses in our understanding of the evolution of the Universe rather than problems with the theory of stellar evolution. Not all astronomers would agree with that, but I would argue that the physics of stellar evolution is probably on firmer theoretical and observational ground than the physics of the cosmos.

The study of stellar evolution is rich and detailed. In my Astronomy 162 course at Ohio State, we take about 4 weeks to cover all the material. In this lecture, I want to illustrate the highlights of what we know about the evolution of stars in general by highlighting the evolution of a particular star near and dear to all of us: The Sun.

To speak more easily of the timescales and sizes involved, I introduce three relatively unfamiliar units:

1. The Gigayear (Gyr), or 1 Billion Years
2. The Megayear (Myr), or 1 Million Years
3. The Astronomical Unit (AU), which is the current radius of the orbit of the Earth. 1 AU is about 150 Million km.

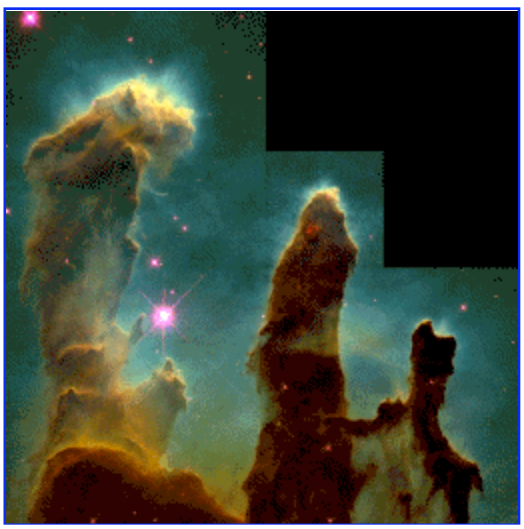
I will be using metric units throughout.

In Darkness Born

The sun formed out of a dark cloud of cold molecular Hydrogen gas and dust.

- Starts out as a dense globule of gas.
- Breaks away from the parent cloud.
- Slowly collapses and heats up.

Overall, the formation process for a star the mass of the Sun takes about 50 Myr.



Credit: NASA & AURA/Space Telescope Science Institute

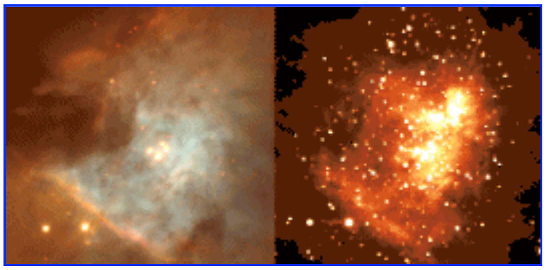
Molecular gas cloud fragments in the Eagle Nebula (M16) star-formation complex. This spectacular Hubble Space Telescope image shows regions of molecular gas and dust, most with faint embedded protostars, being illuminated by a hot young star off the edge of this field of view. The individual lumps breaking off the ends of these "elephant trunks" of gas are comparable in size and mass to the pre-stellar clumps out of which stars like the Sun might form. In this region, however, it appears that many of these clumps are being evaporated by the hot UV radiation from the nearby hot stars before they have a chance to form into low-mass stars.

The Proto-Sun

The proto-Sun slowly contracted while embedded deep within its birth cloud.

At this stage it was only visible as a bright infrared source, since only infrared light can penetrate the surrounding gas and dust clouds.

For example, below are two views of a present-day stellar nursery, the Orion Nebula.


Credit: OSU Astronomy Department

The view on the left is what is seen in visible light. On the right is the same view at infrared wavelengths. Notice how only a handful of faint red stars are seen at visible wavelengths, while in the infrared, we can peer through the dusty Orion molecular cloud and see the rich cluster of young stars recently formed deep within. The quartet of bright stars in the center of the nebula, known collectively as the "Trapezium", will eventually blow away much of the surrounding gas and dust. When that happens in a million years or so, the rich cluster will be visible in the night sky of earth.

A disk of material formed around the proto-Sun, out of which the planets were formed.

Hydrogen Ignition

Collapse of the proto-Sun continued until the core temperature reached 15 Million K:

At this point:

- Fusion of Hydrogen into Helium ignited in the core, releasing energy.
- The extra fusion energy raised the internal pressure enough to stop the gravitational collapse of proto-Sun.
- Sunlight and a fast solar wind streaming off the infant Sun blew away the remaining gas cloud, except for a dense disk of gas and solid particles that formed in the equatorial plane of the proto-Sun.

The material in the equatorial disk steadily coagulated into the planets.

After a few million years, the remaining gas was blow away, and the young Sun emerged as a star shining in the night sky, surrounded by its retinue of 9 planets. The infant solar system was still filed with debris that would take roughly another billion or so years to clear away.

A Star is Born

Hydrogen ignition occurred 4.5 Gyr ago.

