Introduction to Astronomy

Lecture 3:

The birth of stars and planets

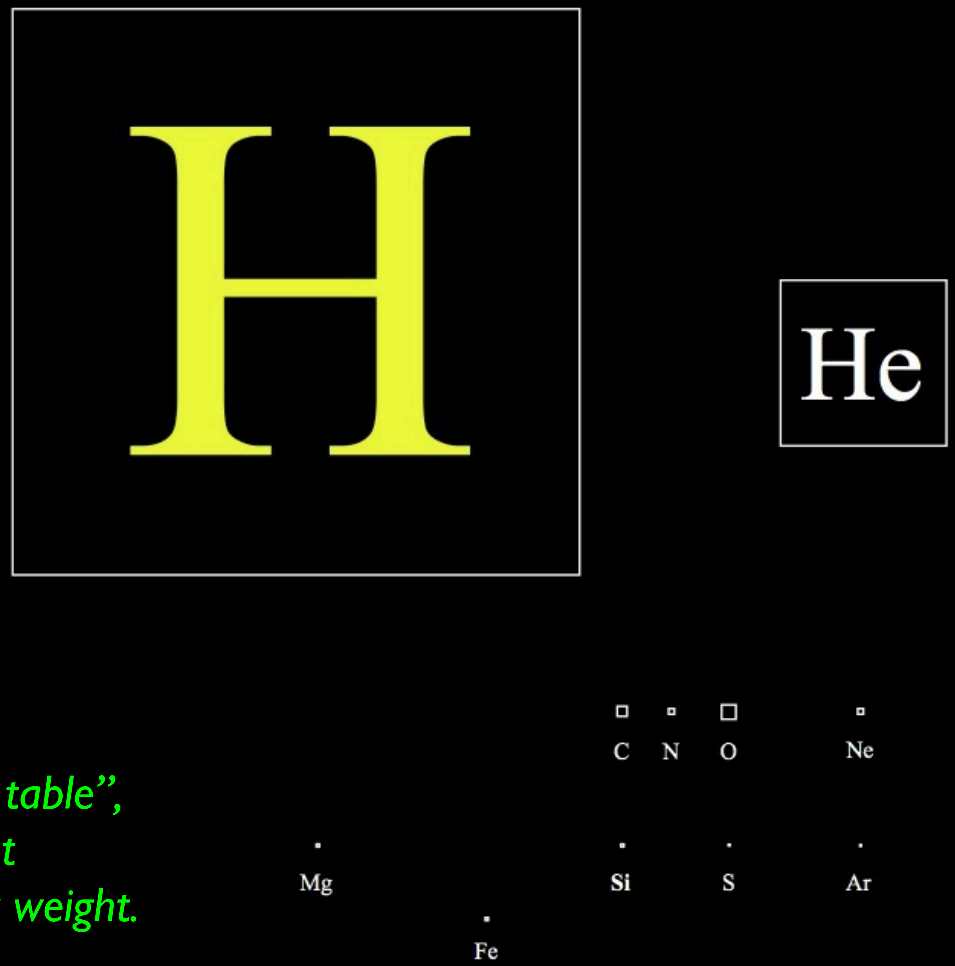
University of Sydney
Centre for Continuing Education
Spring 2012

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*

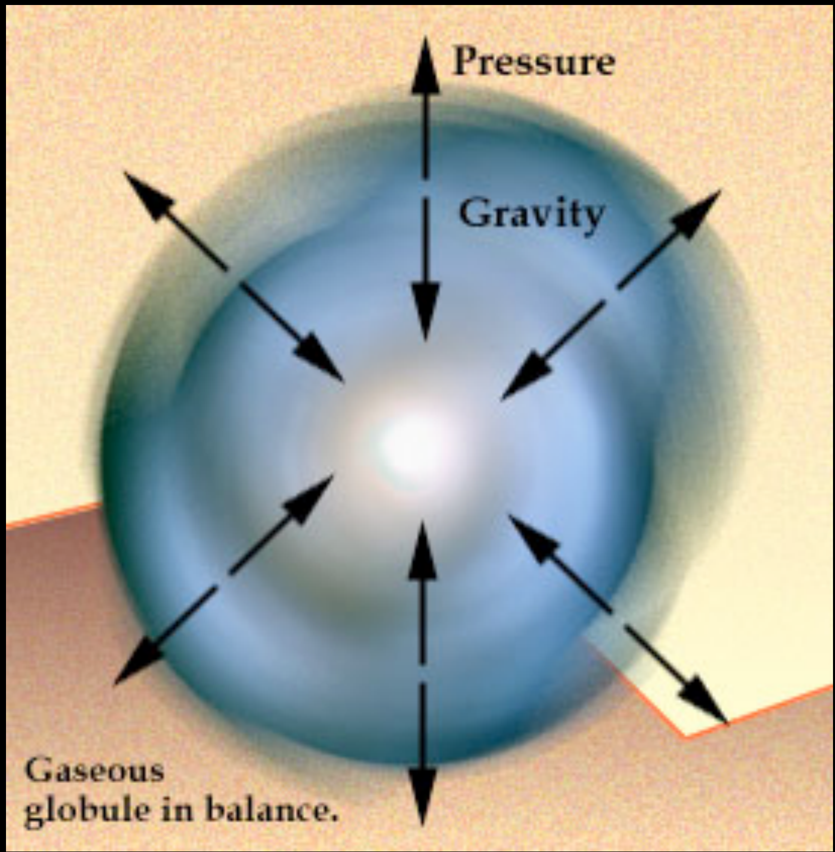
The cloud starts to collapse under its own gravity.

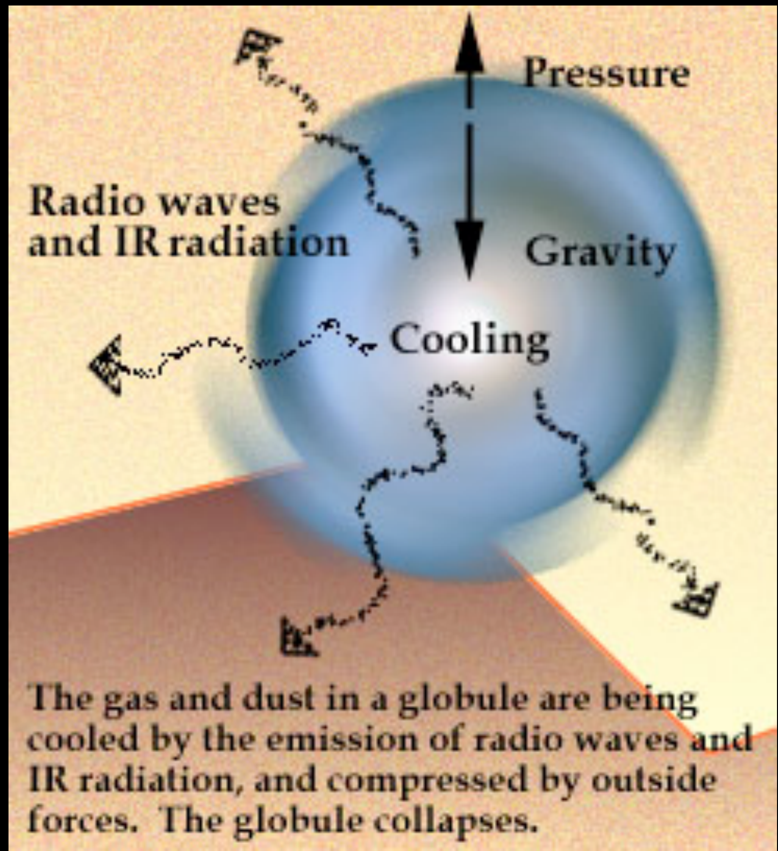
Gravity is the weakest of the four forces which govern our universe – gravity, electromagnetic force, strong nuclear force, and weak nuclear force – but in the end is the most important, because there is no repelling component to gravity.

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.

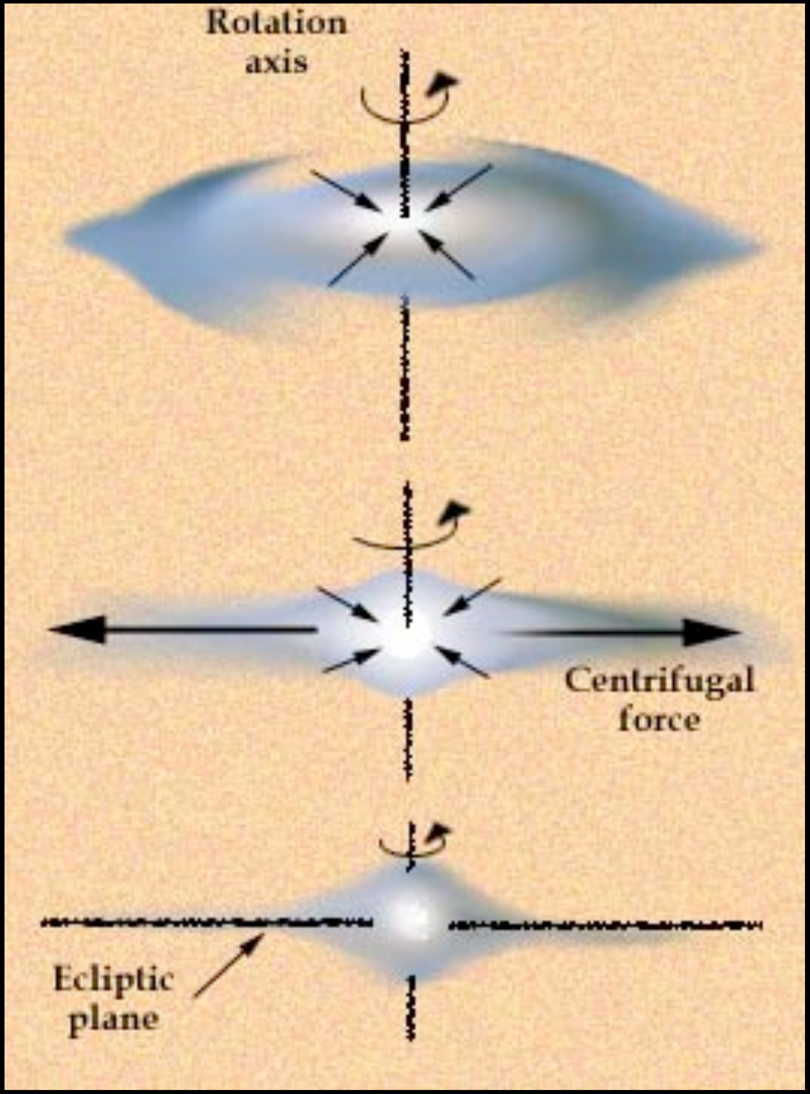
So when our interstellar cloud starts gets big enough, it starts to collapse. Two important effects work to stop the collapse.

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





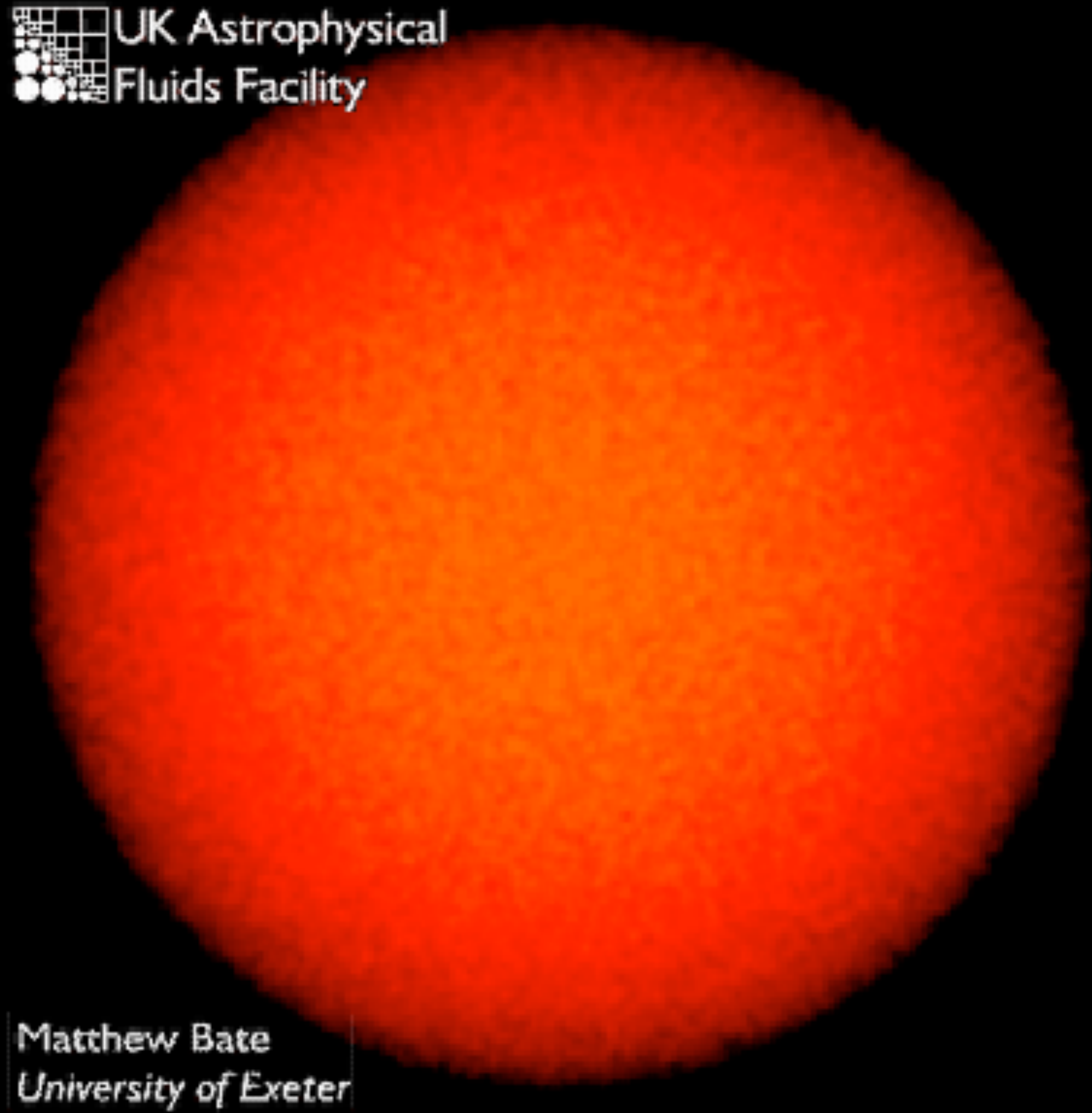
- As the cloud contracts, its speed of rotation increases and the fragment will develop into a central dense cloud surrounded by a swirling disk of gas.



