Tony Fairall - AST 1000 - PART 7
OUR GALAXY AND OTHERS

THE LOCAL PORTION OF OUR GALAXY

Our Sun is believed to be less than half of the age of the galaxy. This alone suggests ongoing star formation - but there is clear evidence in the presence of high-luminous upper main sequence stars, which have only very short lifetimes. The Orion Association possesses many very young stars and active star formation is apparent from infrared observations within the Orion Nebula complex. In general, the Sun and neighbouring stars are considered to be 'Population I'. Such a population is relatively rich in heavy elements - apparently inherited from earlier generations of stars. As shown earlier, our Sun is much more luminous than average, but there are still some stars getting on towards a million times more luminous (such as the three in the Belt of Orion).

Perhaps a third of local mass exists not in stars, but as interstellar matter. Interstellar matter is scarce in the immediate vicinity of the Sun, perhaps because we are situated within the bubble blown by an ancient supernova. In other places, such as the Orion Association, it exists in relatively dense clumps.

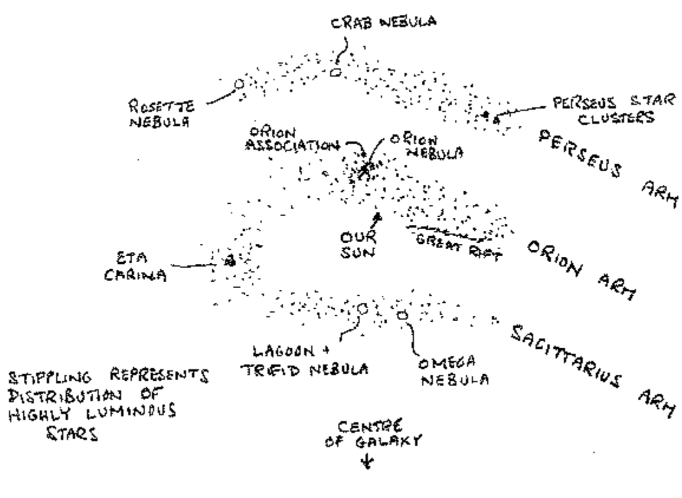
Interstellar matter is 99% gas and 1% dust. The transparent gas is, like the composition of the stars, mainly hydrogen. Much is cold and invisible to optical telescopes. Only in the close neighbourhood of very hot stars, that give off ultra-violet light, is the hydrogen ionised. As the electrons recombine, so they cascade down the hydrogen's atoms energy levels radiating characteristic emission lines. For hydrogen, the most prominent is the 'Balmer Alpha' line in the red. Thus red emission nebulas are seen to surround very hot stars - the gas exists elsewhere, but it is only here that it is luminous.

Dust exists in micron-sized grains. Stars seen through clouds of dust appear reddened (like the setting Sun), but many clouds are dense enough to be completely opaque. These clouds are strongly concentrated towards the plane of the Milky Way, so they are often seen in silhouette against the general starry background.

Cooler clouds, some very massive, are also rich in molecules - many of them organic in nature. Such molecules would be destroyed once star formation is initiated.

Stars appear to form in clusters, rather than individually, from such clouds. In our portion of the galaxy, we see numerous 'open clusters', of which the Hyades and Pleiades are the nearest examples. The mutual gravity of the component stars is usually insufficient to hold the cluster together, so that in time, its stars are disposed in space.

