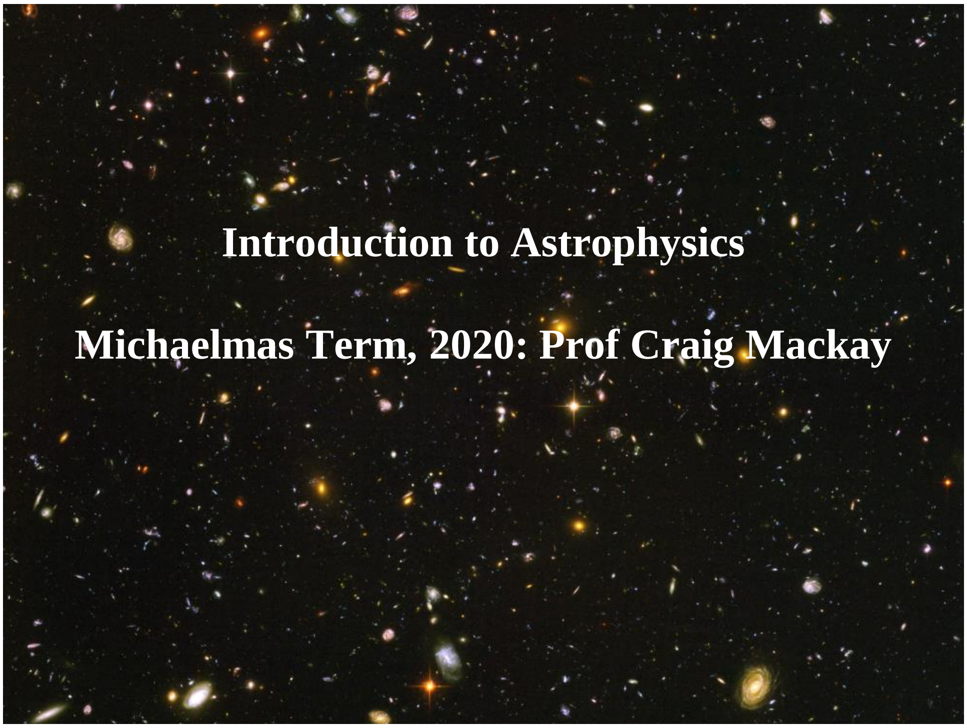


Introduction to Astrophysics

Michaelmas Term, 2020: Prof Craig Mackay

Aims of this non-examinable Course:

- Provide an overview of what we see in the sky.
- Explain how we make our observations.
- Introduce jargon and basic concepts and definitions.
- Stimulate interest.
- Make students more comfortable with using qualitative arguments about astronomical topics.
- Encourage use of order-of-magnitude estimates.

INTRODUCTORY ASTROPHYSICS.
Michaelmas Term, 24 Lectures

Scale and content of Universe.[2]
Sizes and masses. Magnitudes, HR diagram, Distance determination, The Sun as a typical star, overview of stellar lifecycles, Newtonian mechanics, orbits, tides, blackbodies, continuum radiation mechanisms, spectra, line radiation. [4]
Telescopes, instruments and observational techniques E-M radiation, gamma-rays, X-rays, UV, visible, IR, mm, radio, transparency of the atmosphere, Major space-based and ground-based facilities, S/N calculations. [2]
White dwarfs and neutron stars WD origin, structure, neutron star origin, structure, discovery of pulsars, observed properties, evolution, beaming, magnetic fields, magnetic dipoles, pulse timing, the utility of pulsars, gravitational waves. [2]
Close Binary Stars observations, visual binaries, spectroscopic binaries, eclipsing binaries, masses and radii, consequences of a supernova, equipotentials, mass transfer, accretion discs, magnetic stars, evolution in binary systems, cataclysmic variables, the variety of binary systems, stellar mass black holes. [2]
Supernovae and Hypernovae Types, energetics, rates, light curves, spectra, pre-cursors, remnants, radio-active decay, Gamma Ray Bursts (GRBs), discovery, searches, observations, long and short duration GRBs, collapsar-hypernova model, merging of neutron stars and black holes, fireball-shock model, beaming. QSOs as a probe of the intergalactic medium. [2-3]
Active Galactic Nuclei Discovery, observations, classification, energetics, standard model, host galaxies, reverberation mapping, jets, superluminal motion, unified models, QSO population evolution, black holes in non-AGN galaxies. [2-3]
Clusters of Galaxies Structure and content, galaxies within them, hot X-ray gas, magnetic fields, dark matter, virial mass, tidal stripping, S-Z effect, cooling flows. [2]
Gravitational Lenses Basic physics, Young diagrams, Einstein rings, critical surface mass density, strong lensing by galaxy clusters, caustics and critical lines, cluster masses, weak lensing, determining the hubble constant, micro-lensing, constraints on halo objects. [2]
Exoplanets Discovery methods, statistics of known exoplanets, pulsar planets, hot jupiters, transits, planet formation, dust, proto-planetary discs, Hill radius, future observations, life. [2]
Books
† Carroll, B.W. & Ostlie, D.A. An Introduction to Modern Astrophysics (Addison-Wesley) 2017.
Shu, F.H., *The Physical Universe*, chaps. 5-10, University Science Books, California, (1982).
Accretion Power in Astrophysics (Cambridge Astrophysics) Hardcover – 17 Jan. 2002 by Juhan Frank, Andrew King, Derek Raine. CUP

3

Recommended textbooks:

- It is difficult to find individual texts that cover a significant part of the course. The closest that there is to a proper course textbook is Carroll B W & Ostlie D A, "An Introduction to Modern Astrophysics",Addison-Wesley (2017).
- This book is very good indeed because it does go through much of the mathematics that is the foundation of many of the topics will be dealing with. It is a good place to find background information on a topic that you might be having difficulty with and generally it is extremely helpful. Cost ~£65 on Amazon, ~£35 for Kindle. Note that there are many copies of earlier editions still about.
- Otherwise it is worth looking in recent journals such as Scientific American, Science, Nature, etc. for review articles on particular topics. You get free access to all these by working from any *.cam.ac.uk machine address. Ask Mark Hurn if you have problems of access.
- And of course the last resort of any research worker these days is Google! Also look at the citation version of Google called Google Scholar which is really helpful with essay work. It is at: http://scholar.google.com/.

4

HANDOUTS :

- Our present intention is to produce a PDF file of each module (there are 10 PDFs covering 24 lectures).
- The files can be quite substantial as we have a bit under 700 slides to get through!
- We also will be recording each lecture using Zoom and putting those videos online, one per lecture.
- This is intended to allow anyone who is isolating for any reason or just cannot get out of bed in time to access the course.
- The location of all these files will be at:
- https://www.vle.cam.ac.uk/course/view.php?id=206701

5

Introductory Tour of the Universe

- The first lectures in this course will give a general background by introducing many of the different kinds of astronomical objects in the universe.
- Largely pictorial, but many of the basic ideas will be talked about in relatively general terms.
- Nearly everything we know about the universe has been learned through the detection of electromagnetic radiation by telescopes and instruments both on the ground and in space.

6

How do we Measure Distances?

- Only for the nearest things can we actually measure the distance. Almost everything else requires a brightness measurement or a velocity measurement combined with assumptions about what we are looking at.
- For nearby objects we use parallax (astrometry).
- For further away things, measure brightness (photometry), make some assumptions about the object's intrinsic brightness and use the inverse square law.
- We can also measure the apparent size (astrometry), guess intrinsic size and derive distance.
- For the most distant things we measure the redshift spectroscopically and use Hubble's law to infer a distance.
- Whenever we make one of these assumptions we must be conscious that it affects our conclusions.

How do we Measure Masses?

- We never actually measure a mass. However we believe in Newton's laws and Kepler's laws and together they allow us to work out masses from orbital parameters. Usually this means we need to measure velocities.
- We can measure line of sight velocities from the Doppler shift using a spectrograph.
- We then make some assumptions about orbit or system dynamics to derive mass.
- We can also measure mass distributions directly by gravitational lensing (astrometry and photometry).

9

Units of Distance and Mass

- Radius of Earth's orbit = 1 Astronomical Unit (AU)

- 1 AU = 1.496×10^{11} m (about 8.25 light minutes)
- The sun and the moon each sub tend ~0.5 arc minute on the sky

- A parsec is the distance from the Sun of an object such that the radius of the Earth's orbit subtends 1 arcsec at the object.

- 1 parsec = 206265 AU = 3.262 light-years = 3.1×10^{16} m

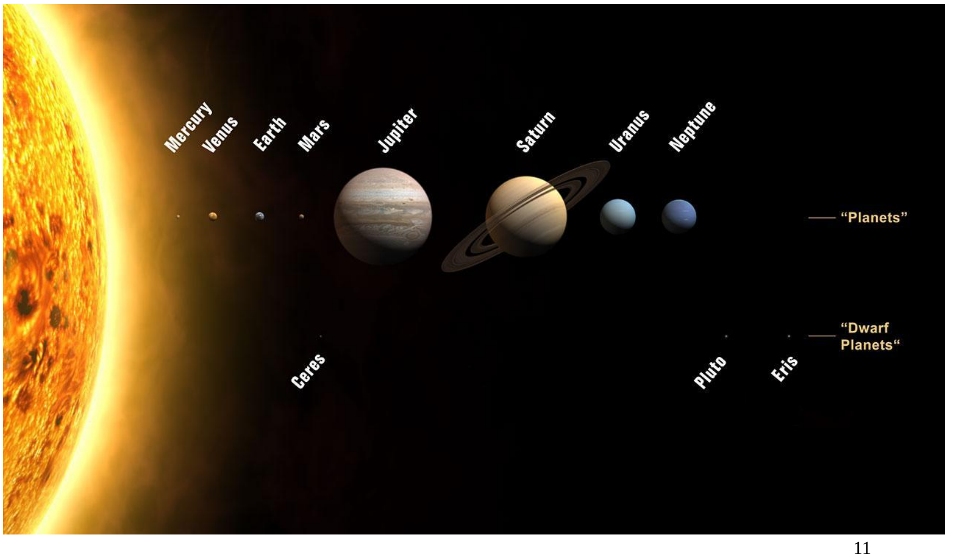
- Mass of Sun = $M_\odot = 1.989 \times 10^{30}$ kg

- Radius of Sun = $R_\odot = 6.96 \times 10^8$ m

- We often measure astronomical parameters in terms of their multiples of solar or terrestrial or galactic units.