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.

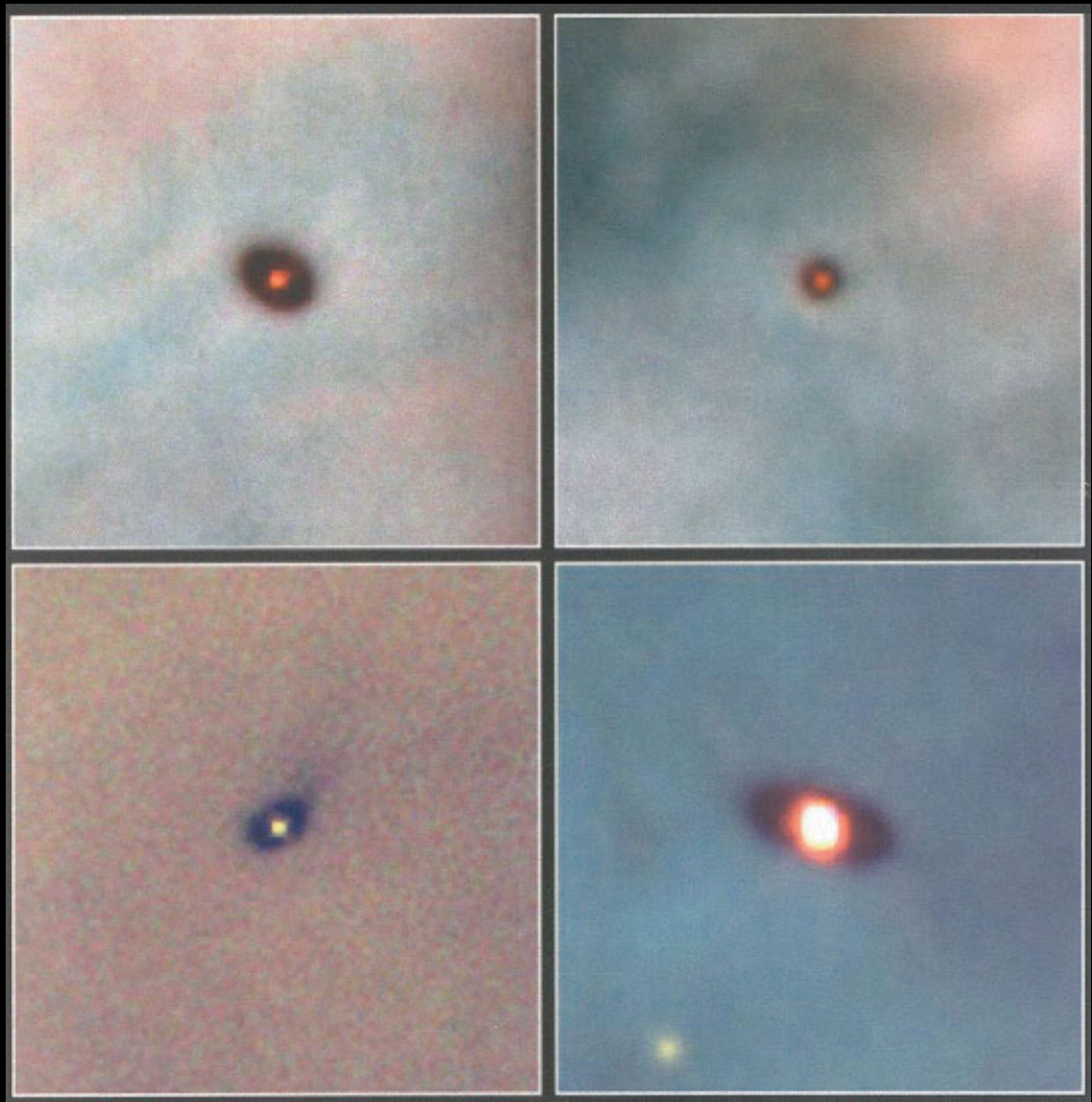


A simulation of the collapse of a 50 solar mass gas clou
across, eventually forming a cluster of about 50 stars (E

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

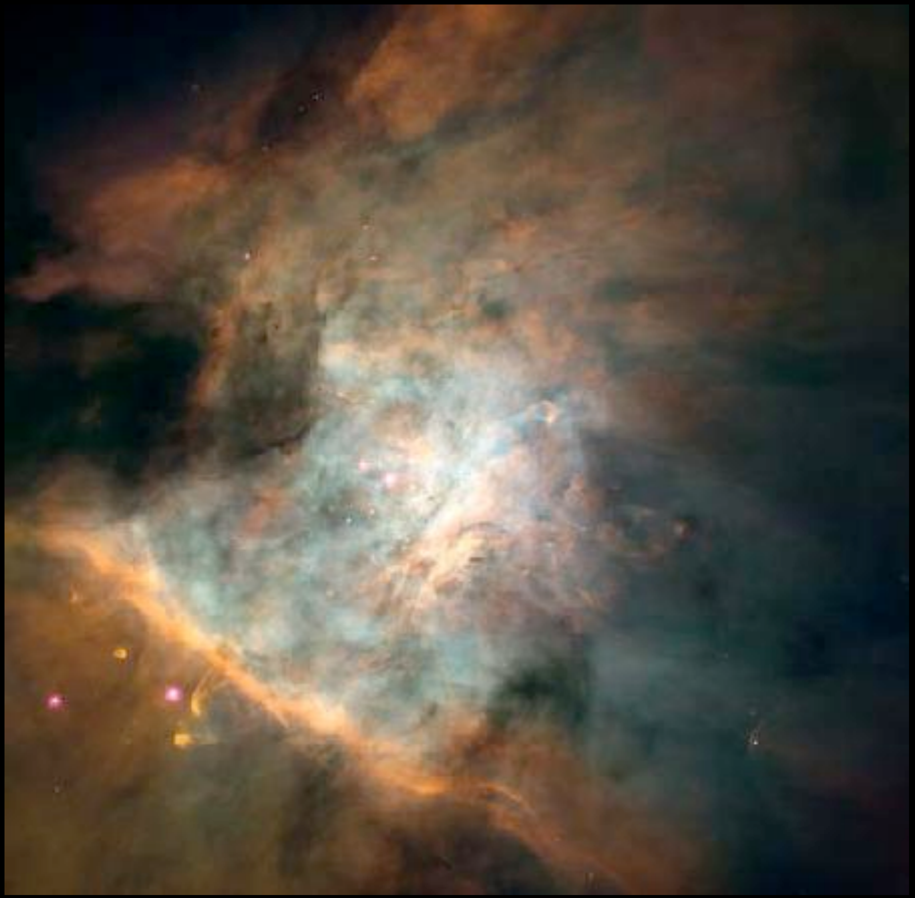
These disks will eventually be where planets form.

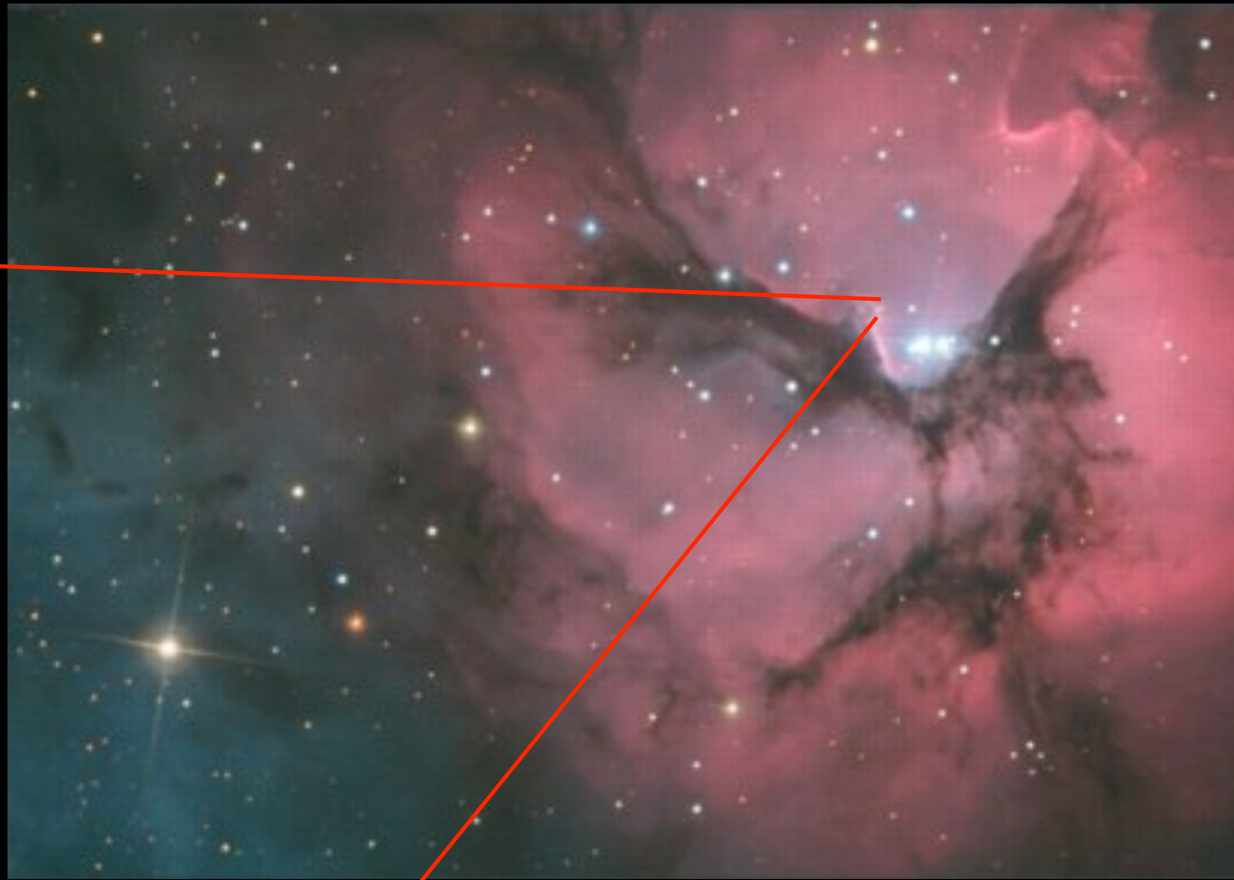
In the meantime, the protostar is continuing to contract and heat up. The temperature in its core increases, until hydrogen nuclei begin to fuse to form helium. This further increases the temperature and hence the pressure at the core, and halts the collapse.

A star is born.