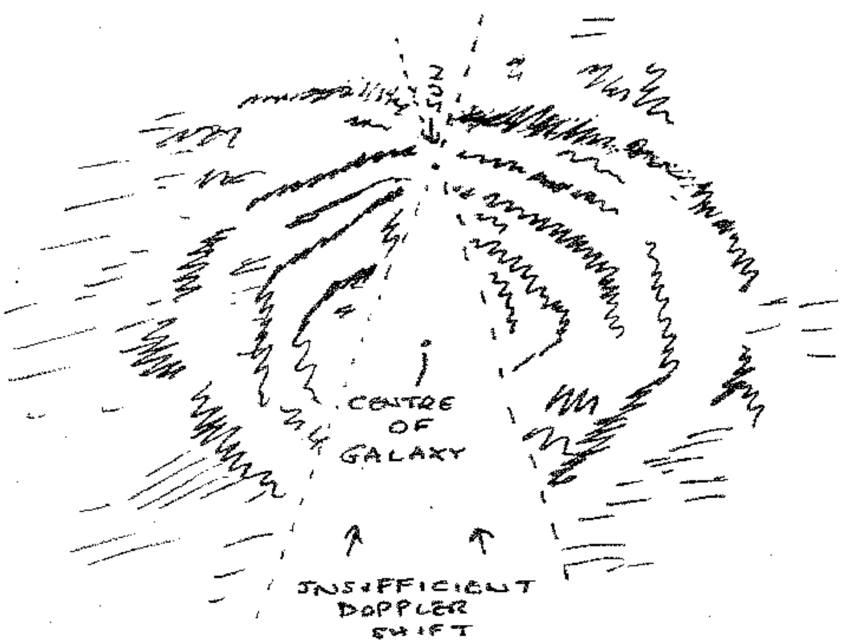
A MORE DETAILED MAP OF LOCAL SPIRAL STRUCTURE



Although our galaxy exhibits spiral structure, there are just as many stars between the spiral arms as there are in them. The reason why spiral arms stand out is because they contain highly luminous stars (i.e. young and short lived). Consequently they also contain emission nebulae. If known emission nebulas and young star associations are mapped, they reveal evidence of three spiral arms - though only an incomplete segment of each is revealed.

It is now understood that the spiral pattern is a form of wave motion. The spiral wave pattern rotates with the galaxy, but not as fast as the constituents of the galaxy's disk. The constituents therefore 'overtake' the spiral arms. Thus our Sun is in the process of entering and passing through the Orion Arm. Eventually it will pass through the Perseus arm. Spiral arms are therefore a region of gas compression - sometimes 'shock waves' of extreme compression exist on their inner edges. Such a shock wave initiates star formation, providing the highly luminous stars (and emission nebulae) that make the spiral arm, The highly luminous stars are, however, so short lived that they die as the arm passes. The less luminous stars, like our Sun, survive.

MAPPING THE GALAXY IN NEUTRAL HYDROGEN



While our view of the galaxy, at optical wavelengths, is very limited, radio waves pass unhindered through the dust clouds. Radio emission comes from interstellar gas. Even cold neutral hydrogen gives off copious radio emission at 21 cm wavelength (as a result of the electron in the ground state flipping its spin). Consequently the radio sky at 21 cm is dominated by the emission from the hydrogen gas in the disk of the galaxy. It is also possible to record the velocity of approach or recession of the gas in the galaxy according to its Doppler shift. If we assume the gas is in circular orbits about the centre of the galaxy and have a model of orbital velocity versus distance from the centre, we can deduce the position of the emitting gas in the galaxy and hence obtain a map.

This technique is fairly successful for gaseous arms that lie closer to the centre of the galaxy than we do, but it is subject to great uncertainty further out because our model of velocity vs distance has been considerably revised. There are also local peculiarities, such as an 'expanding' arm near the galactic centre.

THE CENTRAL BULGE AND HALO OF THE GALAXY

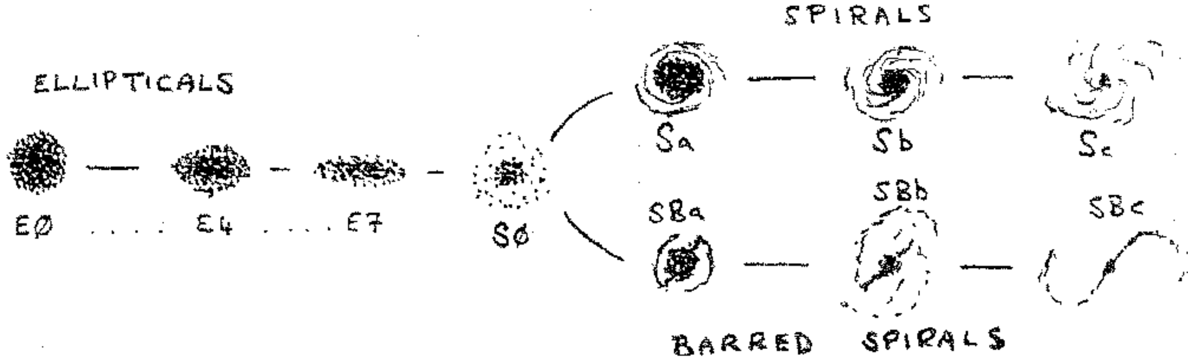
The great concentration of stars in the centre of the galaxy bulges out above and below the plane of the disk. Consequently part of it can be seen optically and Schmidt telescope photographs reveal vast numbers of stars - even though the densest portion towards the centre itself is hidden by the Milky Way. A view in the far infrared (infrared light is less affected by the dust clouds) reveals a view of our spiral galaxy seen edge-on - just as seen with other edge-on spiral galaxies. Such views underline the Sun's position in the outer part of the galaxy. The distance to the central bulge can be established by identifying recognised variable stars (especially RR Lyrae, of known absolute magnitude).

