Proc. of AP Akademi of Sciences
Vol. 6, No. 2, 2002, pp.87-98.

ASTRONOMY AT THE MILLENNIUM

JAYANT V. NARLIKAR

Inter-University Centre for Astronomy and Astrophysics
P.O.Bag 4, Ganeshkhind, Pune 411007

This paper will highlight the important developments in astronomy in the last decade of the twentieth century and in the opening years of the twenty-first. On the observational front, the discovery of extra-solar planets, the detection of gamma-ray bursts and studies of the distances of extragalactic supernovae with implications for the expansion of the universe are the major developments highlighted here. On the theoretical front, the paper reports on the speculations in very high energy physics that have implications for cosmology, the role of the cosmological constant and the quasi-steady state cosmology proposed as an alternative to the big bang.

Introduction

The closing years of the last century saw the continuation of the spurt for science and technology, with new ideas and inventions following one after the other at breakneck speed. Astronomy has also witnessed this momentum both in theory and observations. On the latter front, the last decade of the twentieth century saw the Pathfinder land on Mars, the Hubble Space Telescope finally taking off, the observations of gamma rays getting a boost through the launch of the Compton gamma-ray satellite, the launch of the X-ray facility Chandra, and the establishment of the twin Keck Telescopes as the largest (10m) dishes for optical astronomy. The list can in fact be extended on and on; but the above examples will illustrate the point.

Theorists would not be left far behind either. The immediate challenge in astrophysics comes from the discovery of a new astronomical phenomenon. Thus when one finds a gamma-ray burst with tremendous energy emitted in a very short time, one is faced with the question of what it was that stored so much energy in so compact a space. The speculations of the very early universe demand physical theories well beyond the energy level at which they can be tested and confirmed as valid. Indeed one may also extend these speculations to models of the universe as a whole to explore new and alternative scenarios to the generally accepted *big bang* models. We will take a look at all these issues, albeit briefly, in this paper.

Extra-solar planets

Are there planetary systems around other stars? If the distant planets in our own solar system are faint, how can we observe any planets around the stars which are many light-years away? They cannot be visible to us, but still their existence can be proved! The trick is like this.

(2)

When Mercury goes round the Sun, we know the reason to be the gravitational force of the Sun. According to Newton's third law of motion, Mercury exerts a force on the Sun equal in magnitude and opposite in direction to the Sun's force on Mercury. But the Sun does not seem to budge from its position! Because, the mass of the Sun is huge; whereas in comparison, Mercury's mass is small. So Mercury cannot push the Sun around.

But if in the place of Mercury there were a large planet like Jupiter, then the Sun would have been noticeably affected by its gravitational force. It would at least have wobbled a little. When a distant star so wobbles, astronomers conjecture that it has a planet going around it.

In 1991, while studying pulsars, observers at the radio telescope at Jodrell Bank, had drawn a similar conclusion. They found a pulsar wobbling and concluded that there is a planet near it. The period of wobble was one year.

Pulsar is a very dense neutron star. If the whole solar mass is compressed into a sphere of diameter 20-25 kilometres, it will be dense like a neutron star. A pulsar rotates very fast around its axis and like the light-beam from a lighthouse it sends very regular pulses of radio waves from it. This accurate periodicity of the pulsar makes it an ideal clock.

The conclusion of the scientists at Jodrell Bank, however, turned out to be wrong! The pulsar is seen to wobble, because we observe it from the Earth. The period of such a wobble is one year, because the Earth completes a revolution in one year. So this wobble was not related to a *probable* planet.

In 1992, Aleksander Wolszczan studied the pulsar with catalogue no. PSR 1257 + 12 in detail and proved that there are at least two planets which revolve around it. The mass of one of those planets is 2.8 times the mass of the Earth and the mass of the other is 3.4 times the Earth-mass. The first one completes a revolution around the pulsar in 66.6 days, while the second one completes its revolution in 98.2 days.

In 1995, Michel Mayor and Didier Queloz in the Heute Provence Observatory of France, observed the wobbling of the star 51-Pegasi and deduced that a planet orbits around it. Their observations were very accurate and the mathematical calculations based on their records could determine the mass and the orbit of the planet. Its mass is more than 150 times the mass of the Earth and a little over half the mass of Jupiter and it rotates around the star at a distance of 5 percent of the distance between the Earth and the Sun. The parent star is much like the Sun, and is about 40 light-years away from us.