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

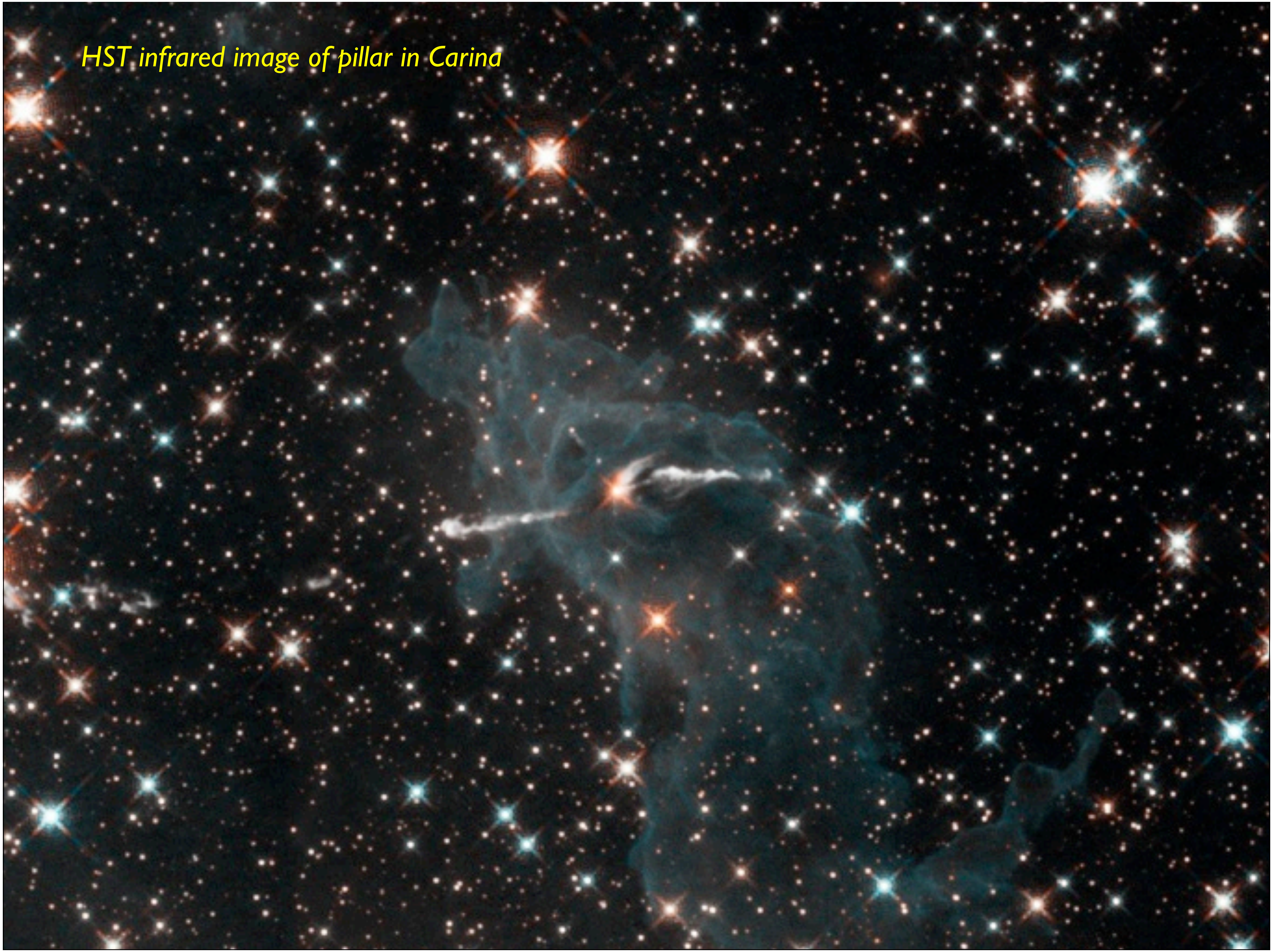
Young stars are often born in clusters. The Orion Nebula contains several young star clusters.





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


HST visible image of pillar in Carina


HST infrared image of pillar in Carina

Young star cluster in the Rosette Nebula

Planet formation

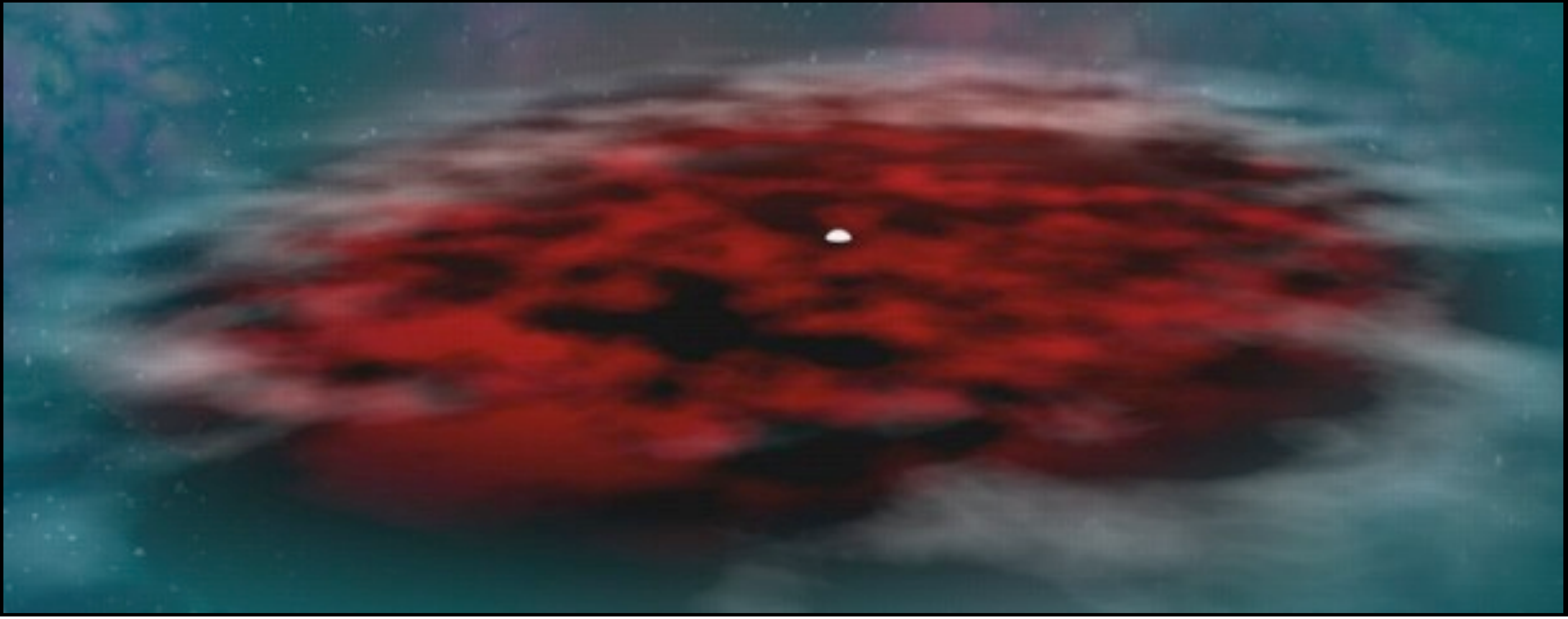
So we have formed a star. But what about the planets?

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.

Phase 1: Coagulation

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.

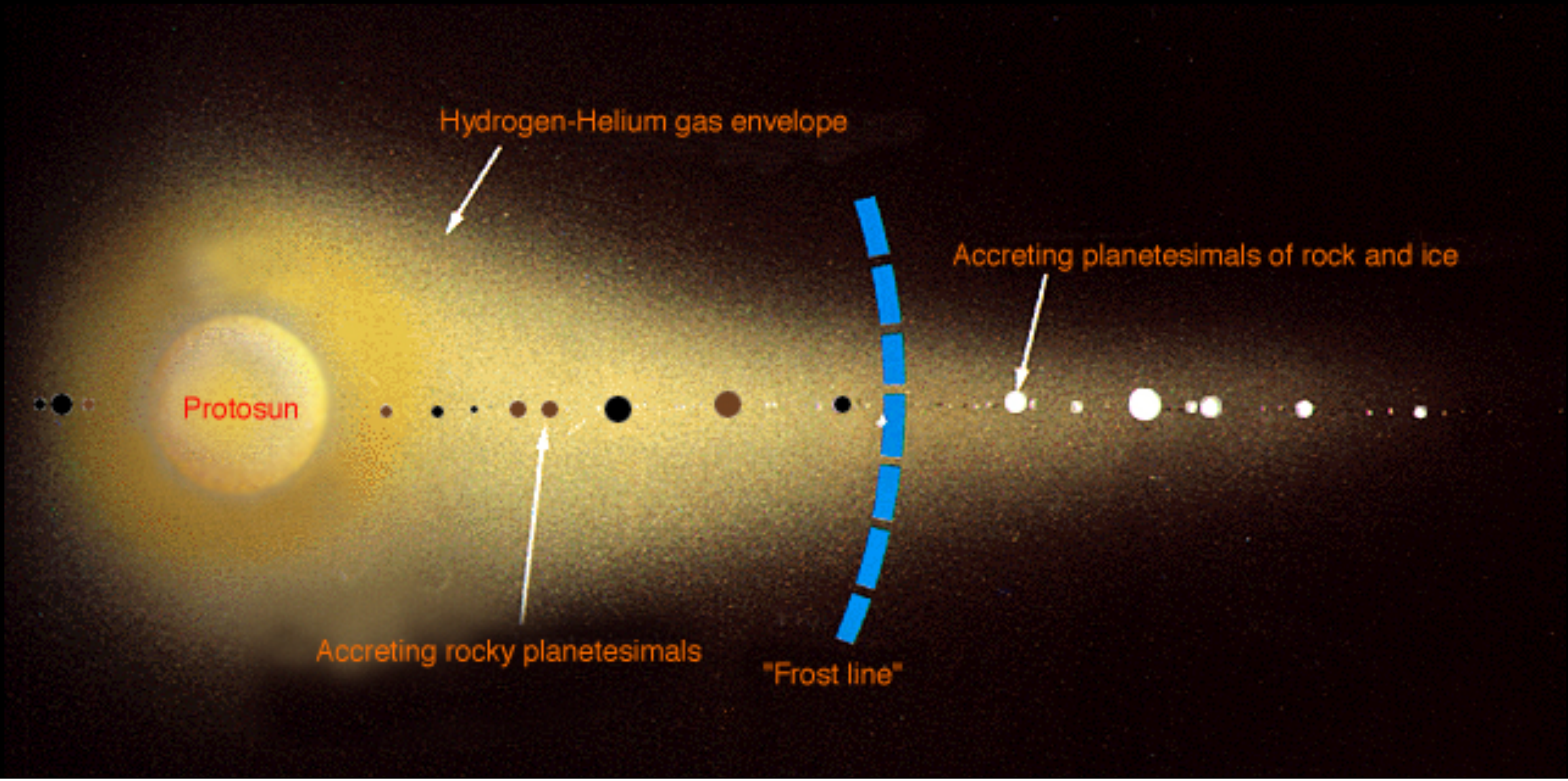


The disk is hotter near the centre, close to the protostar, so different materials condense out at different radii.

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

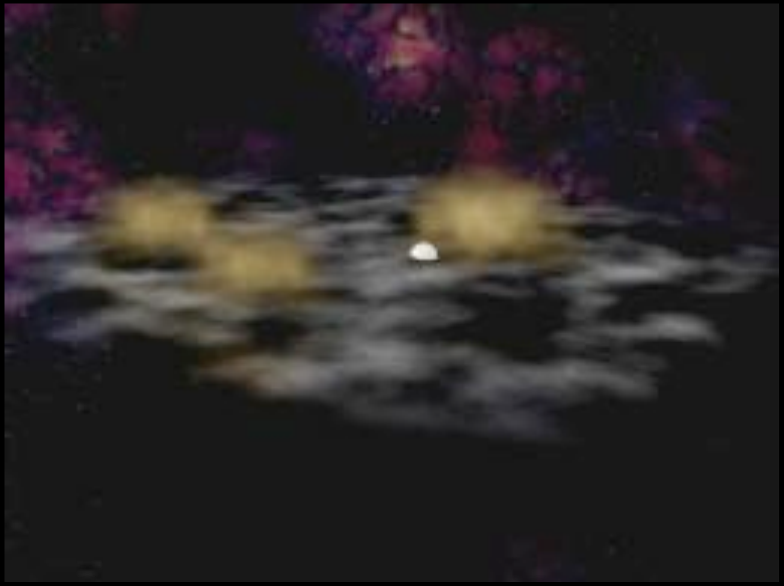
Below about 270 K water ice condenses, as well as ammonia and methane.

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



Phase 2: Accretion

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



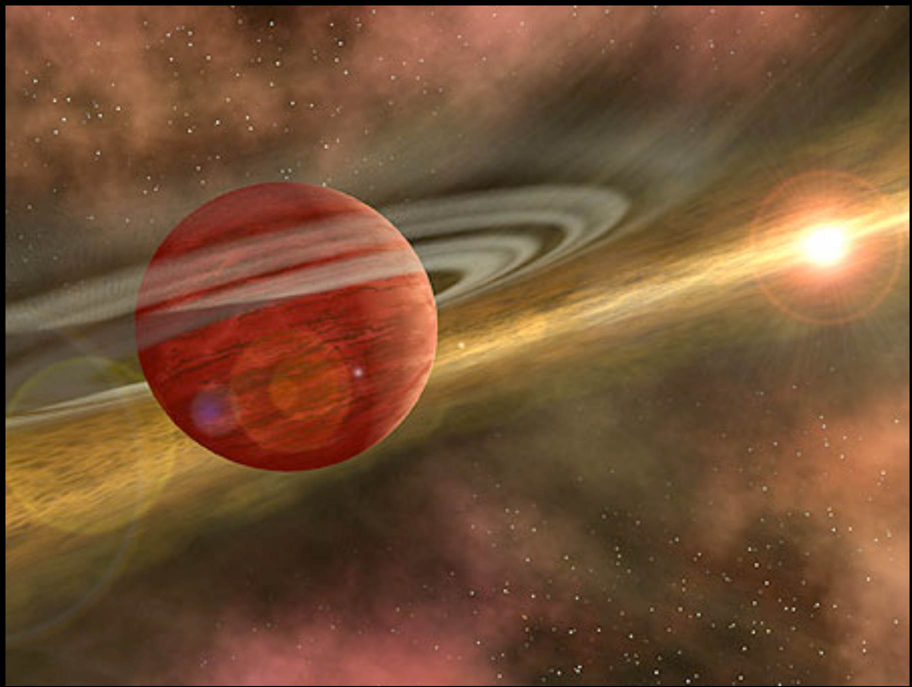
Phase 3: Runaway growth

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.