Except at the very centre of the galaxy, there is little gas in the central bulge. Hence there is no ongoing star formation and the existing stars are in general a much older population - Population II. Stars that would have formed the top end of the main sequence - i.e. blue and highly luminous - have long since died, so the general population appears more yellow-orange, compared to the general blue colour of Population I.
Clustering around the central bulge - and not confined to the plane of the galaxy - is a swarm of about a hundred 'globular clusters'. Each contains around 100 000 stars and their mutual gravity is easily enough to hold them together (even if the entire cluster oscillates from one side of the bulge to the other). In our galaxy, all the globular clusters are population II.
The central bulge does not have an abrupt edge, but diminishes to form a three-dimensional halo about the galaxy. The star density is extremely low, but some halo stars are apparent even out by our Sun. Since they do not rotate with the disk, they appear to have high velocities (when their proper motions and radial velocities are measured). Also they are old stars, considerably weaker in heavy elements.

THE NUCLEUS OF OUR GALAXY
The very centre of our galaxy is hidden from optical view, but can just be detected in the infrared. Radio shows a clear view and reveals complex structure - including a miniature spiral pattern about a central source known as Sagittarius A. Observations with the Hubble Space Telescope show stars moving very rapidly in orbit about an unseen object. Their velocities indicate the mass of the central object to be approximately 4 million solar masses, presumably a black hole.

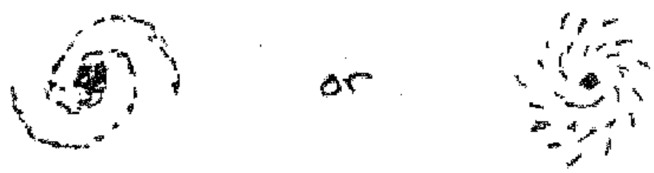
BLACK HOLES
Einstein's theory of General Relativity – verified by numerous experiments – recognises that heavy masses cause a 'stretching' of space-time, like placing a lead weight on a rubber sheet. It predicts that should sufficient mass be concentrated into a small enough volume (i.e. even beyond the density of a neutron star), then space-time would be so stretched - like the lead weight falling through and the rubber sheet 'running' – that not even light can escape. Black holes are surrounded by a spherical 'event horizon' within which light cannot escape. Hence the term 'black holes'.
The radius of the event horizon of a black hole stellar remnant would be in the region of 15 kilometres. By contrast, the black hole in the centre of our Galaxy would have an event horizon with a radius of approximately 10 million kilometres, far larger than the Sun. However supermassive black holes, such as we will encounter below, in relation to active galaxies might have event horizons with radii approaching the diameter of the Solar System.

OTHER GALAXIES
Except in the band of obscuration caused by the Milky Way, photography of the sky reveals vast numbers of galaxies. It is estimated that if deep CCD images could be made over the entire sky, we would detect some 10 billion galaxies, though most would appear as little more than distant blurs. Nearer galaxies can be seen quite clearly - they exhibit a variety of orientations and appearances. A



good general classification of galaxy type is provided by the Hubble scheme.

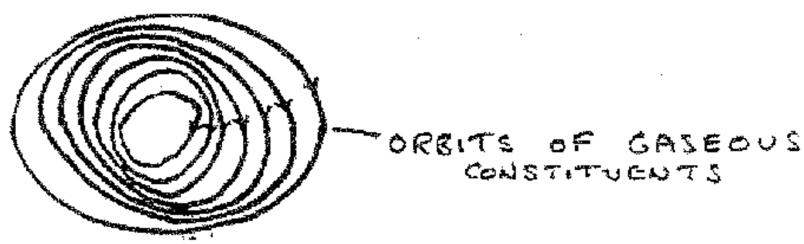
The classification of the 'ellipticals' is based on their apparent, and not necessarily, the true shapes. The scheme does not accommodate the finer details of spirals, e.g. the occurrence of rings or whether the spiral arms are 'global' or 'flocculent'.