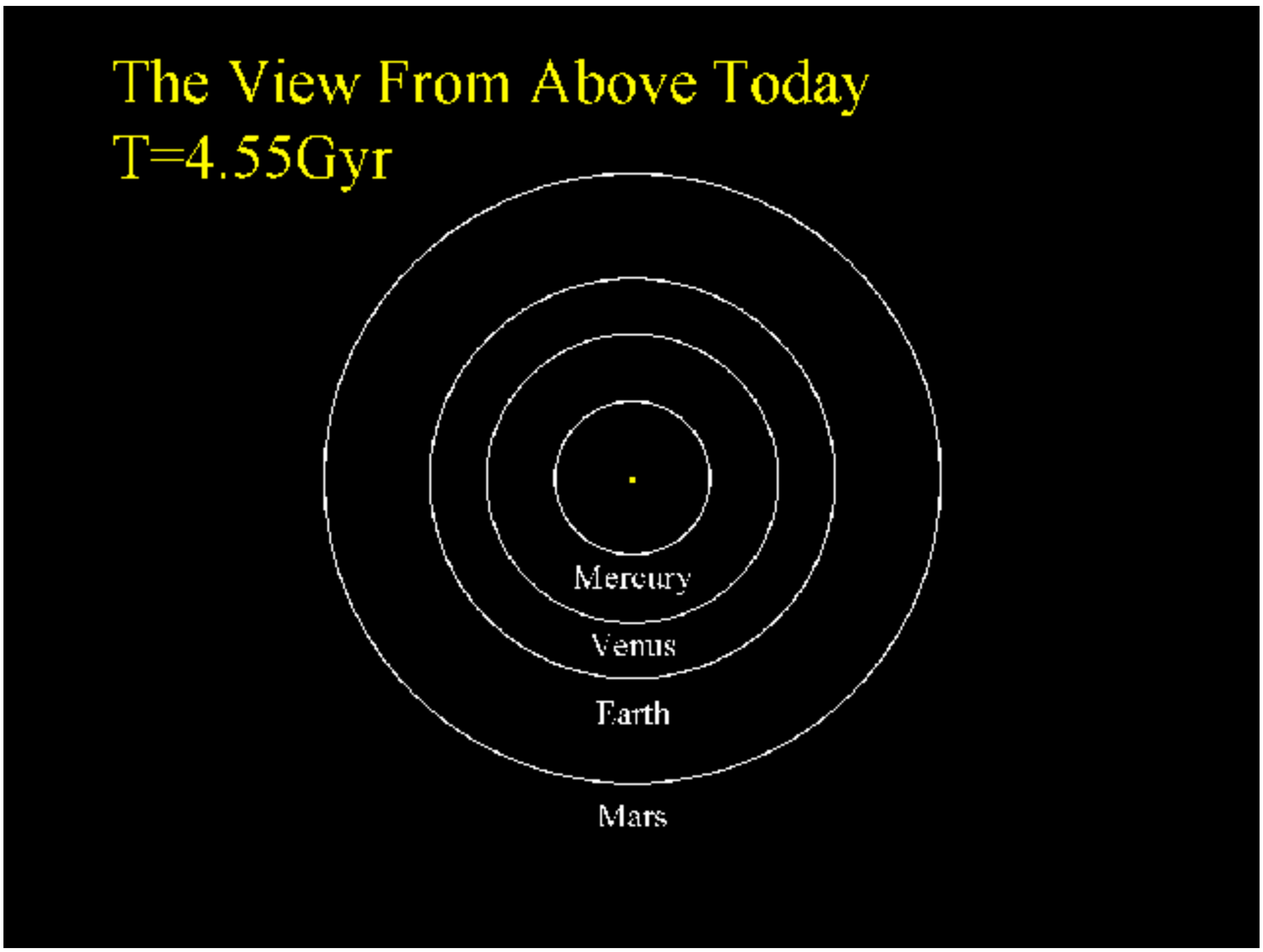
There is sufficient Hydrogen available in the central core of the Sun to sustain nuclear fusion at a fairly constant rate for almost 11 Gyr.

The young Sun started out with slightly different properties than we see today:

- a little smaller: 0.90 R_{sun}
- a little fainter: 0.70 L_{sun}
- a little cooler: 5586 K

There is some evidence in the fossil record of the different properties of the young Sun, as reflected in how sunlight affected life on Earth. This evidence is still hard to read precisely, but it largely confirms in outline the fact that Sun has steadily, if slowly, evolved over the life of the Earth.

The Sun Today



The Sun today is a middle-aged star with the following properties:

Age:	4.55 Billion Years

Mass:	1 $M_{sun} = 1.99 \times 10^{33}$ g
Radius:	1 R_{sun} = 700,000 km
Luminosity:	1 $L_{sun} = 3.83 \times 10^{26}$ Watts
Temperature:	5779 K
Fuel Supply:	50% of the core Hydrogen has been consumed.

The values of the mass, radius, and luminosity (total power output) of the Sun are so large that we will use the current Sun as our basis of comparison when discussing its subsequent evolution.

"Quiet Adulthood"

The Sun evolves very slowly over this time as it consumes Hydrogen in its core:

- grows slightly larger
- gets slightly brighter
- temperature gets slightly hotter then slightly cooler.

Otherwise, very little else happens, so far as the Sun is concerned. For the planets, however, the change in total solar radiation has an impact. For one particular planet, the impact is quite dramatic.

Mid-Life Crisis for the Earth

T=5.6 Gyr (1.1 Gyr from today):

- Sun will be 10% brighter than today.
- Extra solar energy causes a Moist Greenhouse Effect.

The Earth's atmosphere will dry out as water vapor is lost to space. Such a situation will probably spell the end of large surface life on Earth. Some types of marine life and simpler life forms will likely survive in the oceans and localized pools of water.

Venus on Earth

T=8 Gyr (3.5 Gyr from today):

- Sun will be 40% brighter than today.
- Extra solar energy results in a Runaway Greenhouse Effect

The oceans will evaporate into space, and conditions on the Earth will be like those on Venus today. Such conditions will probably mean the end of all forms of terrestrial life.