10

Relative Sizes of Solar System bodies



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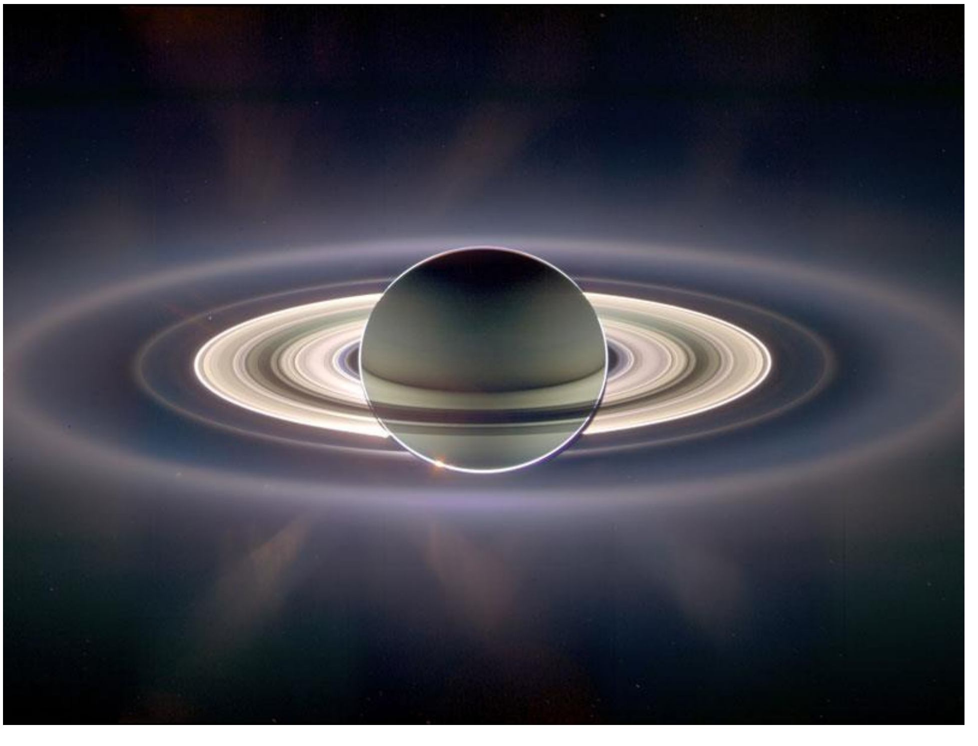

Local Neighbourhood Scales and Sizes

- If we modelled the Sun as a grapefruit then the earth would be orbiting the grapefruit at a distance of about 10 m and about 1 mm in diameter.
- On this scale the whole solar system would be about 1 km in diameter.
- The nearest star would then be in New York!
- We are living in one of the highest density parts of the universe, on the inside of the spiral arm about 8000 parsecs (8 kpc) or 25000 light years from the centre of a Galaxy.
- This helps us appreciate the incredible scales and distances we are working with routinely.
- As a consequence many of the numbers we use are expressed as logarithmic numbers just to make them manageable.
- Do not be surprised if you simply cannot imagine such scales: most astronomers feel just the same as you do about it!

13

Sizes and Masses

- The mass of the Sun totally dominates the mass of the solar system.
- Jupiter is x1000 times smaller, and the Earth is nearly 1 million times smaller.
- However most of the angular momentum is in the planetary system.

Size is $\log_{10}$(distance in parsecs)
Mass is $\log_{10}$(mass in solar units)

	SIZE	MASS
Earth	-9.4	-5.5
Earth ↔ Moon	-7.9	
Sun	-7.3	0.0
Jupiter	-8.3	-3.0
Sun ↔ Pluto	-3.7	
Oort cloud (comets)	-0.3	

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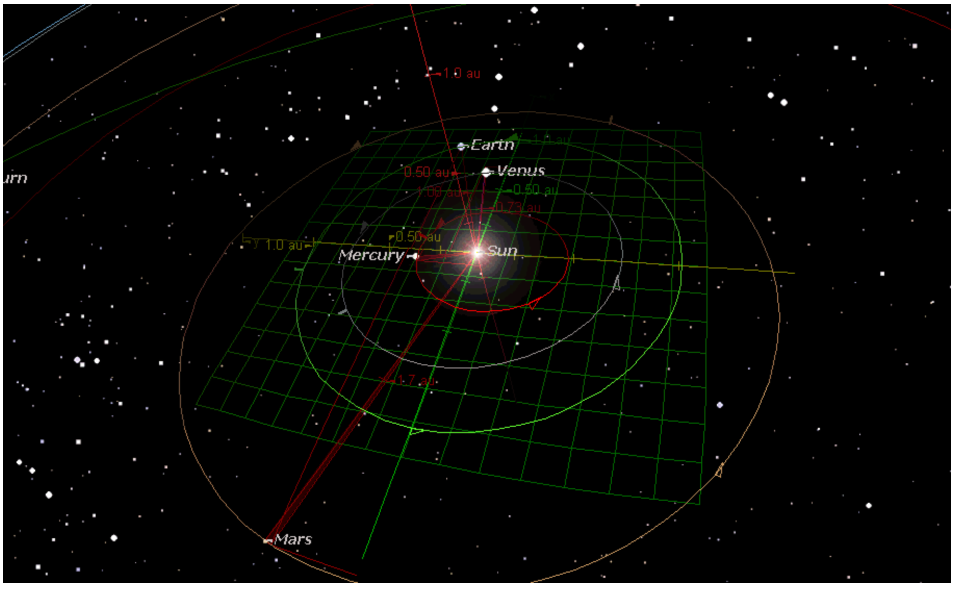
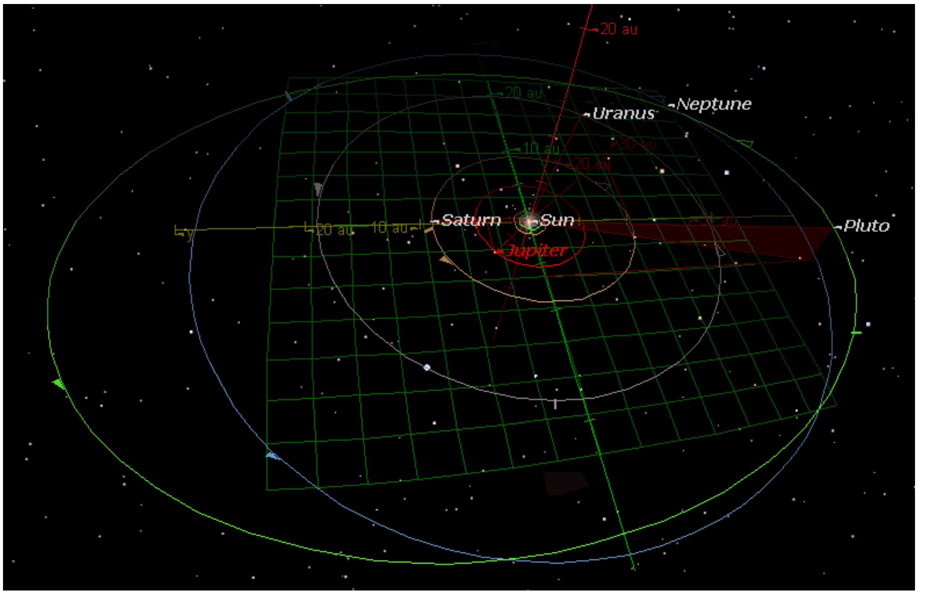
The Inner Solar System



The Outer Solar System



Dwarf Planets in the Solar System

- In August 2006, Pluto was reclassified as a “dwarf planet”, along with two other bodies (2003UB313 and Ceres) found in orbit around the Sun.
- What is meant by the word “planet” is not particularly clear at present.

- Pluto: discovered in 1930 and has a moon named Charon. It is orbital period is about 248 years, its diameter is 2274 kilometres and its distance from the Sun is 39.5 AU.
- 2003UB313(Xena) was discovered in 2003 and is on a highly elliptical orbit varying from 37.8 to 97.6 AU from the Sun. It is presently at its greatest distance from the Sun and orbits it in 558 years. It has a diameter of 2400 km. In 280 years time it will be close enough to the Sun for the frozen methane and nitrogen that presently covers its surface to evaporate. Its orbit is tilted at 45° to the ecliptic. It also has a moon.
- Ceres: discovered in 1801 by Piazzi. Originally classified as a planet and then demoted to an asteroid. Orbital period is 4 years, 219 days and a distance of 2.8 AU (between Earth and Jupiter). Its diameter is 950 km.

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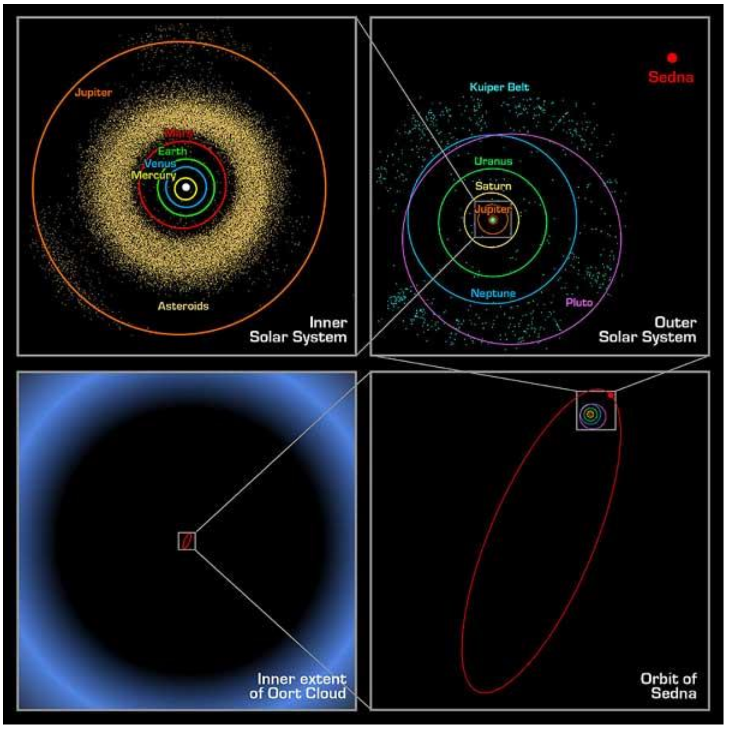

Sedna

- Another new “planet” discovered in our solar system.
- Orbital period is about10,000 year and its surface temperature is -240 deg C.