Furthermore, the classification takes no account of true physical size. Ellipticals may range from 1 to 50 kpc in diameter, spirals over 5-200 kpc.
Some peculiar distorted galaxies have been explained by tidal interactions, when galaxies have close encounters with one another.

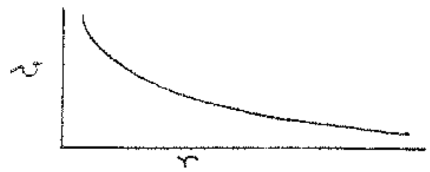
ELLIPTICAL GALAXIES
Are like overgrown globular clusters. Generally they show little overall rotation, the ellipticity is apparently not caused by the rotation. Their shapes are generally believed to be tri-axial (different dimension on each axis). Colours and spectroscopy show their stellar content to be Population II. Normally they have little interstellar gas.

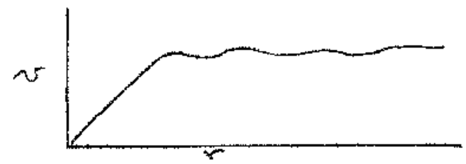
SPIRAL GALAXIES
The central bulge of a spiral galaxy is effectively an elliptical galaxy, though there may be some overall rotation. The star density diminishes outward into the halo. Together with the globular clusters, it is a three-dimensional distribution. Observations of the dynamics of stars generally reveals the presence of a central black hole; the larger the central bulge, the more massive the hole. The spiral structure, and Population I content, on the other hand is a two-dimensional disk. The disk system has much more angular momentum than the bulge and halo and rotates around the centre of the galaxy in somewhat similar fashion to the rotation of the planets in the solar system. Apparently, the gaseous constituents of the galaxy are forced into a disk by the action of mutual collisions (gas clouds can collide, whereas stars are highly unlikely to do so). Spiral compression waves develop in the disk. As described above, these lead to star formation, including the high luminous but short-lived stars that mark the spiral arms.



DARK MATTER IN GALAXIES
If the mass of a spiral galaxy were concentrated towards its centre, the orbital velocities in the disk would decline with increasing radius (as happens in our Solar System). Surprisingly, orbital velocities do not decline, suggested the presence of a massive, yet invisible, halo. The only possible explanation for this is that there is considerable unseen mass in the outer parts of the galaxies. In a

sense, the visible part of a galaxy is like an iceberg. The nature of this unseen mass is a matter of considerable speculation, of which low mass stars or 'MACHOS' (Massive compact halo objects) is the more conservative view, however observations have not yet given any support to their existence. (This topic will be discussed again in the next chapter.)



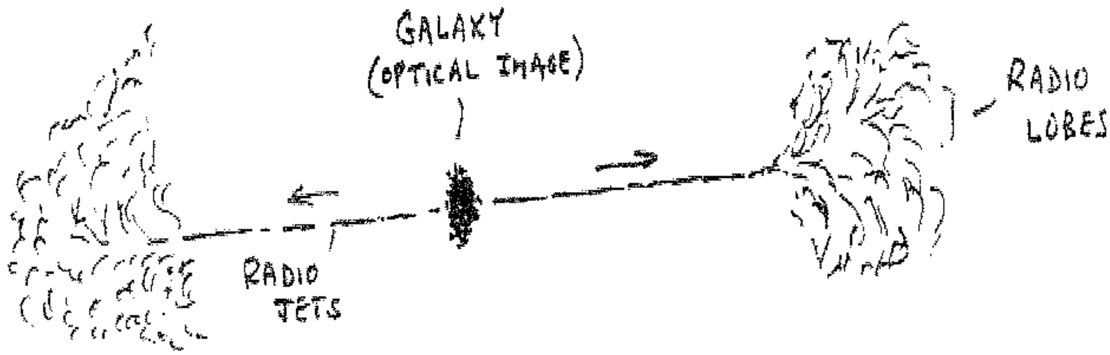


GALACTIC NUCLEI AND ACTIVE GALAXIES

As with our own Galaxy, many black holes have been detected in the nuclei of other galaxies. There is a tendency for galaxies with larger central bulges to have more massive black holes. For most galaxies (like ours) energy output from the nuclei at their centres is mild. For some - apparently those with 'supermassive' black holes - the energy output is considerable with vast amounts of non-thermal radiation (radio, infrared, optical, ultraviolet, X-ray and possibly gamma-ray) - hence termed 'active galaxies'.

