

Astronomy in the Millennium

Highlights of Astronomical Ideas and Discoveries during 1000-2000 A.D.

Jayant V. Narlikar

Inter-University Centre for Astronomy and Astrophysics

Pune 411 007

Introduction

It is hard to summarize even the highlights of such a dynamical subject as astronomy, which can claim to be the oldest of all sciences. Here is an attempt to select a few instances which are regarded as landmarks (or spacemarks?) in the evolution of human perception of the universe.

Perhaps I should begin with India! For nearly a thousand years ago astronomy flourished in India, whereas it was dormant in Europe where the Greek contributions of an earlier millenium had become fossilized. The Arabs were playing a major role in conveying and recording astronomical findings from India and the Orient in general. The golden age of Indian astronomy, which had begun in the fifth century A.D. with Aryabhata was coming to a close in the twelfth century with Bhaskara II. However, the Siddhantashiromani of Bhaskara (1150 A.D.), with its contributions to astronomy and mathematics has survived to tell us of the advances in these fields in those times. Certainly the use of triginometry and algebra were used in India in astronomical observations of stars and planets and calculations of events like eclipses, occultations, etc.

Unfortunately, the momentum in India died down in the following centuries and it picked up in Europe with the advent of Copernicus, Galileo and Kepler in the 15th-17th centuries. We will take up the story there.

Advent of the Heliocentric Theory

From sometime in the first half of the sixteenth century to sometime in the second half of the seventeenth, a major revolution took place in man's perception of his position in the universe. This period may seem too long in modern terms but seen in terms of the slow motion progress of science in earlier times, it was very important and far reaching.

In the golden era of Greek astronomy, Hipparchus (190-120 B.C.) and Ptolemy (A.D. 85-165) had perfected the geocentric theory which described the stellar

and the planetary system as revolving around the fixed Earth. The stars were relatively easy to describe in this framework, but the planets with their apparently irregular motions were more difficult to fit in.

Guided by Aristotle's penchant for circles as paths for natural motions, the Greeks wanted to describe a typical planetary path as a circle whose centre moved on another circle, whose centre moved on a third circle...and so on, with the final circle in the series going around the fixed Earth. These circles came to be shown as *epicycles*, and Ptolemy's book *Syntaxis* which became better known through its Arab translation as *Almagest* was regarded as the last word in the subject for fifteen centuries.

It was against this well entrenched belief in the fixed Earth theory which had become a religious dogma in Europe that we must view the Copernican revolution. First in a monograph called *Commentariolus* and later in the detailed volume *De Revolutionibus Orbium Caelestium* which he saw completed in 1543 when he was on his death bed, Nicolas Copernicus proposed the heliocentric theory.

Copernicus showed that the motions of the planets are considerably simplified if one shifts the centre point from the Earth to the Sun, with the former also moving around the latter. He too had to use epicycles to describe planetary paths, however. It was Johannes Kepler in the early seventeenth century who first obtained the correct picture of planetary paths. He showed that they move in elliptical orbits with the Sun as one of the two foci. Thanks to the work of Kepler and his contemporary Galileo Gallilei who launched a major campaign not only against the geocentric theory but also against the entire Aristotelian natural philosophy, the Copernican revolution reached a successful completion.

However, the bulk of the controversy surrounding the heliocentric theory arose because it was trying to replace what had become a religious tenet, namely, that the Earth is firmly fixed in the universe.

Does the Earth Move?

'Eppur si muove' ('Yet, it does move') said Galileo in 1633 even after recanting and supporting the geocentric theory. Is the Earth fixed and the Sun goes round it or vice versa? The debate had been a long standing one. The relativist today may say: does it matter? Aren't the laws of physics the same, whichever frame of reference you find convenient to use? Indeed, in a purely two-body system the question of what goes round what is undecidable.

But astronomers have more than two bodies to deal with. Apart from the planets in our neighbourhood, there is the background of stars. With respect to that background the question of what goes round what does become

meaningful. And it is in principle decidable. Aristarchus of Samos in Greece, back in the third century B.C. was the main proponent of the heliocentric theory. His idea was put to a test: at six month intervals the stars should appear to change their direction because of the change of the observer's vantage point as the Earth moves through space.