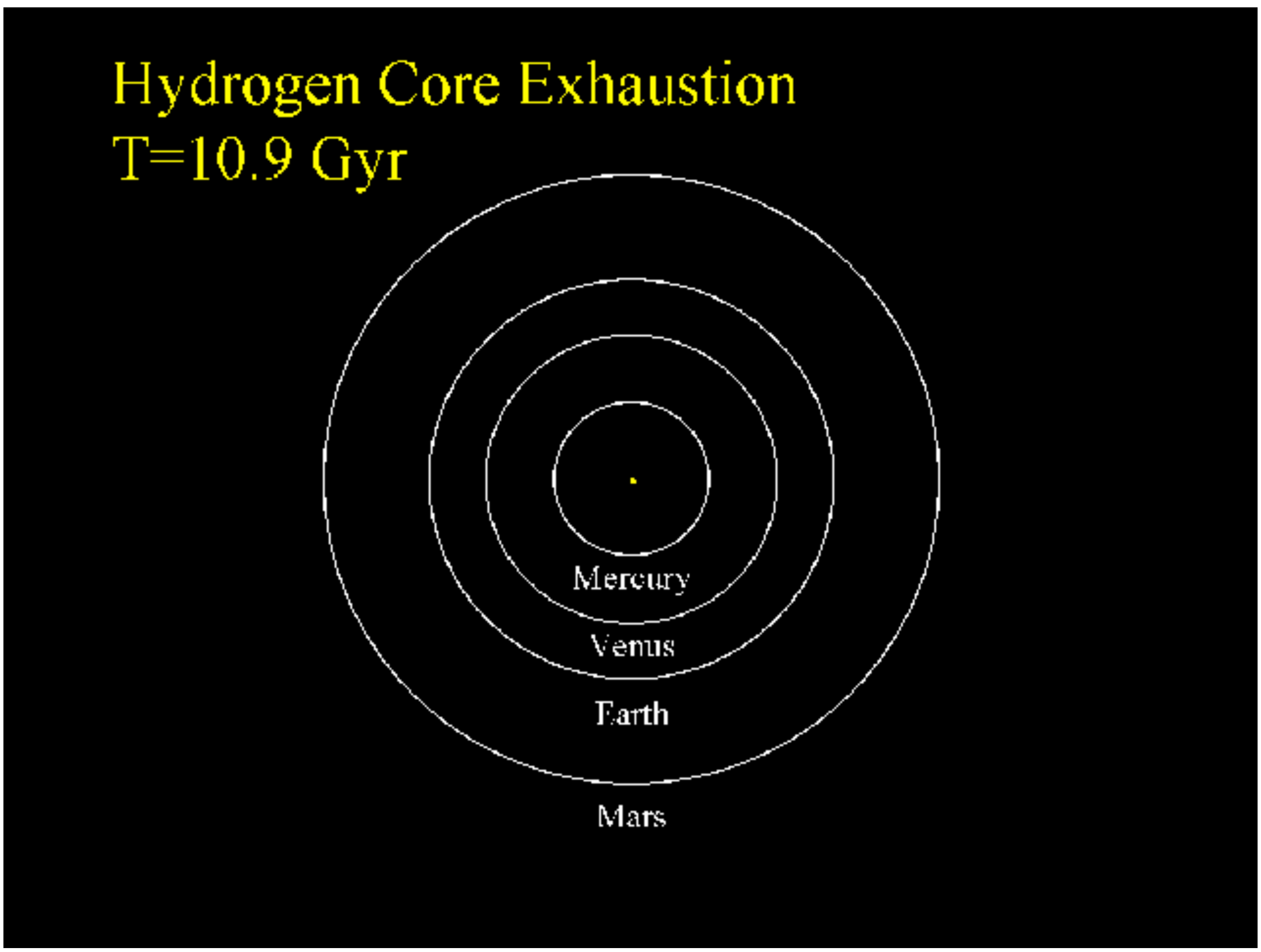
Core Hydrogen Exhaustion (T=10.9 Gyr)

At an age of about 10.9 Gyr:

- The sun's core runs out of Hydrogen
- The inert Helium ash that has built up steadily in the core over the last 11 Gyr becomes unstable and starts to collapse under its own weight. This causes the core to heat up and get denser.
- The last remaining regions of Hydrogen fusion get moved out into a thin shell surrounding the collapsing Helium core.

When this occurs, the sun will:

- Grow a little Bigger: 1.58 R_{sun}
- Gets a little Brighter: 2.21 L_{sun}

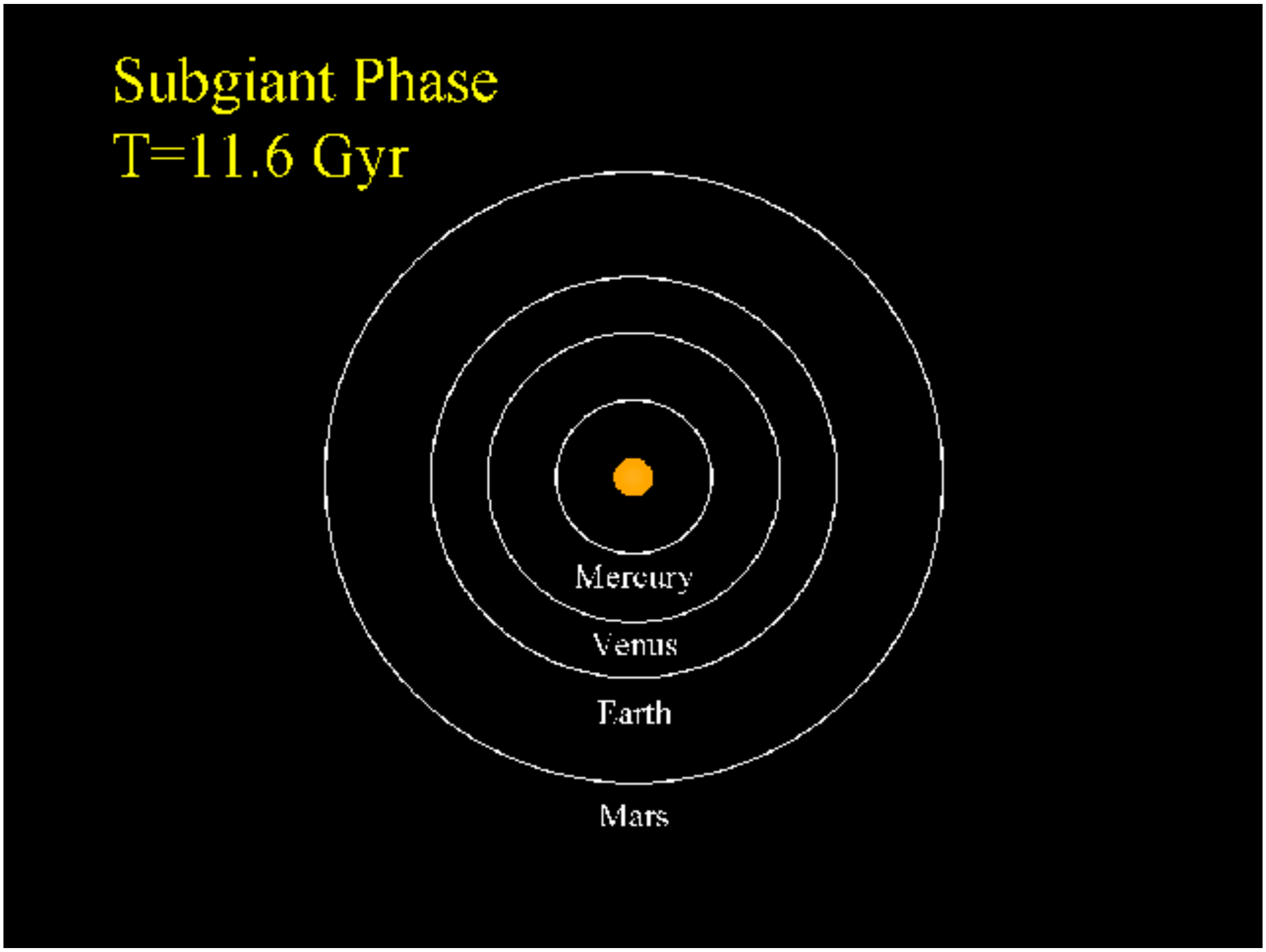


"Lively Old Age"

Slow evolution over the next 700 Myr:

- Brightness stays about constant at 2.2 L_{sun}
- Grows in radius from 1.6 to 2.3 R_{sun}
- Cools from 5517 down to 4902 K

At T=11.6 Gyr, the sun becomes a Subgiant star.