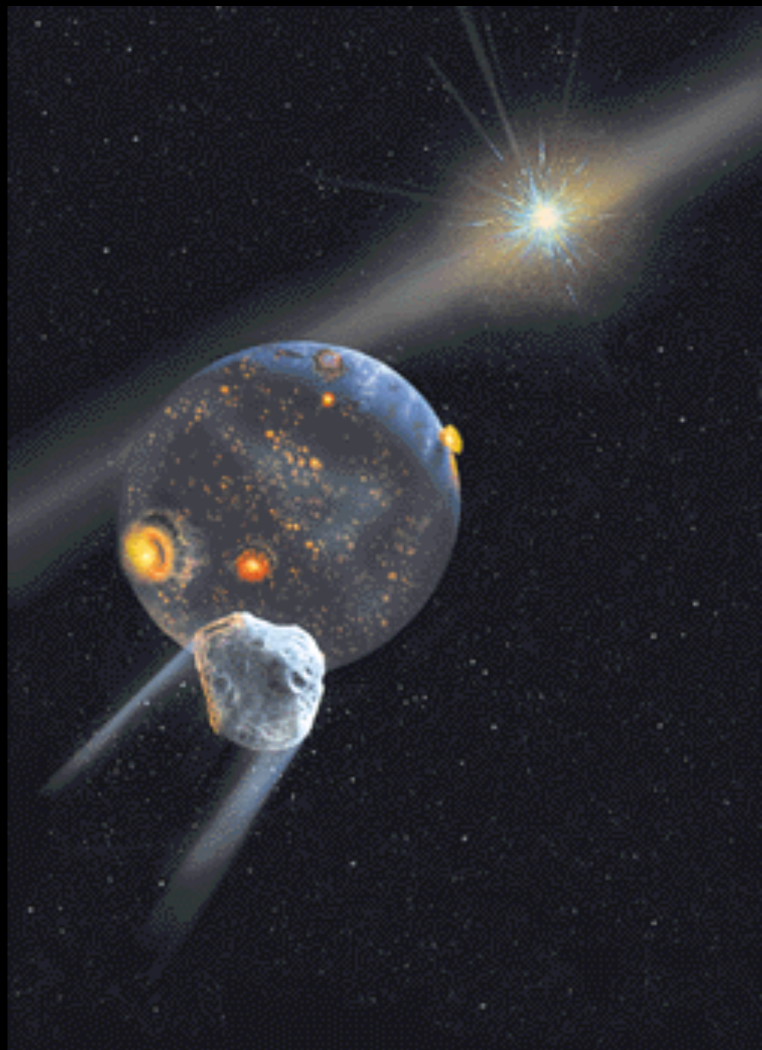
The giant planets appear to have formed by first accreting a core of several Earth masses of rock and ice. Once this solid mass had accumulated, the planet starts accreting gas more and more efficiently. Jupiter and Saturn grew much larger than Uranus and Neptune because they formed closer to the Sun, 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.

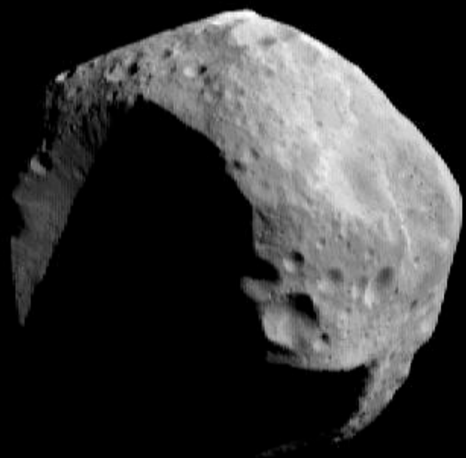


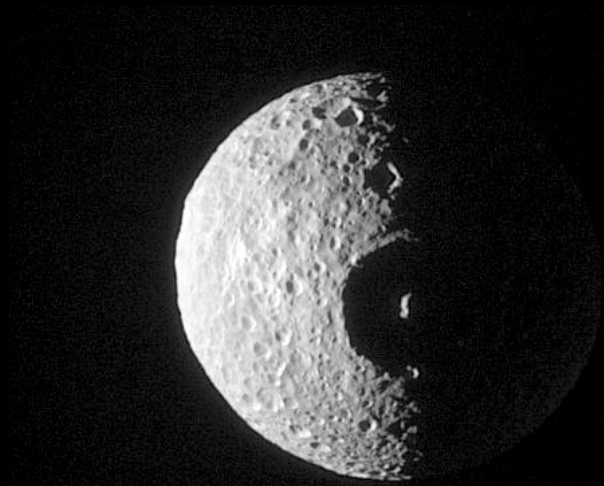
Phase 4: The era of carnage

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.

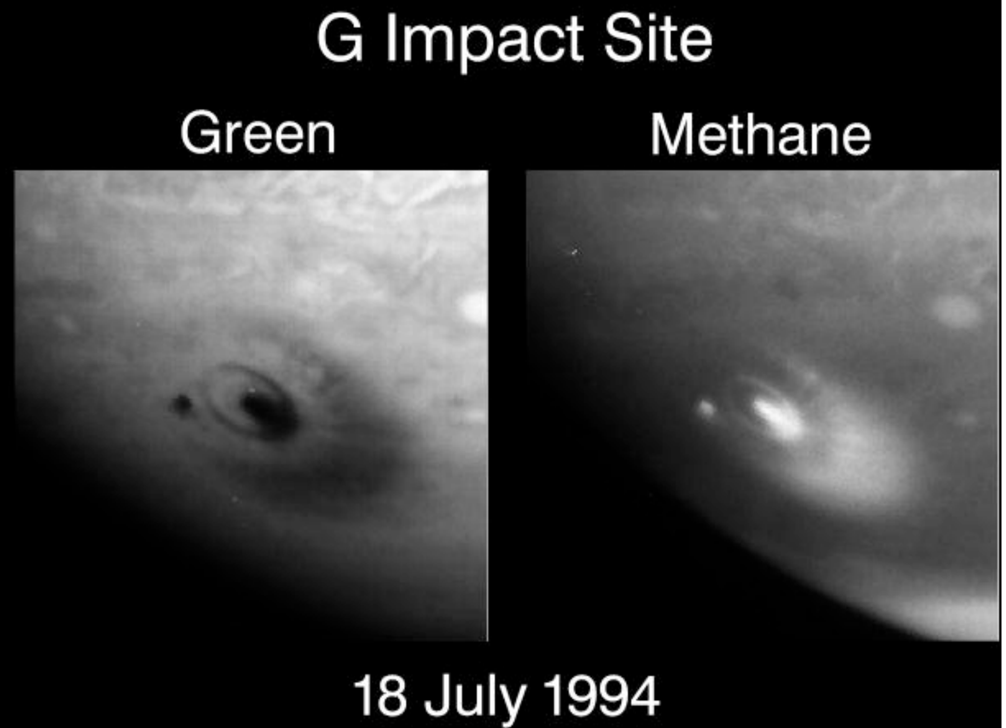




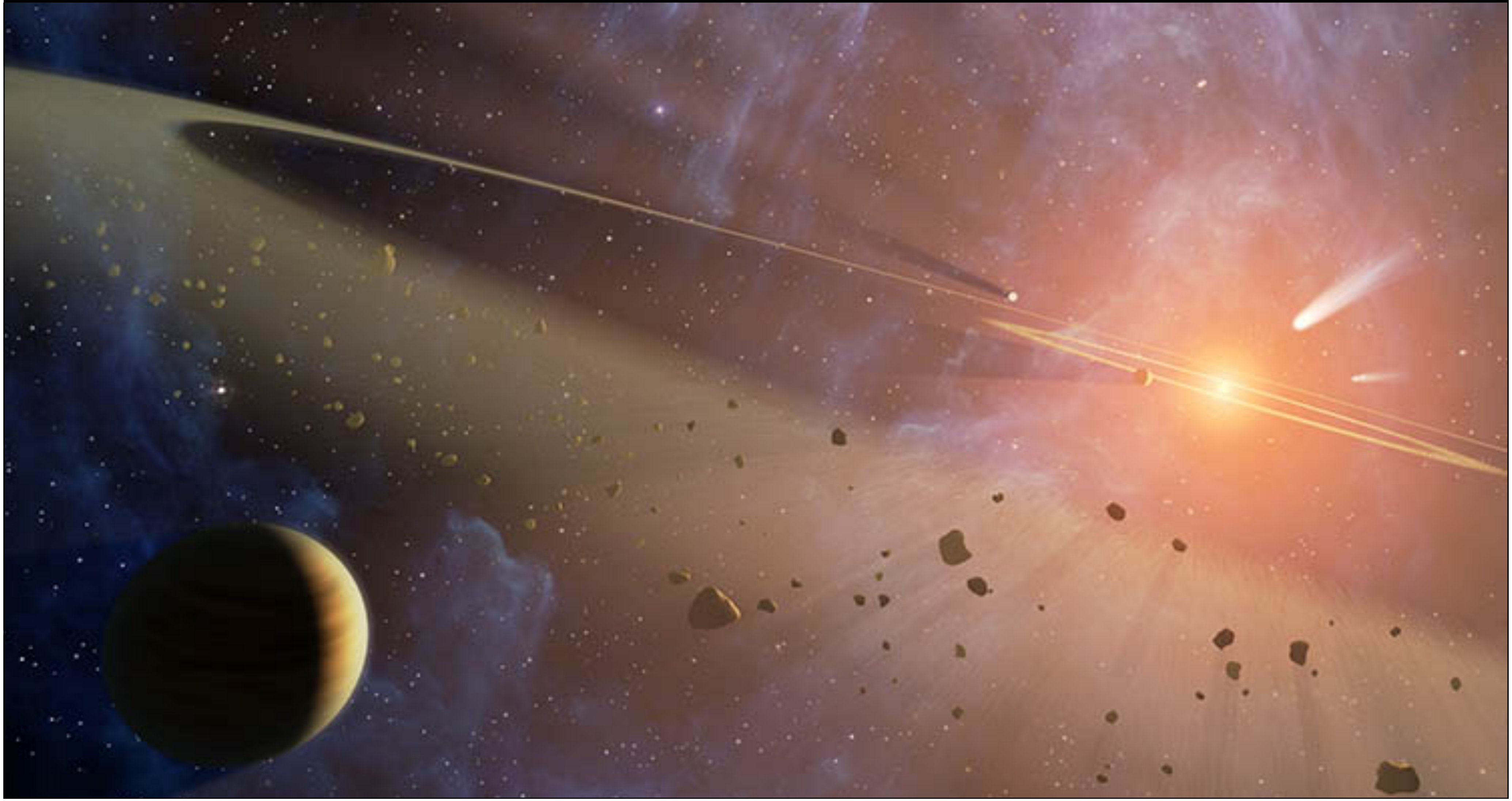
(from left) Mercury, Mathilde, Callisto and Mimas

The bombardment of the Solar System has not stopped, only reduced in intensity. In July 2004, 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.



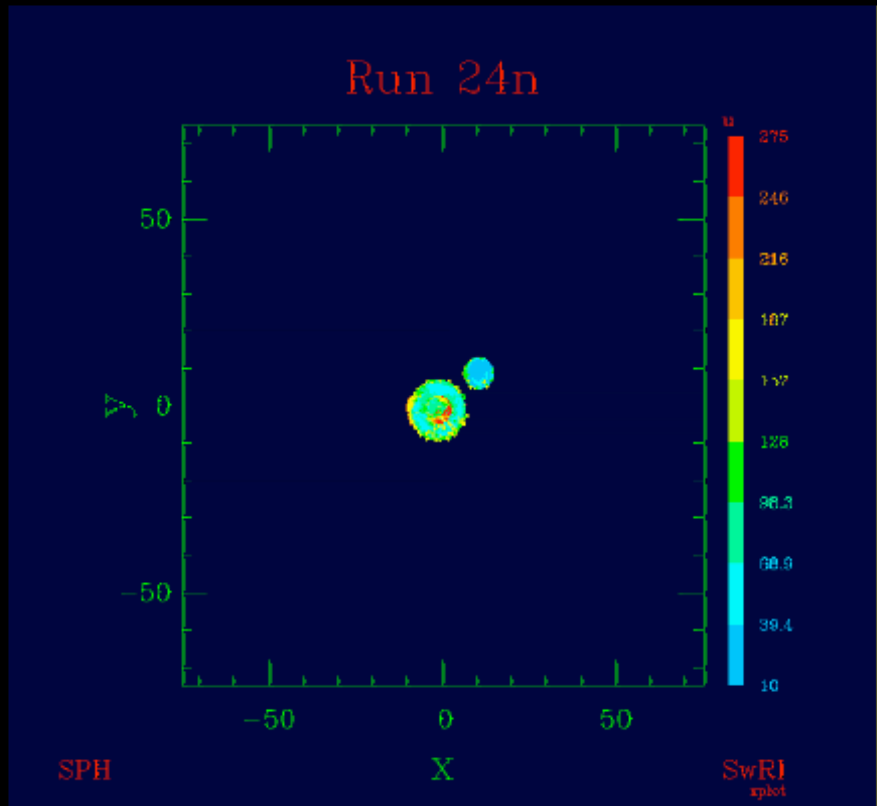
Since the last few impacts were so violent, the last stage of planetary accretion was far from orderly. The random nature of the impacts means the last final state of the planets is impossible to predict theoretically.



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.