The idea was right but Aristarchus lost the debate for two reasons. First, he and his contemporaries had grossly underestimated the stellar distances and had expected appreciable angular changes of star directions, which were not found. Second, the astronomical techniques of his times were not accurate enough to measure the changes of the order of 0.1 arc second that were in fact there.

Even Galileo, despite his confidence in the heliocentric theory, did not have the correct test of his claim. His notion that the Earth's motion causes tides of oceans was wrong. The real tests of the hypothesis came in the 18th and 19th centuries. The parallax test proposed by Aristarchus was first used by Bessel for a reliable result in 1838 for the star 61 Cygni, whose parallax is about 0.3 arc second. An earlier test of the Earth's motion came in 1725 from aberration measurements by Bradley who measured the change in the direction of light coming from a star as perceived from the moving platform of the Earth.

The “How” and “Why” of Planetary Motion

The true motions of planets around the Sun began to be understood, thanks to the pioneering work of Johannes Kepler.

Kepler started as an assistant to the famous astronomer Tycho Brahe from Uraniborg, Denmark. Tycho did not believe in the Copernican heliocentric theory and had collected a lot of observational data on planetary positions from his well equipped observatory in the hope of disproving the theory and proving his own version of the geocentric theory. However, he died in 1601 without realizing his dream. On his deathbed he enjoined Kepler to complete the mission with the help of data already collected.

With painstaking efforts lasting nearly two decades, Kepler completed his work only to find that the data corroborated the heliocentric view, but in a way not imagined even by Copernicus. For, till Kepler announced his results, circular trajectories, the epicycles, had played the key role in describing the planetary orbits. Kepler found that the typical planetary orbit is an ellipse with the Sun as one of its two foci. Kepler not only determined the shape of the orbit but also described the mathematical pattern of how planets move along their respective orbits with the Sun as the common focal point. The next step to understand was *why* the planets moved in that fashion.

In the end, it was left to Issac Newton in England to complete the picture. Taking off from Galileo's ideas on motion and inertia, Newton formulated his laws of motion. Given Kepler's laws as empirical facts, Newton was able to explain them within his dynamical framework and in this process made his great discovery of the law of universal gravitation.

For, Newton's laws of motion related the acceleration of a body to the force acting on it. From Kepler's laws, it was possible for Newton to find the planetary acceleration and hence the force acting on the planet. This is how he arrived at the inverse square law of gravitation.

With his characteristic genius, Newton used his newly discovered methods of calculus to work out the inverse problem, viz, what is the orbit if the force is given as per the inverse square law? The answer came out to be the orbits found by Kepler.

The publication of *Philosophiae Naturalis Principia Mathematica* (The Mathematical Principles of Natural Philosophy) in 1687 by Newton represents the culmination of human efforts over recorded history to understand how and why the planets move across the sky.

The Universality of the Law of Gravitation

Folklore has it that the fall of an apple in his orchard at his residence, the Woolsthorpe Manor, inspired Issac Newton to think of law of gravitation. However, the real quantitative evidence for the inverse square law came from the data on the motions of the Moon and the planets. But the question still remained as to how wide in its applicability is the law of gravitation. Here too astronomy, rather than terrestrial laboratory experiments, provided further inputs.

Even during Newton's lifetime, his friend and scientific colleague Edmund Halley made the important prediction that the comets that had previously visited the Earth's neighbourhood in the years 1456, 1531, 1607 and 1682 were one and the same comet that was following a periodic and highly eccentric orbit under the Sun's gravitational field and that it would next visit in the year 1758. Halley calculated the comet's orbit using Newton's laws of motion and gravitation. The comet did visit exactly as predicted, although, Halley was not alive to witness this triumph. The comet itself has since been named after Halley.

There were other post-Newtonian triumphs of the law of gravitation. The discovery in 1845, of planet Neptune came out of the application of the law of gravitation to understand the small but unmistakable discrepancy in the orbit of planet Uranus: Uranus was not moving exactly along its Keplerian

orbit. Adams in England and Leverrier in France independently deduced the existence of a new planet from its possible effect on the orbit of Uranus. Galle of the Berlin Observatory was able to confirm the location of the planet as predicted.

