Introduction to Astronomy
Lecture 3:
The birth of stars and planets

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THE UNIVERSITY OF SYDNEY

In tonight's lecture

- Forming stars
  - *where stars come from*
- Forming planets
  - *how the planets come together*
- Measuring stars
  - *how we find the brightness and distance of stars*


Forming stars



Our story begins with the vast clouds of gas between the stars.

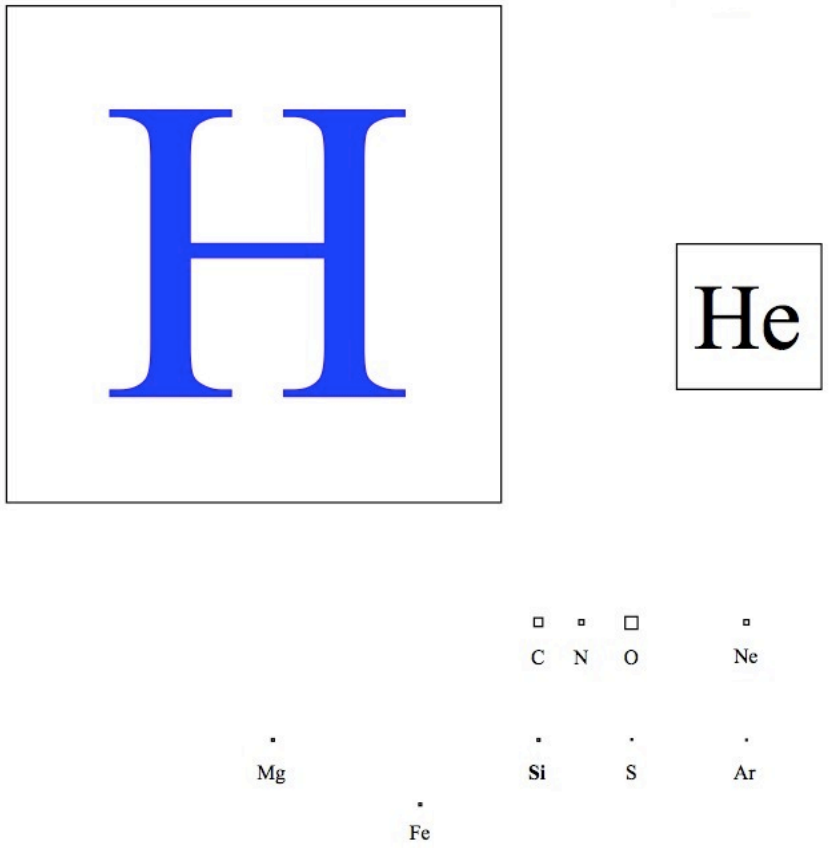
The Great Nebula in Orion, M42

This gas is made up mostly of hydrogen and helium, formed in the Big Bang. However, a small but vital fraction consists of heavier elements like oxygen, carbon and silicon. As we will see in coming weeks, these elements were manufactured deep in the cores of stars, and returned to the interstellar medium when those stars expired. Without these heavier elements, no rocky planets could form.



The Crab Nebula, left behind by the supernova explosion of 1054 AD

The interstellar material from which the solar system formed consists mostly of hydrogen and helium, with other elements less than one-thousandth as abundant as hydrogen.



The "Astronomer's Periodic table", with the size of the element indicating its abundance by weight. (Figure by Ben McCall)

Star formation takes place in the densest regions of clouds, called *dark nebulae*. A famous example is the Horsehead Nebula.

In these regions, shrouded by dust, molecular gas forms and clumps together and the density increases, until the densest regions start to collapse under their own gravity.





The *Hubble* view of the nebula shows the intricate structure of the cloud, with a young star still embedded in the nebula at top left.




Here is a dark nebula you can see: the *Coalsack Nebula*.

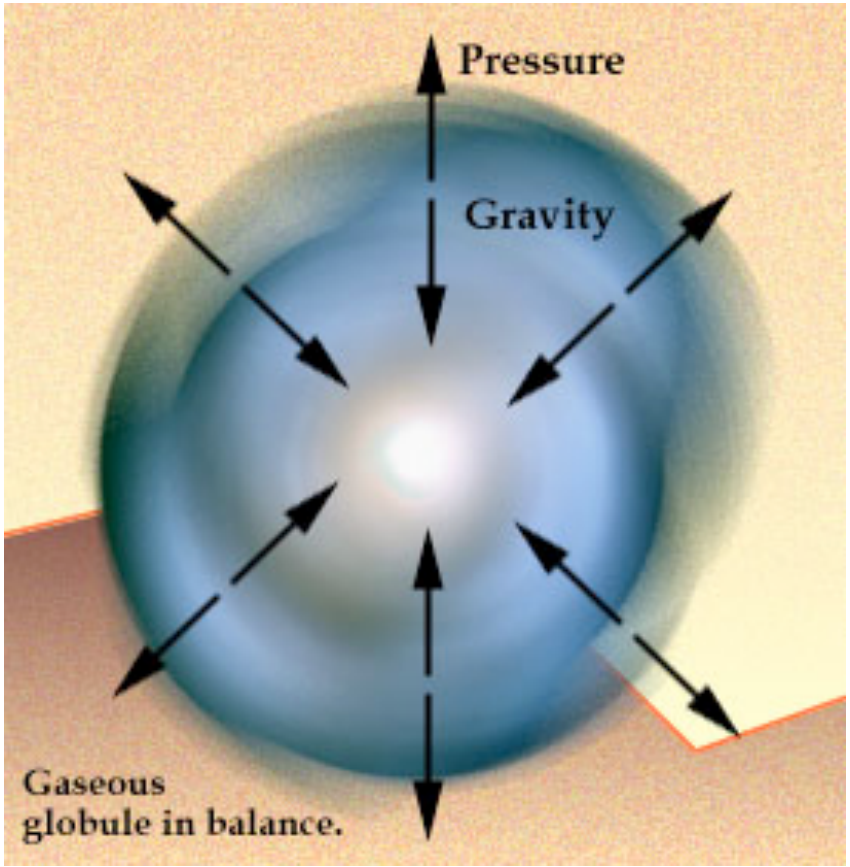
The cloud starts to collapse under its own gravity.

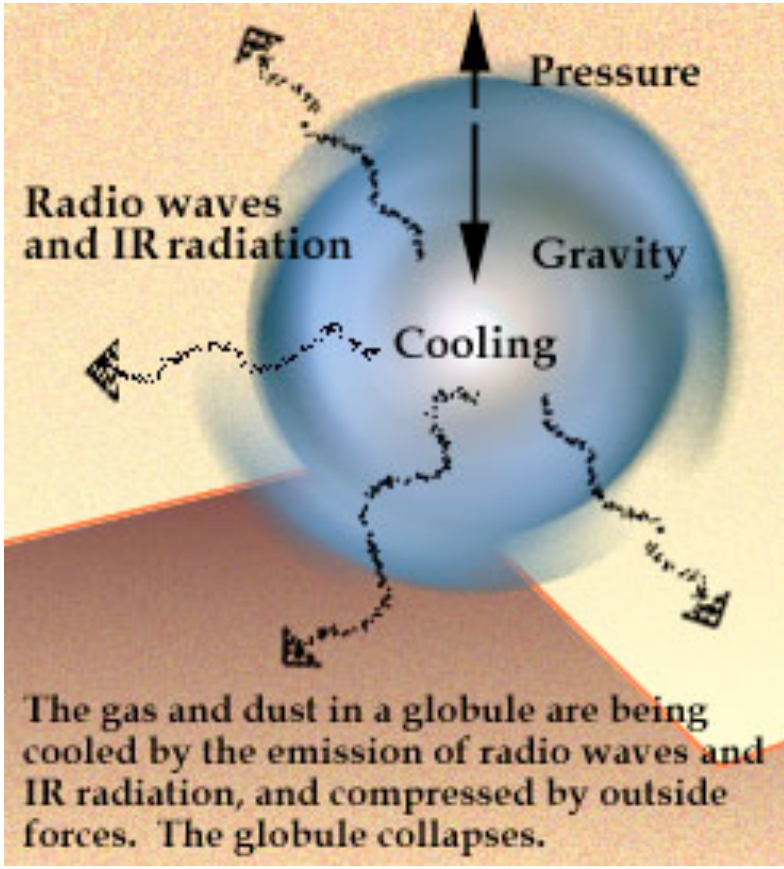
Gravity is the weakest of the four forces which govern our universe – gravity, electromagnetic force, strong nuclear force, and weak nuclear force – but in the end is the most important, because there is no repelling component to gravity.

Every particle in the universe is attracted to every other particle, and the pull is only stopped if some other force stops it, like gas pressure.

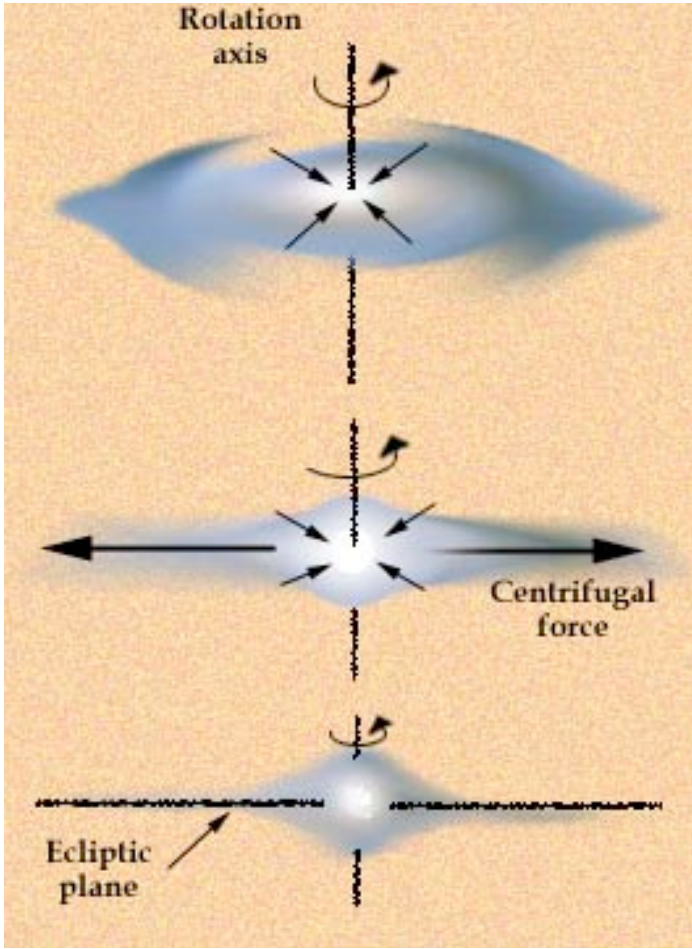
So when our interstellar cloud starts gets big enough, it starts to collapse. Two important effects work to stop the collapse.

As it collapses, the cloud heats up: this increases the pressure, which slows the collapse.





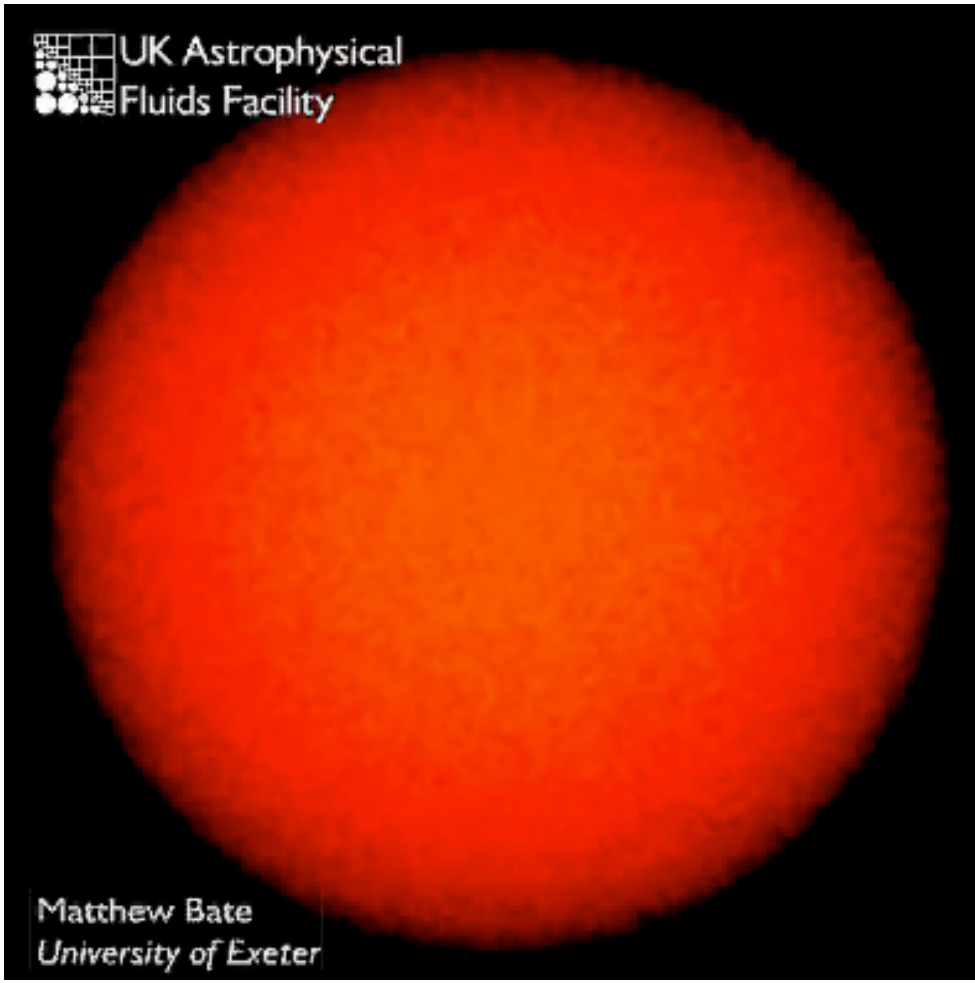
As the cloud contracts, its speed of rotation increases and the fragment will develop into a central dense cloud surrounded by a swirling disk of gas.



The cloud speeds up because it must conserve angular momentum; the same thing as happens when an ice skater pulls her arms and legs in to speed up a spin.



The collapsing cloud breaks into hundreds of fragments, each of which continues to collapse: the Sun was born in a cluster of young stars, all born from the same gas cloud.