Onset of Rapid Growth

T=11.6 Gyr:

Onset of a 600 Myr period of relatively rapid growth in size.

T=12.15 Gyr:

Strong stellar wind begins to kick in, over the next few Myr the Sun will shed some 28% of its total mass by losing the outer parts of its envelope to the wind.

Lower mass of the Sun results in less central gravity in the Solar System, and the planets slowly move outwards in their orbit in response:

- Venus moves out to about 1 AU
- Earth moves out to about 1.4 AU

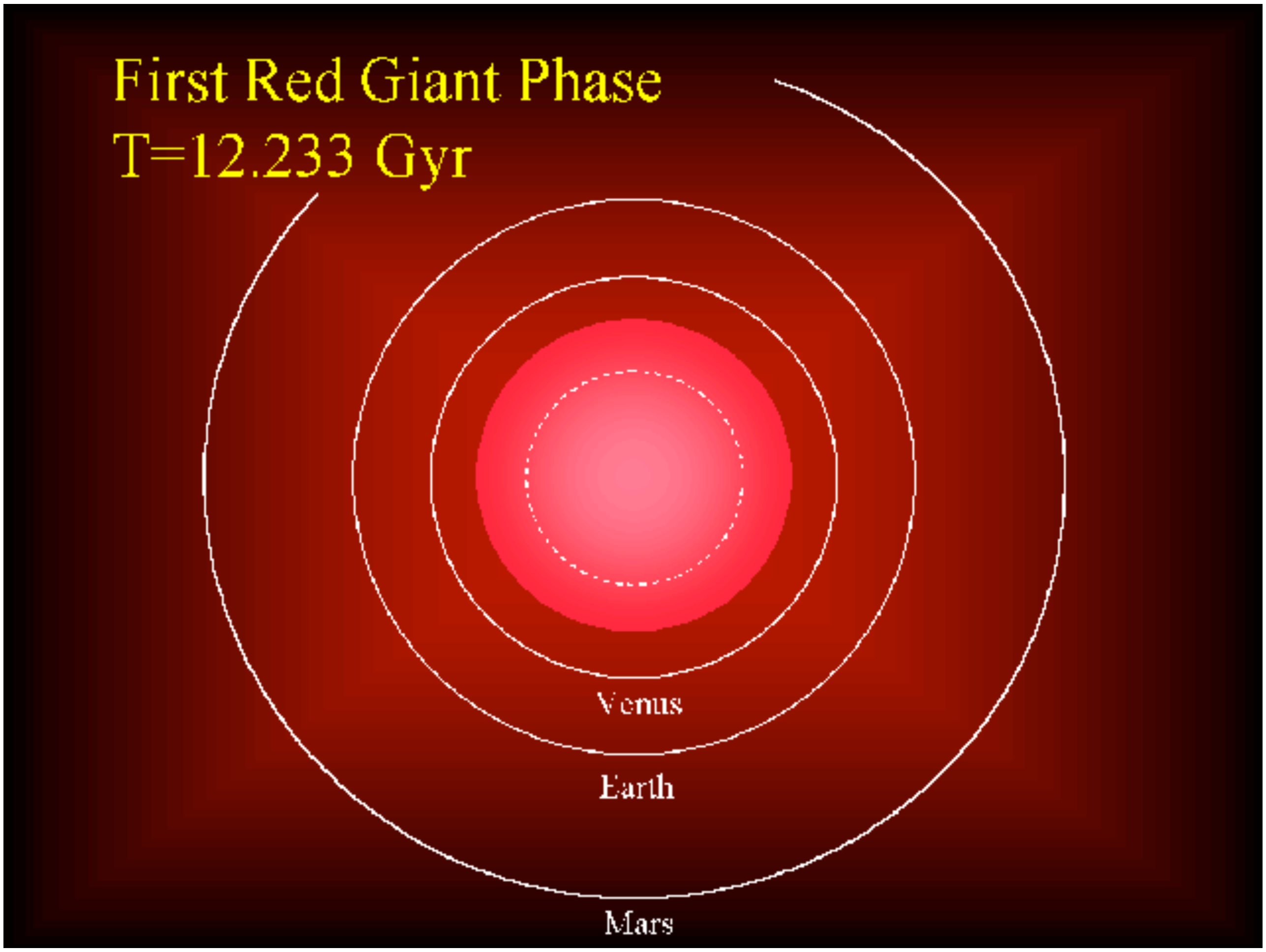
Red Giant Phase

T=12.233 Gyr:

This growth of the Sun (with accompanying mass loss from a strong stellar wind) continues as the Sun evolves into a Red Giant Star:

- Bigger: 166 R_{sun} (0.775 AU)
- Brighter: 2350 L_{sun}
- Cooler: 3107 K

The bloated outer atmosphere of the Sun engulfs Mercury, destroying it.



The dashed line shows the present orbit of Mercury.

The Helium Flash

T=12.233 Gyr:

At the same time that the Sun reaches maximum size as a Red Giant, the Helium core has reached at temperature of about 100 Million degrees. When this happens, Helium fusion ignites in the core, providing a new source of central energy for the Sun:

- Helium fuses into Carbon & Oxygen, releasing energy, although not as efficiently as Hydrogen fusion into Helium before.
- Hydrogen is still fuses into Helium in a thin shell surrounding the fusing Helium core, but it contributes only a small fraction of the total energy being generated.

This new source of nuclear energy has the effect of reversing the previous growth of the Sun.