Thus, our solar system is not the only one to contain planets! It is not unique in that respect. Of course, the *wobble method* is effective in detecting only those systems where the planets are massive (Jupiter-like) and/or are relatively close to the parent star.

In April 1999, scientists from the San Francisco State University reported the finding of three planets going around the star Upsilon Andromedae, located at a distance of about 44 light-years. The star showed wobbles which led to the suspicision that it was caused by the existence of a planet. However, when the wobble was analysed over a long enough period, it indicated the existence of not one, but *three* planets. The main discoverers of this system are Geoff Marcy and Debra Fischer of the San Francisco State University and the University of California at Berkeley; Paul Butter from the Anglo-Australian Observatory and Steve Vogt from the University of California at Santa Cruz.

Wobbles like these are detected by using the Doppler effect. The spectrum of the star shows shift of lines which tell the observer about its to-and-fro motion arising from the wobble.

The examples cited so far had planets moving in rather eccentric orbits. This means the distance of the planet from the parent star varies quite a bit during its period of revolution. Had the earth moved along such an orbit, it would have encountered a wide variation of temperature during the year, a variation far too large to allow life in its present form to survive. The search for extrasolar planets has scored another success in recent times by finding planets whose orbits are nearly circular, like the Earth's orbit. This discovery enhances the possibility of detecting life on such planets.

Gamma-ray bursts

The advent of space technology had proved to be a boon for astronomers because it enabled them to launch telescopes at various heights in the Earth's atmosphere so as to catch those electromagnetic waves that cannot reach the Earth's surface as they get absorbed by the atmosphere. Thus in the 1970s we saw astronomies with X-rays and ultra-violet followed later by those in infrared and microwaves. Although gamma-rays also had detectors, the early ones did not have good enough pointing accuracy and high enough sensitivity. By 1991, technology had improved to an extent that these defects were things of the past. The Gamma-Ray Observatory (GRO) was launched in 1991 with several sophisticated devices. It was later named *Compton*, after the Nobel prize winning physicist A.H. Compton, well known for his work on Compton scattering.

One of the very interesting findings of the *Burst And Transient Source Experiment* (BATSE) on this telescope was that of gamma-ray bursts (GRBs). The GRBs are short events lasting from ≤ 1 second to $\sim$ 1000 seconds only, in which tremendous burst of energy is emitted in the form of gamma rays. The BATSE on GRO has prepared extensive catalogues of the gamma ray burst events and they seem isotropically distributed in the sky. This indicates that they all lie outside our Milky Way Galaxy. The GRO became inoperative in the year 2000, but in its decade long existence, it has played a major role in making us aware of the enormous significance of gamma ray astronomy.

It is a long-standing experience of observational astronomy that whenever a sophisticated new observing facility is created, it detects something unexpected. The Compton-GRO was no exception. Although the earlier gamma-ray detectors had detected gamma-ray bursts, the positional accuracy of these later detections enabled astronomers to estimate their distances through the process of *optical identification*.

It may be mentioned here that it is common practice now-a-days to observe the same astronomical source at different wavelengths. The practice started with radio astronomy in the 1950s. When we observe a radio source we also try to look at the same direction with optical telescope. Provided we know the direction very accurately, we can be confident that we are looking at the same object in radio and optical wavelengths. This is known as optical identification of the source.

The one great advantage of optical identification is that if the source is located outside our Galaxy, then its spectrum will show a shift of all wavelengths towards the red end. That is, the wavelength of a line instead of being at its expected value of λ_0, is shifted to

$$\lambda = \lambda_0(1+z) \tag{1}$$

where the quantity z is called the *redshift*. Hubble's law then tells us that the distance of the object is given by

$$D = cz/H, \tag{2}$$

where H is called Hubble's constant and c is the speed of light.

The common explanation of the Hubble law is that the universe is expanding. That is if we typify a distance scale by the symbol S, then the distance between any two galaxies would increase or decrease in proportion to how the scale factor S changes with time. Thus if the value of the scale factor is S_0 at the present epoch, then at the epoch when light left a galaxy showing redshift z in order to arrive here now, the value of the scale factor was $S_0/(1+z)$. This means that the universe has been expanding. The above linear law holds for small redshifts and needs to be re-expressed with z replaced by a function $f(z)$ depending on the model of the expanding universe chosen. We will return to this issue later.