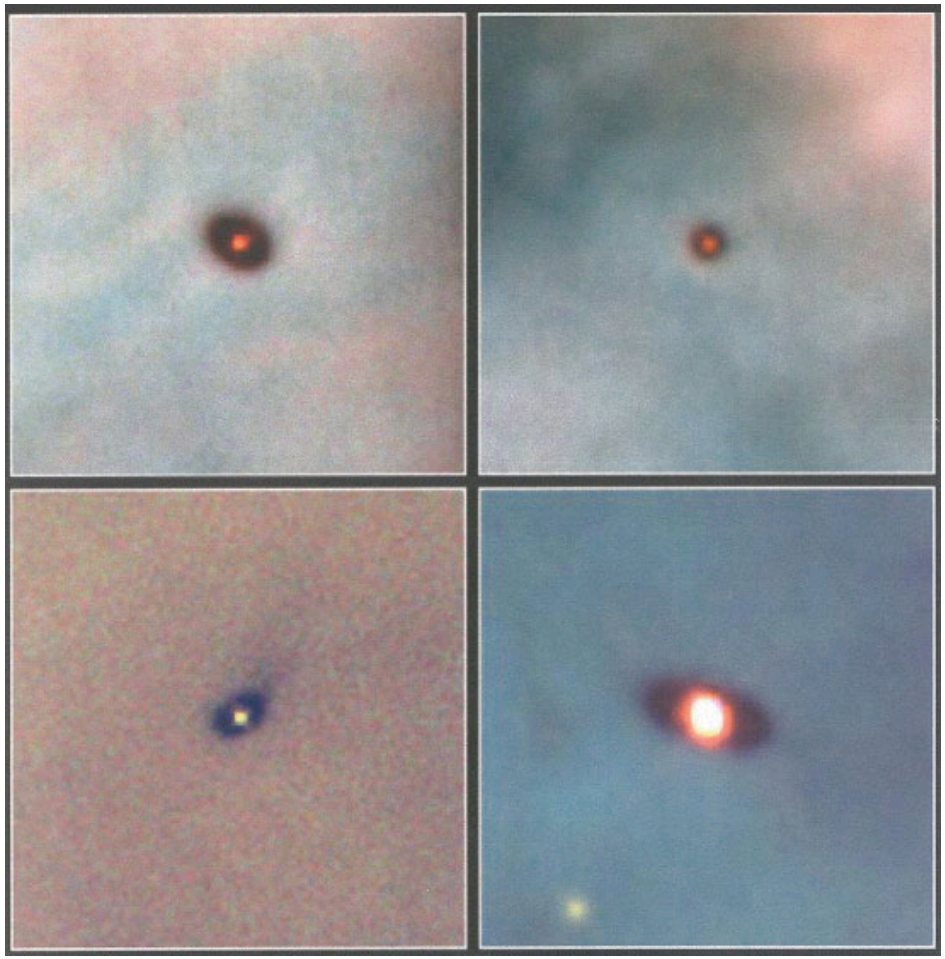
A simulation of the collapse of a 50 solar mass gas cloud, 1 light-year across, eventually forming a cluster of about 50 stars (Bate et al. 2002)

Inside each disk, the central region collapses fastest, and begins to heat up: the cloud is collapsing from the inside. As the density increases, the cloud becomes opaque, trapping the heat within the cloud. This then causes both the temperature and pressure to rise rapidly. The collapsing cloud is now a protostar, surrounded by a disk of gas.



Artist's impression of a young star surrounded by a dusty protoplanetary disk.

We can actually see these disks around newborn stars.



Hubble images of proto-planetary disks in the Orion nebula

These disks will eventually be where planets form.

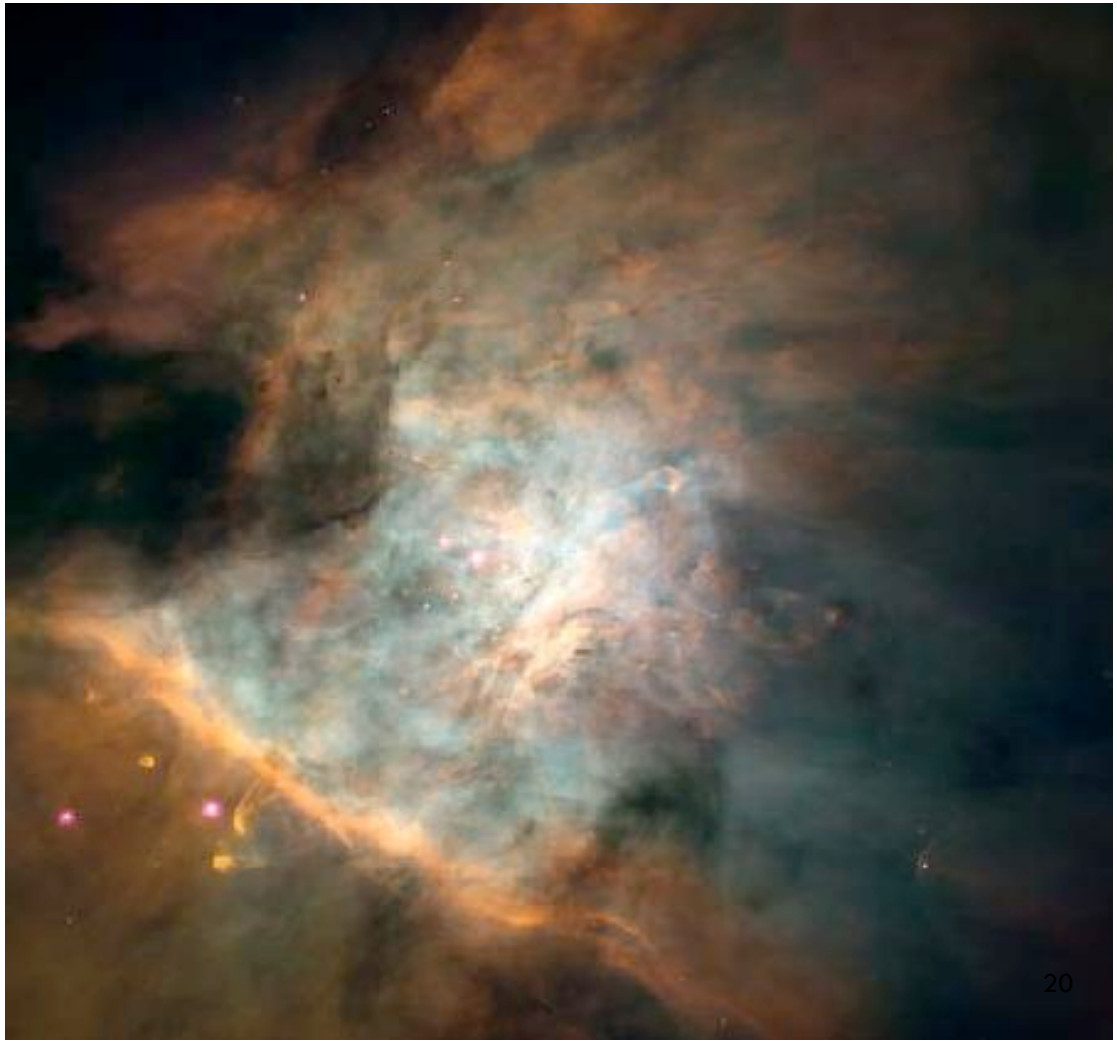
In the meantime, the protostar is continuing to contract and heat up. The temperature in its core increases, until hydrogen nuclei begin to fuse to form helium. This further increases the temperature and hence the pressure at the core, and halts the collapse.

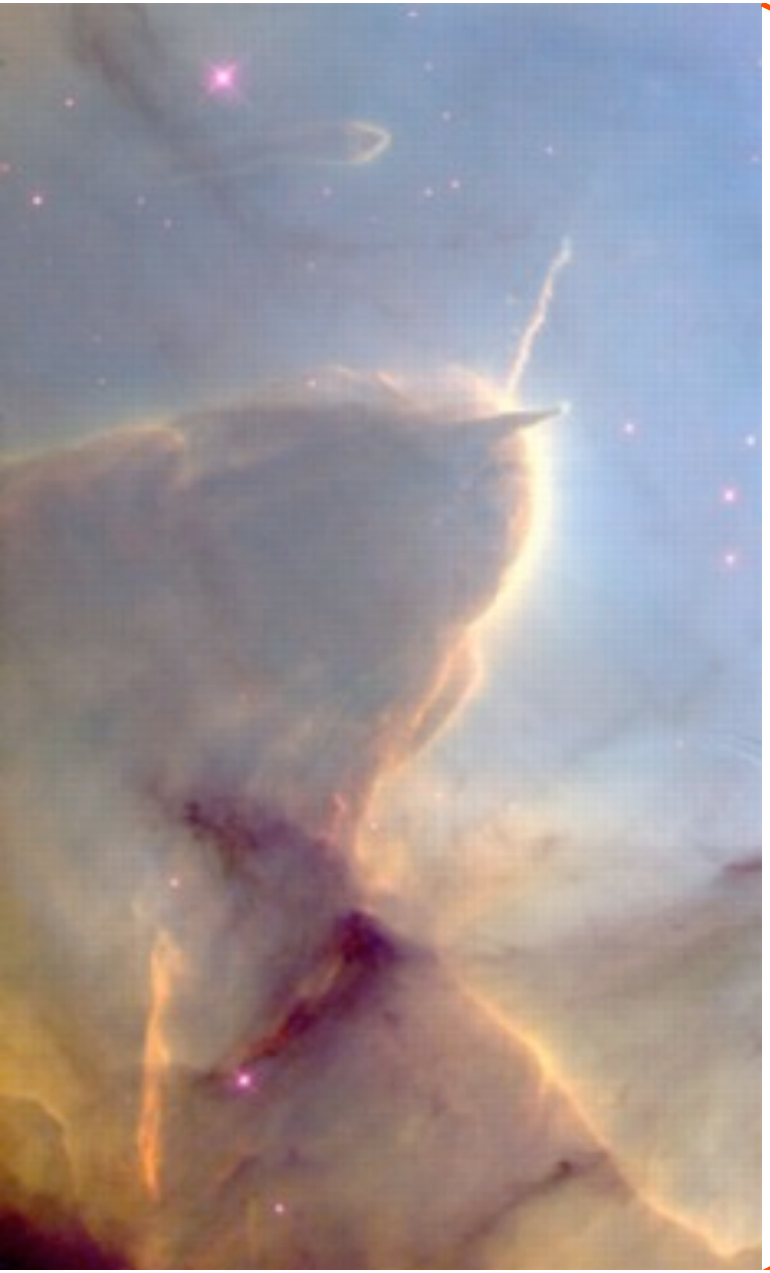
A star is born.

Here is an animation illustrating the formation of a star from a molecular cloud.

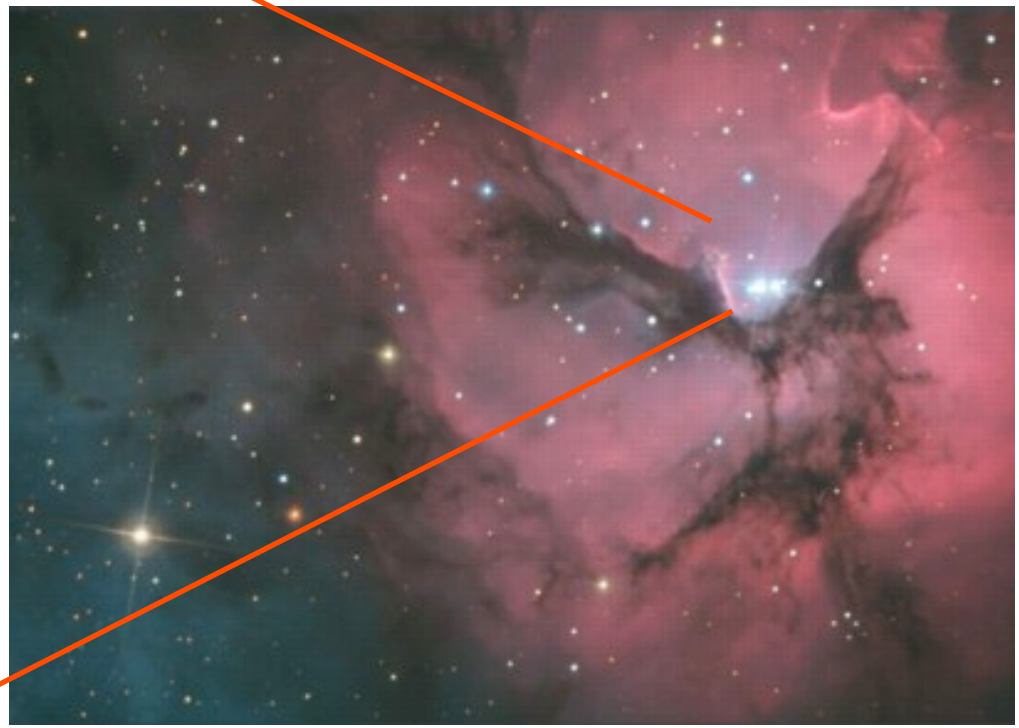


Young stars are often born in clusters. The Orion Nebula contains several young star clusters.





Newborn stars in the Triffid Nebula are sculpting pillars in the surrounding gas and dust.