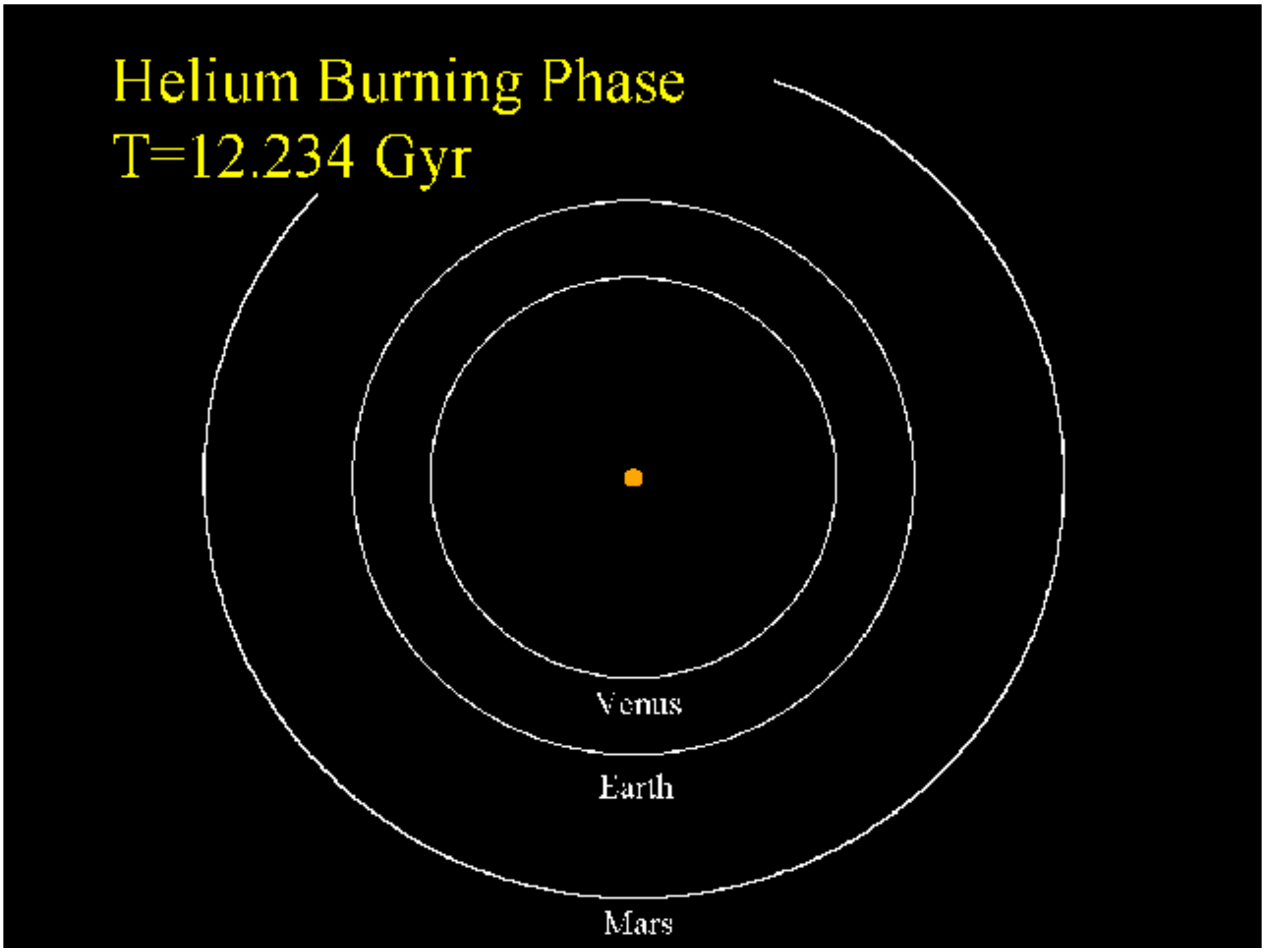
This results in the Sun rapidly rearranging its internal structure, shrinking in size as it does over a roughly 1 Myr period.

Helium Burning Phase

T=12.234 Gyr:

The Sun, with a new source of nuclear energy, settles down for a period of stability as a Helium Burning Star:

- Smaller: 9.5 R_{sun}
- Fainter: 41 L_{sun}
- Hotter: 4724 K



Sun now settles in for a 110 Myr period of relative stability, shining fairly steadily as a Helium-burning star.

The strong stellar wind of the Red Giant phase tapers off during this period.

An All Too Brief Retirement

The Sun burns He to C&O in its core for 110 Myr. As it consumes Helium, C & O ash begins to collect in the core as before, forcing small changes to the Sun's internal structure. The accommodation of this new structure leads to outward changes in the Sun.

As a result, the Sun begins to slowly grow in size again:

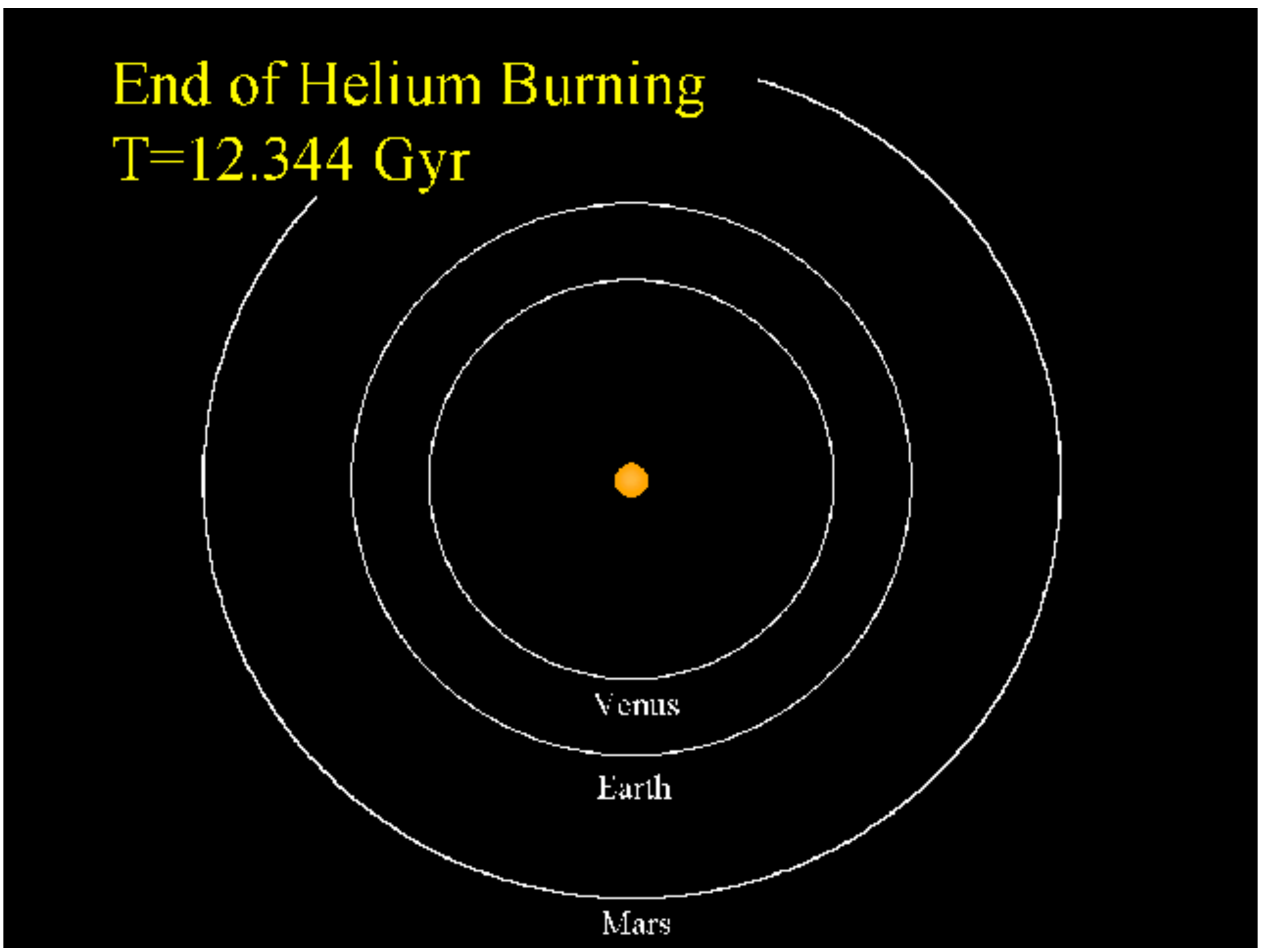
- Bigger: 18 R_{sun}
- Brighter: 110 L_{sun}
- Cooler: 4450 K

Helium Core Exhaustion

T=12.344 Gyr

The Sun's core finally runs out of Helium:

- The C-O ash core begins to collapse rapidly
- This shoves the Helium & Hydrogen fusion regions that remain out into thin shells surrounding the collapsing C-O core.



This leads to the onset of a second rapid growth phase like after the Hydrogen core was exhausted. Only this time, the growth is much more rapid, requiring 20 Million instead of 600 Million years.

Unlike the last time, however, the collapsing C-O core will not get hot enough for Carbon fusion to ignite. This requires a temperature of 600 Million degrees. The Sun is too small in mass to get a core this hot. It appears to happen only in stars of 4 times the mass of the Sun or more.

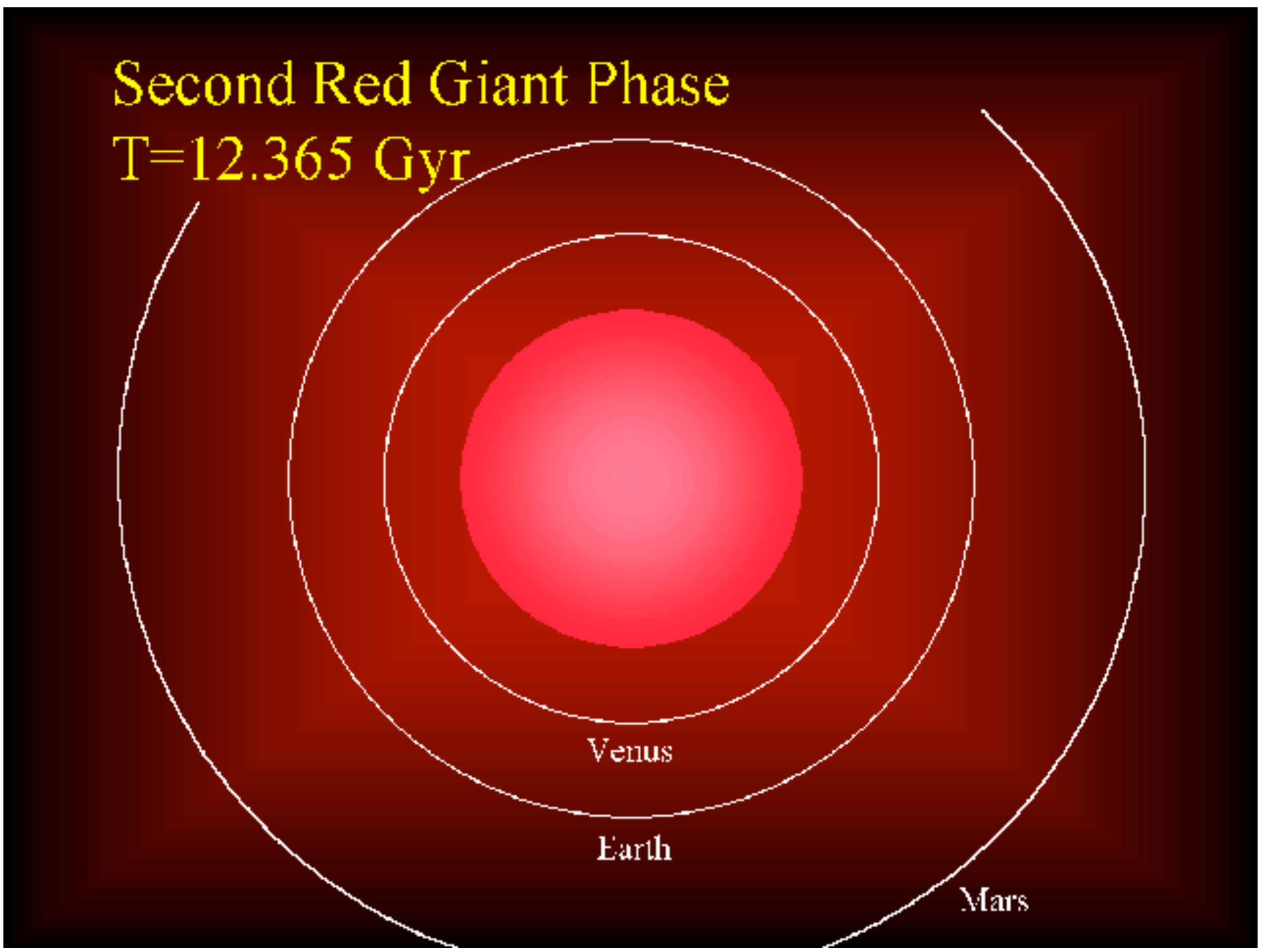
This starts to spell the beginning of the end for the Sun. With no more sources of nuclear energy to tap, the Sun will reach a crisis.