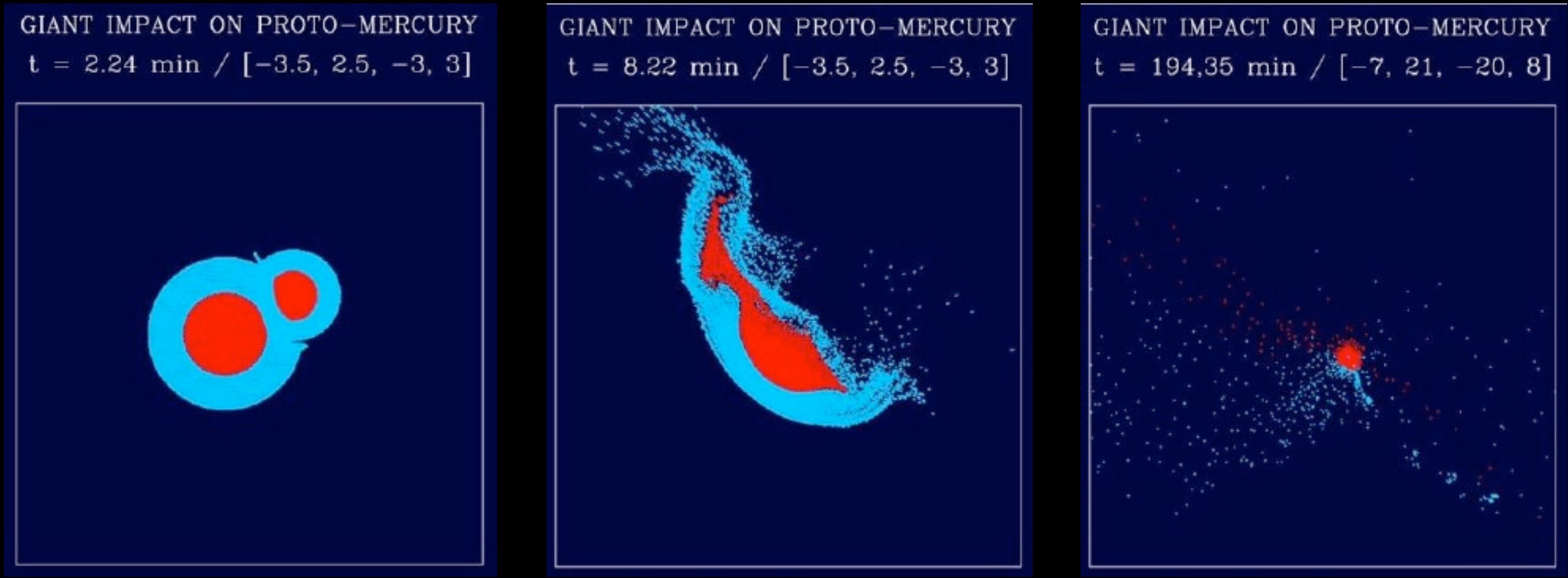


Animation showing the impact of a Mars-size proto-planet with the young Earth. The animation covers only 24 hours, ending with the Earth surrounded by a disk of debris, from which the Moon will coalesce.

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.

This may explain the following odd features of the planets.

Mercury: Mercury's giant iron core may also be the remnant of a giant impact. An off-axis collision with a proto-planet of comparable size may have vaporised the silicate-rich mantle of the proto-Mercury, leaving behind an iron-rich core.



Simulation of a glancing impact on a proto-Mercury. Much of the lighter mantle material (blue) is ejected from the inner solar system altogether, leaving a remnant rich in core material.

Mars: The Martian crustal dichotomy could have been formed by a giant impact, if it only struck a glancing blow.

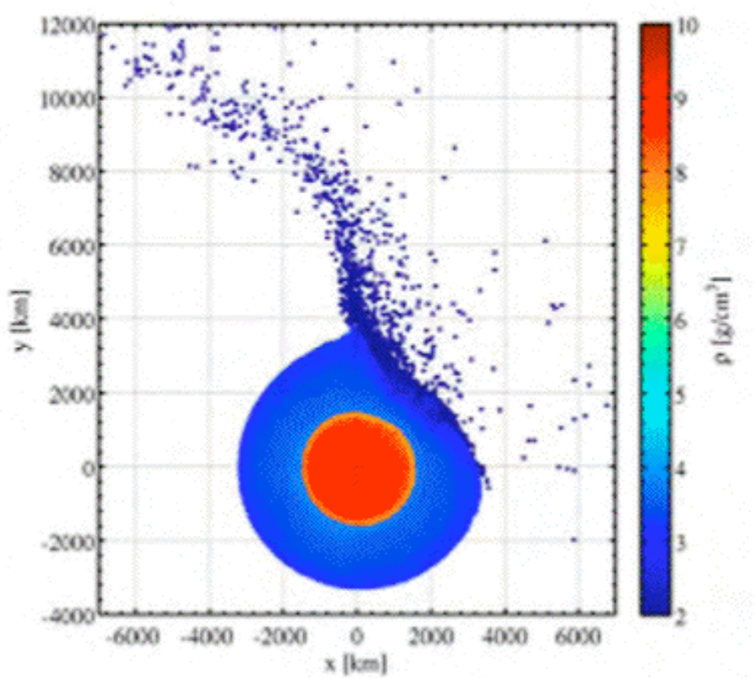
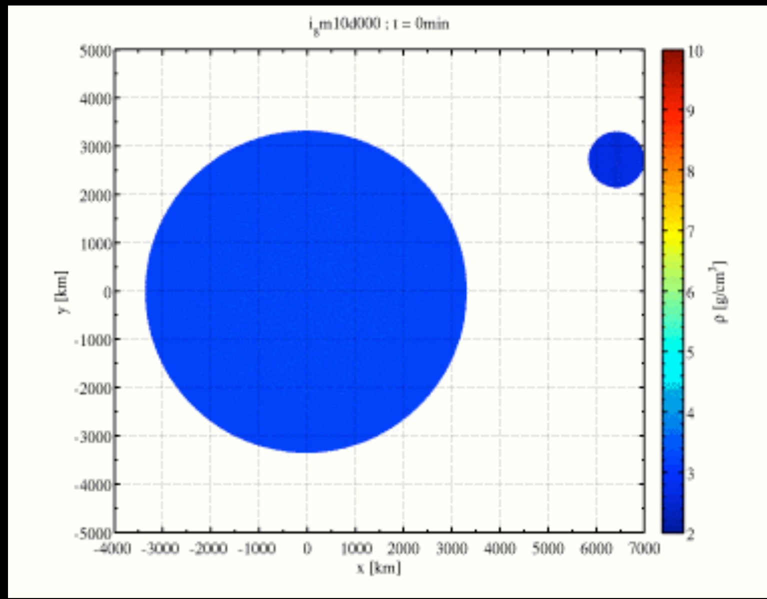
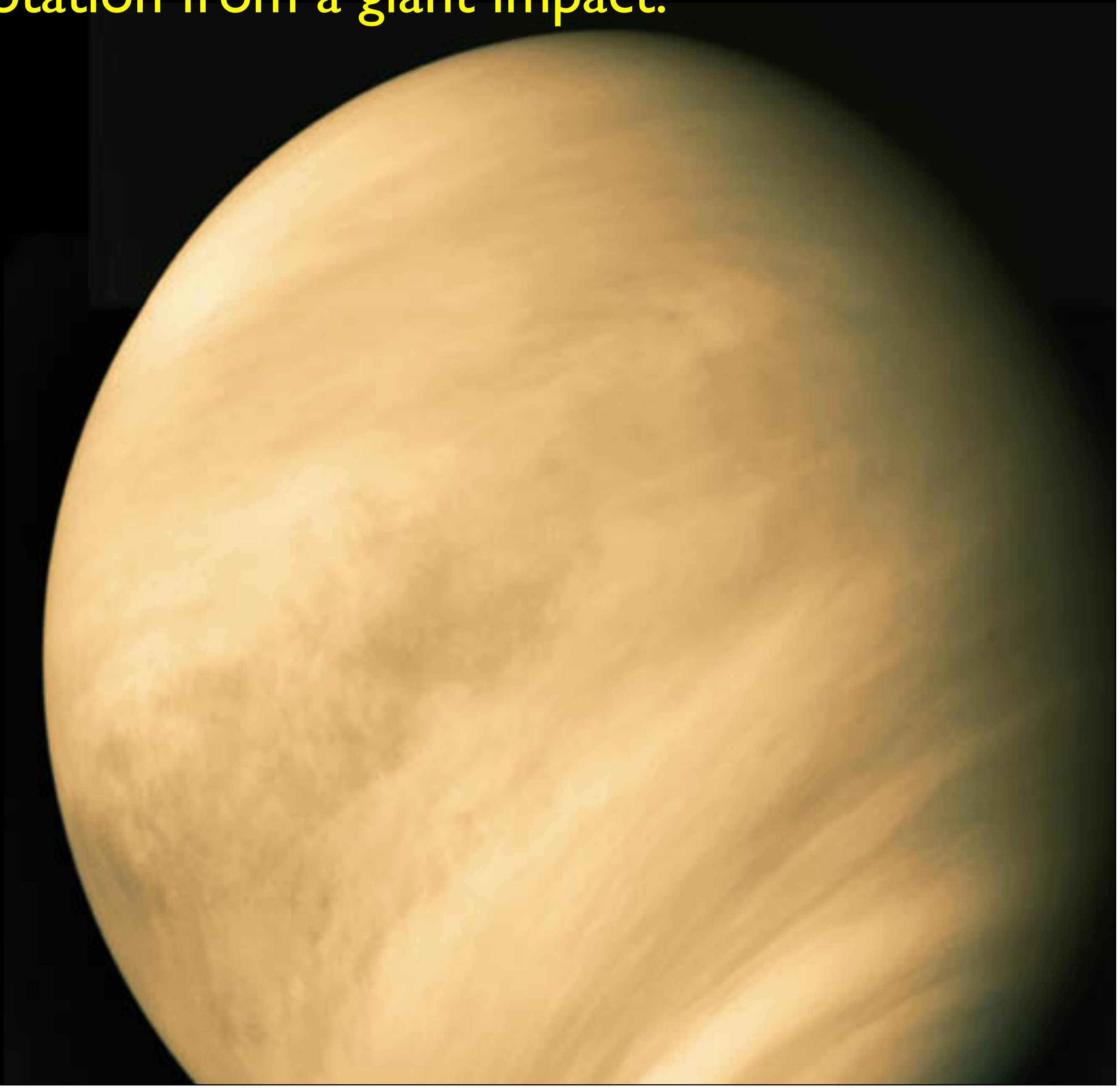


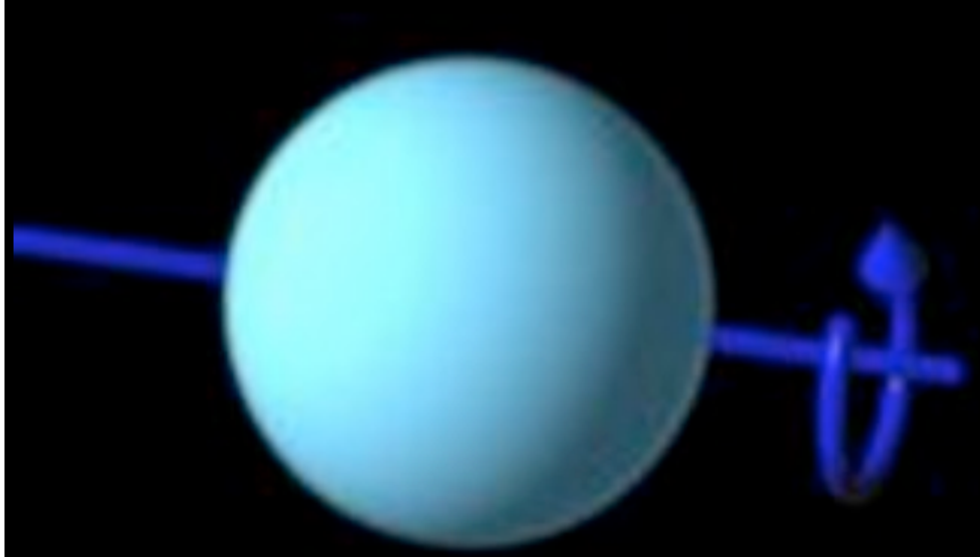
Figure 1. Snapshot of an impact simulation: t = 25 min after impact. Half-space shown. Impact parameters v = 6 km/s, $D_{impactor}$ = 860 km, 1.45×10^{29} J, D_{crater} ~ 8000 km, impact angle = 30 deg.

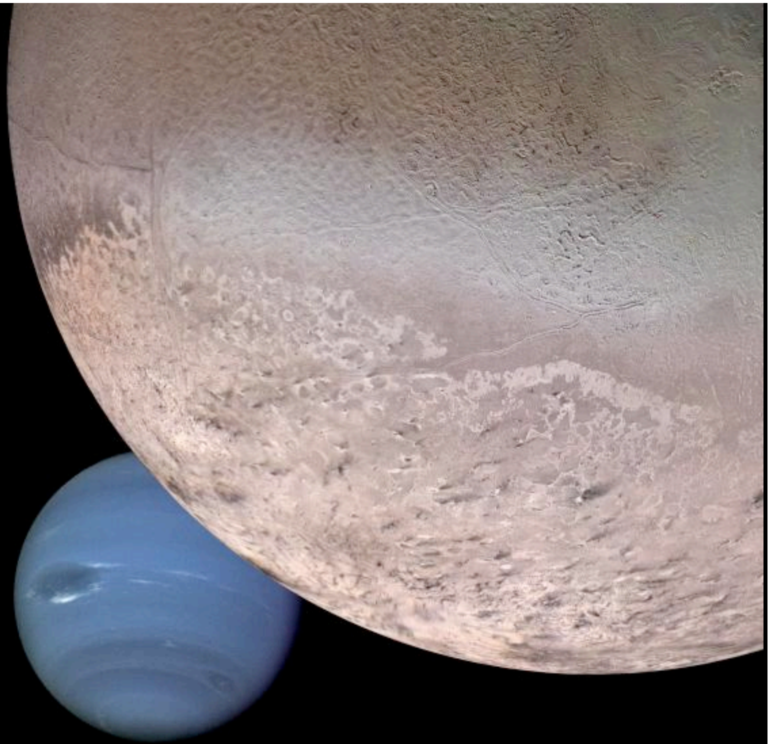


Venus: Venus may have acquired not only its tipped axis but also its slow rotation from a giant impact.