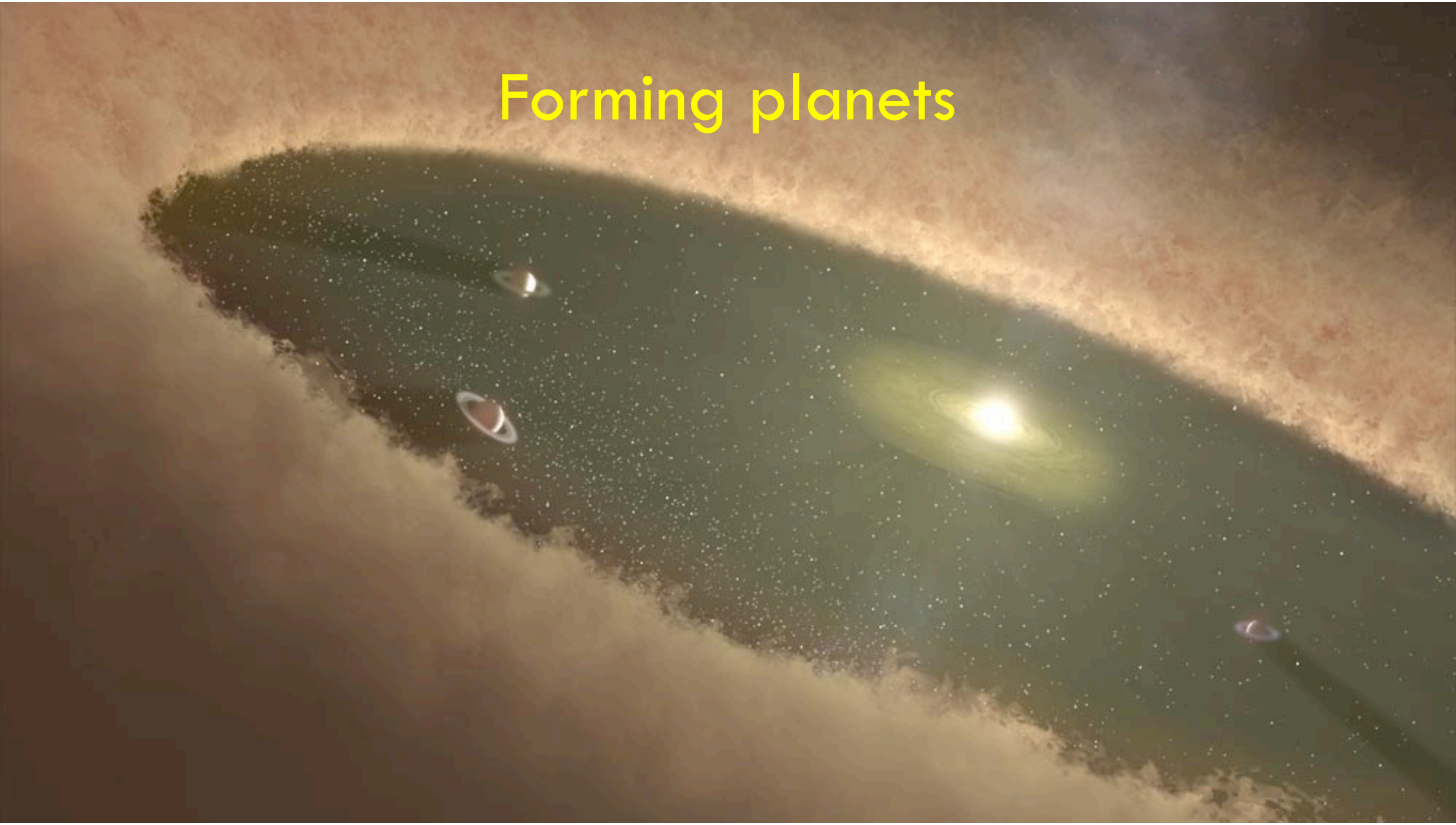



HST visible image of pillar in Carina


Infrared image of the same region



Young star cluster in the Rosette Nebula

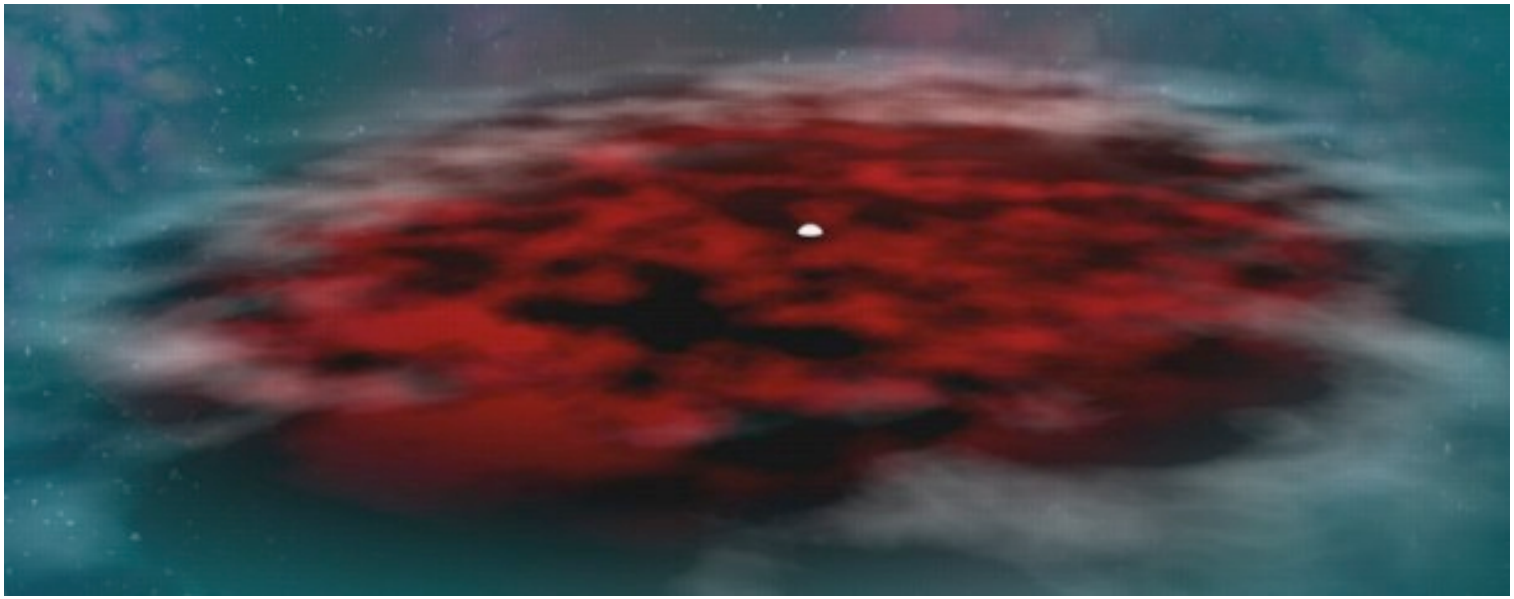

Forming planets

So we have formed a star. But what about the planets?

Clearly the planets form in the disk of gas and dust surrounding our newborn star. But how?

According to current theory, assembling a planet proceeds in several phases.

The disk starts out with the same elements which were in the molecular cloud. It consists almost entirely of gas, with a tiny amount of dust. Which molecules form depends on local conditions in the disk. Different molecules have different temperatures at which they can “freeze out” of the disk.

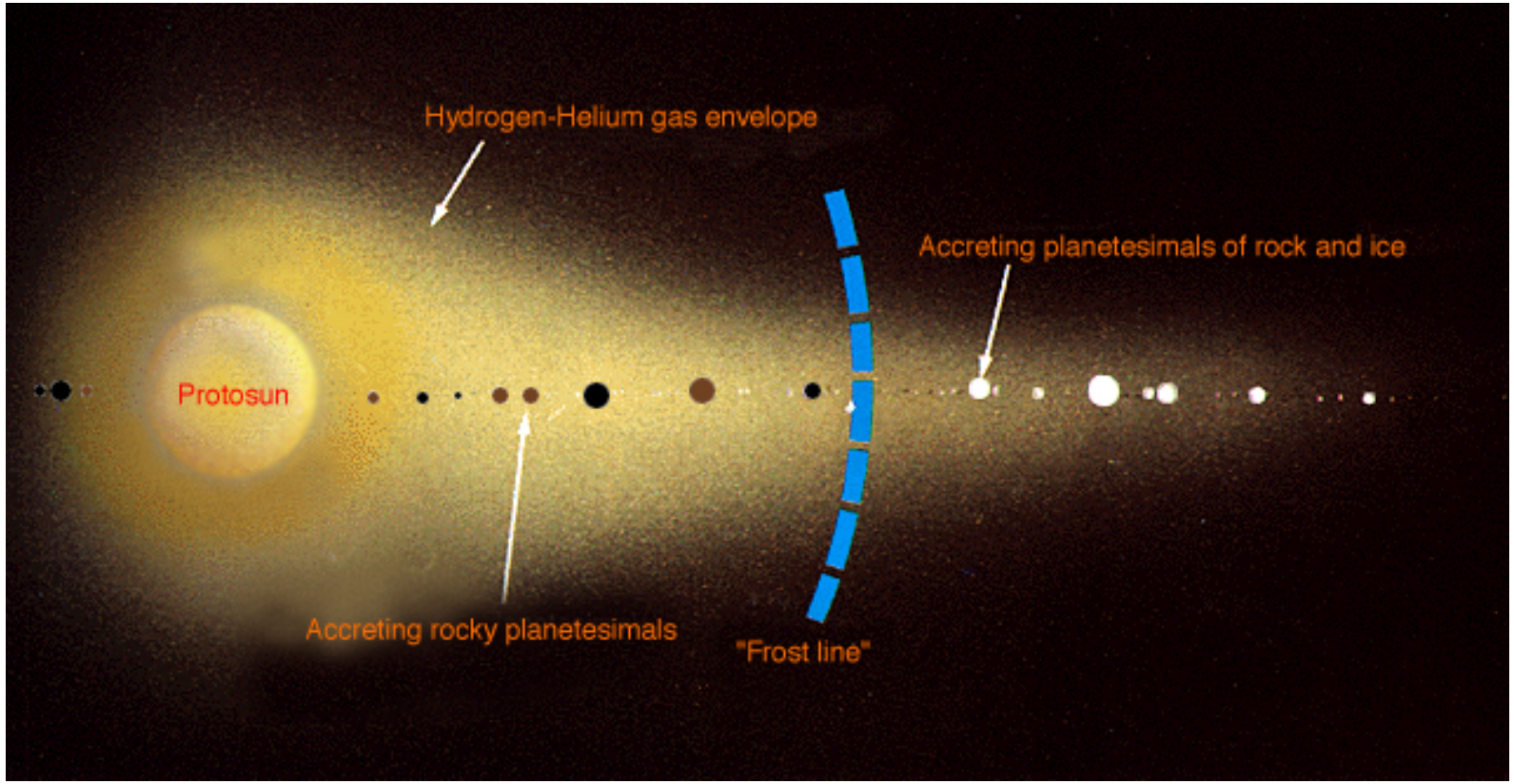


The disk is hotter near the centre, close to the protostar, so different materials condense out at different radii.

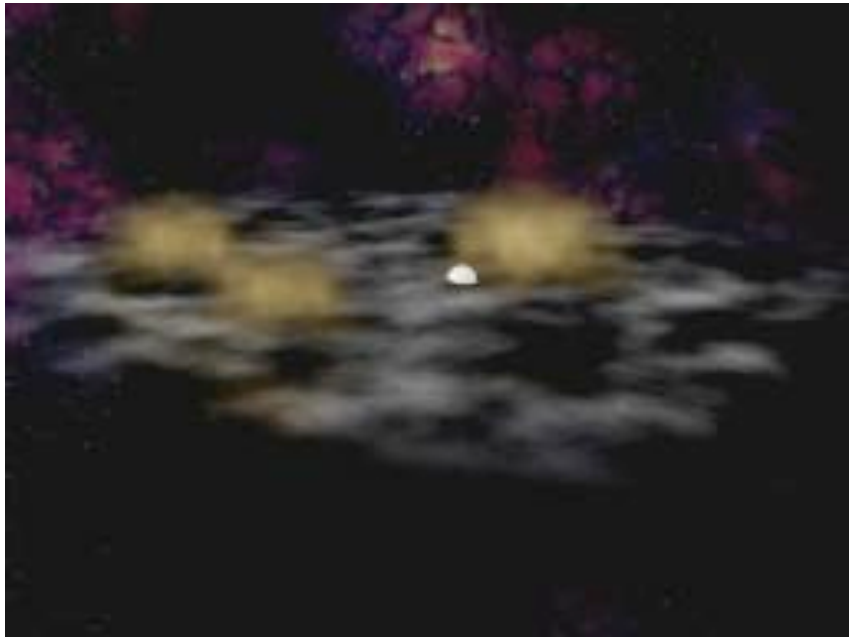
At high temperatures (< 2000K) rocky minerals and metals like iron condense.

Below about 270 K water ice condenses, as well as ammonia and methane.

The distance at which water can freeze out is called the *ice line*. Beyond that distance there is much more mass available.



The next phase is the formation of planetesimals (bodies up to about 1 km in size) through accretion.



Once the particles reach about 1 km in size, gravity starts becoming important. The larger planetesimals can sweep up more material, so the biggest bodies grow much faster than smaller ones – a process known as runaway growth.

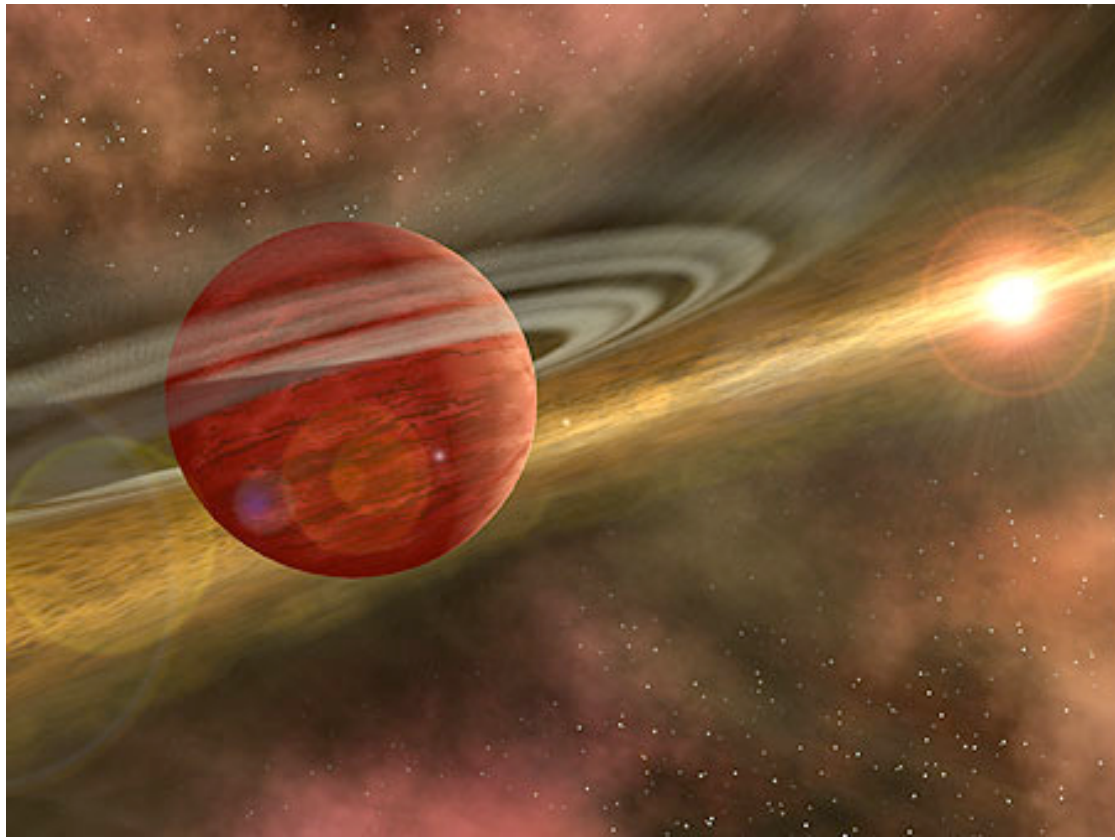
Runaway growth ends when the planetesimal (now called a *planetary embryo*) has consumed nearly everything within its reach.