However, the validity of the law of gravitation beyond the narrow confines of our solar system began to be evident in the 19th century with the observations of binary stars. In 1803, Sir William Herschel first recognized visual binaries and their orbital motions which appeared to follow Keplerian laws. Unlike the rather unequal combination of a massive Sun and a very low mass planet, the binary stars were of comparable masses but one could still study them as examples of Newtonian two-body gravitating systems.

Today the astronomer applies the phenomenon of gravitation to even larger systems like galaxies, quasars, clusters and superclusters of galaxies and even to the entire universe...but we will come to those applications later.

Stellar Studies in Bulk

The nineteenth century saw astronomers take on studies of stars in bulk. Of particular interest were the clusters of stars and the nebulae. With his large telescopes including the 48-inch reflector, William Herschel made pioneering discoveries which led to the first attempt at finding the structure of our Galaxy.

The key feature of this structure which is visible to the naked eye on a clear night is of course the Milky Way, a white band stretching across the sky. By counting stars in different directions, Herschel demonstrated that they are concentrated in the plane of the Milky Way. If we imagine ourselves as located in this plane then looking out, we would see the stars in the “disc” projected as a band. Today, we call this disc of stars the “Galaxy”.

Herschel found the stars to be distributed mainly in the plane of the Milky Way; the nebulae, which were diffuse patches of light, however, seemed to avoid that plane. Unlike the stars, the nebulae have a diffuse cloud-like appearance and Herschel thought them to be components of the Milky Way system. Some indeed seemed to have a central star.

Back in the eighteenth century, the mathematician J.H. Lambert had suggested that by and large the nebulae were large clusters of stars – they were galaxies like our Milky Way Galaxy, but because they happened to be very far away they looked small and one could not make out their starry character. However, Herschel thought otherwise: because these nebulae avoided the plane of our Galaxy he felt that their distribution was somehow related to the structure of the Galaxy. Herschel’s studies also led him to believe that our Sun and the Solar System were located very close to the centre of the Galaxy.

Eventually, these conclusions of Herschel proved to be wrong. The crucial aspect of the cosmos that he had not been aware of was the presence of dust. Like stars, clouds of dust particles are also concentrated in the disc of the Milky Way, thus obscuring the view of all distant objects lying in that plane. Which is why no nebulae are seen in the galactic plane. It was the dust obscuration that also misled Herschel about the true extent of our Galaxy and our location in it. But the real picture emerged only in the present century.

The Discovery of Helium and Astronomical Spectroscopy

In the Total Solar Eclipse (TSE) of 1868, astronomical observations achieved a “first”, namely, the first time that the astronomical setting led to a discovery which was replicated in a terrestrial laboratory years later. This happened in the TSE observations by the French astronomer Pierre Jules Cesar Janssen (1824-1907) at Guntur, now in the Andhra Pradesh state of India. The source of a yellow line in the flash spectrum was identified as a new element which, because of its presence on the Sun (Helios in Greek), was named Helium. The genesis of the name is due to the co-discovery of the new element, Joseph Norman Lockyer (1836-1920). The same element was discovered anew on the Earth in 1895 by Ramsay in a classical investigation as a constituent of the earth’s atmosphere. Today, the cosmologists recognize it as the next abundant element in the universe after hydrogen. There is a postscript to the eclipse episode. During his post-eclipse stay in Simla, Janssen made the first spectrohelioscope, which was used for the daily examination of the Sun. It was the transit of Venus on December 9, 1876, that led to the institutionalization of astrophysics in India. European solar physicists realized the advantage of India’s sunny weather for their research and took the initiative. The Government of India was persuaded that support for the study of the Sun would help prediction of the errant monsoons, so essential to India’s agriculture!

The discovery of helium was a major step in a quiet but significant revolution that was taking place in astronomy in the nineteenth century, a revolution that was to lead to major advances in physics in the early years of the twentieth century. This astronomical revolution was in spectroscopy and some important developments in it were as follows.

1814 von Fraunhofer measured the relative positions of dark lines in the
-15 solar spectrum.

1822 John Herschel discovered the bright spectra of volatilized metallic

salts and suggested in the following year that such lines might be used to detect these elements.

- 1849 J. Foucault pointed out the exact correspondence between the bright and dark lines.
- 1849 George Stokes showed that atoms which emit bright emission lines when hot, absorb lines of the same wavelength when in cold vapour form. Thus, he explained that the dark Fraunhofer lines represent absorption by metallic vapours.
- 1860 The first spectroscopic examination of star began.
- 1867 Angelo Secchi classified stars in four classes according to their spectra.
- 1890 Around this time E. Pickering introduced the Harvard spectral classes O, B, A, F, G, K, M, R, N, ... that are now commonly used.