Uranus: Uranus' extreme tilt (98°) is thought to have been caused by a giant impact. A body of at least 2 Earth masses hit the proto-Uranus at an oblique angle, tilting the spin axis. A large amount of material spun off the equator left a disk in orbit from which the current system of moons eventually assembled. In contrast, if the final impact on Neptune was nearly straight down, it would heat the planet but not leave a disk, explaining the absence of regular satellites around Neptune.





Triton: Triton, with its retrograde and highly inclined orbit about Neptune, is most likely a Kuiper belt object which wandered close to Neptune. There, it was captured into orbit, possibly colliding with (and destroying) one of Neptune's regular satellites. The initial orbit would have been highly eccentric, but tidal interactions with Neptune would have circularised it, taking about a billion years. This tidal energy would have acted as a major heat source.

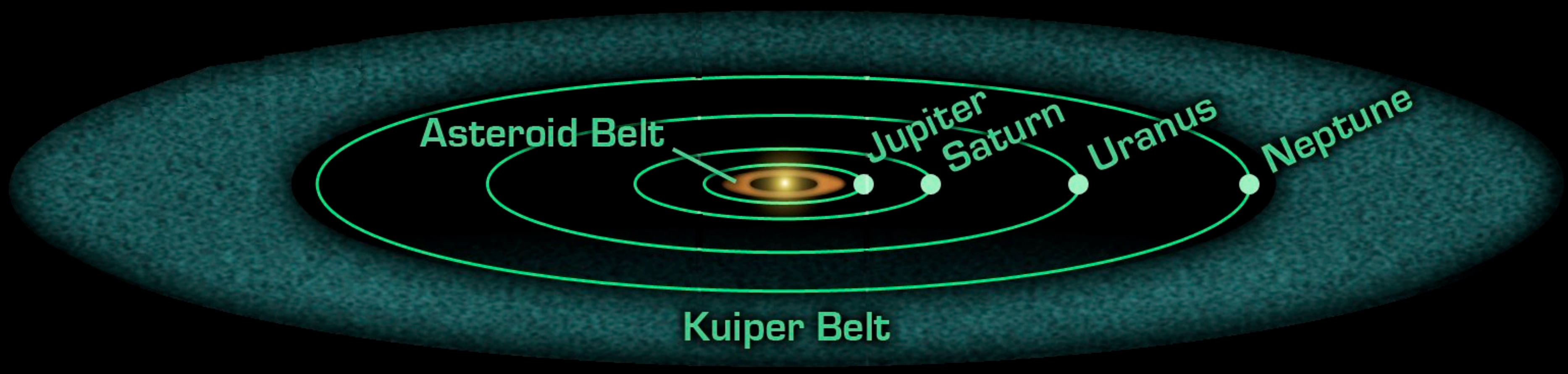
Neptune's original satellite system would have been destroyed by mutual collisions when Triton induced chaotic perturbations in their orbits. *Nereid* was almost ejected from the system, but not quite.

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.



Back to the star

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

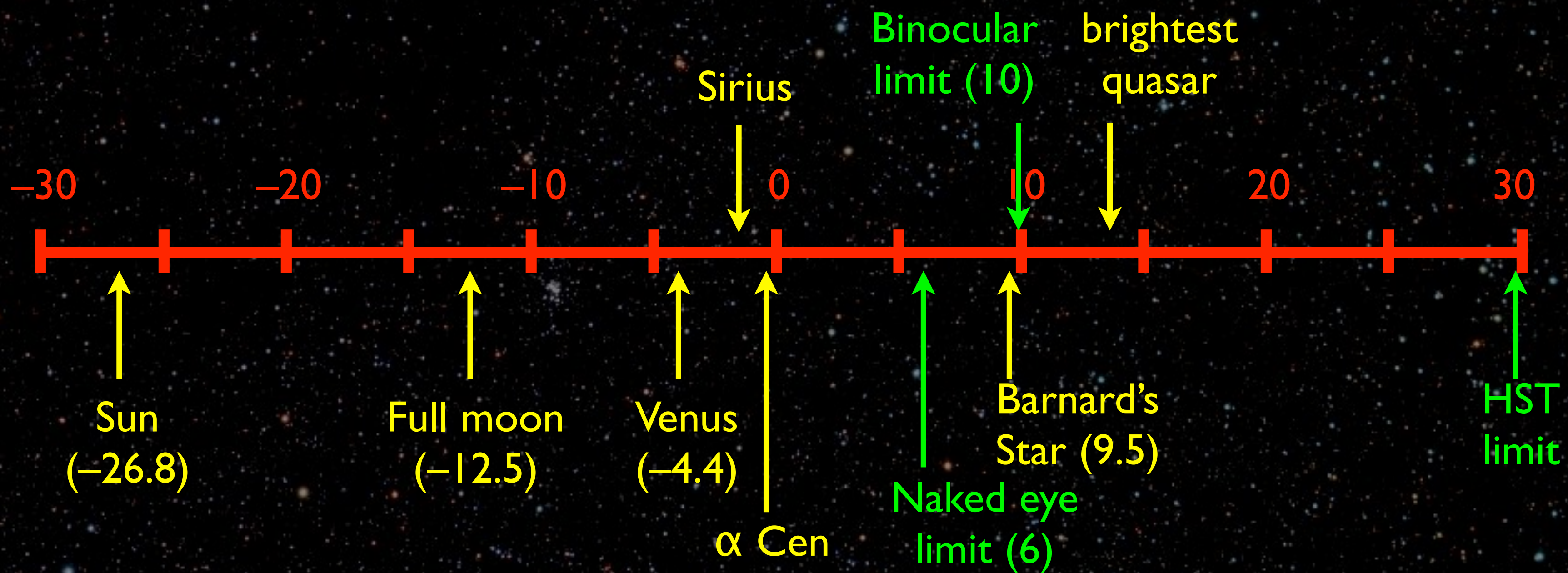
Before we talk about how stars work, we need to back up a little and talk about what stars look like in the sky and how we measure them.

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.

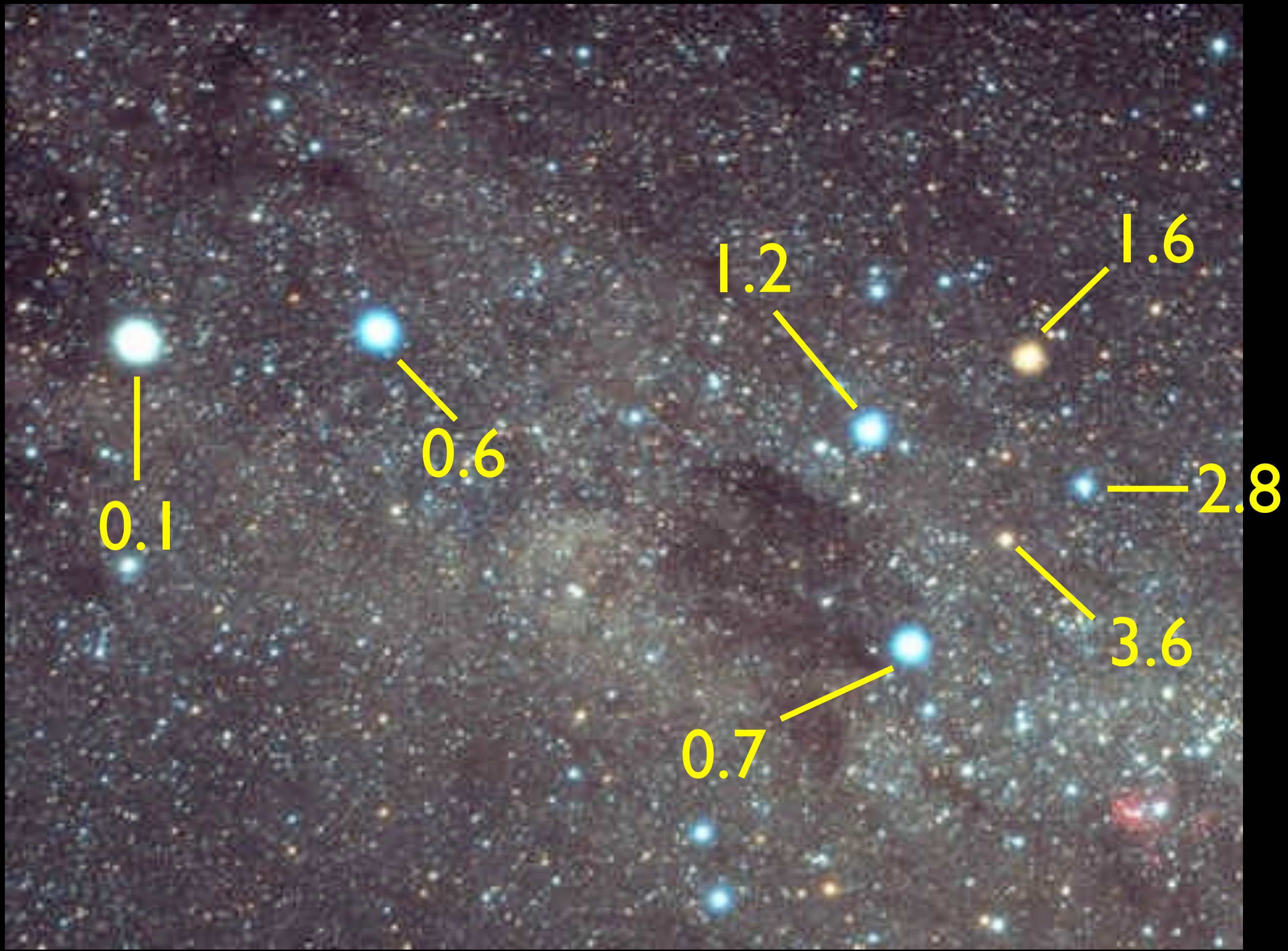


Note that *smaller* magnitudes mean *brighter* stars!

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	0.00
Capella	+0.05
Rigel	+0.08
Procyon	+0.34
Betelgeuse	+0.41
Achernar	+0.47

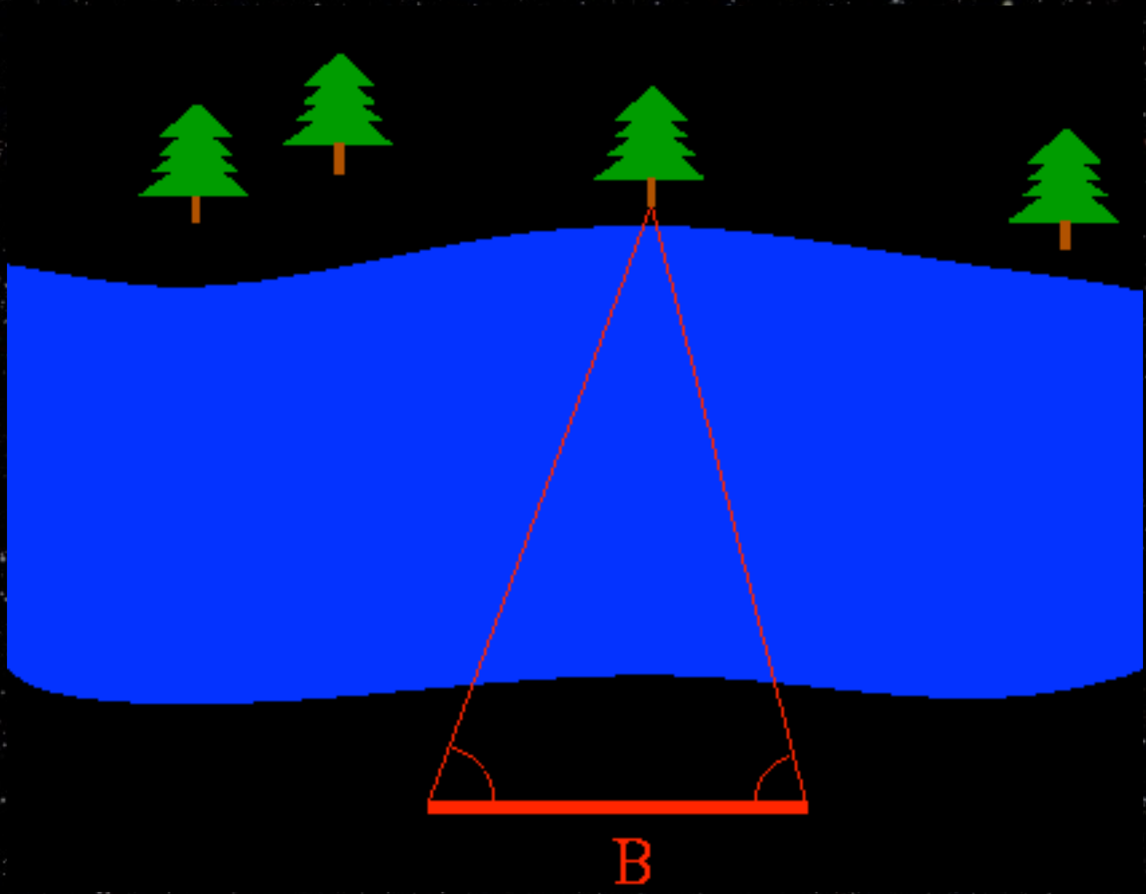
Here are the magnitudes of some of the stars in and around the Southern Cross.