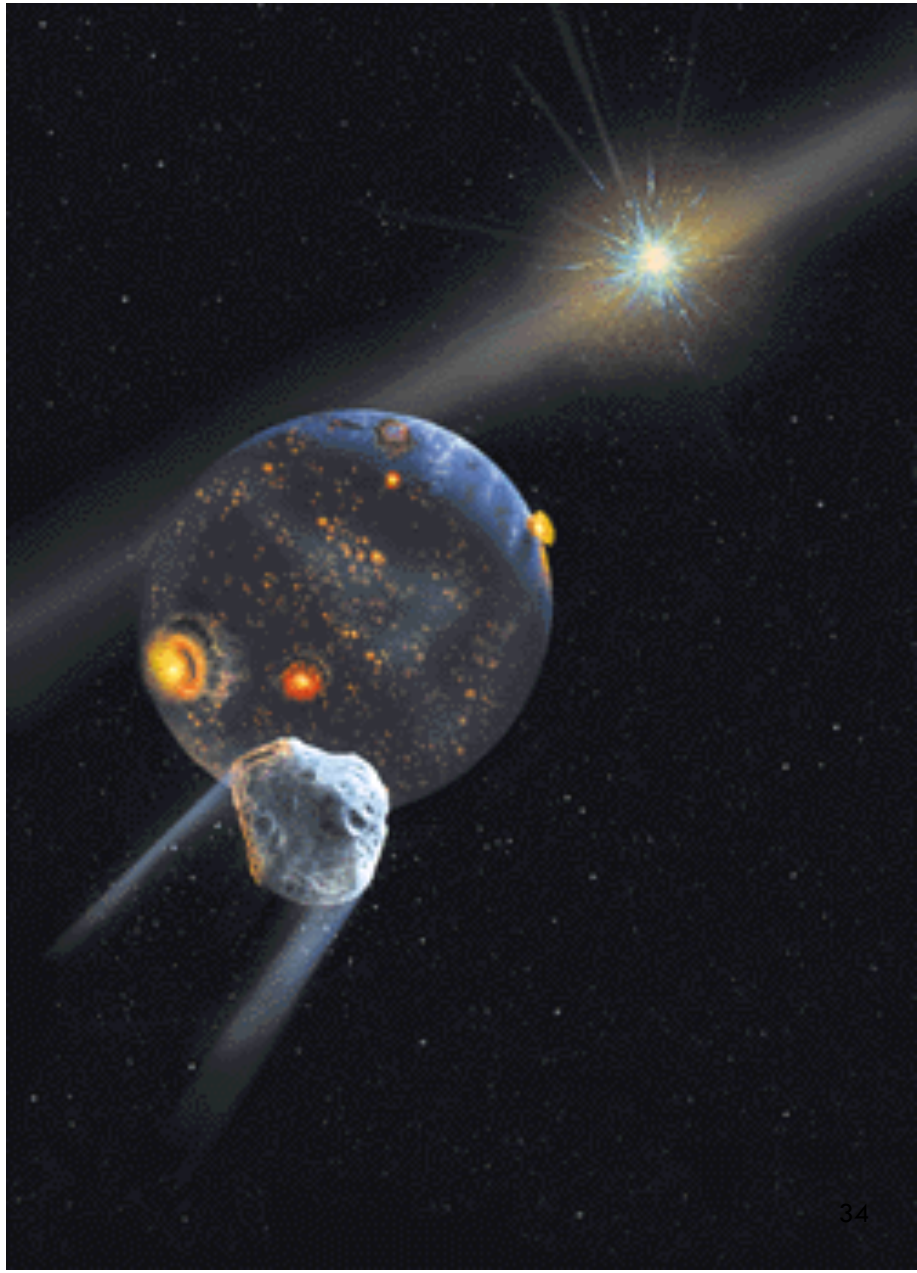
The giant planets appear to have formed by first accreting a core of several Earth masses. This core was more massive than the proto-planets in the inner Solar System because the proto-Jovian planets were beyond the ice line. Once this solid mass had accumulated, the planet starts accreting gas more and more efficiently, in a runaway gas accretion phase. Jupiter and Saturn grew much larger because they formed further in, where the disk was thicker.



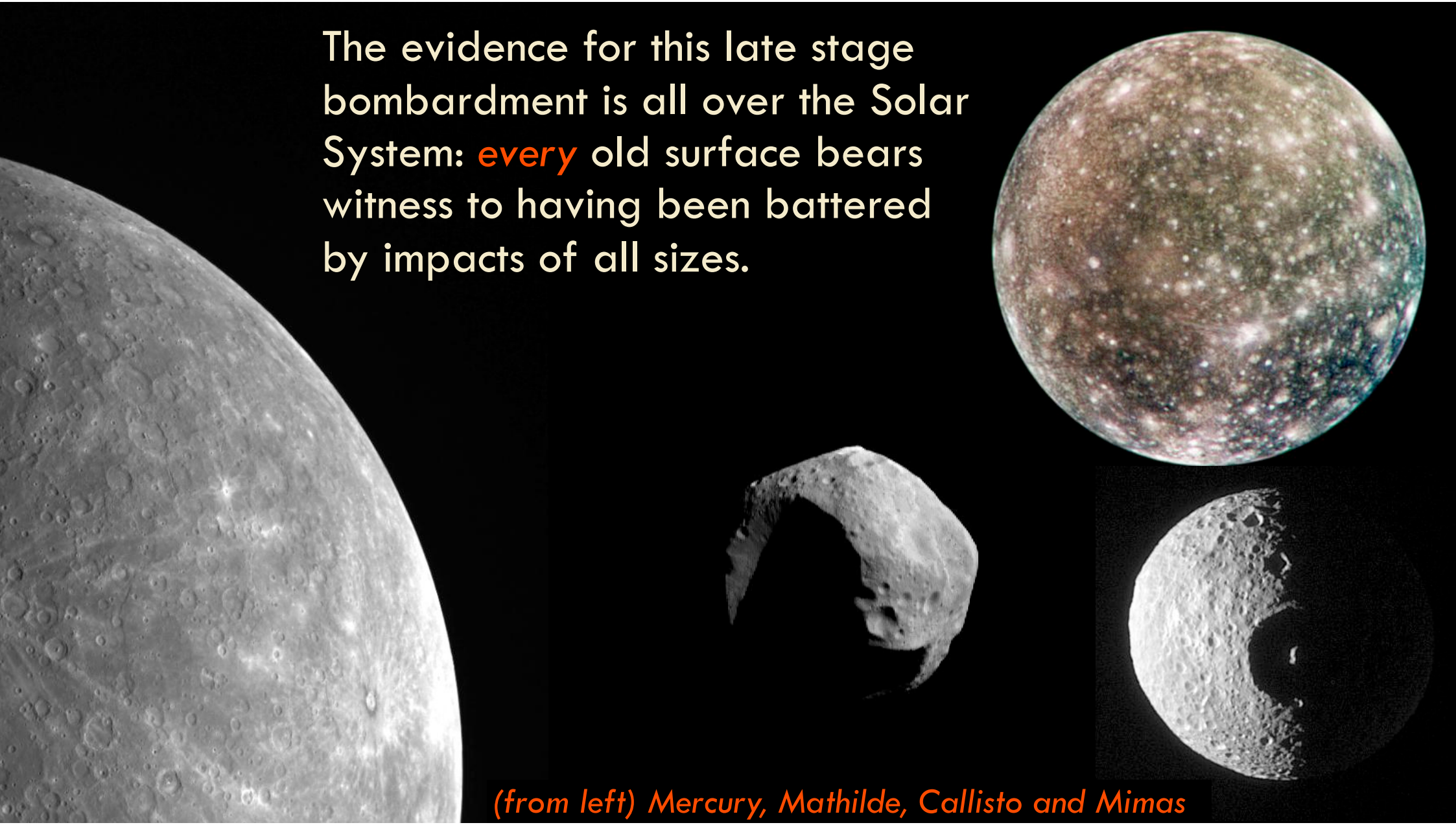
The giant planets were hot when they were accreted. This expanded their atmospheres to vastly larger dimensions than they have today. Gradually they radiated away this heat and shrank, leaving a disk of gas, ice and dust in orbit: a small-scale analogue of the solar nebula. From these disks emerged the regular satellites and ring systems.



Once the protoplanets have reached the size of the Moon or larger, the final stages of planet formation begins, where the hundred or so protoplanets are reduced to the current handful. The planetary embryos perturb each other into crossing orbits, leading to giant impacts. This last handful of impacts has left permanent scars on nearly every member of the Solar System.



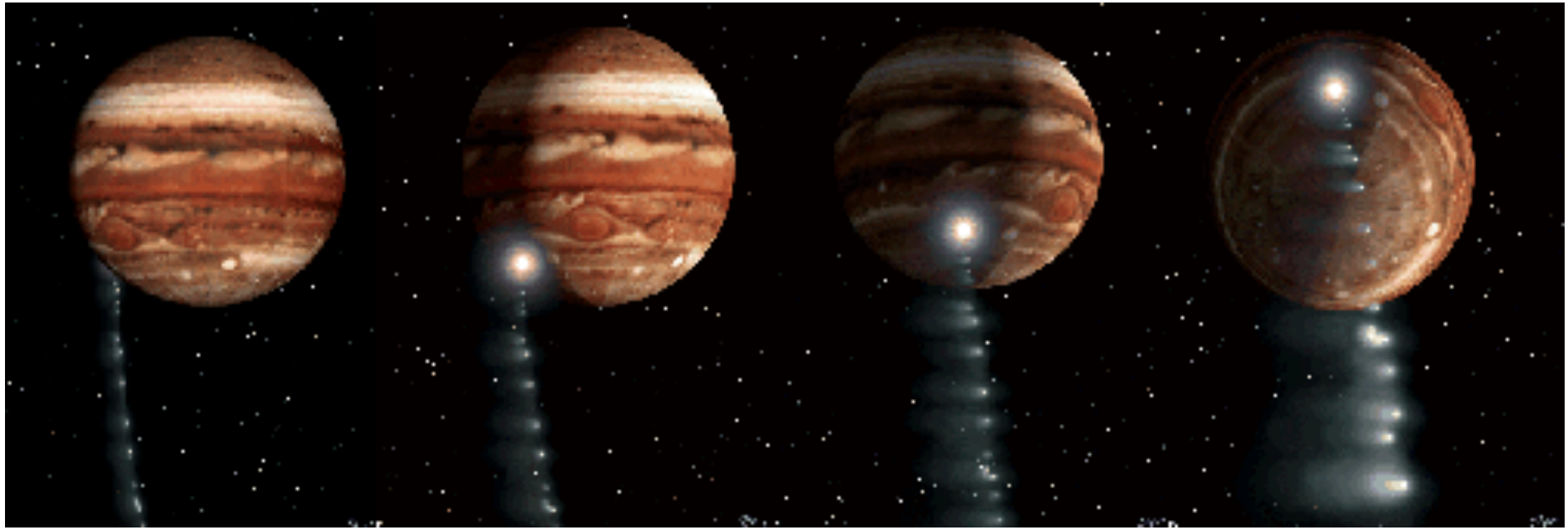
The evidence for this late stage bombardment is all over the Solar System: every old surface bears witness to having been battered by impacts of all sizes.