The Galactic Centre

Late in the eighteenth century, William Herschel had begun measurements of stellar distances, starting with the assumption that stars are basically similar to the Sun. Thus, the fainter the star the farther it would have to be. By counting stars to fainter and fainter magnitudes, Herschel was able to get a qualitative picture of their distribution in what became known as the Galaxy.

In Herschel's picture, the Sun was placed at the centre of the Milky Way. This belief survived throughout the nineteenth century and when towards its end, J.C. Kapteyn planned a large scale programme of spectroscopy and photometry of stars in the Milky Way so as to determine its structure, he was guided by the same belief. The outcome of this work led to the *Kapteyn Universe* in 1922, in which the entire system was believed to be 10,000 light years in diameter and centred on the Sun.

By 1918, however, thanks to the work of Harlow Shapley, picture of a different and larger system was emerging with the Sun well away from the centre. With the help of measurements of angular sizes of globular clusters (these are spherical distributions of stars) Shapley found that the true centre of the Galaxy lies in the direction of Sagittarius. His estimate of the diameter of the Galaxy at 300,000 light years, however, turned out to be too large by a factor three. This was because he had not taken into account the attenuation of starlight by interstellar dust... an effect that became known and established in the 1930s. After an initial period of controversy between the Kapteyn and Shapley schools of thought, the latter prevailed.

Catching Glimpses of the Extragalactic World

While the overall picture of our Galaxy was taking shape, the astronomers were also becoming aware of what lies beyond. As early as 1755, in his book: *Universal Natural History and Theory of the Heavens*, Immanuel Kant laid down what has become known as the "Island Universe" hypothesis. According to this hypothesis, the Galaxy is a stellar system floating like an island in space along with innumerable other such systems separated by enormous distances.

This idea was slow to catch on despite evidence coming through observations. For example, in the beginning of this century spiral nebulae were known as individual entities. But how large and how distant were they? As late as 1920, many astronomers believed that the Galaxy is larger than any other system and that the spiral nebulae were part of it or its satellites. A minority, however, believed like Kant that these nebulae were very distant and were galaxies in their own right.

Harlow Shapley who had been correct in the controversy regarding the Galactic Centre was on the wrong side in this argument. In 1919, for example, there was a debate between Shapley and Curtis with the latter maintaining the Kantian view. A major factor in these arguments was the claim by Van Maanen at the Mount Wilson Observatory that spiral nebulae like M 33, M 81, etc. (M denoting the Messier Catalogue) possessed proper motions, i.e., they moved perpendicular to the line of sight. If this claim was correct then they could not be very far as, otherwise, their transverse speeds would have to be impossibly high.

However, thanks to the work of Edwin Hubble who measured the distances of such nebulae, the Curtis claim gradually prevailed. Moreover, by the mid-1930s Van Maanen's claim lost credibility as it could not be substantiated by others and the doors to the vast extragalactic universe were thrown open.

Hubble's Law and the Expanding Universe

The extragalactic nature of faint nebulae was thus becoming clear thanks to the distance measurements by Edwin Hubble. Hubble was able to demonstrate that these nebulae were galaxies in their own right, containing hundreds of billions of stars like our Milky Way.

Side by side with this development, between 1912 and 1925, V.M. Slipher discovered a novel feature of these galaxies. The spectra of these galaxies showed absorption lines that were generally redshifted. That is, these lines

were seen at longer wavelengths than their standard laboratory values. If one interprets this shift as a Doppler shift, then the implication is that the source of light is moving away from us as observers. The Doppler shift formula tells us that the fractional increase in wavelength multiplied by the speed of light is the speed of radial recession.

When Hubble and his junior colleague Milton Humason combined the redshift observations with their distance measurements, a clear signal emerged. The farther the source galaxy the larger was its radial velocity of recession. In 1929, Hubble was able to express the result as a linear relation:

$$V = H \cdot D,$$

where V is the velocity of recession and D the distance of the galaxy. H is a constant, known as Hubble's constant. The value, Hubble got for this constant was 530 km/second/megaparsec.