Using this technique when the gamma-ray source GRB970508 was optically identified as situated in a remote object, its optical spectrum showed an absorption feature at a redshift of 0.835 (Matzger, et al 1997). Assuming that the absorption is caused by an intervening galaxy at this redshift, the distance of the burst source has to be larger than the distance as estimated by Hubble's law for this redshift. Now, if the amount of energy received in a burst crossing normally a unit area held at distance D is ε then the total energy of the source (assuming isotropy) is

$$E = 4\pi\varepsilon D^2. \tag{3}$$

Clearly, if D is large, so is E. The energy so estimated by gamma-ray observers turned out to be as high as $\sim 10^{52}$. This is believed to be a lower limit, since the above calculation had used a lower limit on D. Typically the burst energy may be as high as 10^{53} ergs.

Over and above that, optical astronomers have now begun to observe such sources for a few days/weeks after the burst and they are finding them to have long optical tails. That is, even after the concentrated burst of energy emitted as gamma rays, the source also emits optical radiation in a continuous fashion that persists for much longer.

What kind of source is this? The question became even more challenging when more such sources were observed. Thus the ball is presently in the theoretician's court, where he has to think of an astrophysical scenario.

Till the GRBs were so studied, the examples of sources of largest energy emitted in a short time were supernovae, where typically about 10^{51} ergs are emitted in the first few hours when a star explodes. We need here something more dramatic with a hundred times as much energy being emitted in a few seconds. Can we think of a stellar explosion on an even more massive scale? *Hypernova* has been suggested as a possible source, although the detailed scenario is still to be worked out. On an even more esoteric note, the collisions of two black holes is suggested, although even here, the details need to be worked out. Meanwhile, observational tracking of such sources will certainly help in pointing to the right answer.

Extragalactic type Ia supernovae

Supernovae have the feature that they generate enormous energy over the time scale of a few days. A strong supernova at its peak intensity may outshine the entire galaxy that it is in. This property has helped astronomers spot supernovae in remote galaxies, since they are very bright and by their sudden brightening they attract attention of the observer. They have been classified as Type I and II, depending on their luminosity and spectral differences. In general the Type I supernovae are associated with white dwarf stars, whereas Type II supernovae leave behind neutron stars or black holes as remnants.

Of these Type Ia supernovae seem to have the property that when they reach their peak intensity, their luminosity lies in a relatively narrow band. Thus they can be treated as *standard candles* for measuring their distances. For, if this standard candle luminosity is L, then at a distance D, the supernova will have a flux

$$l = L / (4\pi D^2). \tag{4}$$

Therefore, if we know L, then from a measurement of l, we can estimate D.

This possibility leads the astronomer to make progress with one of the classic tests of cosmological models. Suppose we have measured D for a supernova in this way, and we also are able to measure the redshift z of the galaxy it happens to lie in. If we are able to do this for a number of supernovae at different redshifts, then we have an observationally determined relation between D and z. Now, as mentioned in the preceeding section, a typical cosmological model has a well defined relation of the form:

$$D = cf(z)/H, \tag{5}$$

where the function f varies from model to model. For example, for the simplest expanding model to come out of general relativity, the so-called Einstein de Sitter model, we have

$$f(z) = 2\,[\,1 + z - \surd(1 + z)]. \tag{6}$$

Thus it will be possible to check whether the data on supernovae fits this particular curve. There is in fact a range of cosmological models coming from general relativity, which depend on two parameters, commonly called the density parameter Ω and the cosmological constant parameter Λ. Briefly, these are defined as follows.

Models based on Einstein's general relativistic field equations tell us that the expanding spaces can have zero, negative or positive curvatures, the first type being called *flat*. The Einstein de Sitter model mentioned above is of this type. For such models, the density of matter (assumed for simplicity as pressure-free *dust*) is given by the expression

$$\rho_0 = 3H^2 / 8\pi G. \qquad (7)$$

In a *non-flat* model, the density is given by

$$\rho = \Omega\rho_0 \qquad (8)$$

Similarly, the cosmological constant parameter is related to the cosmological constant introduced by Einstein by the relation

$$\Lambda = \lambda c^2 / 3H^2. \qquad (9)$$

For the flat case, the Einstein equations give the relation

$$\Omega + \Lambda = 1. \qquad (10)$$

In general, however, the two parameters are independent.