18

ERIS (2003UB313)

- Discovered (i.e. recognised for what it was) in Jan 2005.
- Larger than Pluto.
- This is believed to be scattered disk object. These are objects that are among the most distant and cold objects in the solar system. They are located between 35 and as much as 1000 AU from the Sun.
- Their origin is not entirely understood but it is thought that they were once members of the Kuiper belt which got injected into eccentric scattered orbits through close encounters most likely with Neptune.
- None are as close as Pluto is to the Sun because if they were their orbits would become normalised and therefore circularised.
- Their surface temperatures are in the region of 30K-55K.

- Orbit is eccentric and tilted at 45 deg to the plane of the solar system.
- It has a moon.
- Led to demotion of Pluto from "Planet" to "Dwarf Planet".

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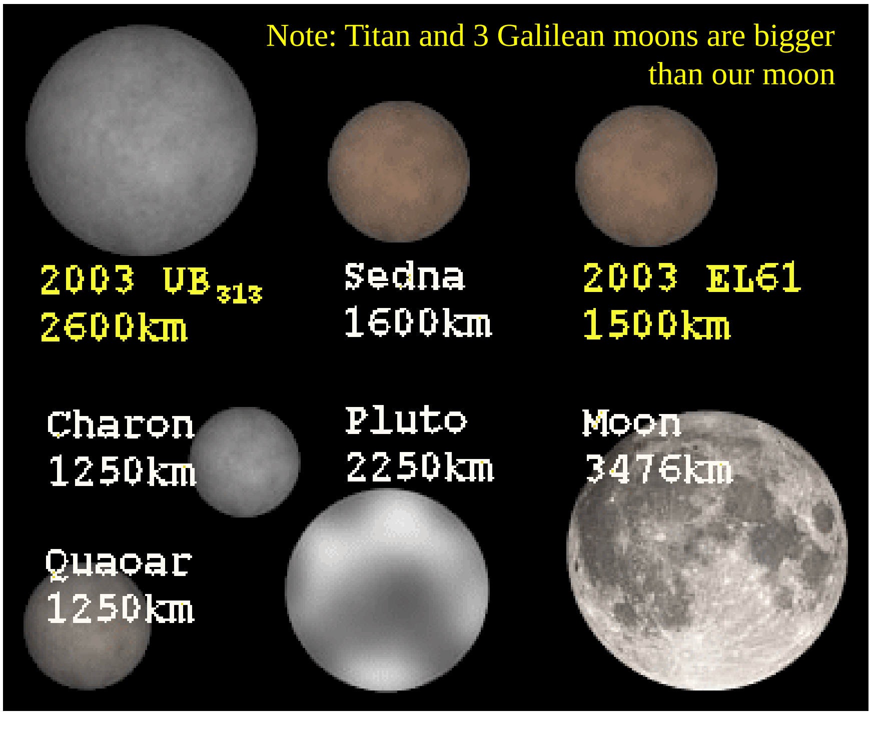
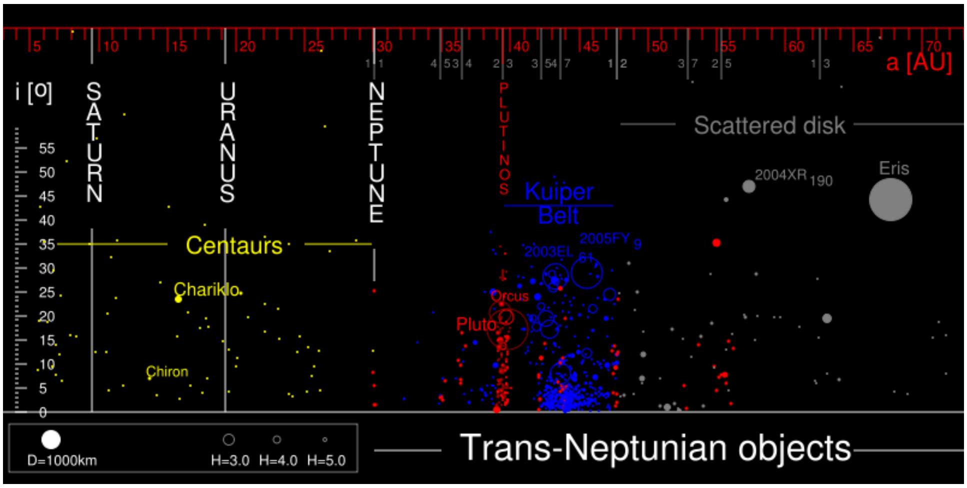


Trans-Neptunian Objects



21

Sizes and Masses of Stars

- Stars have a wide range of sizes (from 10^{-5} times our sun for a neutron star, to nearly 1000x our sun for a red supergiant) and masses (from 1/10th of a solar mass for a brown dwarf to 100x for a massive supergiant).

Size is $\log_{10}$(diameter in parsecs)
Mass is $\log_{10}$(mass in solar units)

	SIZE	MASS
Supergiant star – Red giant	-4.2	1.3
Most Massive star	-5.8	2.1
Puniest star – M dwarf	-8.1	-1.1
Brown Dwarf	-8.3	-2.0
White Dwarf	-9.7	0.0
Neutron Star	-12.2	-3.2

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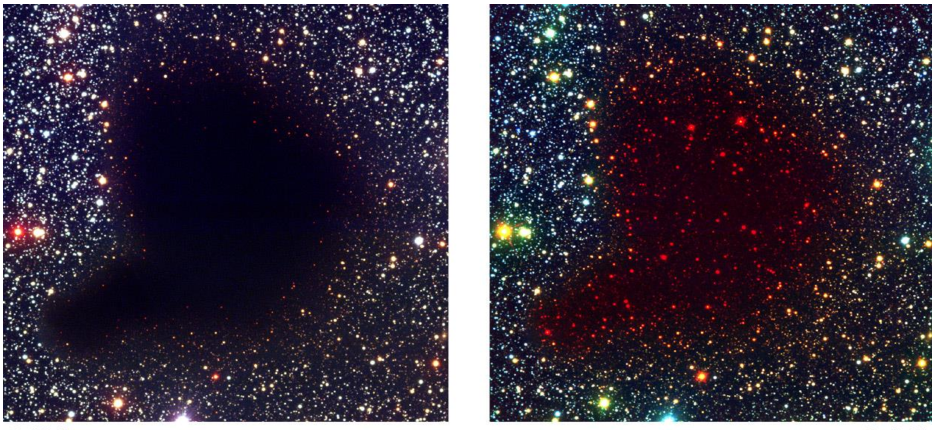
Bok Globule



B, V, I

B, I, K

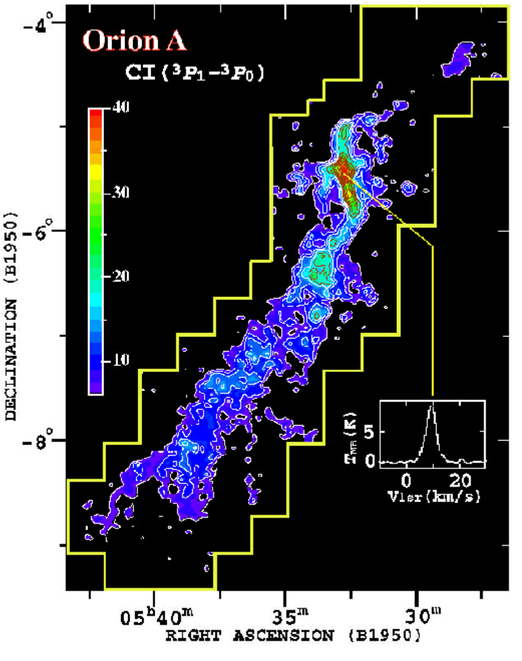
Pre-Collapse Black Cloud B68 (comparison)

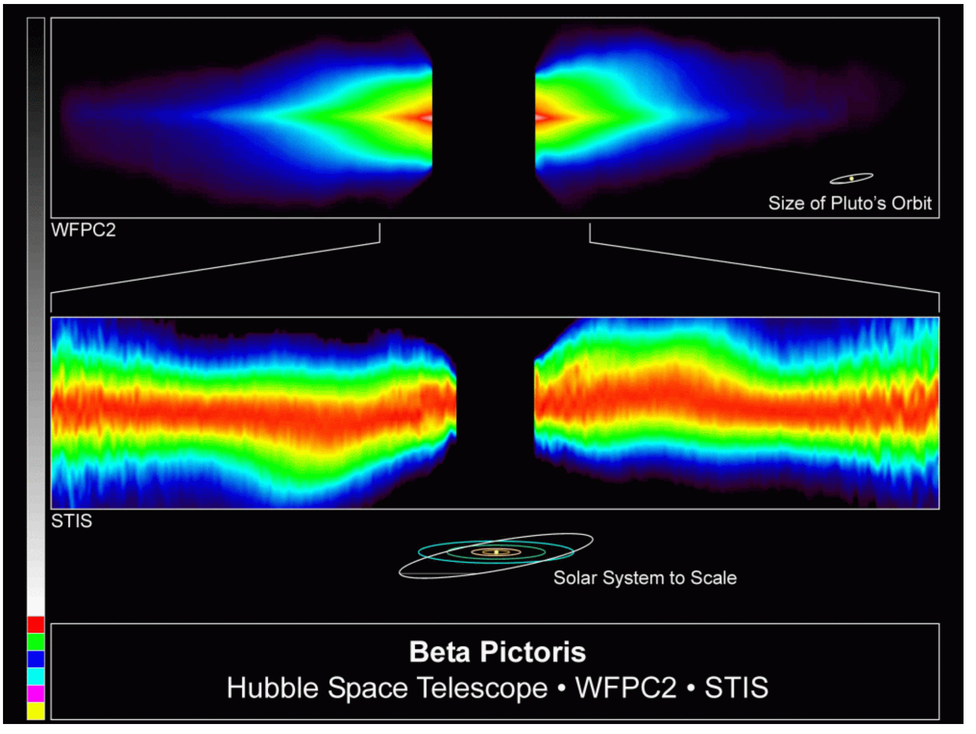
About 0.1 pc diameter and a few solar masses.