Hubble's law as above came to be known, showed for the first time that the large scale universe may not be static but is a dynamic entity. How to model a dynamic universe was therefore a challenging problem for theorists and was to lead them to the foundations of the subject of cosmology. The popular theoretical model to emerge was that in which the universe exploded into existence in a primordial event, usually called the 'big bang'. It has been expanding ever since. Before we proceed further with this story, let us look at another branch of astronomy which was making remarkable progress.

Understanding of Stellar Structure

As astronomers were able to classify stars according to their luminosity and surface temperature, the latter made possible by spectroscopy, astrophysicists began to apply the laws of physics they had learnt in the terrestrial laboratory to stars. Around 1920, the Indian physicist Meghnad Saha laid the foundations of stellar astrophysics by his famous 'ionization equation'. Questions relating to a deeper understanding of stars, such as: what makes a star shine, what are the forces controlling its equilibrium, how does energy propagate outwards within its interior, etc. could now be meaningfully posed.

It was Arthur Stanley Eddington who pioneered the subject of stellar structure. Eddington's equations of stellar structure basically formulated the physics behind the questions posed above. Solving these equations, Eddington could deduce that the stellar interior would typically be made of hot plasma whose temperature falls outwards from a very high central value of upwards of ten million degrees. Likewise its thermal and radiation pressures decrease outwards, thereby supplying the force necessary to keep it in equilibrium against its own gravity.

It is these high core temperatures that hold the key to the secret of stellar energy. Following the ideas of J. Perrin, Eddington argued that temperatures of such high order would induce thermonuclear fusion, leading to the formation of helium from the fusion of hydrogen nuclei.

In a hot plasma, hydrogen nuclei are stripped of their electrons and move freely. But how could four such positively charged particles overcome their mutual repulsion and fuse together? The nuclear physicists were sceptical of Eddington's ideas and felt that even at the high temperatures he was talking about nuclear fusion would not happen. In his classic book, *The Internal Constitution of the Stars*, published in the mid-twenties Eddington poured scorn on his critics: "We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place."

Within a decade, however, the nature of nuclear force whose attractive power at close range dwarfs any electric repulsion, became established and Eddington's conjecture was proved. In 1939 Hans Bethe, a nuclear physicist, constructed solar models in which the then available information on thermonuclear fusion was put in. With this work, it became possible to predict the physical characteristics of a star like its radius, surface temperature and colour, its luminosity, etc., given its mass. For this landmark work, Bethe was awarded the Nobel Prize in 1967.

The Origin of Elements

There were two attacks on the problem of understanding the origin of chemical elements in the universe, both in the 1940s. George Gamow and his younger colleagues Ralph Alpher and Robert Herman explored the avenue provided by big bang cosmology. According to this model, during the period of around 1 - 200 seconds, the universe passed through a density - temperature phase when conditions were suitable for thermonuclear fusion. Gamow believed that this process would generate most atomic nuclei found in the universe.

In the end, it turned out that the process worked only for light nuclei, upto essentially helium. The gap between atomic mass range 5 - 8, caused by the lack of stable nuclei, made the nucleosynthesis process impossible beyond this range.

In 1946, in a paper in the Monthly Notices of the Royal Astronomical Society, Fred Hoyle proposed the alternative route of stellar nucleosynthesis. As stellar models had demonstrated, stars like the Sun are making helium in a slow but steady way by synthesizing hydrogen nuclei. Why not pursue this process further in future evolutionary stages?

Again, the gap in the mass range 5-8 became an obstacle. Although Ed Salpeter had proposed 'jumping' across this gap to make carbon from three helium nuclei, a three-body collision being rare, would not work. In 1954, Hoyle came up with the ingenious solution that the reaction to carbon is a *resonant reaction*. His calculations suggested that this reaction should produce an excited state of carbon which would subsequently decay to normal state. The question was, did such an excited state of carbon exist?

The question was soon settled when Ward Whaling and Willy Fowler at Caltech found it by experiment! And so, not only was the crucial gap bridged, but a way was found to understand the evolution of stars beyond the main sequence. The next important landmark in stellar nucleosynthesis was the comprehensive work of Geoffrey and Margaret Burbidge, Willy Fowler and Fred Hoyle in 1957. Popularly known as the B²FH theory, it explained how most nuclei are formed in stars.