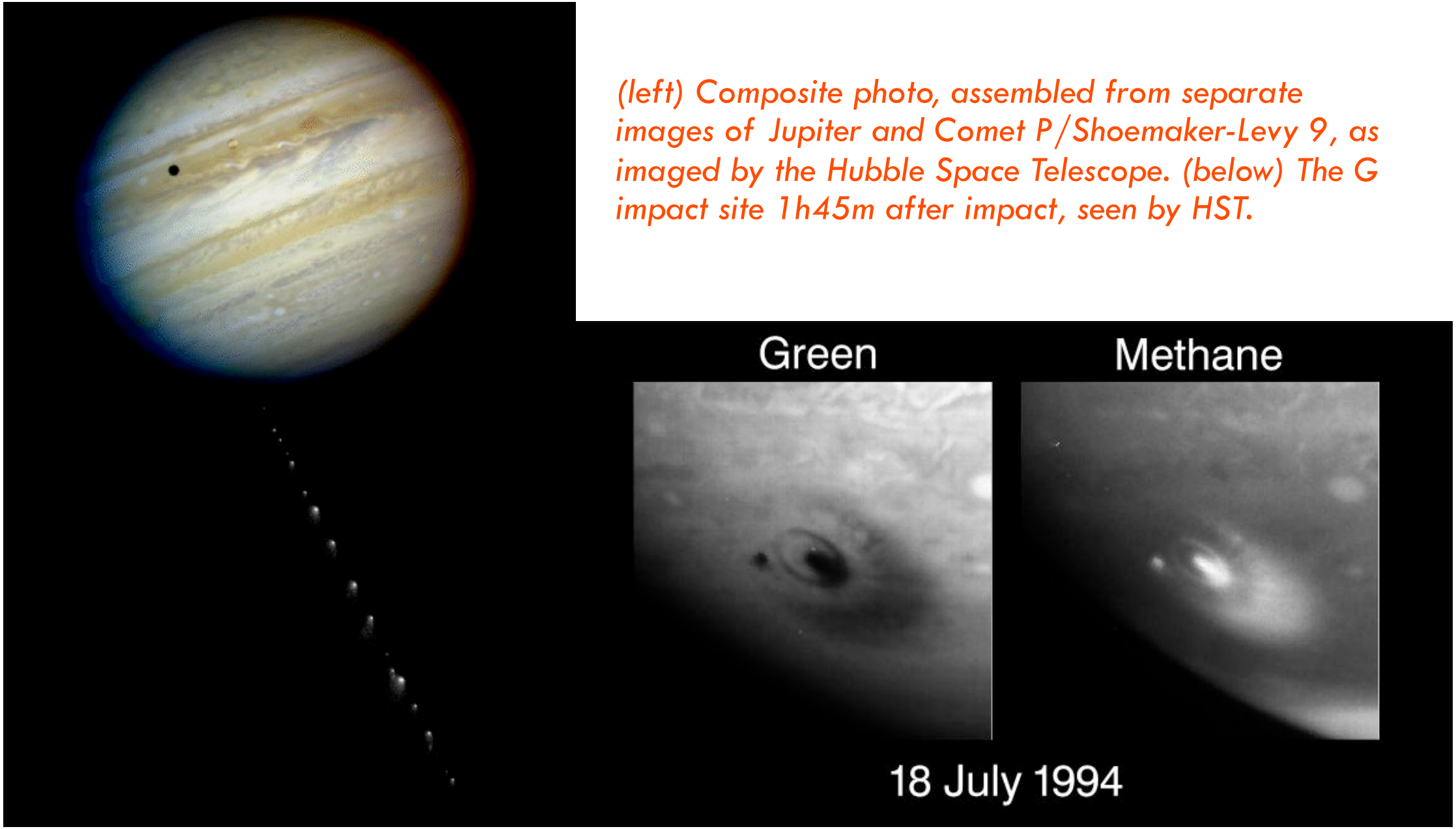


(from left) Mercury, Mathilde, Callisto and Mimas



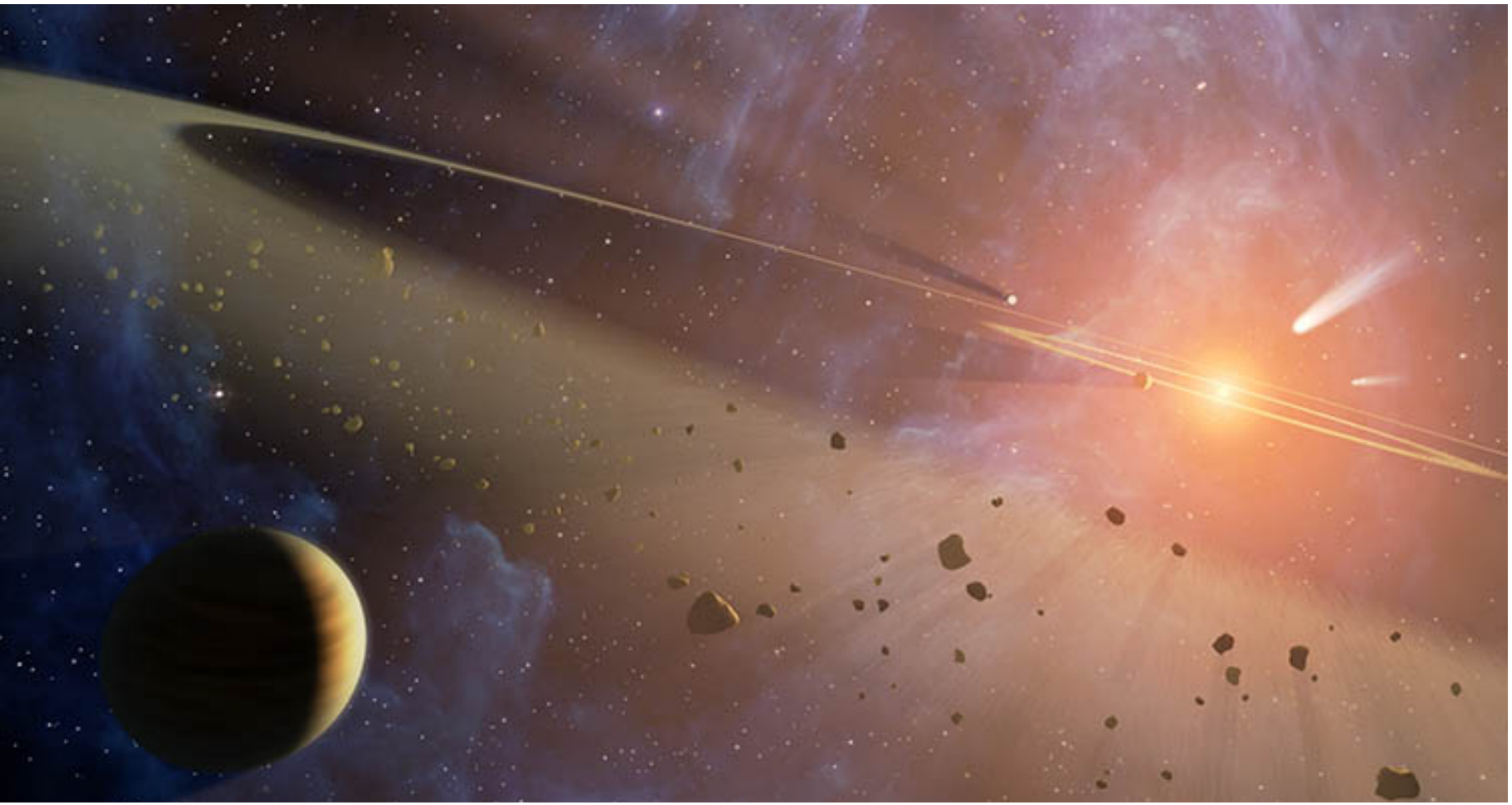
The bombardment of the Solar System has not stopped, only reduced in intensity. In July 1994, we got a chance to see an impact in detail, when Comet Shoemaker-Levy 9 impacted on Jupiter: the very-very-late stages of planetary accretion.





(left) Composite photo, assembled from separate images of Jupiter and Comet P/Shoemaker-Levy 9, as imaged by the Hubble Space Telescope. (below) The G impact site 1h45m after impact, seen by HST.

Since the last few impacts were so violent, the last stage of planetary accretion was far from orderly. The random nature of the impacts means the last final state of the planets is impossible to predict theoretically.

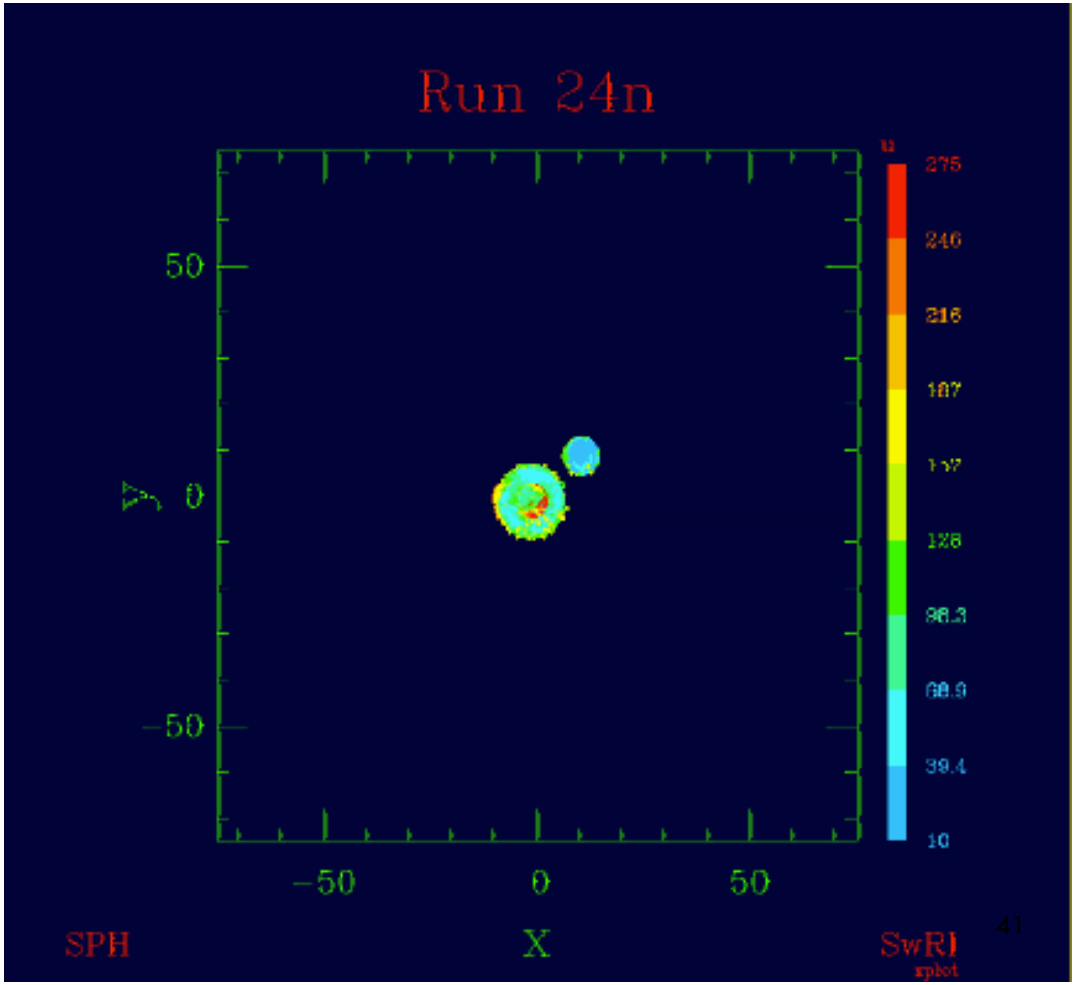


The Earth's moon was formed as the result of a collision between the proto-Earth and another planet-sized body. Material from the impact was thrown into orbit and coalesced into the Moon.



This explains why the other terrestrial planets do not have a moon, because the Moon-impacting event was reasonably unusual.

Calculations showed that the impactor had to be the size of Mars in order to eject enough material into orbit to form the Moon.



Animation showing the impact of a Mars-size proto-planet with the young Earth. The animation covers only 24 hours, ending with the Earth surrounded by a disk of debris, from which the Moon will coalesce.

The impact that made the Moon was just the biggest in a whole spectrum of impacts. For each object the size of Mars colliding with one of the planets, there were ten objects the size of the Moon, and hundreds or thousands of smaller objects. Smaller impacts will tend to cancel out, but the biggest impact can only come from one direction and one angle, and so can have very different results.

Other odd features of the planets may be explained by giant collisions in the late stages of planet formation – Mercury's giant iron core, Venus' and Uranus' tipped axes, Triton's retrograde orbit, and possibly even the Martian crustal dichotomy.



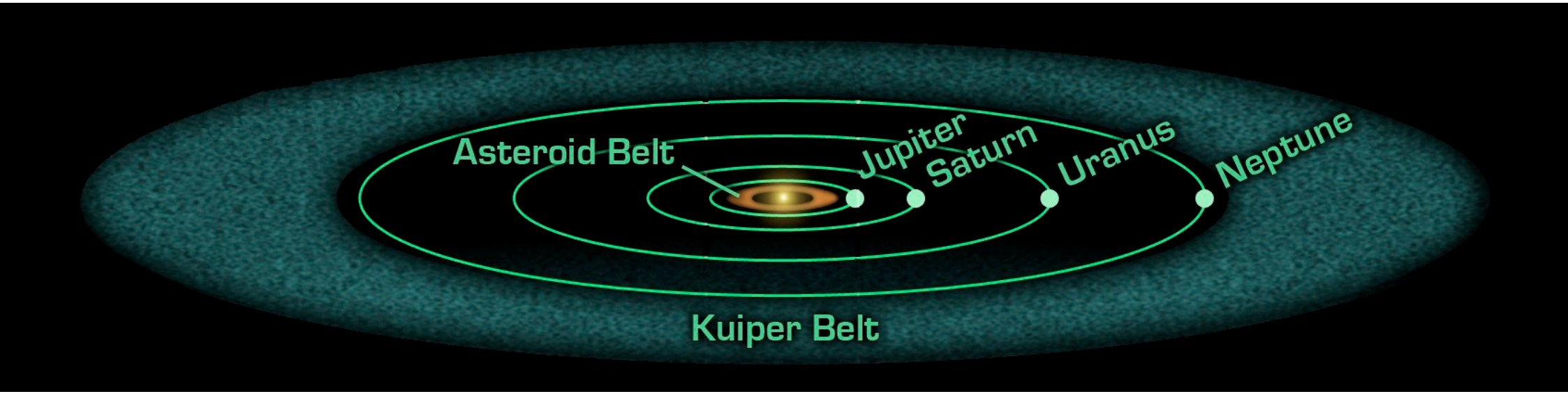
The giant planets acquired their atmospheres during their formation. The much smaller terrestrial planets, however, couldn't hold on to much gas during their formation, and what atmosphere they had was probably lost during the major bombardment.

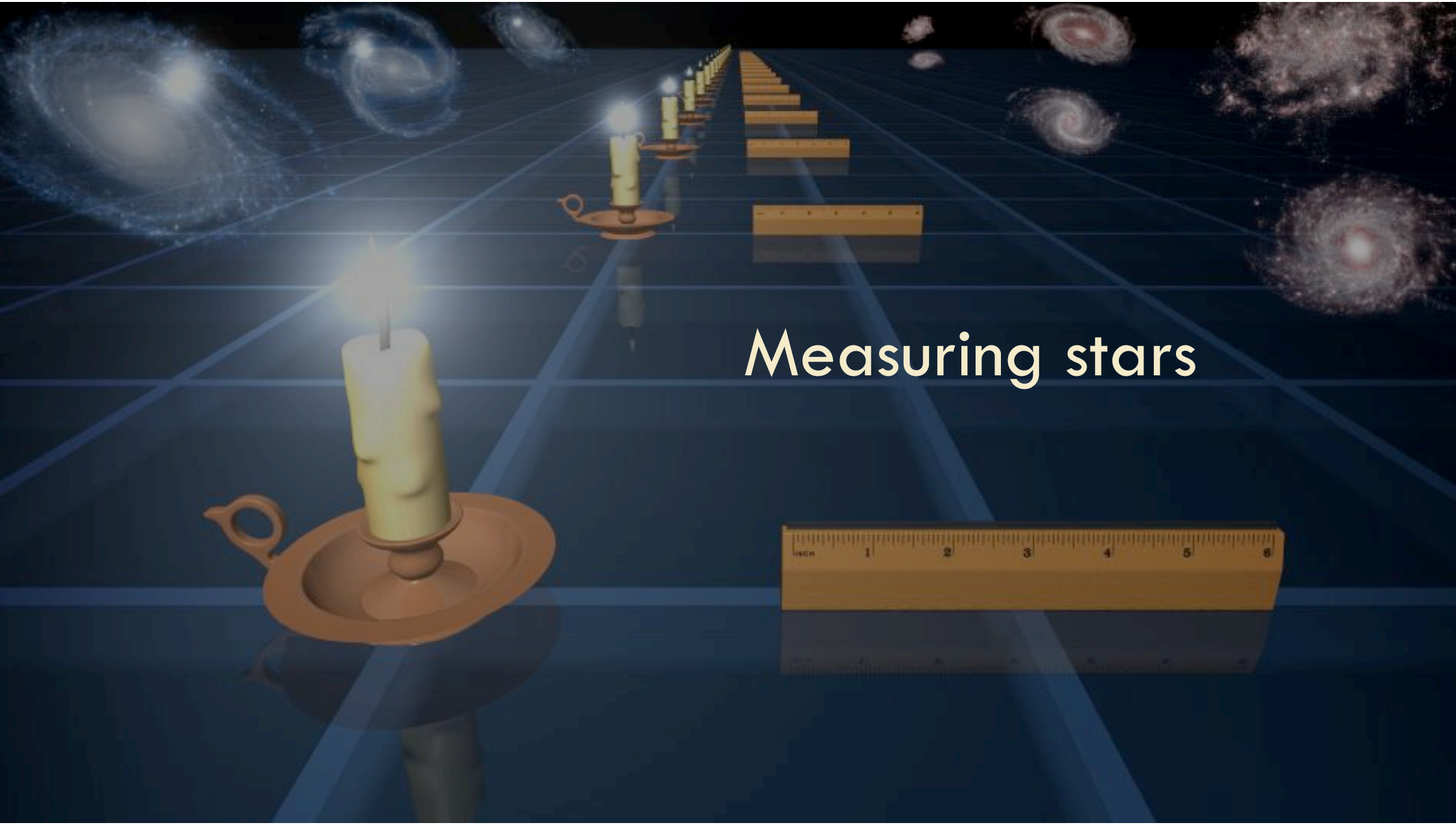


As the impact rate dropped and the planets started to cool, atmospheres accumulated around Venus, Earth and Mars, from volcanic outgassing and comet impacts.

Santa Maria Volcano, Guatamela

Meanwhile, the outer parts of the proto-stellar disk never coalesce into planets. Outside the orbits of the planets, the Sun is left with a disk of icy bodies beyond Neptune – the *Kuiper Belt*.




Measuring stars

Back to the star

Meanwhile, in the centre of this disk where planets are forming, the star has been born.