Multi-colour images. B=0.43um, V=0.55um, I=0.80um, K=2.2um

Giant Molecular Cloud in Orion

- This is a radio map in the middle of the Orion nebula in a molecular line.
- This region is extremely cold, only a few degrees above absolute zero.
- ~10^6 solar masses, and ~50 pc in size.

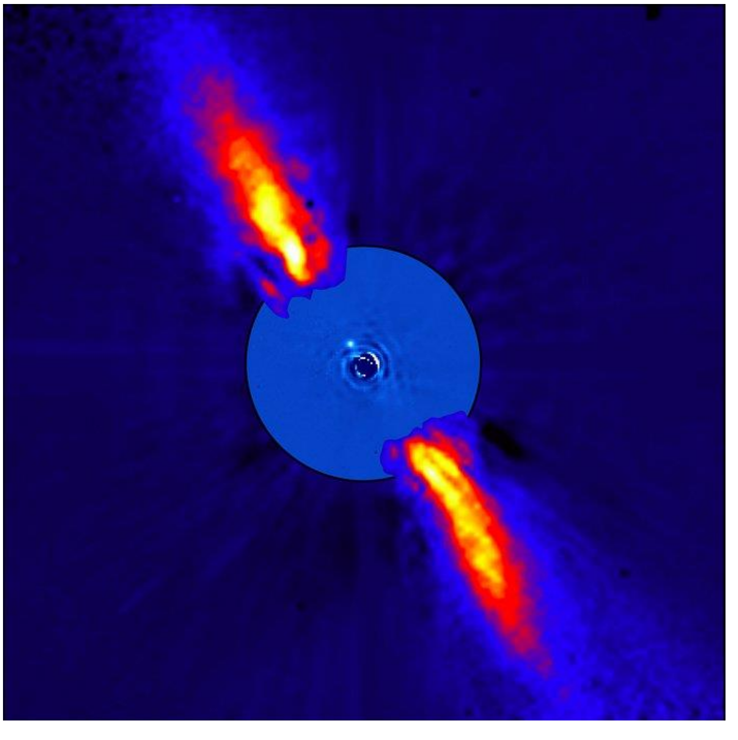




Beta Pictoris

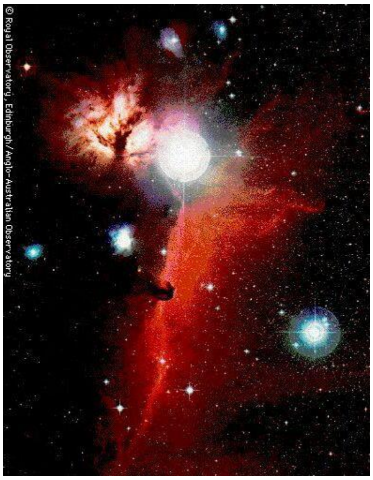
- This image is taken in infrared light so that the disk in which planets are forming now can be traced in closer to the central star.

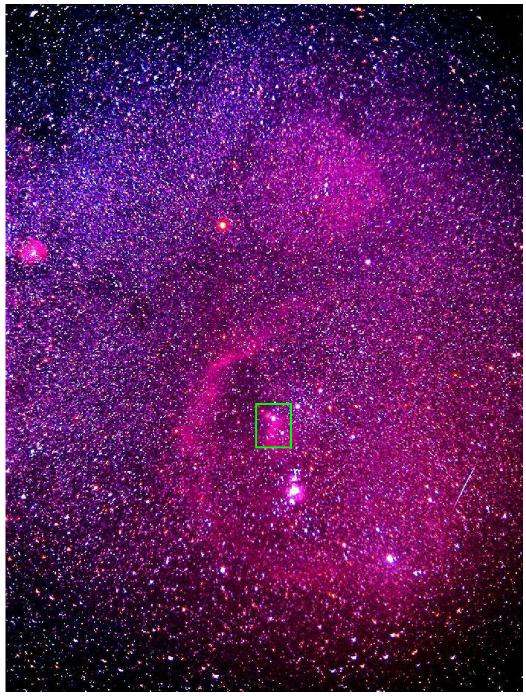
- The distortions from a flat disk are believed to indicate where planets are being formed today.

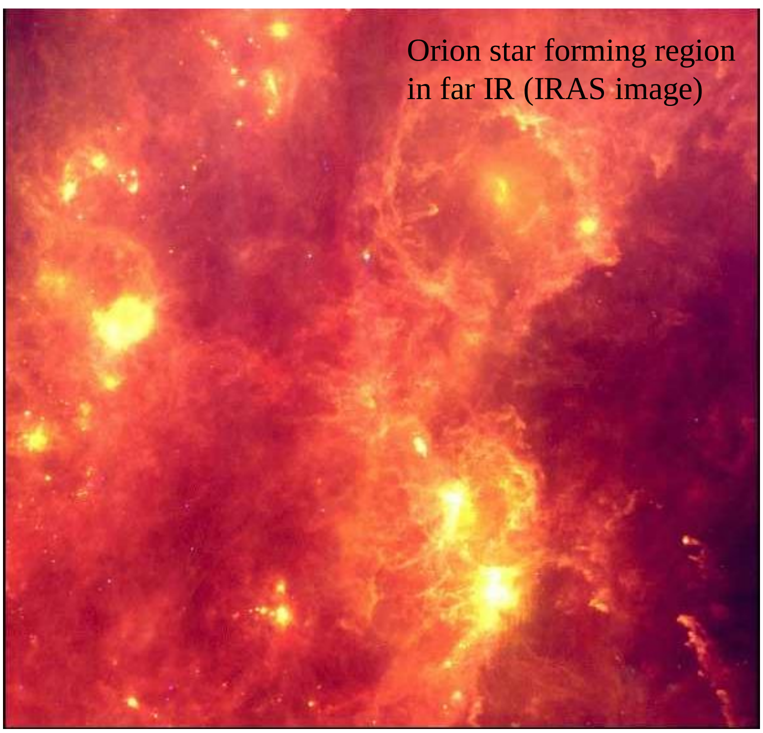


Orion star forming region

A few pc in diameter and ~100 solar masses.

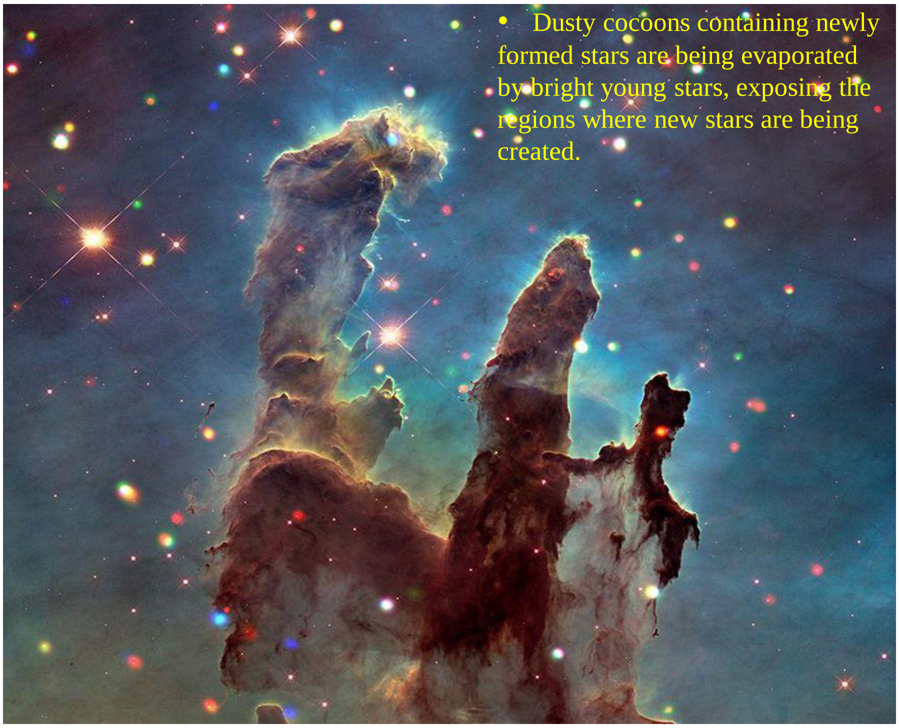




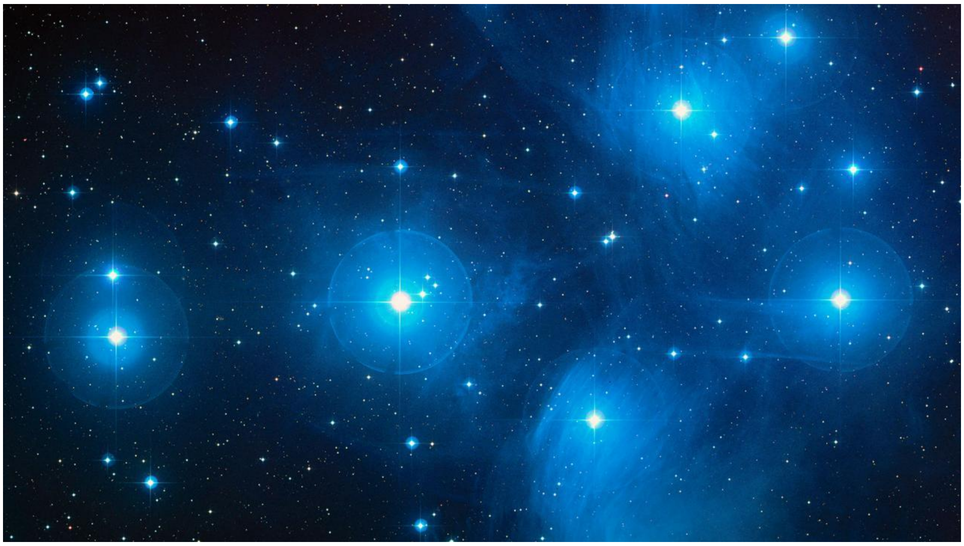


Orion star forming region in far IR (IRAS image)

