Complete Cosmos
Chapter 23: Infinity

The structure of the Universe - galaxies, clusters, strands. How we measure to a nearby
galaxy and to the farthest quasar.

Outline
In the Australian night sky, the unaided eye picks out two satellite galaxies of the Milky Way -
the Large and Small Magellanic Clouds. Within the Large Cloud, in 1987, a supernova erupts -
the first naked eye supernova for nearly 400 years.

We travel beyond - on a tour of the Milky Way's immediate neighbors. From the closest major
galaxy, the Andromeda spiral, to more distant spirals like the beautiful Sombrero Galaxy, 40
million light years distant, and the elliptical radio galaxy Virgo A, a member of the Virgo Cluster-
part of a "local supercluster" of about 1,000 galaxies. Galaxies exist in clusters, which gather as
superclusters, which form strands across the Universe.

The cosmos is measured by "standard candles" - celestial objects of known intrinsic brightness or
luminosity. They are used to estimate distance when their apparent brightness is compared to
their known luminosity. Cepheid variables are an example.

Using the Hubble Space Telescope, such stars have been found in galaxies up to 80 million light
years distant. Cepheids enable astronomers to estimate the distances of the galaxies.

Farther than 80 million light years, another standard candle is needed. It is found in a binary
system - a white dwarf nearing the end of its life. The dwarf draws material from its stellar
partner, reaches a critical mass, and explodes as a Type 1a supernova. The flash intensity is
always the same. This Type 1a supernova is the standard candle that enables astronomers to
measure distances up to a 100 times farther than with Cepheids. Edwin Hubble discovers the
Universe is expanding - with galaxies speeding away in all directions. When galaxies race
outwards, the lines in their spectra are shifted into the red. This "redshift" sizes up the cosmos and
suggests that the distance to its farthest reaches is some 15 billion light years.

In the 1960s, the discovery of superluminous quasars - the most energetic objects in the Universe,
and among the oldest and most distant. A review of radio galaxies, Seyfert galaxies and galaxies
that swing through each other. Some merge to form supergalaxies. Such interactions can trigger
intense bursts of star formation. Within ten billion years, our Milky Way galaxy will collide with
the Andromeda galaxy.

Sub-chapters

Nearest Galaxies

- In the Australian night sky - the Small and Large Magellanic Clouds, two mini satellite
galaxies of the Milky Way.
- A supernova in the Large Magellanic Cloud, seen in 1987. The explosion happened
160,000 years ago - but it's taken that long for its light to reach Earth.
- Andromeda, the closest major galaxy - at over two million light years distant.
- The Silver Coin Galaxy - a spiral 10 million light years away, possibly like our own
galaxy.
- Farther out, to the Sombrero Galaxy, 40 million light years from us. Incredible distances,
but relatively close to home.
Clusters and Superclusters

- The elliptical galaxy Virgo A, a member of the Virgo Cluster of galaxies, about 60 million light years distant. The cluster is part of a supercluster, containing about 1,000 galaxies.
- Superclusters form strands across the Universe. To construct a model of these strands, astronomers use "standard candles", objects of known intrinsic brightness – or luminosity - to measure distance.

Standard Candles

- Cepheid variables are standard candles. The brightness of these stars pulsates with consistent regularity as Cepheids expand and contract. Massive and bright Cepheids pulsate slowly, smaller and dimmer Cepheids more quickly.
- By measuring the true distance and brightness of nearby Cepheids, the distance to remote Cepheids - which appear fainter in distant galaxies, but pulsate with the same regularity - can be calculated.
- Ground-based telescopes only detect Cepheids up to 15 million light years away. The Hubble Space Telescope observes Cepheids to a distance of 80 million light years.

Type-One Supernovae

- Beyond 80 million light years, another form of standard candle - Type 1a supernovae. These occur in binary systems where a white dwarf star draws material from its companion. On reaching a critical mass, the dwarf explodes as a supernova. Since the flash intensity is always the same, these supernovae can be used as standard candles.
- Type 1a supernovae allow astronomers to measure distances up to 100 times farther into space than is possible with Cepheids.
- In the 1920s, Edwin Hubble discovers the Universe is expanding, with galaxies racing out in all directions. As a galaxy speeds away, its spectrum is shifted towards red.

The farther away the galaxy, the faster it recedes and the greater its redshift.

- Redshift is a vital tool for sizing and shaping the Universe. Current estimates suggest the distance to the farthest reaches of the Universe is 15 billion light years.