ACTIVE GALAXIES WITHOUT HIGH-LUMINOSITY NUCLEI

Whatever it is in the centre of the galaxy (and radio intercontinental interferometry shows it to be smaller than a parsec in size), it is capable of shooting out jets (usually two in opposite directions) over enormous distances. The jet material (probably changed particles) impinges on tenuous intergalactic media and spreads out into radio lobes. The jets, being 'cold' are not always visible, sometimes one only sees the lobes or a one-sided jet.



NGC 5128 is the nearest active galaxy. The nucleus is only detectable as an X-ray source. It also has faint extended optical jets. M87 (biggest galaxy in the nearby Virgo cluster) is active but without the extended double lobe radio emission. It has a conspicuous optical jet. Observations made by the Hubble Space Telescope suggest the presence of a very small but very massive nucleus - most likely a black hole.

ACTIVE GALAXIES WITH HIGH-LUMINOSITY NUCLEI: SEYFERT GALAXIES AND QUASARS

Rather than being pumped into radio jets, the energy manifests itself as high luminosity. Spectra show broad emission lines (gas in violent motion) superposed on a non-thermal continuum (accretion disk around black hole?). Relatively rapid light variations indicate that the central energy source is smaller than a light-week or so.

Depending on the luminosity of the nucleus and distance of the active galaxy, it may be classified as a Seyfert galaxy or quasar.

The quasars (quasi-stellar objects) are so called, because the high luminosity of the nucleus makes it extremely difficult to see the host galaxy. Some quasars do show radio jets so the central energy is thought to be the same as in those active galaxies without high luminosity nuclei.
When examined by radio intercontinental interferometry, some quasars have shown apparent superluminal motion - the apparent ejection of clouds at many times the speed of light. It is possible to explain this, without violating the speed of light, if the ejected cloud is moving close to the speed of light and travelling almost directly towards the observer. (At such high velocities, emitted radiation is concentrated in a forward direction - compare to pulsars).
'BL Lac objects' are related to quasars but lack the emission lines in the spectrum. It is thought their light comes directly from the ejecta, rather than the nucleus itself, since it shows polarisation changes in as short a time as 15 minutes.

MODELS FOR ACTIVE GALAXIES
The evidence that the central energy source is physically very small, has led to the favoured 'black-hole' model. Black holes draw things in, not shoot them out. However, electromagnetic effects (the accretion disk acts like a giant generator) may produce high voltages and divert a small portion of the infalling material into jets.
Thus for a galaxy to be active, the central black hole has to be fed with infalling material. The same process seems to manifest itself on a smaller scale as 'mini-quasars' like the star system SS 433 mentioned earlier.