28

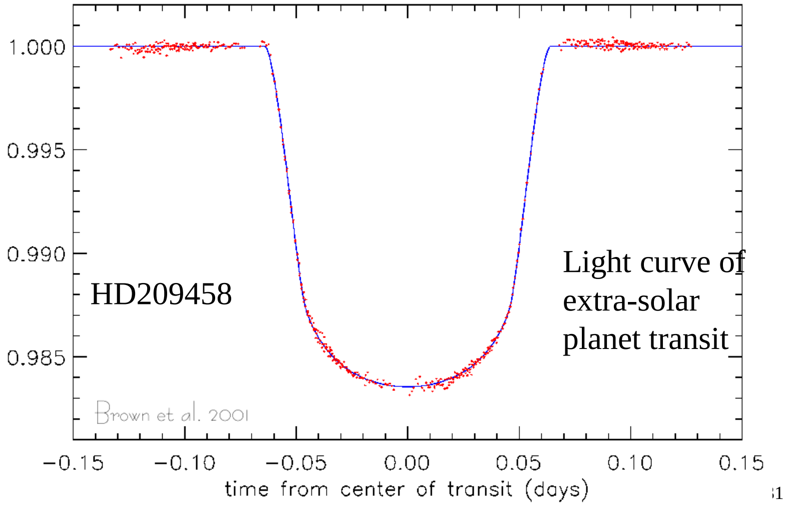


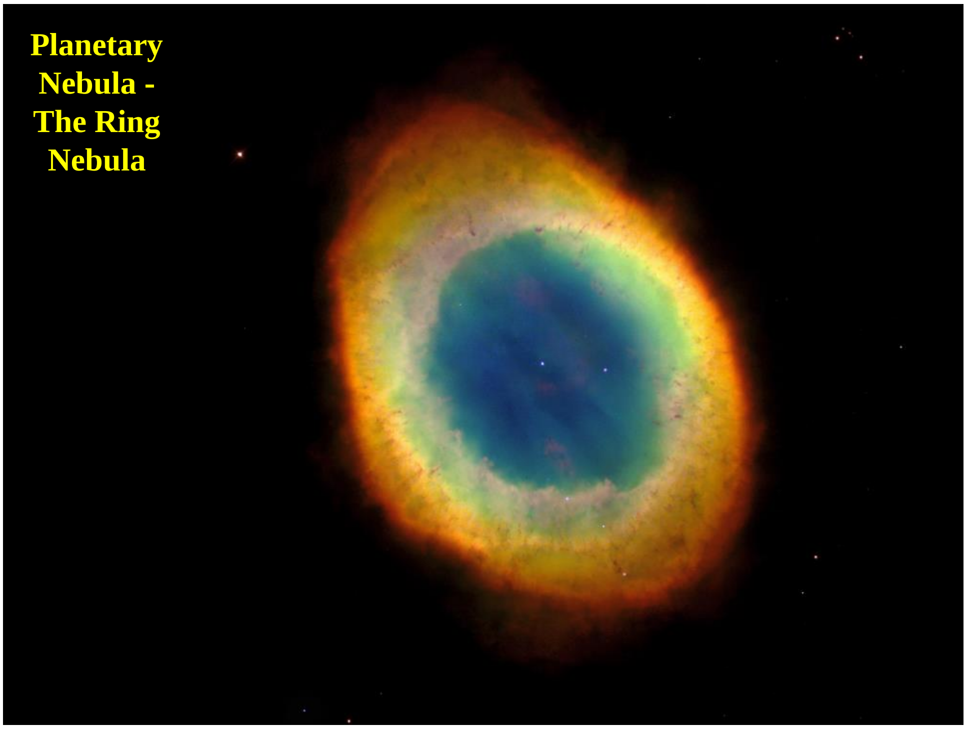
Pleiades – a cluster of recently formed stars (~100 Myrs old)
a few pc in diameter and ~ 100 solar masses.



Extra Solar Planets

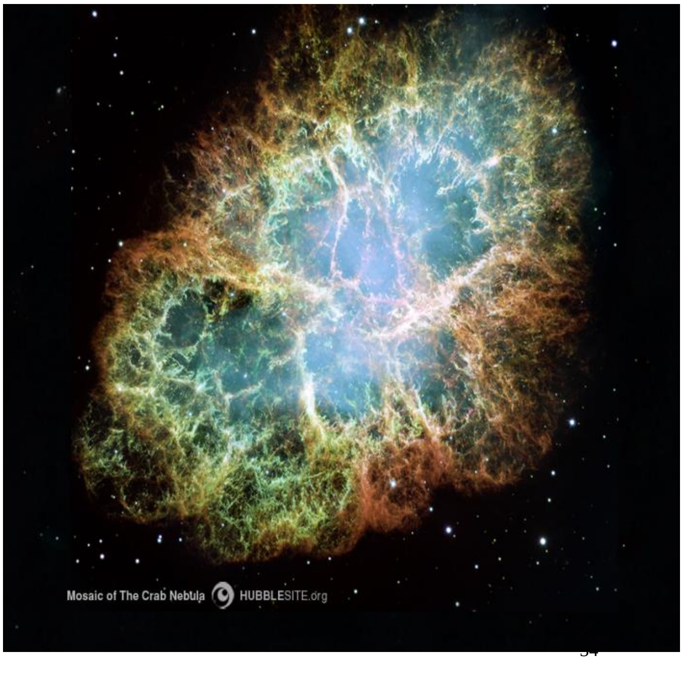
- We can see planets in orbit around distant stars when they occult the light from the central star

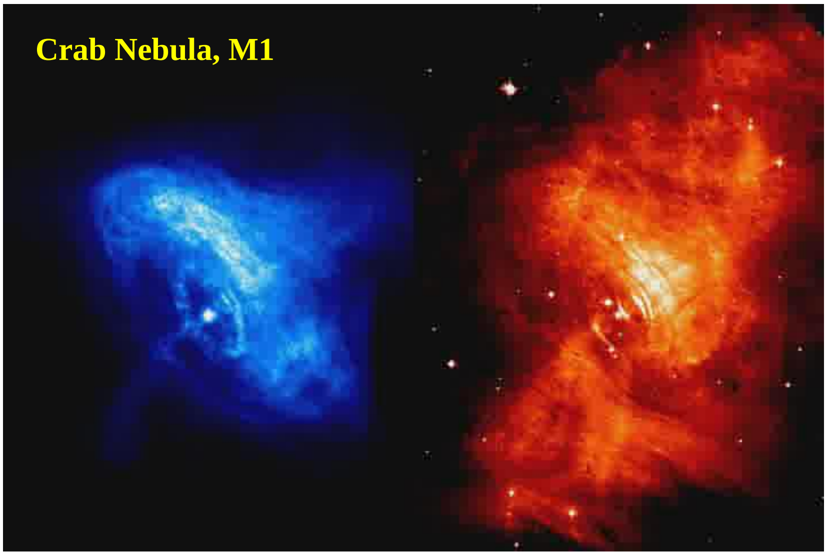




Crab Nebula, M1

- Created by an unusually violent supernova explosion and observed by Chinese astronomers in 1054AD.
- About one kparsec distant, but bright enough originally to be visible in daylight.
- The remnant star is a Pulsar rotating 30 times per second.
- This is a composite, multicolour picture taken by the Hubble space telescope.



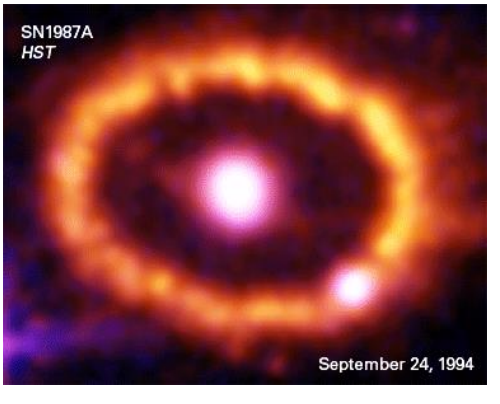


- This extraordinary movie comes from the Chandra x-ray satellite (left hand image) and the HST in visible light (right hand image).
- The central pulsar is still injecting vast amounts of energy into the surrounding nebula that we can see today, 1000 years later.

35

Supernova of 1987 In the Magellanic Cloud

- This has been observed many times by Hubble and we can see the shock wave created by the central star as it strikes rings and shells of gas from a previous eruption.
- As the shock wave expands out more and more gas clouds are excited and can be seen emitting radiation strongly