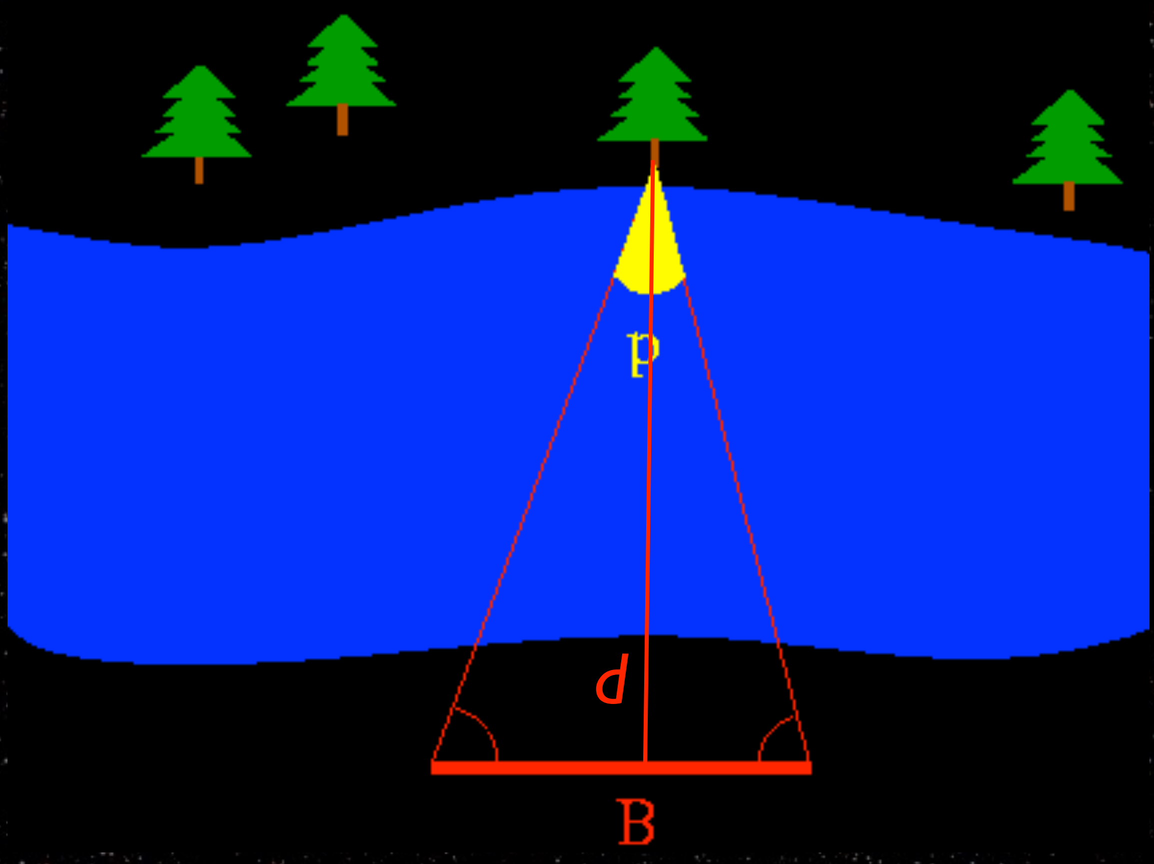
But now we run up against another problem: A star can be bright because it's intrinsically very luminous, or it can be bright just because it's *close* to us.

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. We measure the angle between one end of the baseline and a fixed marker (a tree), and then the angle from the other end of the baseline.



Simple trigonometry gives us the lengths of the sides of the triangle. The angle at the apex *p* is the difference in the tree's apparent position when seen from the ends of the baseline: this is the *parallax*. Knowing B and p, we can work out the distance *d*.

The size of the apparent shift is proportional to the length of the baseline: the longer the baseline, the larger the shift. So the longer the baseline, the further the distance to which you can measure.

Measuring the distance to the stars needs very long baselines indeed.

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

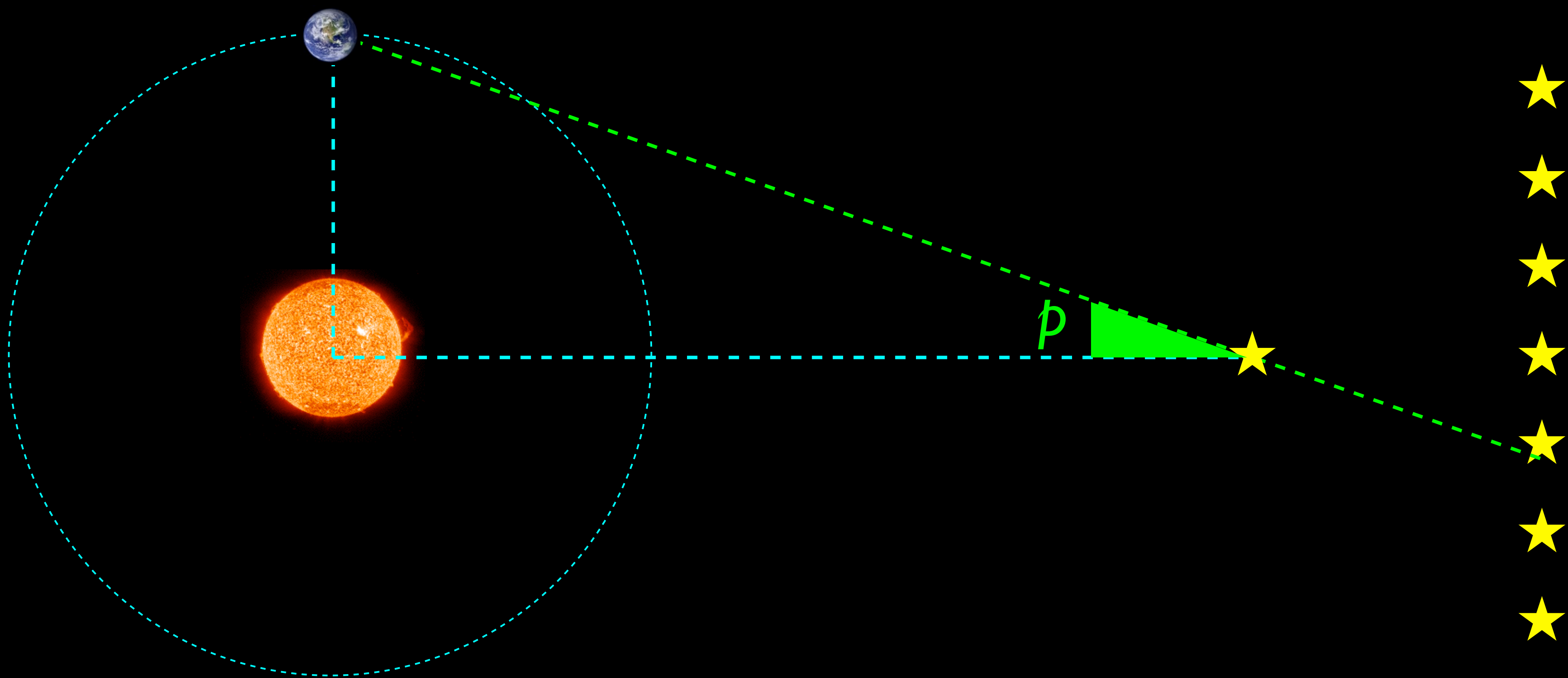
Edmund Halley suggested that the transit of Venus across the face of the Sun could be used to measure its parallax. The different line-of-sight for observers on opposite sides of the world would result in different times for the start and end of the transit, by up to five minutes. Observations of the 1761/1769 transits resulted in an estimate of the distance to the Sun of 153 million km.

Because of the shape of Venus' orbit, transits occur in pairs 8 years apart every ~120 years. There was a transit of Venus in June 2004; the transit on 6 June this year is the last for a century.

Photograph of the 1882 Transit of Venus

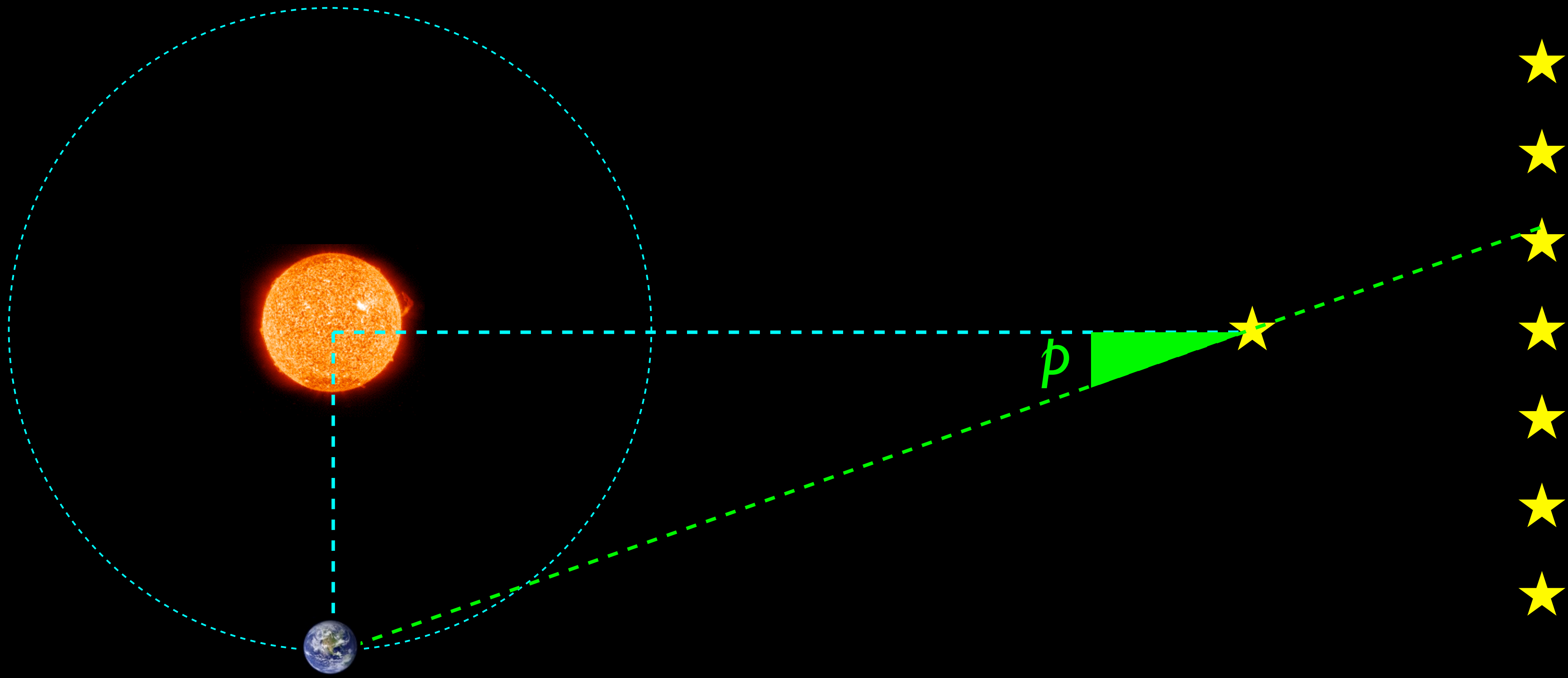
The stars show no measurable parallax, even with the whole Earth as a baseline. We have one more baseline to use, however.

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.

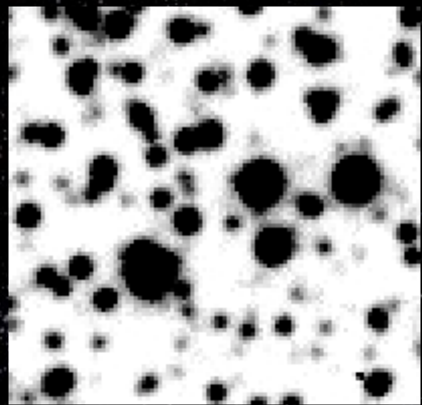


The stars show no measurable parallax, even with the whole Earth as a baseline. We have one more baseline to use, however.

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.