Second Red Giant Phase

T=12.345 Gyr

The Sun experiences very rapid growth over 20 Million years:

- Bigger: 180 R_{sun} (0.84 AU)
- Brighter: 3000 L_{sun}
- Cooler: 3160 K



As it grows, stellar wind gets stronger as the outer portions of the Sun's atmosphere begin to evaporate away into space.

Rapid Mass Loss

Mass loss proceeds rapidly during the second Giant Branch phase.

Eventually, almost 46% of the Sun's original mass will be lost.

The remaining planets move further outward in response to the reduced central mass of the Sun:

- Venus at 1.22 AU
- Earth at 1.69 AU

This is just enough to keep them from being engulfed by the swelling Sun.

The Tremors of Old Age

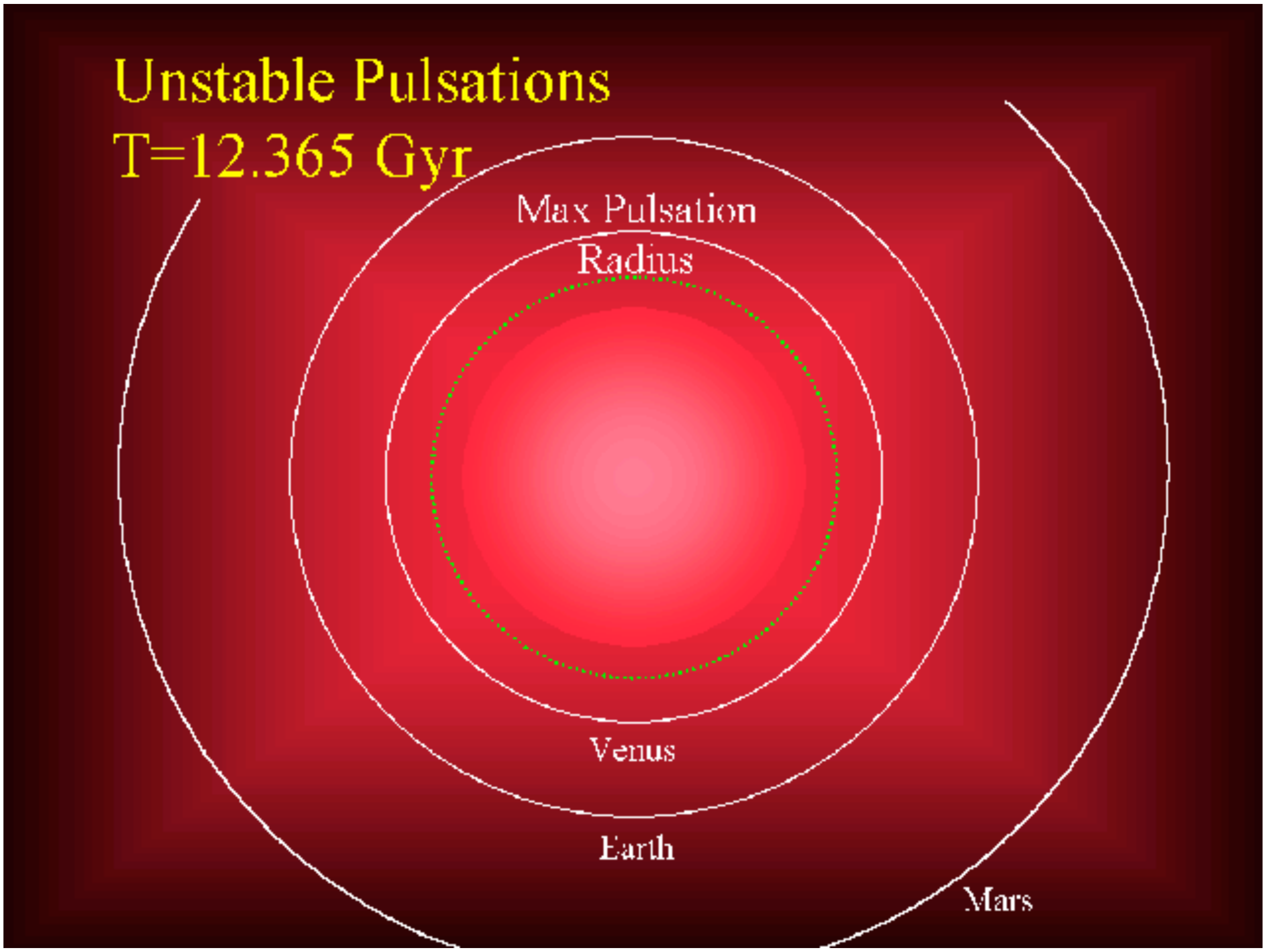
T=12.365 Gyr:

Deep inside the Sun, the thin Helium burning shell riding on top of the inert C-O ash core becomes unstable. This instability takes the form of rapid swings in the nuclear reaction rate which is phenomenally sensitive to small changes in the temperature of the gas (basically, the nuclear fusion rate goes like Temperature to the 40^{th} power!)

Every 100,000 years, the Sun pulses violently:

- Puffs up in size: 213 R_{sun} (~1 AU)
- Gets much Brighter: 5200 L_{sun}
- Some fraction of the envelope is blown off.

Models predict a total of 4 pulses will occur over this period, each ejecting more mass than the last one.



Envelope Ejection

The 4th and Final pulse blows off the last of the envelope over about 100,000 years.

The hot inner C-O core of the Sun is unveiled:

- Size is about the size of the Earth
- Temperature starts out at 120,000K, but then cools off as it loses heat to surrounding space (it has no fusion energy source of its own to make up for the heat losses).
- Brightness starts at about 3500 L_{sun}, then fades rapidly as it cools off.