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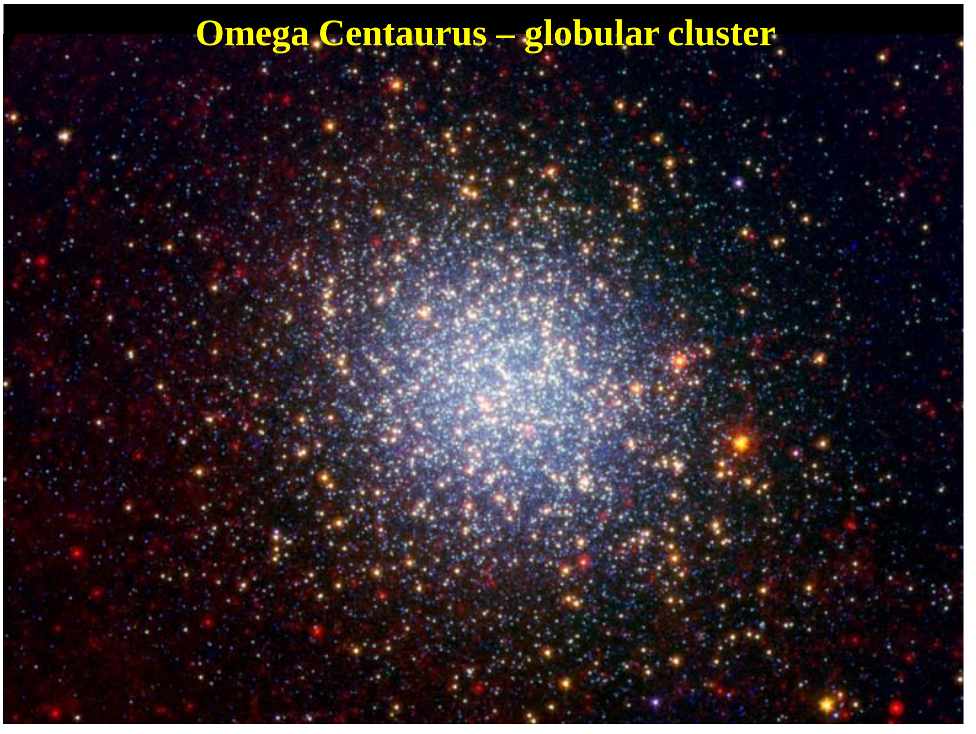
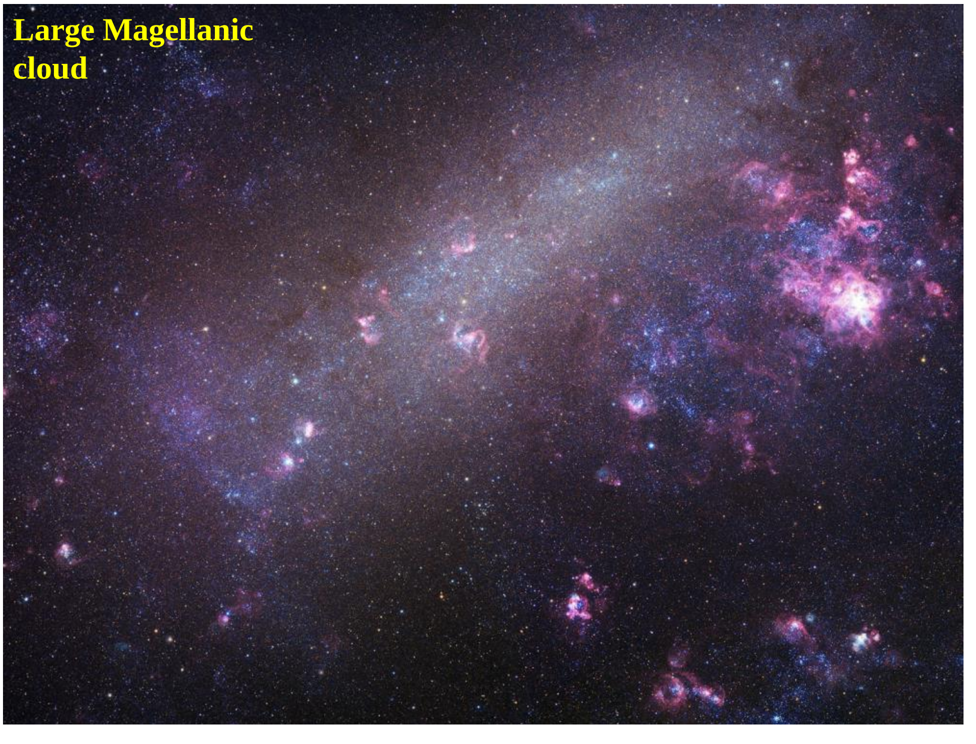
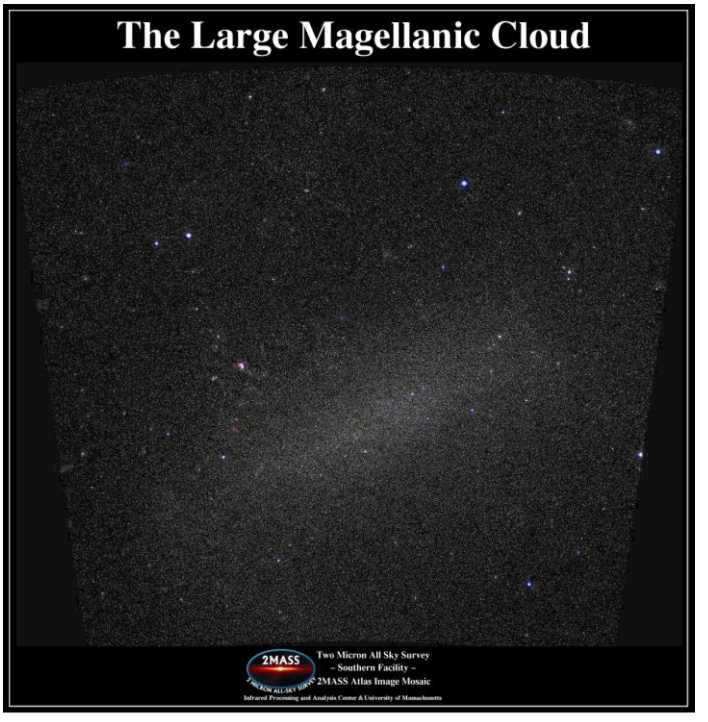
Panoramic View of the Milky Way


Omega Centaurus – globular cluster

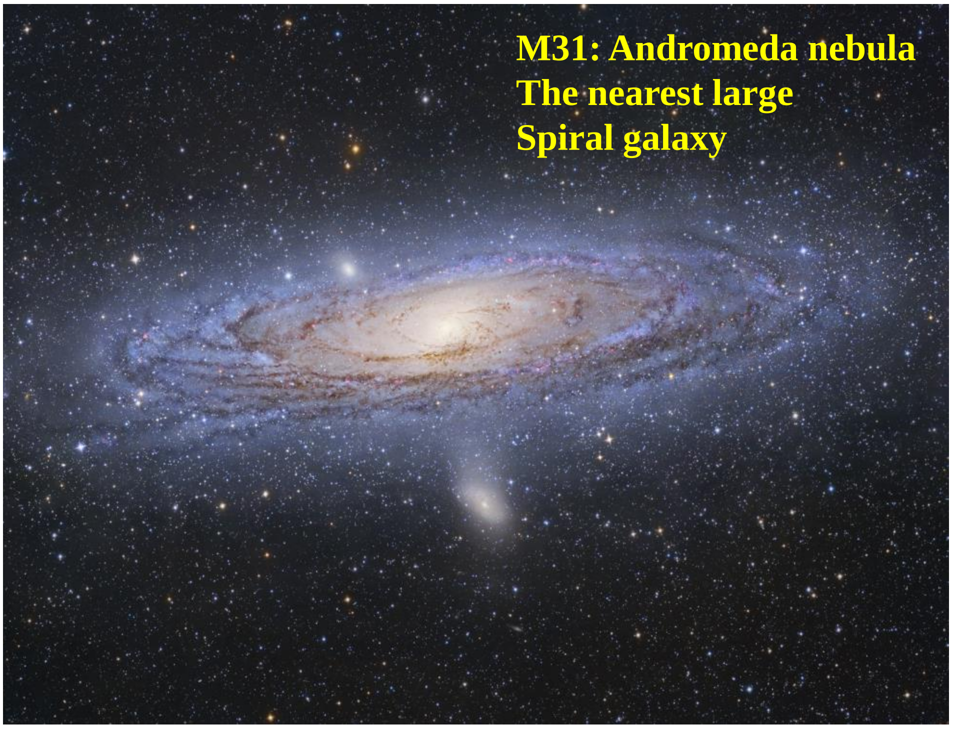

Large Magellanic
cloud

- The Large Magellanic Cloud observed in the infrared so that star-formation regions are relatively difficult to see.
- This technique lets us see through the gas and dust to the background star distribution.



Large Magellanic cloud:

Composite taken in the far infrared by the Spitzer space telescope

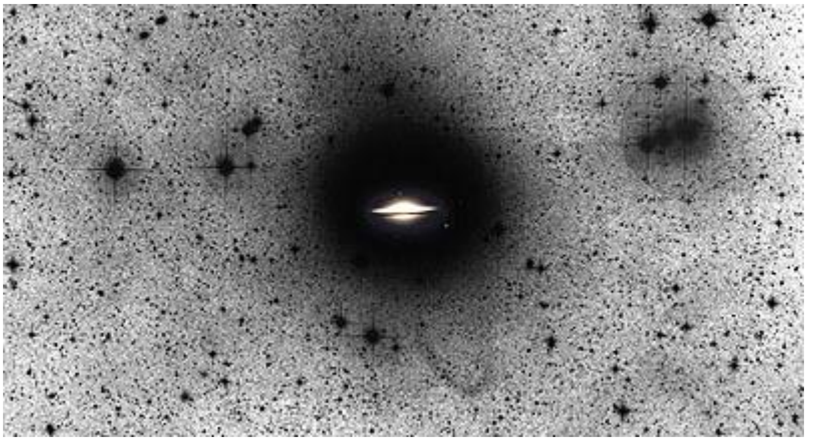

M31: Andromeda nebula
The nearest large
Spiral galaxy


M51
Spiral Galaxy with companion

Spiral Galaxy Properties

Spiral Galaxies have cooler, older stars towards the centre, many spiral arms with active star-formation going on today as the spiral density wave pattern locally compresses the gas in the disk

Galaxy Halos Can Be Enormous



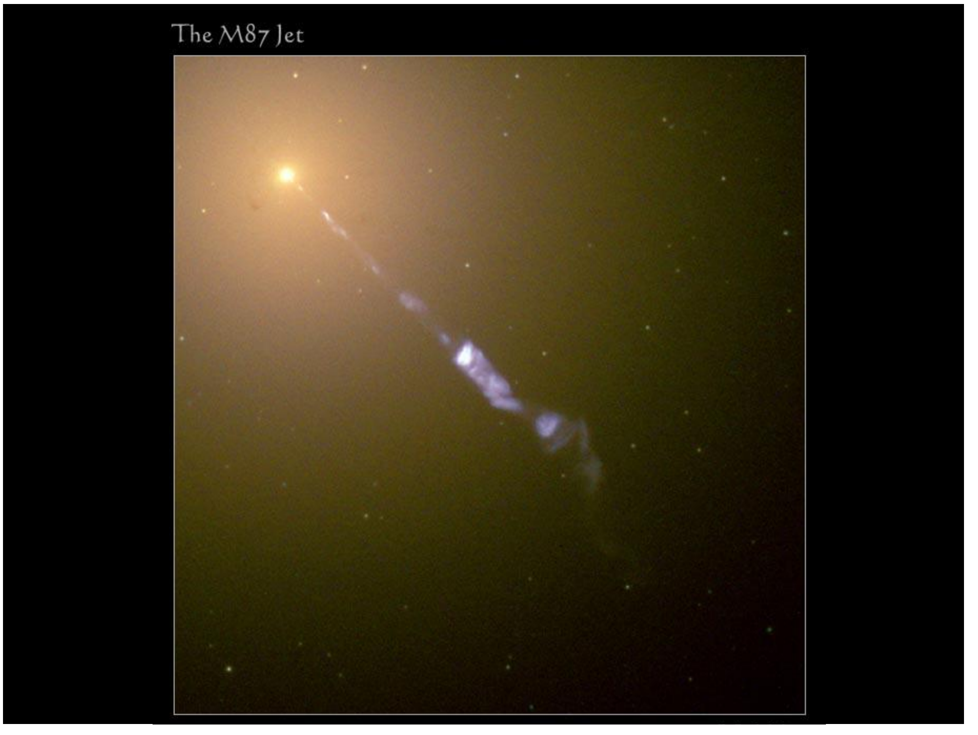
- This picture shows the halo of M104 (Sombrero Galaxy)
- Galaxy halos are made up of a very old population of stars probably formed at the beginning of the life of the Galaxy