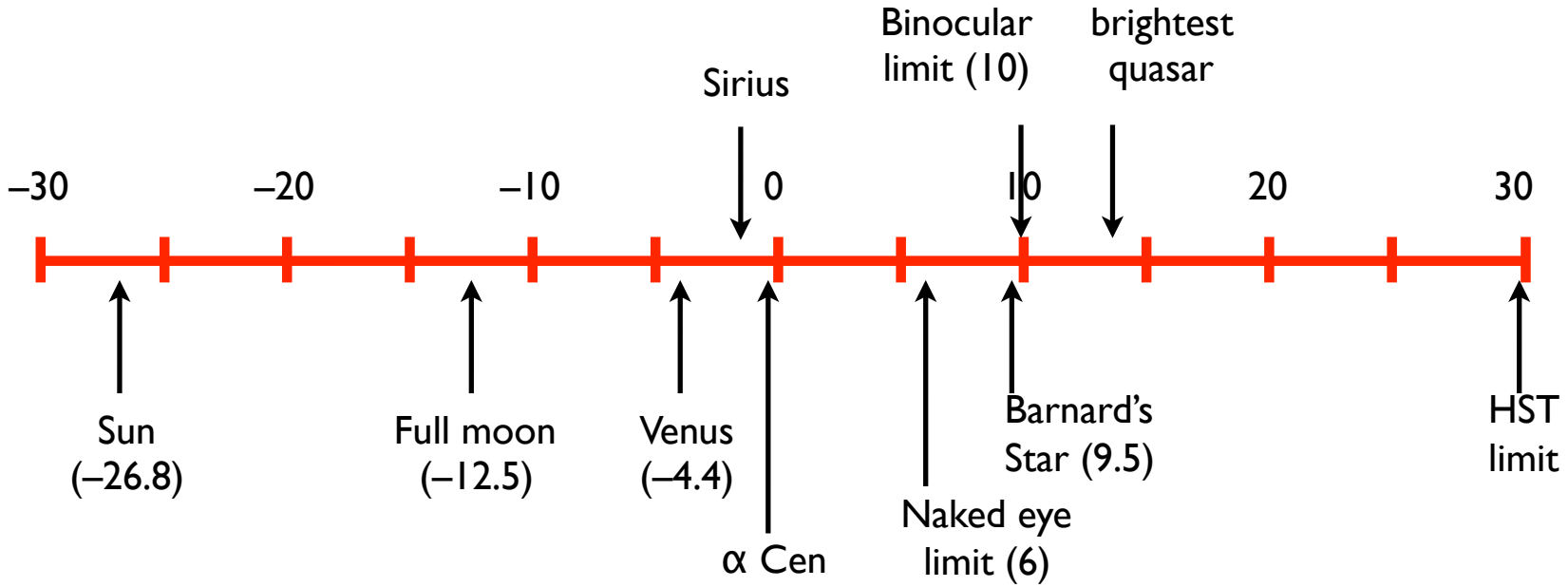
Before we talk about how stars work, we need to back up a little and talk about what stars look like in the sky and how we measure them.

When we look at the night sky, one of the most obvious things to notice is that stars come in different brightnesses.

Star brightnesses were first classified by Hipparchus of Rhodes in about 150 BC. He ranked them into five classes

- Brightest stars: magnitude 1
- Faintest stars: magnitude 5

We still use Hipparchus' system, but refined and extended. Each magnitude is about 2.5 times fainter than the next, so a difference of 5 magnitudes means a factor of 100 difference in brightness.



Note that *smaller* magnitudes mean *brighter* stars!

Here is a list of the ten brightest stars in the sky, with their brightness in magnitudes.

star	apparent mag
Sirius	–1.50
Canopus	–0.73
Alpha Centauri	+0.10
Vega	+0.04
Arcturus	0
Capella	+0.05
Rigel	+0.08
Procyon	+0.34
Betelgeuse	+0.41
Achernar	+0.47

Here are the magnitudes of some of the stars in and around the Southern Cross.

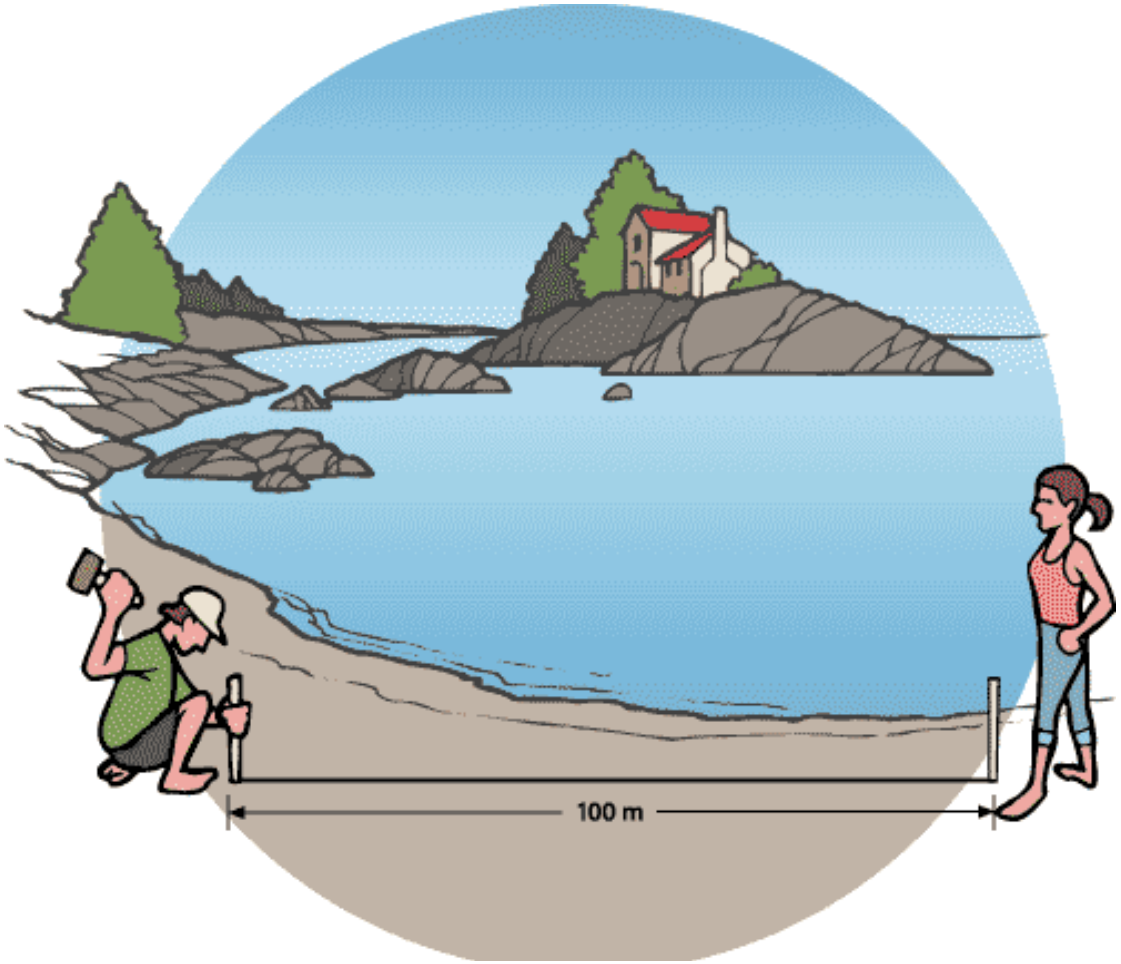




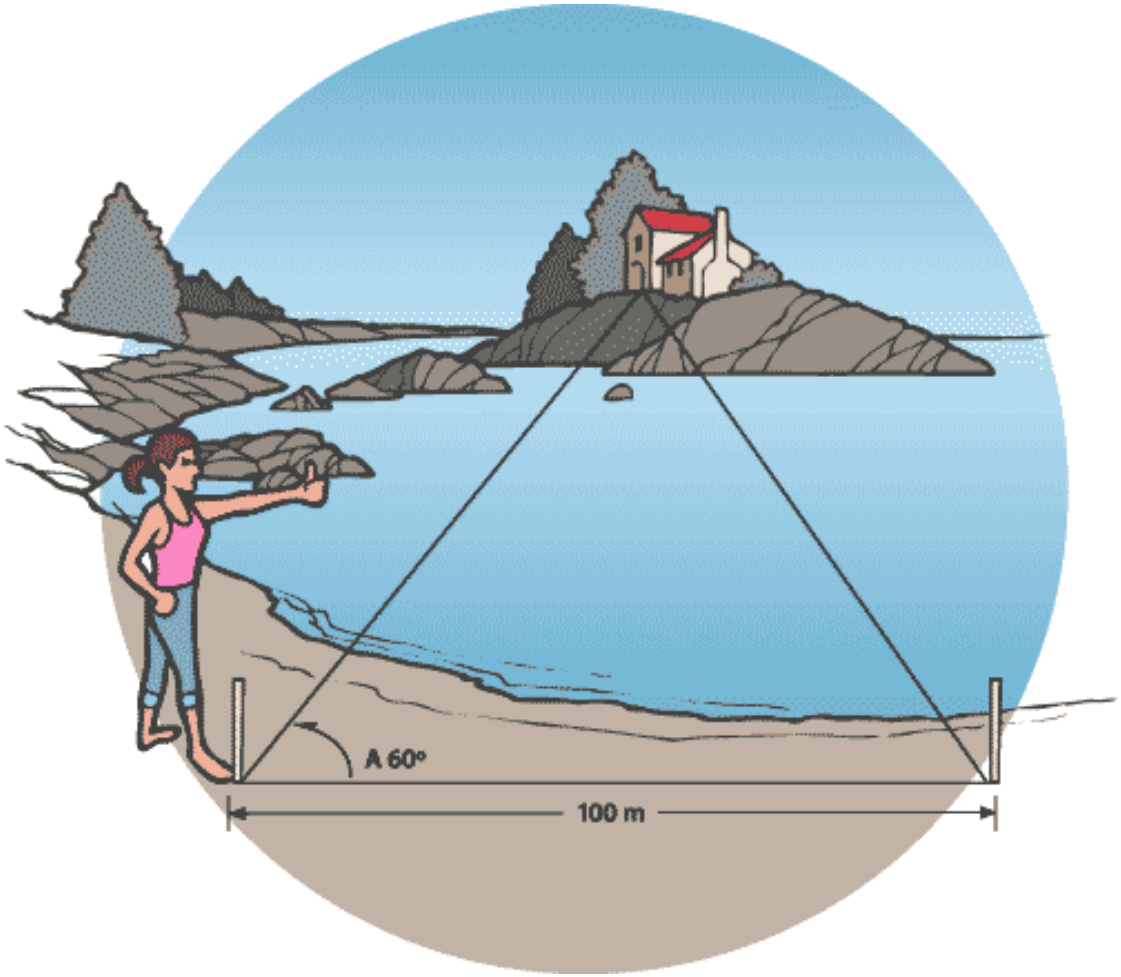
But now we run up against another problem: A star can be bright because it's intrinsically very luminous, or it can be bright just because it's *close* to us.

In order to work how luminous a star really is, we're going to need to work out how far away it is: we need to be able to determine the *distance* to the stars.

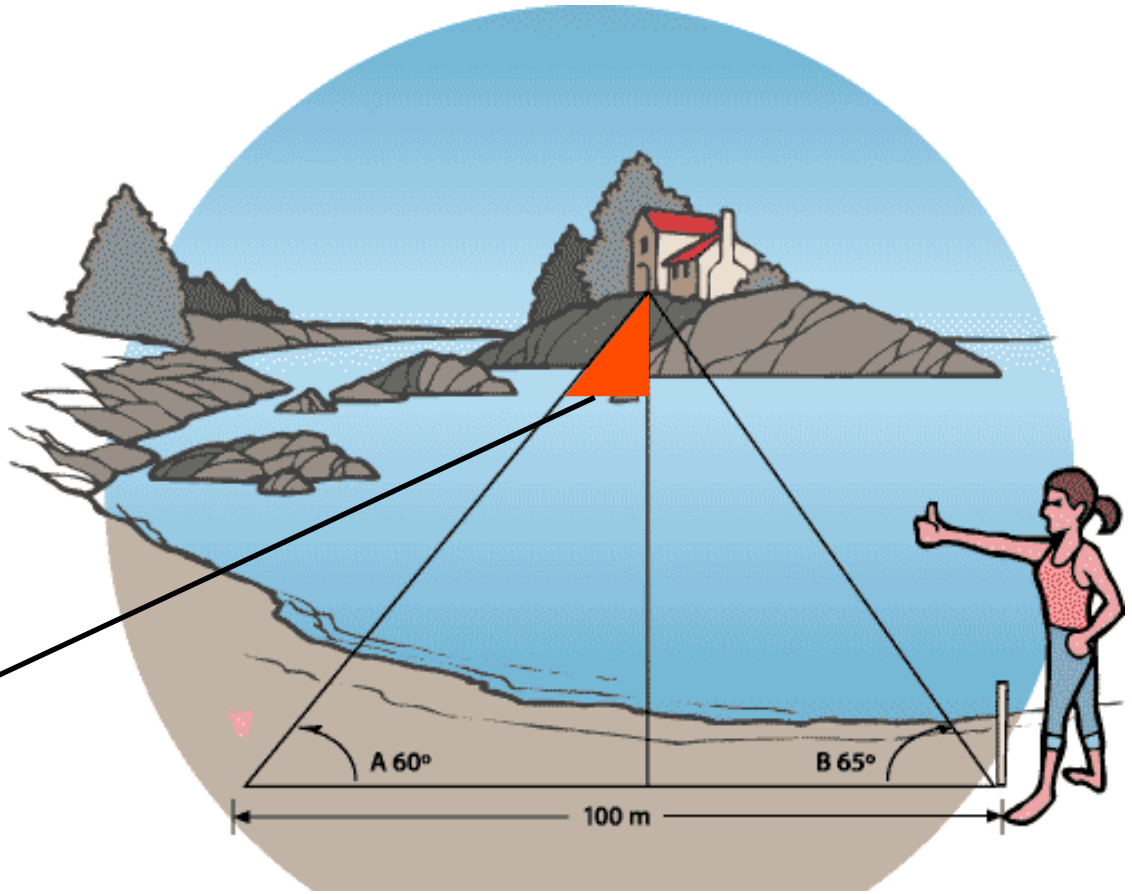
How do we do that? We can measure distances using *parallax*. This is the same technique surveyors use when they want to measure the distance to an inaccessible place.



Suppose we want to measure the distance across a river. We lay out a baseline and measure its length.