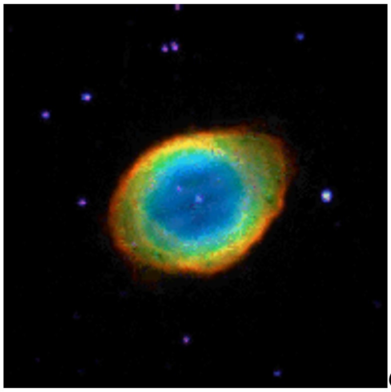
Planetary Nebula Phase

UV photons from the hot naked core ionize and illuminate the ejected envelope.

This gas lights up as a spectacular Planetary Nebula

The glowing envelope of gas expands and disperses in 10,000 years.

Thus the last reward of the Sun for all of the other tribulations at the end of its relatively long life is to enjoy a last, brief flowering as one of the most beautiful and colorful objects in the heavens.


Credit: OSU Astronomy Department

Computer-enhanced color image of the Ring Nebula in Lyra, a Planetary Nebula puffed off the central faint blue star seen in the middle of the ring.

The Final Configuration

The central C-O core of the Sun, now stripped of its envelope and having a mass of only 0.54 M_{sun}, evolves into a slowly cooling White Dwarf the size of Earth.

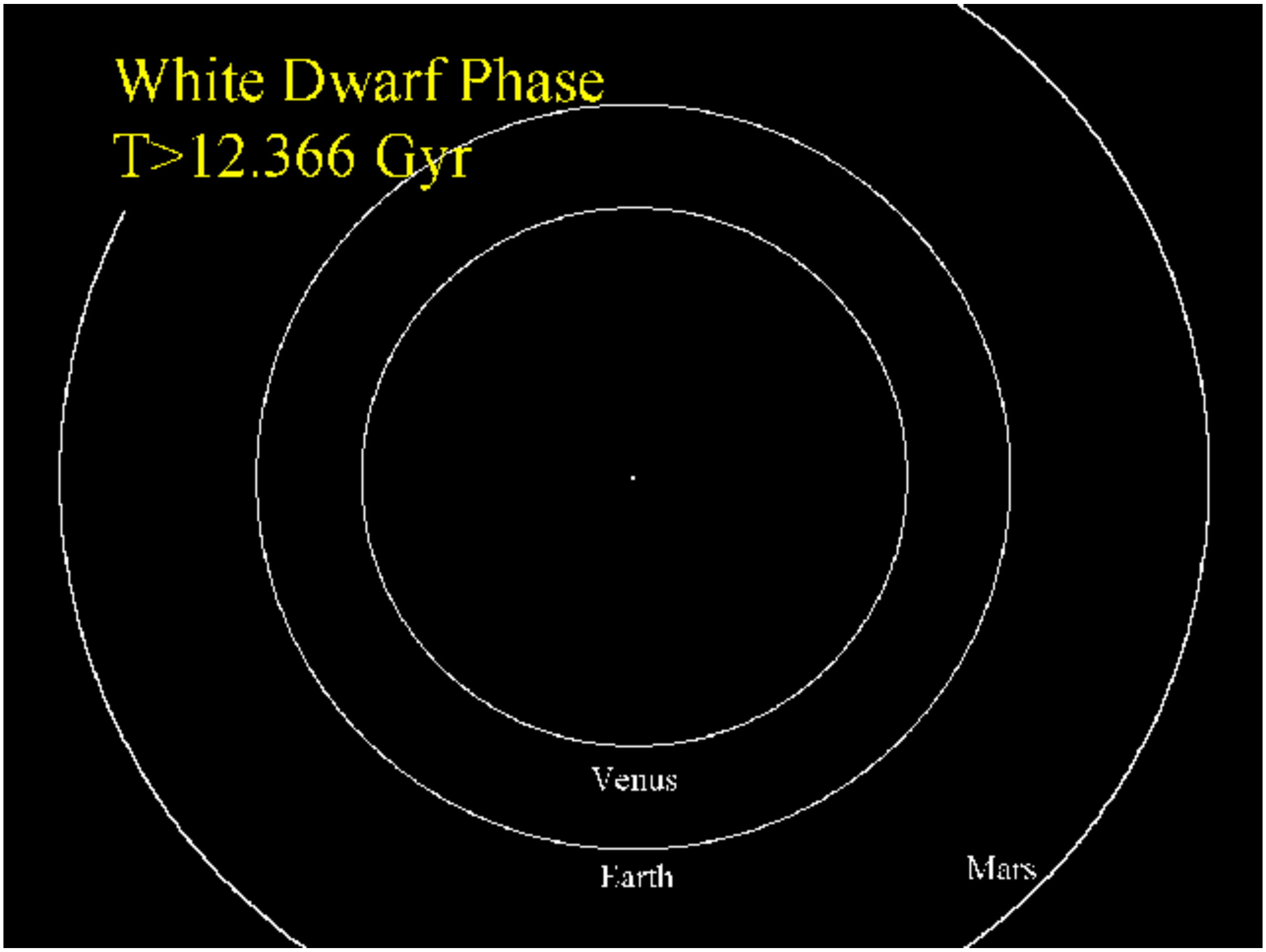
Since it has no more fusion source of its own, it shines only by the leftover heat from its earlier, more exciting days as a hot stellar core.

As it cools off slowly over time, it fades in brightness, finally becoming as cold and dark as empty space around it.

Because a white dwarf is so tiny, it radiates very inefficiently, so it takes Trillions of years for it to cool off completely. Because we think the Universe is only about 15 Billion years old, it is not yet old enough for the first generation of white dwarfs to have cooled off.

Remaining planets settle into their final orbits:

- Venus at 1.34 AU
- Earth at 1.85 AU
- Mars at 2.8 AU



And so on proportionally for all of the others. Since the Sun has lost all of the mass it can, this will represent the final configuration of the Solar System for the future.

The Seven Ages of the Sun

Hydrogen Burning Phase:	11 Gyr
First Red Giant Phase:	1.3 Gyr
Helium Burning Phase:	100 Myr
Second Red Giant Phase:	20 Myr
Unstable Pulsation Phase:	400,000 yr
Planetary Nebula Phase:	10,000 yr
White Dwarf Phase:	forever...

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