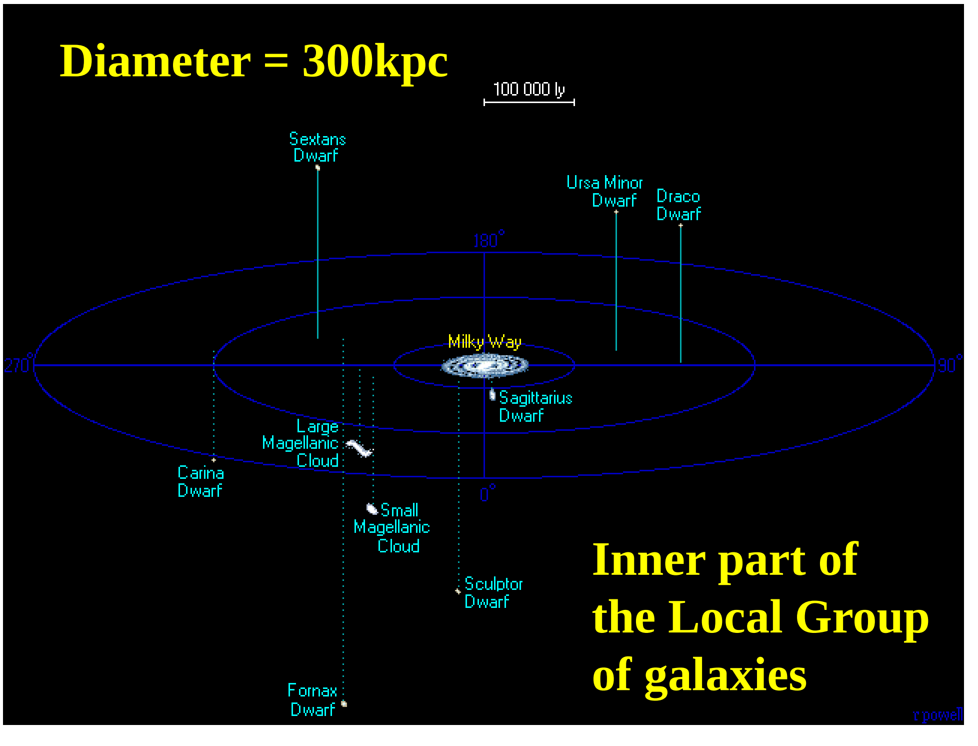
47

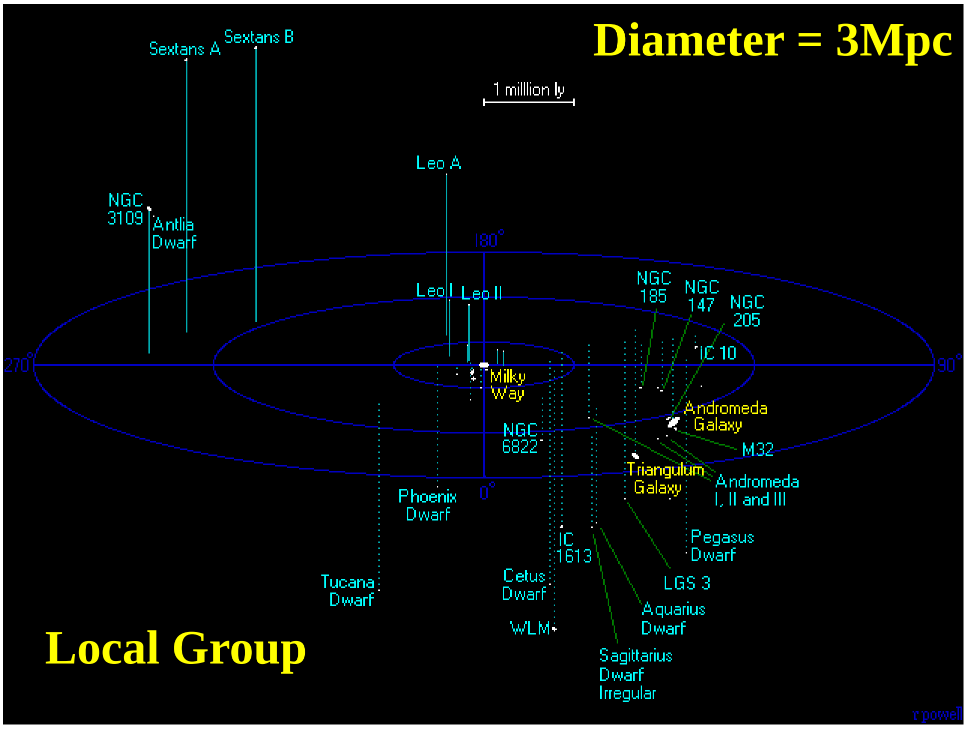
Supergiant elliptical galaxies

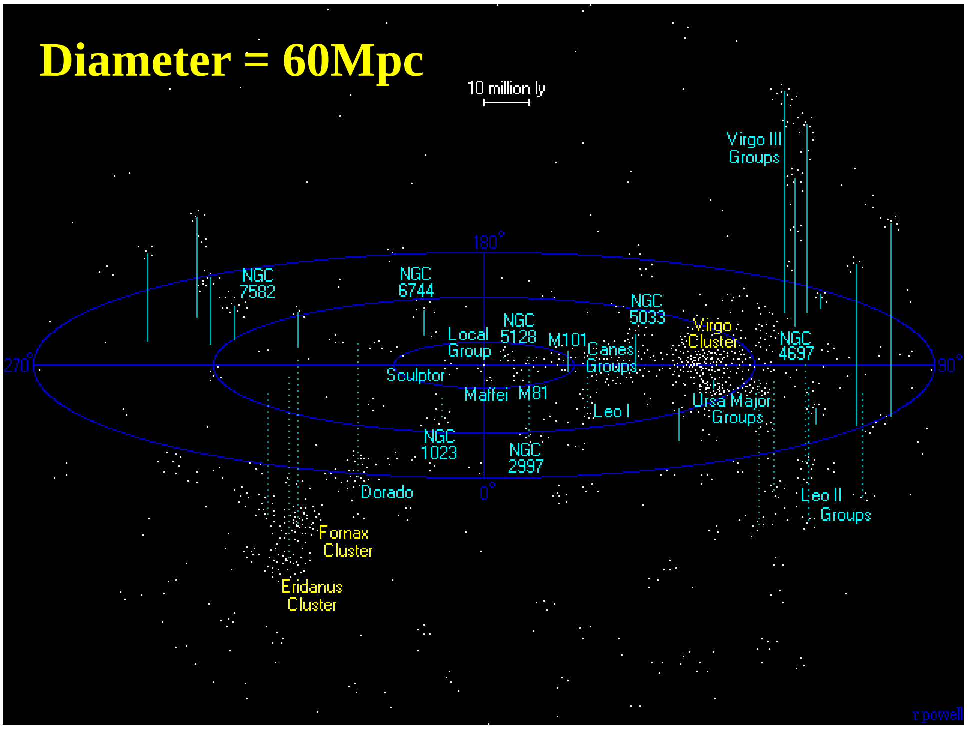
- This is an example of a giant elliptical galaxy, a supergiant elliptical Galaxy at the centre of the Virgo cluster.
- It contains very little dust and is mostly made up of old stars.
- It has a rich system of globular clusters which you can see clearly on this picture.
- There is a very unusual high-energy jet extending from its active galactic nucleus.
- It is a strong radio and x-ray emitter.

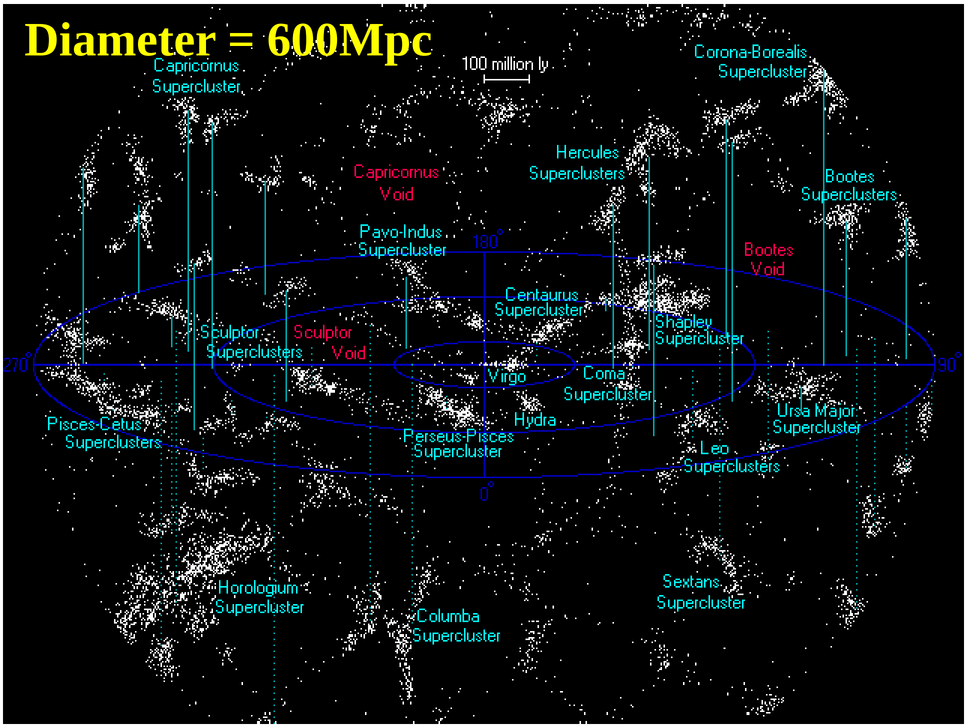
- Typical elliptical galaxies do not have such an exotic nucleus.