Quasars

- Quasars are discovered in 1963, as astronomers locate sources of intense radio noise. At first, quasars appear as ordinary stars, but their redshifts put them billions of light years distant.
- Radio galaxies and Seyfert galaxies. Like quasars, all three are fuelled by supermassive black holes.
- Black holes at the heart of quasars are immense, consuming the equivalent of 600 Earths a minute. Quasars are the most energetic objects in the Universe - and among the oldest and most distant, with enormous redshifts.

Colliding Galaxies

- Colliding and interacting galaxies come in all shapes and sizes.
- The Antennae Galaxies are an example not of collision, but of two galaxies swinging through each other, like cosmic pendulums. Their gravitational interaction ejects two great tails like the antennae of an insect. The Antennae are a firestorm of starbirth.
- The Cartwheel Galaxy is an example of an intruder galaxy ploughing into another larger - vast disruption.
- Most spectacular of all is a collision from which neither galaxy emerges – both merging
to form a supergalaxy. In ten billion years' time, this may happen to the Milky Way as it collides with Andromeda.

**Background**

*Redshift - A Measure of Distance*

The wavelength of visible light - or of any other electromagnetic radiation – is stretched to a longer wavelength when the source of that light is moving away from the observer. This phenomenon also affects the wavelengths of any dark absorption lines or bright emission lines in the spectrum of a galaxy - a spectrum that is, in fact, an average of the spectra of every star in the galaxy.

If a galaxy is moving away from the observer, the wavelengths of all the lines in its spectrum will be stretched to longer wavelengths. The lines, therefore, will appear shifted towards the long wave or red end of the spectrum. This is called the redshift. The greater the speed the galaxy is moving away from the observer, the greater will be the redshift.

Redshift is a most important tool in cosmology. It demonstrates that galaxies are receding from us and that the Universe is expanding. This was discovered by the American astronomer Edwin Hubble. Using the 100-inch Hooker reflector at the Mount Wilson Observatory, California, Hubble observed that all galaxies - apart from those in our immediate neighborhood - show redshifts in their spectra. The more distant the galaxy, the greater the redshift. In other words, the farther, the faster.

Later, Hubble found that galaxies were receding from us at speeds that were proportional to their distances from us. This was formulated in what came to be known as Hubble's Law. In reality, the galaxies are not receding from us at all. No matter from which galaxy you observe the expansion, you will see all the other galaxies receding with speeds proportional to their distances.

Initially, the cause of the redshifts in the spectra of galaxies was misinterpreted. It was thought that galaxies were racing through space as though blasted outwards by some huge explosion. Later it was realized that the Universe appears to be expanding not because the galaxies themselves are moving through space, but because the space between the galaxies is expanding.

As light emitted by the galaxies traverses this expanding space, its wavelength is increased, producing a redshift. The redshift is consistently proportional to distance and is a vital tool for estimating cosmological distances. Measurements for relatively close-by galaxies are compared with galaxies farther afield. Although there is some debate over the exact relationship between speed of recession and distance, there is no question about the usefulness of redshift in measurement.

A good analogy for understanding the concept of the expanding Universe is to think of a currant bun baking in an oven. Each currant is a galaxy and the dough is the space between them. As the bun cooks, it expands and the currants move away from each other. The currants farthest away from any single currant seem to move away faster. There is no real center to the expansion. Furthermore, the currants are not moving through the dough - the inflating dough is pushing them outwards. The cosmological redshift is a result of a similar process on a truly Universal scale.

*The Rate of Expansion and the Age of the Universe*

In the 1920s, Edwin Hubble found that for all galaxies outside our local group, the lines in their optical spectra were shifted towards the red or longer wavelengths. Today, most astronomers...
support Hubble's interpretation - that each galaxy or cluster of galaxies is receding from every other one at speeds proportional to their distances. If galaxies are moving apart now, they must have been very close together at some time in the past. This idea is central to the theory of the Big Bang. The relationship between speed of recession and distance is known as Hubble's Law - and the constant of proportionality is called Hubble's Constant, which is generally quoted in units of kilometers per second per megaparsec (km/sec/Mpc).

Assuming that the Universe has been expanding at constant speed, it is possible to calculate the age of the Universe simply by dividing the distances of the galaxies by their speeds. This interval is called the Hubble Time. If the mutual gravitational attraction between galaxies is gradually slowing the rate of expansion, the galaxies must have been moving apart faster in the past than they are now. In this case, the actual age of the Universe will be less than the Hubble Time.

