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

Presented by

Dr Helen Johnston School of Physics

Spring 2015





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

Page 2

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)



Ar

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.



The University of Sydney

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 University of Sydney



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)

Matthew Bate University of Exeter



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



a disk of gas.

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

rapidly. The collapsing cloud is now a protostar, surrounded by

We can actually see these disks around newborn stars.



The University of Sydney

Hubble images of protoplanetary 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.



Page 19

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.

Page 28

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



The University of Sydney

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



Page 30

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.

Green





Methane





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 Moonimpacting 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 The which the Moon will coalesce.



41

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.

Asteroid Belt Jupiter Un
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!

The University of Sydney

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.



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.



The University of Sydney

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



The University of Sydney



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 (pa
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





The University of Sydney

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)	star		apparent mag	distance (pc)
Sirius	-1.50	2.6	Proxima Ce	entauri	11.5	1.3
Canopus	-0.73	96	Alpha Cent	auri	0.1	1.3
Alpha Centauri	+0.10	1.3	Barnard's S	itar	9.5	1.8
Vega	+0.04	7.9	Wolf 359		13.5	2.3
Arcturus	0.00	11.6	Lalande 21	185	7.5	2.5
Capella	+0.05	13.1	Sirius		-1.5	2.6
Rigel	+0.08	184	Luyten 726	-8	12.5	2.7
Procyon	+0.34	3.5	Ross 154		10.6	2.9
Betelgeuse	+0.41	131	Ross 248		12.2	3.2
Achernar The University of Sydney	+0.47	45	Epsilon Erid	ani	3.7	3.3 Page 63

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. Distance 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 (
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:

- W5: Pillars of Star Formation, from Astronomy Picture of the Day 2014 December 16 http://apod.nasa.gov/apod/ap141216.html •
- 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: from Astronomy Picture of the Day 2006 Jan 19 http://apod.nasa.gov/apod/ap060119.html •
- 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/ ٠
- 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 ٠ http://cosmos.colorado.edu/cw2/courses/astr1120/text/chapter9/I9S3.htm
- Collapsing globules: from NASA's Observatorium: Birth of Stars http://observe.arc.nasa.gov/nasa/exhibits/stellarbirth/opening1.html ٠
- 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 by Jim and Janet Castano/Adam Block, Astronomy Picture of the Day 2003 ٠ 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/ap0111230.html
- Pillar in Carina: from APOD 2009 Oct 1 http://antwrp.gsfc.nasa.gov/apod/ap091001.html ٠
- 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 ٠
- Star formation: from "Cultivating a Planetary Garden: How Long Does it Take?" http://www.jpl.nasa.gov/news/news.php?feature=927 ٠
- Proplyd: from Astronomy Picture of the Day 1996 October 17, http://antwrp.gsfc.nasa.gov/apod/ap961017.html ٠
- Protostellar disk: from "MIRLIN Star/Planet Formation Page" http://cougar.jpl.nasa.gov/HR4796/anim.html ٠
- Ice line: from Windows to the Universe http://www.windows.ucar.edu/tour/link=/jupiter/atmosphere/J_evolution_3.html ٠
- Disk around proto-Jupiter: http://www.gps.caltech.edu/classes/ge133/ ٠
- Runaway growth: from http://www.usm.uni-muenchen.de/people/gehren/vorlesung/4.1_Himmelsmechanik/kosmogonie/dia_10.html ٠
- Newly formed Neptune: by Don Dixon, from Scientific American, September 1999 issue ٠ 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 ٠

The University of Sydney

- Moon formation: from Wikipedia http://en.wikipedia.org/wiki/Giant_impact_hypothesis
- Pillar in Carina: from APOD 2009 Oct 1 http://antwrp.gsfc.nasa.gov/apod/ap091001.html
- Moon origin paintings: image by Fahad Sulehria http://www.novacelestia.com/images/earth_impact_moon_space_art.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/
- Rulers in space: from "How to Measure the Universe" http://www.nasa.gov/mission_pages/galex/pia14095.html
- 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
- Evolution of a sun-like star: from ESO, "Brightness Variations of Sun-like Stars: The Mystery Deepens", http://www.eso.org/public/usa/news/eso0948/