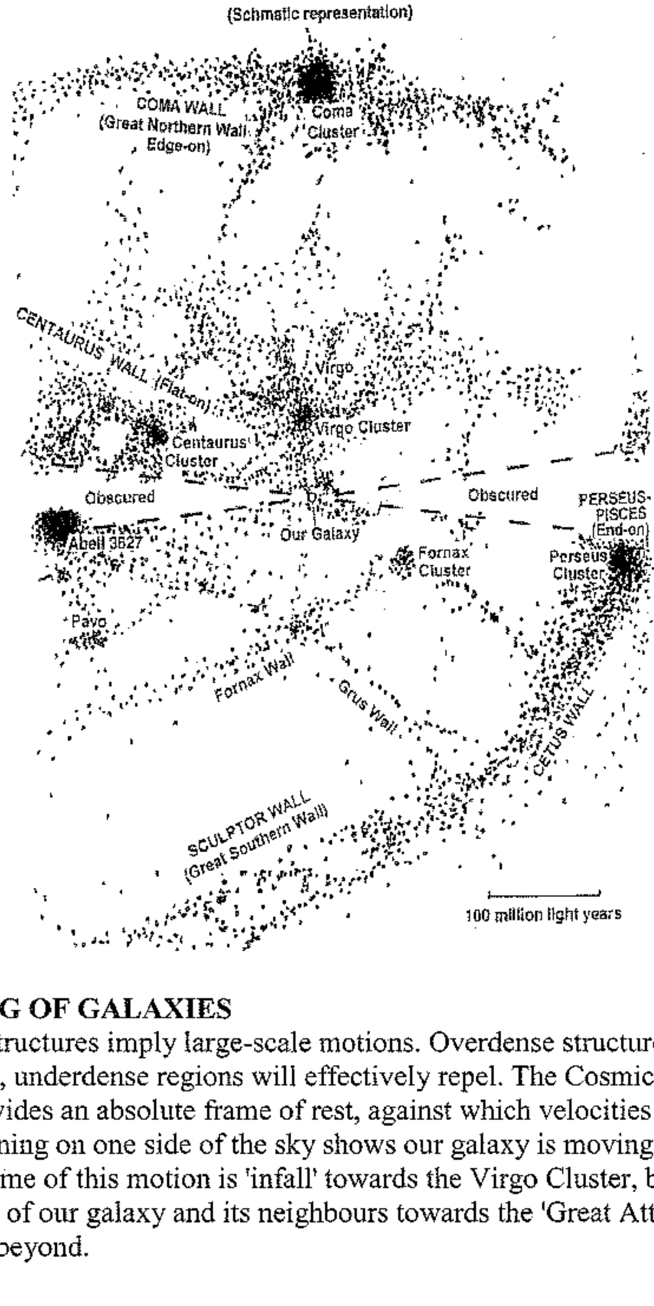
CLUSTERS OF GALAXIES
Galaxies tend to congregate into groups and clusters. Groups and poorer clusters tend to be rich in spiral galaxies, Rich clusters, however, tend to have entirely elliptical and SO galaxies. The mutual gravitational forces between the galaxies tend to pull them together. For example, in the case of our local group of galaxies, the expansion of the universe initially pulled our Galaxy and the Great Galaxy in Andromeda apart. But gravity has overcome this and now the galaxies are moving towards each other, eventually to merge in billions of years to come. Such interactions must be much more common in the denser clusters, and apparently explain why spiral galaxies would not last long in such an environment.
Rich clusters also contain large amounts of very hot intergalactic matter - hot enough to produce X-ray emission. In the same way that the rotation of galaxies indicates the presence of dark matter, so the dynamics of galaxies in clusters indicates the presence of considerable dark matter. In certain cases, the matter in clusters acts as a 'gravitational' lens that may enhance and distort the images of distant background galaxies.

LARGE-SCALE STRUCTURES

On a larger scale, galaxies congregate in a three-dimensional labyrinth of large-scale structures (as indicated in the second last diagram in 'Our Place in the Universe').

Local large-scale structures, shown in the accompanying schematic diagram, tend to be concentrated near a 'Supergalactic' plane (i.e. the plane of the paper). Our galaxy is found to lie on the fringe of the Local (Virgo) Supercluster, which in itself is a protrusion of a still larger structure, the 'Centaurus' Wall. 'Wall' crudely describes a large flattened irregular structure; in the map, the plane of the Centaurus Wall is close to that of the Supergalactic plane. Large bubbly voids seem to separate this structure from the 'Coma Wall' (Great Wall) and Perseus-Pisces (more of a ribbon than a wall.

LOCAL LARGE-SCALE STRUCTURES
IN THE UNIVERSE
(Schmatic representation)



STREAMING OF GALAXIES

Large-scale structures imply large-scale motions. Overdense structures will draw further galaxies towards them, underdense regions will effectively repel. The Cosmic Microwave Background radiation provides an absolute frame of rest, against which velocities can be measured. The very slight brightening on one side of the sky shows our galaxy is moving at 600 km/s (in the Centaurus direction). Some of this motion is 'infall' towards the Virgo Cluster, but the remainder represents the streaming of our galaxy and its neighbours towards the 'Great Attractor' in the Centaurus Wall-and possibly beyond.

STAR FORMATION IN GALAXIES

Galaxies generally divide into two populations: 'Red' galaxies, where star formation has long since ceased and 'Blue' galaxies with ongoing star formation. The degree of star formation also increases as we look further into space, and further back in time.

Star formation may have peaked when the universe was less than a half of its present age. Since then, it has been on the decline.

GALAXIES AT GREAT DISTANCES

Deep photography (e.g. the 'Hubble Deep Fields' and the 'Hubble Ultra Deep Field' from the Space Telescope) reveal abundant galaxies several billion or more light years out. Many galaxies, this far back in time, seem more irregular in appearance than galaxies of today. We are seeing a time when star formation rates were much higher. Also, galaxies were considerably closer to one another than they are today, and interacted more frequently with one another. There is a general realisation than many modern galaxies have grown from mergers in this distant past.