Although measurements of Hubble's Constant have been made for over 60 years, it is not known as precisely as astronomers would like. Its value probably lies somewhere between 50 and 100 km/sec/Mpc, which implies that the age of the Universe is between ten and 20 billion years. The large uncertainty in the value of the Hubble Constant and, consequently, in the value of the Hubble Time, arises principally from difficulties in determining the distances to galaxies which are far enough away for their motion to be dominated by the expansion of the Universe, rather than by "local" gravitational effects.

The Cosmological Distance Scale
Close to home, the distances of galaxies can be determined from the apparent size of so-called HII regions - glowing clouds of hydrogen gas where stars are forming. Distances can also be measured from the properties of Cepheid variable stars. These vary rhythmically in brightness over several days and there is a direct link between a Cepheid's pulsation rate and its true brightness. Once a Cepheid's light variations are measured and its true brightness found, its distance can be calculated. At greater distances, astronomers can use the observed explosions of Type 1a supernovae. These can be seen at 100 times farther into space than Cepheid variables. In 1992, using the Hubble Space Telescope (HST), astronomers observed Cepheid variables in the faint spiral galaxy IC 4182, 16 million light years away. Back in 1937, a type 1a supernova also occurred in this galaxy. Both observations enable a tying together of the Cepheid and Type 1a supernova cosmological distance "ladders". They indicate a value for the Hubble Constant of about 45 km/sec/Mpc, implying the Universe is between 14 and 20 billion years old. This age is compatible with the ages of the oldest known stars, but contradicts other work, which favors a somewhat higher value for the Hubble Constant. In December 1993, during the first Servicing Mission, a new, much improved Wide-Field / Planetary Camera was installed on the Hubble Space Telescope. Subsequently, astronomers were able to detect Cepheid variables in the large Virgo Cluster of galaxies, estimated at about 60 million light years distant, as well as in galaxies out to 80 million light years. A problem soon arose when some measurements indicated a value for the Hubble. Constant consistent with an age for the Universe of only 11 billion years, younger than the age of the oldest stars known!

The Hipparcos satellite helped to resolve the issue. Its precise measurements of the distances to stars indicated that the Universe is between 13 and 15 billion years old. Hipparcos also reduced the age of the oldest stars to between 12 and 13 billion years, so the conundrum disappeared.

The ultimate goal is to refine the value of the Hubble Constant - and hence the scale and age of the Universe - to within ten per cent.
At greater distances, the methods of distance measurement become increasingly inaccurate. Eventually distances can only be estimated by measuring the redshift and relying on the accuracy of Hubble's Law. Unfortunately, for the most distant objects – particularly quasars - we cannot be absolutely certain that this method is valid.

Links for Further Information
A page of introductory information about quasars.

Frequently asked questions about quasars - a good and detailed page.
http://www/phys.vt.edu/~astrophy/faq/quasars.html

Mapping the distant Universe. An educational page detailing new methods for identifying high redshift galaxies - clear explanations, plus images and diagrams.
http://astro.caltech.edu/~ccs.ugr.html

Good picture of a quasar-galaxy collision, with useful accompanying text and links.
http://www/sai.msu.su/apod/ap951022.html

Close-up picture of the Antennae Galaxies, with accompanying text and links.
http://phys.suwon.ac.kr/~kdh2/tdpic/ast971027.html

Introductory information about the Cartwheel Galaxy, including definitions of terms and a description of events.
http://www.ccsn.nevada.edu/other/Planetarium/galaxy.html

Photograph of the Cartwheel Galaxy with accompanying text.

Image of the Andromeda Galaxy with explanatory text and links.
http://www/phy.mtu.edu/apod/ap961009.html

Image of the Sombrero Galaxy with text and links.
http://www.phy.mtu.edu/apod/ap980223.html

Questions and Activities for the Curious
1. Why are the Magellanic Clouds so named?

2. Give examples of spiral, elliptical and irregular galaxies and describe the appearance of each type.

3. What is the Local Group of galaxies? Name some galaxies from within this grouping, apart from the Milky Way.

4. In what way are Cepheid variables used to measure distance?

5. How far into space can Cepheids help astronomers measure distances from ground-based telescopes and from the Hubble Space Telescope?

6. What is a Type 1a supernova and how is it used as a "standard candle"?
7. What is redshift and how did Edwin Hubble use it to demonstrate that the Universe was expanding?

8. What happens when galaxies collide with each other.