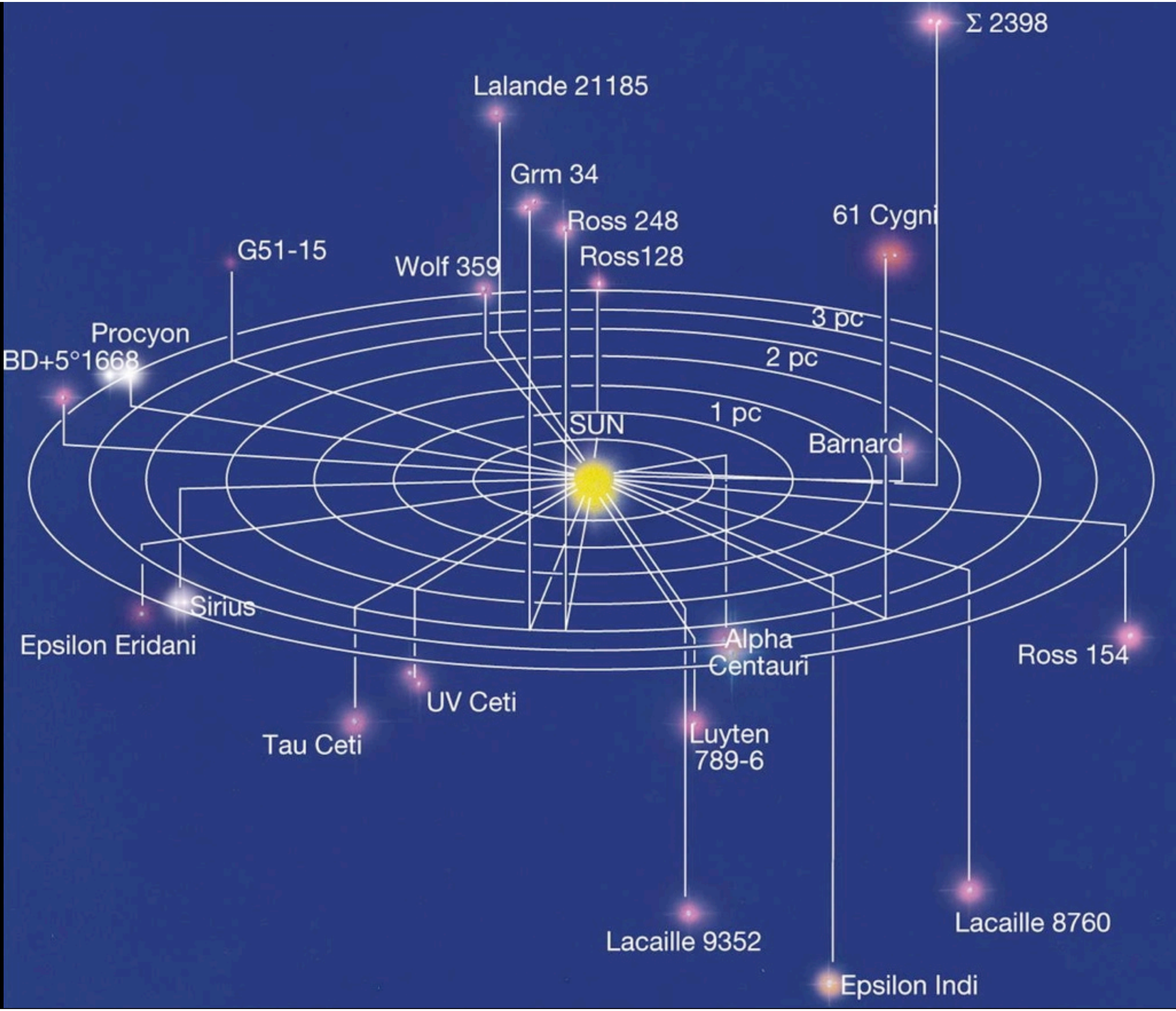
Here are two images of a nearby star, showing the motion due to parallax.



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

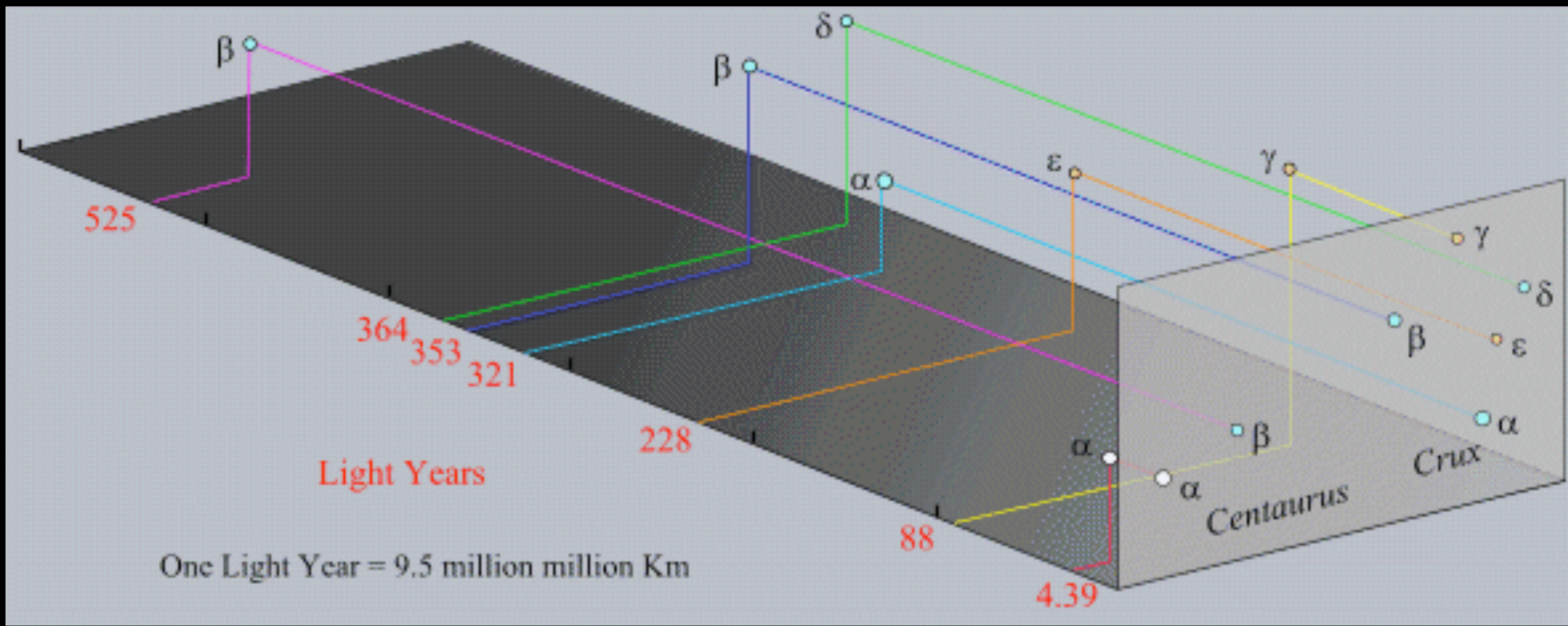

Σ 2398
Lalande 21185
Grm 34
Ross 248
61 Cygni
G51-15
Wolf 359
Ross128
3 pc
Procyon
BD+5°1668
2 pc
1 pc
SUN
Barnard
Sirius
Epsilon Eridani
Alpha Centauri
Ross 154
UV Ceti
Tau Ceti
Luyten 789-6
Lacaille 9352
Lacaille 8760
Epsilon Indi

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 magnitude	d (pc)
Sirius	–1.50	2.6
Canopus	–0.73	96
Alpha Centauri	+0.10	1.3
Vega	+0.04	7.9
Arcturus	0.00	11.6
Capella	+0.05	13.1
Rigel	+0.08	184
Procyon	+0.34	3.5
Betelgeuse	+0.41	131
Achernar	+0.47	45

star	apparent magnitude	d (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

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.

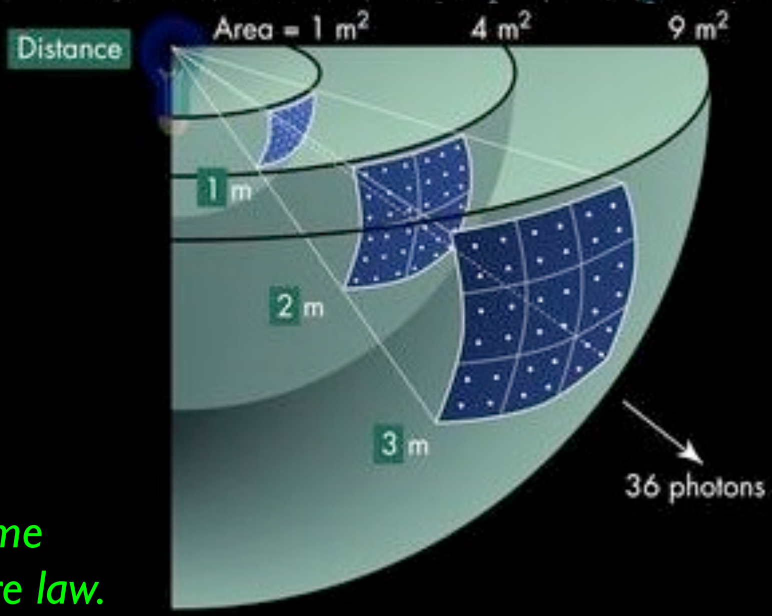


Absolute magnitudes

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 law.

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:

- Hubble image of the star forming region Hubble-X in the galaxy NGC 6822: from Astronomy Picture of the Day 2001 February 16 http://antwrp.gsfc.nasa.gov/apod/ap010216.html
- Orion nebula:
- Crab Nebula: from Astronomy Picture of the Day 2002 July 14 http://antwrp.gsfc.nasa.gov/apod/ap020714.html
- Horsehead Nebula: AAT image by David Malin, http://www.aao.gov.au/images/captions/aat036.html; Orion in gas, dust and stars: image by Rogelio Bernal Andreo (Deep Sky Colors), from APOD 2009 Sep 29 http://antwrp.gsfc.nasa.gov/apod/ap090929.html
- Hubble view, from HubbleSite Press Release, 24 April 2001, http://hubblesite.org/newscenter/newsdesk/archive/releases/2001/12/
- Simulation of molecular cloud collapse: from Matthew Bate's Animations, http://www.astro.ex.ac.uk/people/mbate/animations.html
- Rotation and collapse: from STARS AND GALAXIES A Hypertext Course by Richard McCray http://cosmos.colorado.edu/cw2/courses/astr1120/text/chapter9/l9S3.htm
- Collapsing globules: from NASA's Observatorium: Birth of Stars http://observe.arc.nasa.gov/nasa/exhibits/stellarbirth/opening1.html
- Animation of the birth of the solar system: from Chris Tinney's home page http://www.aao.gov.au/local/www/cgt/cgthome/homepage.html
- Great Nebula in Orion: mosaic of HST images by C. O'Dell and S. Wong, Astronomy Picture of the Day 1999 May 22 http://antwrp.gsfc.nasa.gov/apod/ap990522.html
- Triffid Nebula: photo byJim and Janet Castano/Adam Block, Astronomy Picture of the Day 2003 September 1 http://antwrp.gsfc.nasa.gov/apod/ap030901.html; HST image of pillars and jets: Astronomy Picture of the Day 2001 December 30 http://antwrp.gsfc.nasa.gov/apod/ap011230.html
- 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
- 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
- Ice line: from Windows to the Universe http://www.windows.ucar.edu/tour/link=/jupiter/atmosphere/J_evolution_3.html

- Disk around proto-Jupiter: http://www.gps.caltech.edu/classes/ge133/
- Runaway growth: from http://www.usm.uni-muenchen.de/people/gehren/vorlesung/4.1_Himmelsmechanik/kosmogonie/dia_10.html
- Newly formed Neptune: by Don Dixon, from Scientific American, September 1999 issue http://www.sciam.com/article.cfm?articleID=00050729-BAAC-1C73-9B81809EC588EF21
- Comet Shoemaker-Levy: Hubble images, from HubbleSite News Archive, http://hubblesite.org/newscenter/newsdesk/archive/releases/1994/26/ and http://hubblesite.org/newscenter/newsdesk/archive/releases/1994/32/
- Planet formation: http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2008-19a
- Moon formation: from Wikipedia http://en.wikipedia.org/wiki/Giant_impact_hypothesis
- Moon origin paintings: image by Fahad Sulehria http://www.novacelestia.com/images/earth_impact_moon_space_art.html
- Moon formation animation: from "SwRI, UCSC researchers identify the Moon-forming impact", http://www.swri.edu/press/impact.htm
- Proto-Mercury impact: from "Pieces of Mercury Found in Virtual Collision", http://www.space.com/060404_mercury_formation.html
- Mars dichotomy simulation: from New Scientist http://space.newscientist.com/article/dn11387-did-a-giant-impact-create-the-two-faces-of-mars.html
- Volcano: Santa Maria, by Jeffrey Johnson http://earth.unh.edu/johnson/VOLCANO_PAGES/SANT.htm
- Southern Cross and Centaurus: from http://webpages.charter.net/alsonwongweb/centauru.htm
- Earth: View of the Earth from space, Eastern hemisphere, from "The Blue Marble: True-color global imagery at 1 km resolution" http://earthobservatory.nasa.gov/Newsroom/BlueMarble/; Mars, from Hubble Release, 5 July 2001, http://hubblesite.org/newscenter/newsdesk/archive/releases/2001/24/
- 1882 transit of Venus: from Wikipedia, http://en.wikipedia.org/wiki/Transit_of_Venus
- Motion due to parallax: from DISTANCES TO NEARBY STARS AND THEIR MOTIONS: An Introductory Astronomy Lab, http://www.astro.washington.edu/labs/parallax/parallax_distance.html
- Nearest stars: from The Big Blog Theory, March 2010 http://thebigblogtheory.wordpress.com/2010/03/
- Distances of stars in the Southern Cross: from "Distances" by Peter Caldwell, http://users.netconnect.com.au/~astronet/dist.html. Used with permission.
- Eta Carinae in infrared: from Astronomy Picture of the Day 2000 June 13 http://antwrp.gsfc.nasa.gov/apod/ap000613.html
- Hubble Space Telescope image of Wolf 359: from http://oposite.stsci.edu/pubinfo/PR/96/aas96sum.html