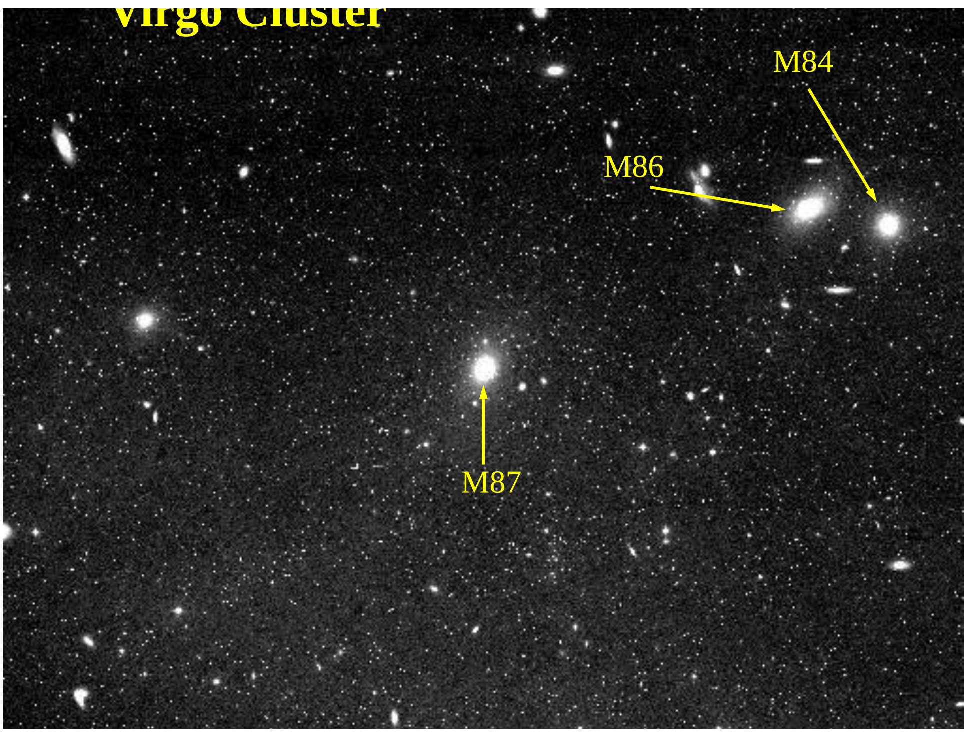

The M87 Jet


Diameter = 300kpc
100 000 ly
Sextans Dwarf
Ursa Minor Dwarf
Draco Dwarf
180°
Milky Way
270°
90°
Sagittarius Dwarf
Large Magellanic Cloud
Carina Dwarf
0°
Small Magellanic Cloud
Sculptor Dwarf
Fornax Dwarf
Inner part of the Local Group of galaxies


Diameter = 3Mpc
Local Group
1 million ly
Sextans A
Sextans B
NGC 3109
Antlia Dwarf
Leo A
180°
270°
90°
0°
Leo I
Leo II
NGC 185
NGC 147
NGC 205
IC 10
Milky Way
Andromeda Galaxy
M32
NGC 6822
Triangulum Galaxy
Andromeda I, II and III
Phoenix Dwarf
IC 1613
Pegasus Dwarf
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
Sagittarius Dwarf Irregular


Diameter = 60Mpc
10 million ly
Virgo III Groups
180°
270°
90°
0°
NGC 7582
NGC 6744
NGC 5033
NGC 5128
Local Group
M101
Canes Groups
Virgo Cluster
NGC 4697
Sculptor
Maffei
M81
Leo I
Ursa Major Groups
NGC 1023
NGC 2997
Dorado
Leo II Groups
Fornax Cluster
Eridanus Cluster


Diameter = 600Mpc
100 million ly
Capricornus Supercluster
Corona-Borealis Supercluster
Hercules Superclusters
Capricornus Void
Bootes Superclusters
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster


Virgo Cluster
M84
M86
M87

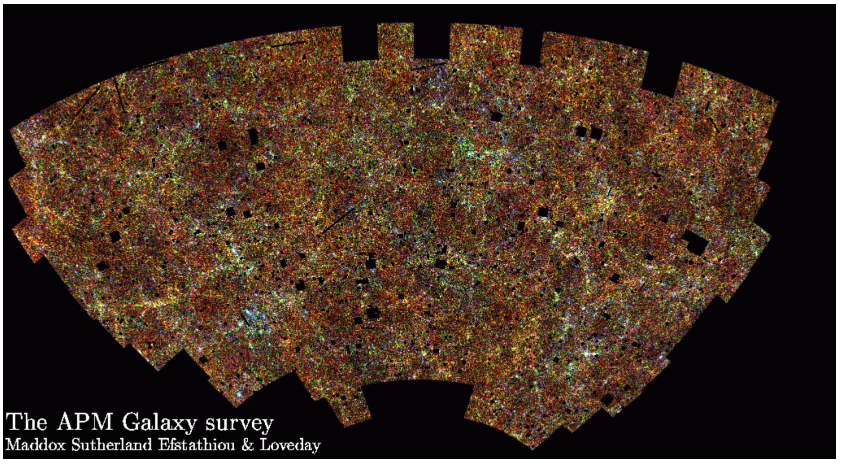
Abell 370

A distant cluster of galaxies, Abell 370. Its redshift is z=0.375 so at a distance of ~1600Mpc.

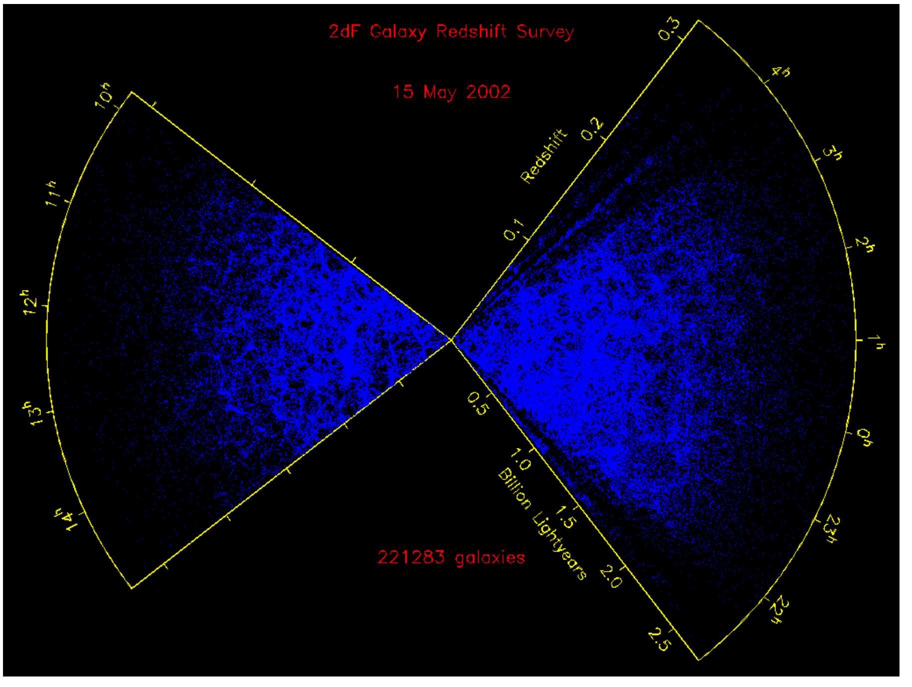
Abell 1689

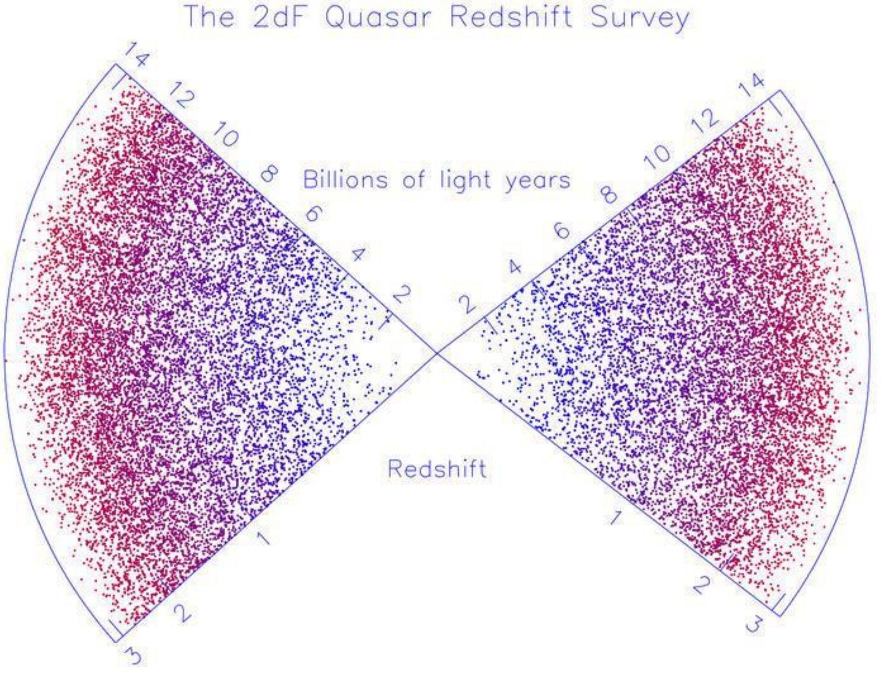
Cluster of galaxies showing many gravitationally lensed arcs. These are distorted and magnified pictures of much more distant objects. They give us a great deal of information about the distribution of matter, including dark matter in clusters of galaxies.

Large-Scale Galaxy Surveys



- Each tile is 6x6degrees and corresponds to a photographic Schmidt plate.
- APM=Automated Plate-measuring Machine, was here at the IoA until 2004.
- The picture shows the distribution of millions of galaxies over a large sky area.
- 2dF survey measured the redshift (spectroscopically) of ~100,000 galaxies in a strip across this area of sky.


2dF Galaxy Redshift Survey
15 May 2002
221283 galaxies
Redshift
Billion Lightyears


The 2dF Quasar Redshift Survey
Billions of light years
Redshift

Summary

- We have seen the incredible range of scales and sizes there are in the universe.
- There are many different kinds of objects which look at first sight quite different but the physics that connect them is relatively simple and appears to be universal.