Did this supplant the primordial nucleosynthesis theory of Gamow, et al? Not quite! That theory was to make a comeback, as we shall see next.

Cosmic Microwave Background

In 1964, Arno Penzias and Robert Wilson at the Bell Telephone Laboratory, Holmdale, New Jersey made an unexpected discovery while testing their horn shaped antenna for some galactic observations in the microwaves. Working at 7.35 cm wavelength, they found that after subtracting contributions from all known sources, there still remained an isotropic background of radiation. If the radiation were in thermal equilibrium, its equivalent black body temperature came to around 3.5K. What was this radiation due to?

We just described the primordial nucleosynthesis theory of George Gamow and his collaborators. A by-product of that work was a deduction, first published by Gamow's collaborators Ralph Alpher and Robert Herman in *Nature* in 1948, that the early hot era of nucleosynthesis would leave behind a relic radiation background.

The Gamow idea of primordial nucleosynthesis and relic radiation was, however, independently resurrected in the early 1960s by R.H. Dicke and P.J.E. Peebles in Princeton and by Ya.B. Z'eldovich in Moscow. The Princeton group had in fact begun to set up an antenna to detect the radiation, when the news of the discovery by Penzias and Wilson reached them. They could interpret the isotropic background found by Penzias and Wilson as the relic of big bang.

This discovery of an isotropic microwave background radiation (MBR) has been considered the most significant discovery in cosmology since Hubble's Law. Moreover, it was considered the strongest support for the big bang hypothesis. In 1978, Penzias and Wilson were awarded a Nobel Prize for this discovery. The strength of this evidence grew as further observations led to a confirmation that the spectrum of MBR is indeed that of a black body with a presently estimated temperature of 2.73K. ('K' measures temperature on the absolute or *Kelvin* scale. The absolute zero stands for nearly -273 degrees Celsius.)

Astronomical Telescopes

We have been remiss in missing out an important series of achievements on the observational front, namely the discovery and development of optical telescopes. The pioneer, of course, was Galileo Galilei who in 1609 first used a modified version of the telescope invented a few months earlier by Hans Lippershey in Holland. The potential of the telescope for astronomy was demonstrated by Galileo's discovery of the sunspots, lunar craters and the inner four satellites of Jupiter. After an initial mistrust of this new instrument, the telescopes gained in popularity amongst astronomers and instruments with bigger and better lenses came into operation. There was, however, the problem that because of dispersion of light through a glass lens there was chromatic aberration in the images produced, besides other problems like difficulties of focussing images sharply.

For this reason, the refracting telescopes were gradually replaced by the reflecting types where a primary mirror, preferably paraboloidal in shape, performed a much better job than a lens. The prototype of the basic instrument was made by no less a person than Isaac Newton. This model was gradually improved upon and telescopes with bigger mirrors were made. The large telescope made by William Herschel in the late eighteenth century was of 48 inch diameter and had a forty foot long tube. The reflecting telescopes are more compact than the refracting ones and it is, of course, easier to prepare and maintain one surface (of a mirror) than two (of a lens). They come with various arrangements for focussing the images, such as Cassegrain, Coude, prime focus, etc.

By the second decade of the twentieth century, a large telescope with 100-inch diameter was constructed on Mount Wilson in Southern California. This telescope played a leading role in opening out the extragalactic world to the astronomers and in establishing the phenomenon of the expanding universe.

An even bigger telescope was in operation by 1949. It was the biggest working telescope in the world for nearly half a century, and it was located on Mount Palomar further south in California. Its primary mirror has a diameter of 200 inches (5 metres). Naturally this telescope played a major role in the studies of the large scale structure of the universe. The last three decades have seen the building of several telescopes in the 4-metre class. In more recent times telescopes even bigger, with 8-10 metre diameter mirrors are in use.

And we should also mention the various new 'astronomies' to have emerged in the last fifty years, using telescopes for radio waves, x-rays, ultraviolet and infrared rays, etc. These have added further dimensions to astronomy.

The Discovery Of Quasi-Stellar Objects

Perhaps the event which contributed most towards enlivening extragalactic astronomy this century was the discovery in 1963 of the quasi-stellar objects.