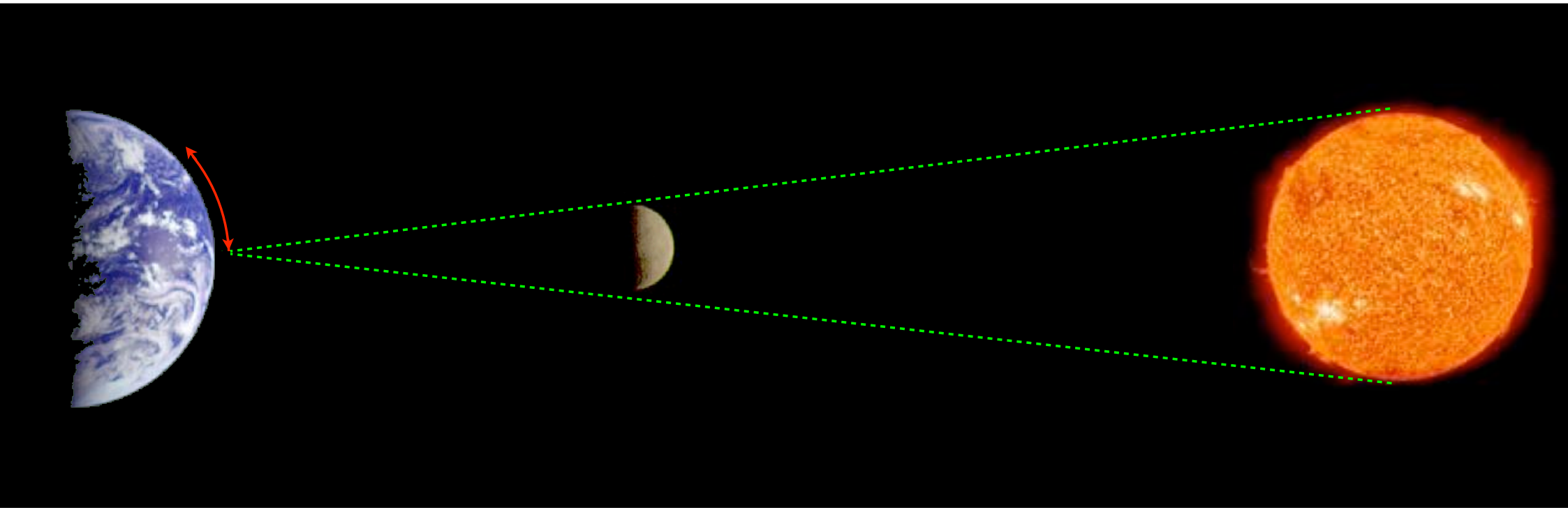
Suppose we want to measure the distance across a river. We lay out a baseline and measure its length. We measure the angle between one end of the baseline and a fixed marker (a house)



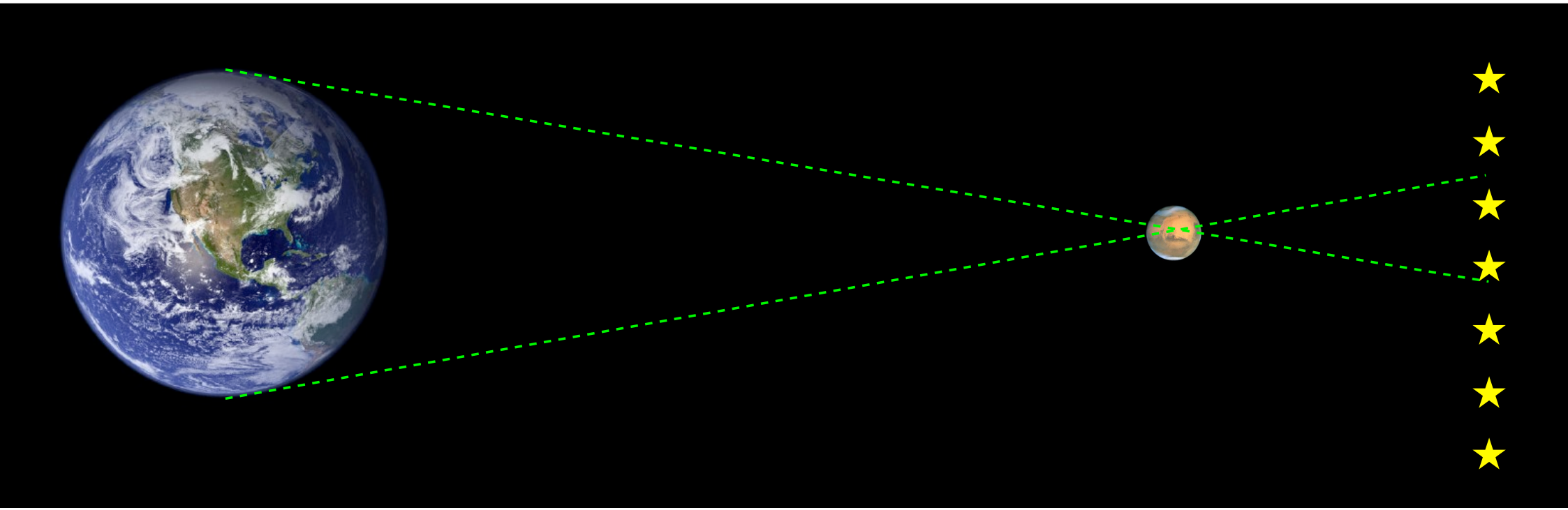
Simple trigonometry gives us the lengths of the sides of the triangle. The angle at the apex p is the difference in the house's apparent position when seen from the ends of the baseline: this is the parallax (actually, half this angle).

The longer the baseline, the smaller the angle you can measure.

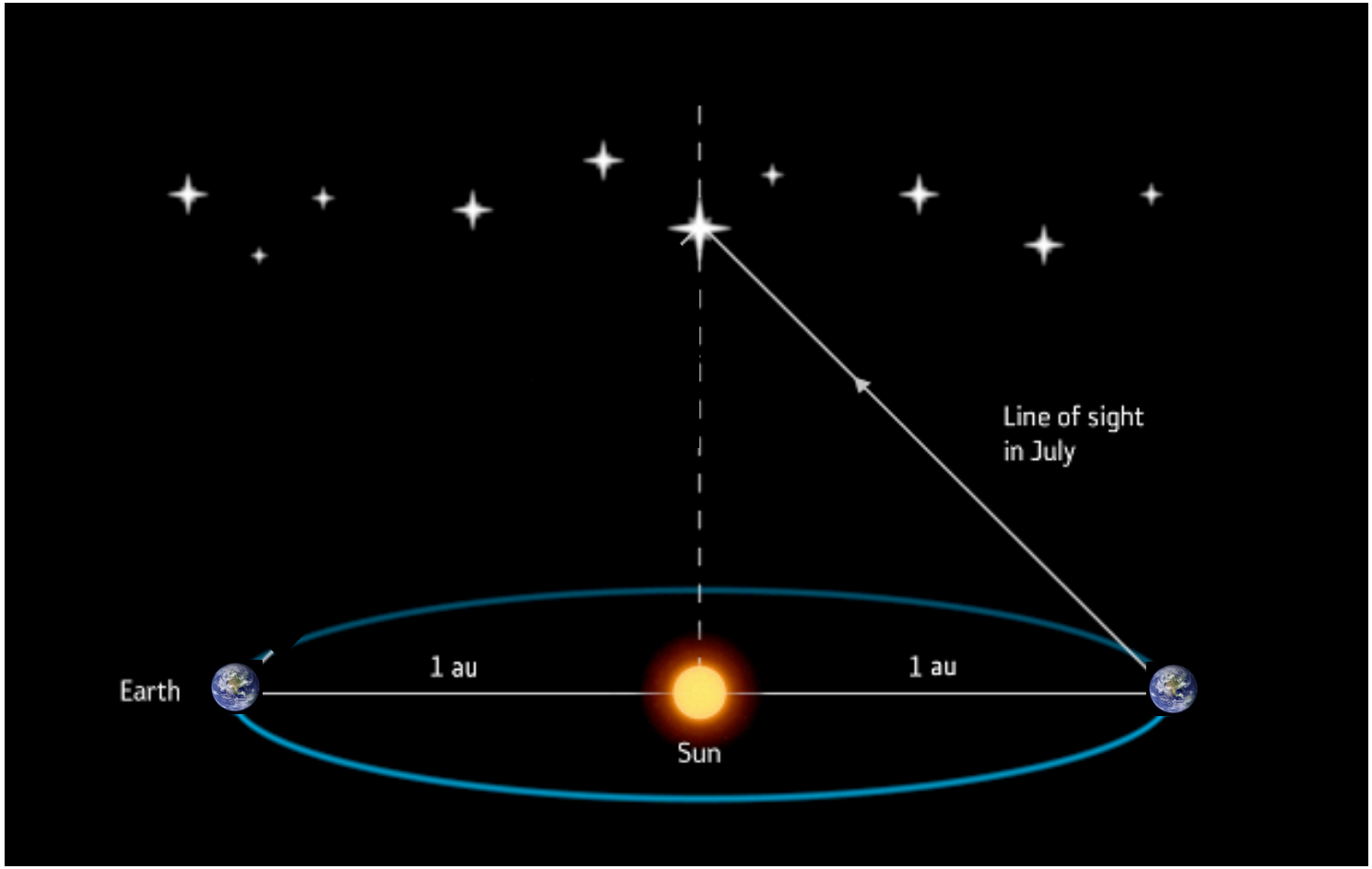
In about 150 BC, Hipparchus of Rhodes estimated the distance to the Moon using the distance between Alexandria and the Hellespont (~500 km apart)



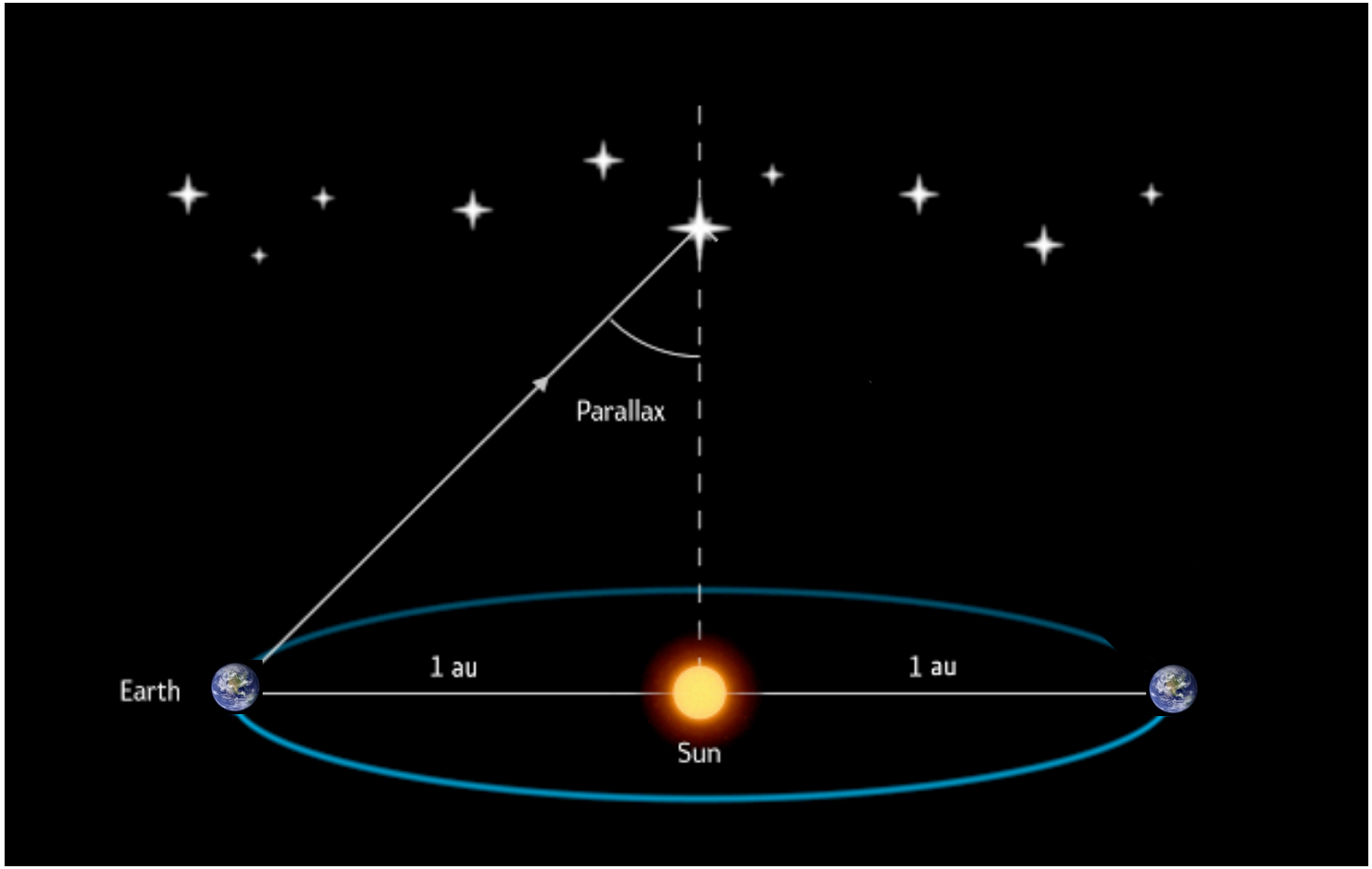
Giovanni Cassini used a baseline of the diameter of the Earth to measure the distance to Mars.



In order to measure distances to stars, the only baseline long enough is the size of the Earth's orbit.

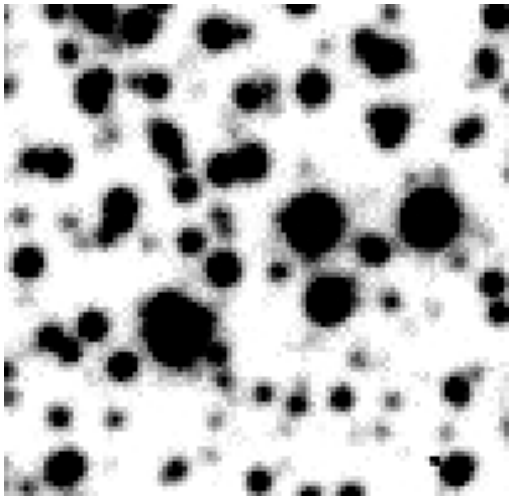


In order to measure distances to stars, the only baseline long enough is the size of the Earth's orbit.



If we observe a star from opposite sides of the Earth's orbit, we should be able to detect a very small shift in a nearby star's position compared to distant stars.