As the adjective 'quasi-stellar' suggests, these objects have a star-like appearance (in contrast to the fuzzy appearance of galaxies), and they had earlier been mistaken for stars. The appreciation of their rather extraordinary nature came about, thanks to a cooperation between optical and radio astronomers.

Radio astronomers C. Hazard, M.B. Mackay and A.J. Shimmins took the first step in this venture in 1962, when they used the then new method of lunar occultation. The radio source 3C 273 was going to be occulted by the Moon and the drop in its radio flux during the period of occultation could be used to pinpoint the position of the source very accurately. These observations were carried out by the trio at Parkes Radio Astronomy Observatory.

The accurate position coordinates of the source were conveyed to the optical astronomers using the then largest telescope of 5 metres on the Palomar Mountain. With the help of optical plates, the source was identified with a 13th magnitude star. However, it was only when Maarten Schmidt at the Palomar Observatory took the spectrum of the object that its extraordinary nature became clear. The spectrum had emission lines, which are somewhat unusual for a star, but even more importantly, they showed a redshift of 0.158, which was unheard of for a star. Thus the source was not a star. What was it?

Shortly thereafter, another radio source 3C 48 was identified with another starlike object and this one had a redshift even higher, of 0.367. Astronomers realized that they were finding a new population of sources. What was the cause of their high redshifts?

Assumptions that the redshift was Doppler or gravitational in origin were tried, but they placed almost impossible constraints on the early models. The third option, that of cosmological redshift (due to expansion of the universe), was known for galaxies and could be applied to these sources. This placed them well beyond the Galaxy and, therefore also demanded that they were even more powerful emitters of light than the typical galaxy.

This requirement coupled with the compact size of the source meant that it had its energy reservoir within a very tiny volume compared to a galaxy. In the early part of 1963, Fred Hoyle and William Fowler proposed that the energy source lay in the gravitational field of a compact supermassive object, later to be identified with the name 'black hole'.

Today, around 10,000 quasars have been found and they have provided a wealth of menu to astronomers and astrophysicists. The former have to contend with multi-wavelength observations ranging from radio to X-rays, while the latter have to provide models of high energy astrophysics using at times, inputs from general relativity.

Molecules in Space

In 1944 van de Hulst had derived the important result that the atom of neutral hydrogen has two states for its electron, an upper energy state when it is spinning parallel to the proton and a lower energy state when it is spinning anti-parallel to it, and a transition from the former to the latter gives rise to a wave 21 cm wavelength. In the early days of radio astronomy, this wavelength played a major role in identifying the presence of neutral hydrogen as the predominant component of the interstellar medium.

Nevertheless, astronomers by and large were not prepared to accept the presence of molecules distributed in giant clouds in the interstellar space, as proposed, for example by Fred Hoyle with R.A. Lyttleton in 1940. Although, Andrew McKeller discovered CH and CN by using optical methods, the real burst of activities began when in 1963, OH was discovered by S. Weinrab, A.H. Barrett, M.L. Meeks and J.C. Henry at the radio wavelength of 18 cm.

Because molecular transitions occur at such energies that the resulting photons are by and large emitted in the millimetre wavelengths (rather than at the radio wavelengths), antennas suitably designed for receiving radiation at such wavelengths began to be set up. The lead was taken by the NRAO at Green Bank in the USA and by the CSIRO in Australia. Thus in 1968, water and ammonia were discovered at wavelengths of 1.35 cm and 1.26 cm respectively as predicted by Charles Towns in 1955.

The sixties and the seventies saw molecular astronomy come into its own, with the realization that there are giant clouds with molecules filling the

interstellar space. A typical molecular cloud is around a light year across, whereas, there may be hundreds of such regions in a giant molecular cloud extending to 100 light years. The process of star formation takes place in the relatively denser molecular clouds.

But what has been impressive is the wealth of molecules found, organic as well as inorganic. The latter are naturally larger. For example, HC_9N (cyano-octa-tetrayn), is an example of a molecule with 11 atoms. Other more familiar molecules include, methanol, acetaldehyde, dimethyl ether, etc. The origin of these molecules and their interaction in space form topics for the newly emerging branch of 'astrochemistry'.

The presence of organic molecules in space has also strengthened the speculation that extraterrestrial habitats for life may exist in the Galaxy. Perhaps the greatest discovery of the next millennium, perhaps the next century, will be that we are not alone in the universe.