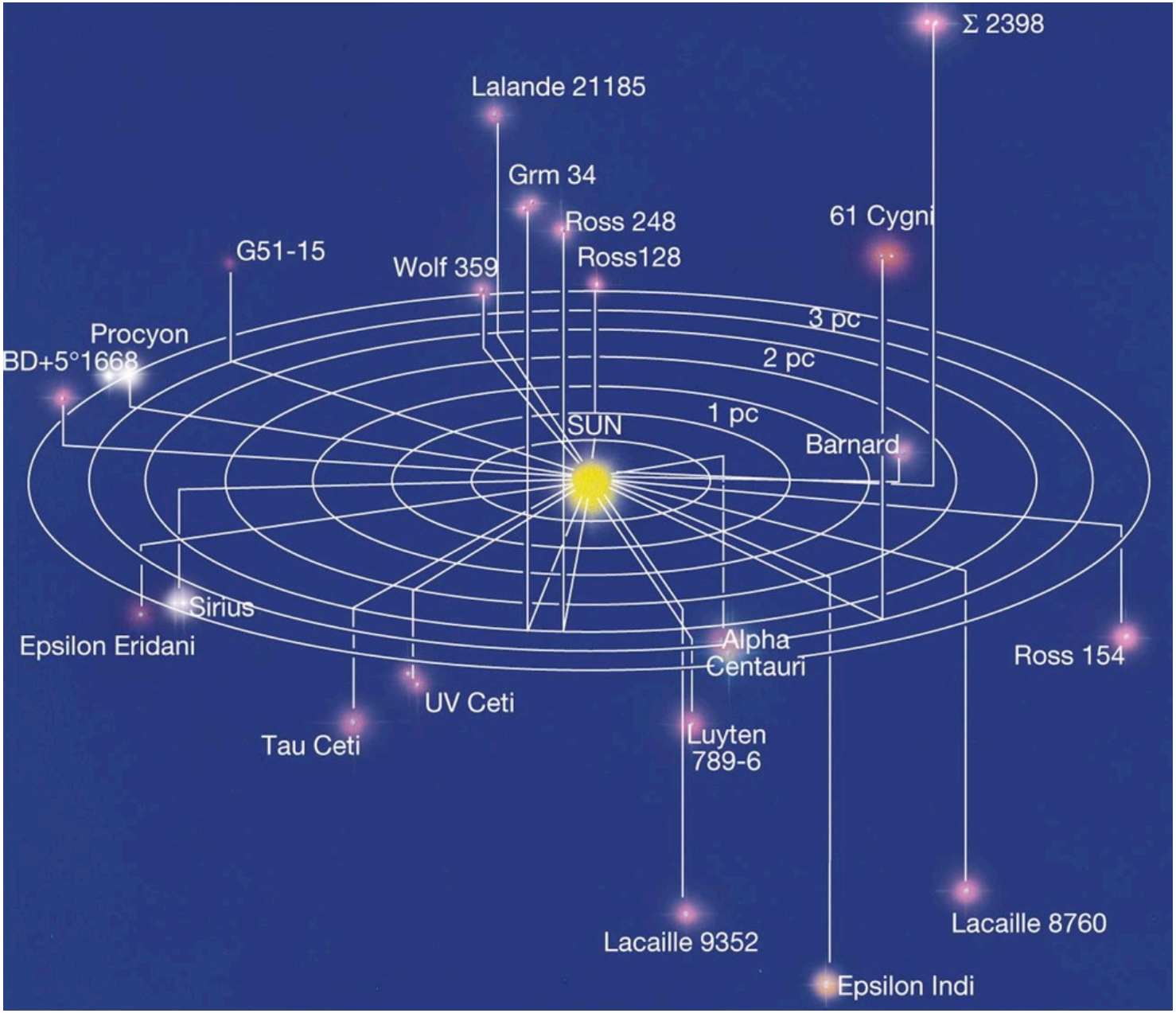
Here are two images of a nearby star, showing the motion due to parallax.



A *parsec* is the distance at which a star has a parallax of 1 arc second; 1 pc = 3.26 light years.

So now we can measure the distances to stars. Here is a list of the ten *nearest* stars to our Sun.

star	apparent mag	distance (pc)
Proxima Centauri	11.5	1.3
Alpha Centauri	0.1	1.3
Barnard's Star	9.5	1.8
Wolf 359	13.5	2.3
Lalande 21185	7.5	2.5
Sirius	–1.5	2.6
Luyten 726–8	12.5	2.7
Ross 154	10.6	2.9
Ross 248	12.2	3.2
Epsilon Eridani	3.7	3.3

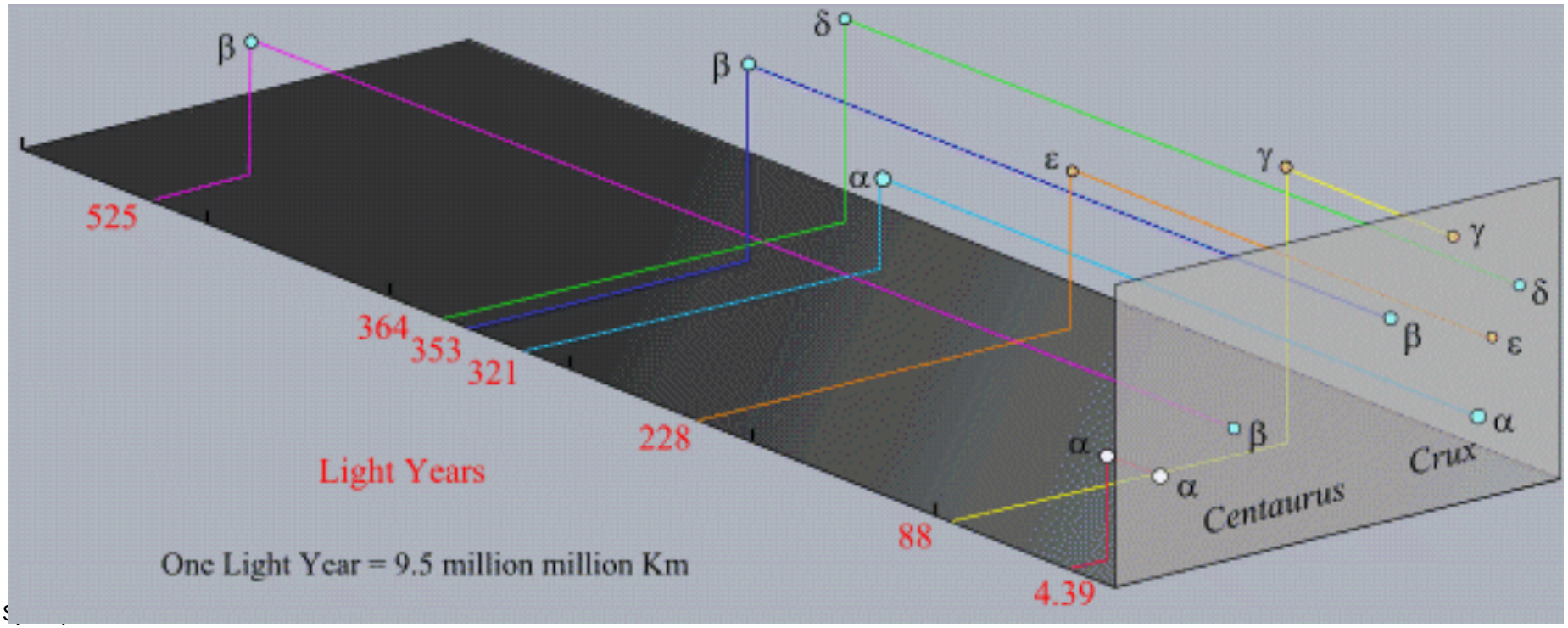

Σ 2398
Lalande 21185
Grm 34
Ross 248
61 Cygni
G51-15
Ross128
Wolf 359
3 pc
Procyon
BD+5°1668
2 pc
1 pc
SUN
Barnard
Sirius
Epsilon Eridani
Alpha
Centauri
Ross 154
UV Ceti
Tau Ceti
Luyten
789-6
Lacaille 8760
Lacaille 9352
Epsilon Indi

Now compare those tables of the brightest and nearest stars again. Some bright stars are at enormous distances, and some near stars are very faint.

star	apparent mag	distance (pc)
Sirius	–1.50	2.6
Canopus	–0.73	96
Alpha Centauri	+0.10	1.3
Vega	+0.04	7.9
Arcturus	0	11.6
Capella	+0.05	13.1
Rigel	+0.08	184
Procyon	+0.34	3.5
Betelgeuse	+0.41	131
Achernar	+0.47	45

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Proxima Centauri	11.5	1.3
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Ross 154	10.6	2.9
Ross 248	12.2	3.2
Epsilon Eridani	3.7	3.3

So if we look at the stars of the Southern Cross, we see they are very different distances. alpha and beta Centauri are nearly the same brightness, but beta Cen is 120 times further away, which means it must be intrinsically much brighter.

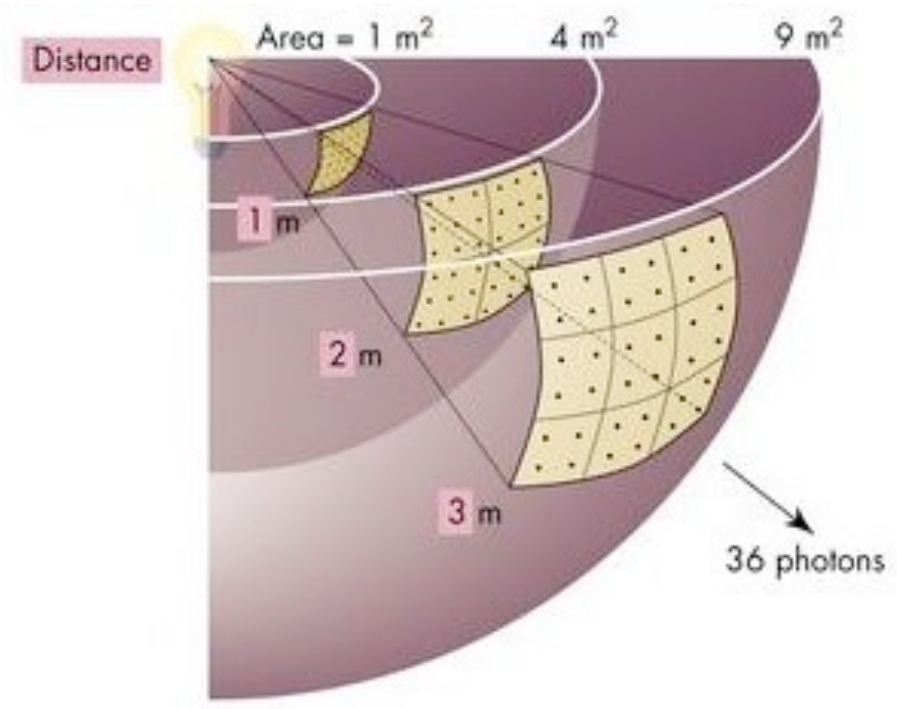


Absolute magnitudes

So the (apparent) brightness of a star is not a very useful quantity. We need something better to describe what the star is like.

The *inverse square law* means that once we know the distance to a star, we know how bright it really is.

The *absolute magnitude* of a star is the magnitude it would have if it were at a distance of 10 pc.



A star which is twice as far away as another of the same luminosity is only a quarter as bright: the inverse square lav

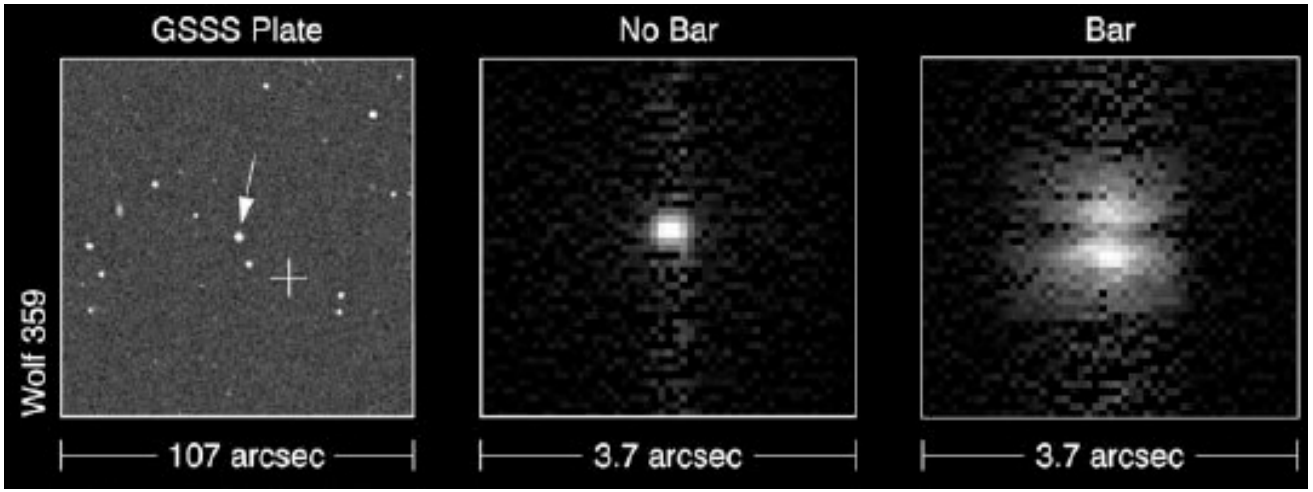
Here are the absolute magnitudes of some stars. Since 5 magnitudes difference means a factor of 100 difference in brightness, this means that Eta Carina is *50 billion* times brighter than Wolf 359.

Star	Absolute magnitude	Distance (pc)
Eta Carina	–10	3400
Betelgeuse	–7.2	184
Canopus	–2.5	30
Vega	0.6	8
Sirius	1.4	2.6
Alpha Centauri	4.4	1.3
Sun	4.8	–
Epsilon Eridani	6.1	3.3
Barnard's Star	13.2	1.8
Wolf 359	16.7	2.3

During the 19th century Eta Carinae brightened enormously, reaching magnitude –1 by 1848. Since then, it has faded and brightened, and is now at magnitude 6.2. This is an infrared image showing the star embedded in its vast nebula, also called Eta Carinae.



Hubble has taken a picture of Wolf 359, in order to look for planets. By blocking out the light from the star, astronomers were able to search for brown dwarf or planet companions. None were found.



So we can say something about at least some stars: their distance, their true brightness. Given that we can't touch them, what else is there to learn?

"On the subject of stars, all investigations which are not ultimately reducible to simple visual observations are ... necessarily denied to us. While we can conceive of the possibility of determining their shapes, their sizes, and their motions ... we shall not at all be able to determine their chemical composition or even their density... I regard any notion concerning the true mean temperature of the various stars as forever denied to us."

– Auguste Comte, "Cours de la Philosophie Positive (1835)


Next week
we'll look at how we found out how stars work,
and then at how stars evolve and change after
their birth.

Further reading

- "**The birth of stars and planets**" by John Bally and Bo Reipurth (Cambridge, 2006) is a great book for those who'd like to know more about the subject. It's written by two experts in the field, is entirely non-technical, and has fantastic illustrations all the way through.
- "**The Story of the Solar System**" by Mark Garlick (Cambridge, 2002) is by that rarest of creatures, an artist who is also a scientist. The book itself is at a reasonably elementary level, describing the birth, life and death of the Solar System, but the paintings he has done to go with each page are wonderful.
- **"The Big Splat: or How our moon came to be"** by Dana Mackenzie (John Wiley & Sons, 2003) is a very readable book about theories of the origin of the moon, and how we arrived at the current consensus. An extremely enjoyable read.
- There's a beautiful illustrated timeline of the Solar System at The Lunar and Planetary Institute's "**Evolution of Our Solar System: A Journey through Time**" at http://www.lpi.usra.edu/education/timeline/
- The quest for the distance to the stars is well described in "**Parallax: The Race to Measure the Cosmos**" by Alan. W. Hirshfeld (WH Freeman, 2001). A lovely read.

Sources for images used:

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- Pillar in Carina: from APOD 2009 Oct 1 http://antwrp.gsfc.nasa.gov/apod/ap091001.html
- Rosette Nebula: CFHT picture by J. C. Cuillandre & G. Fahlman, Astronomy Picture of the Day 2002 March 17 http://antwrp.gsfc.nasa.gov/apod/ap020317.html
- Star formation: from "Cultivating a Planetary Garden: How Long Does it Take?" http://www.jpl.nasa.gov/news/news.php?feature=927
- Proplyd: from Astronomy Picture of the Day 1996 October 17, http://antwrp.gsfc.nasa.gov/apod/ap961017.html
- Protostellar disk: from "MIRLIN Star/Planet Formation Page" http://cougar.jpl.nasa.gov/HR4796/anim.html
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