We may mention that the simple interpretation of the λ-term is that it describes a force of repulsion between any two particles, in direct proportion to their distance. A positive Λ therefore suggests an *accelerating* universe, in which any two parts are pushing each other away from themselves.

In the last decade of the twentieth century, the *Supernova Cosmology Project* began to work in a dedicated fashion to look for extra-galactic supernovae. The supernovae have a serendipity about them, in the sense that one cannot predict that in a particular galaxy a supernova will go off in the near future. One has to take whatever supernovae explode in whatever galaxy. The database on D and z is built up in the above manner. Various corrections have to be applied to the basic data which we will not go into here. The ultimate aim of the exercise is to build up a large collection of (z, D) pairs so that one may estimate the parameters Ω and Λ, from the best-fit theoretical curve. This exercise has led to somewhat startling results. To understand their significance, let us look at the history of the z-D test briefly.

When Hubble (1929) first announced the redshift-distance relationship, his redshifts did not even exceed 0.01; yet the work inspired the idea of the expanding universe. As theoreticians developed models of expansion, they could see that as stated above, the measurements of distances at large z will tell us which model of expansion fits the data best. As observing techniques improved in the 1950s and 1960s, various methods were tried for estimating D and the above test was applied to redshifts as high as around 0.46

(Sandage, 1972). The indications from such tests were that the universe is decelerating. Models with zero cosmological parameter thus fitted the data reasonably well. The error-bars on these results were, however placed somewhat optimistically, so that the claim was that any model suggesting an accelerating universe, such as the steady state model (see section on Alternative cosmologies) was ruled out.

By the end of the 1970s, however, it was realized that the distance estimators used in such tests might not be reliable and therefore the conclusions drawn had to be treated with caution. Indeed interest in this test had dwindled, until the late 1980s when the possibility of using the type Ia supernova as a standard candle, rekindled it.

The Supernova Cosmology Project (Perlmutter, et al, 1999) and other studies of supernovae had by 1999 led to the conclusion that the universe is in fact accelerating! That is, the models with $\Lambda = 0$ were definitely ruled out. In fact the best-fit model was one with $\Lambda = 1.32$ and $\Omega = 0.73$. If one felt that the spatial sections have to be flat, so that equation (10) holds, then the best fit is obtained with $\Lambda = 0.72$ and $\Omega = 0.28$.

Why should equation (10) hold? To understand the theoretical compulsions for this belief we will next turn to the theoretical developments.

Very high energy physics and cosmology

Particle physics deals with ideas on the ultimate basic structure of matter. Nineteenth century brought science to the stage where atomic structure of matter was accepted and served as the basis of chemistry. The dawn of quantum theory and probes of the atom in the first quarter of the twentieth century, led to the concept of an atom with a nucleus containing neutrons and protons with electrons circulating around them in different discrete orbitals. The next thirty years led to probes of the nucleus and the discovery of the strong and weak forces, followed by the idea that the nucleons are themselves made of three *quarks*. The quarks which are *glued* together by particles called *gluons*, are thus particles serving as the basic structures for neutrons and protons; but are they the ultimate building blocks of matter?

Hardly so! But to know the structural hierarchy further, we need to break these particles by making them collide at very high energy. For, as per the uncertainty principle of quantum theory, large momenta are needed to probe small sizes, and large particle momenta mean large energies. Thus the last century saw the constructions of particle accelerators of increasing energy, with the major such facilities at CERN and Fermilab laboratories. It was by going up to particle energies of the order of 100 GeV, that physicists were able to validate experimentally the theoretical ideas of Abdus Salam, Steven Weinberg and Sheldon Glashau, unifying the electromagnetic interaction with the weak interaction.

This success inspired particle theorists to work towards their holy grail of unification of all physical interactions. However, theoretical ideas today seem to suggest that the next step in this direction is to effect grand unification by combining the electromagnetic, the weak and the strong interaction, but that to achieve this, one needs to energize the particles to energies as high as ~ 10^{16} GeV. Likewise, to bring gravitation also into the fold, one needs to go up the energy ladder by a futher three orders of magnitude.

However, the march of particle physics towards unification and an understanding of the ultimate structure of matter were held up on the experimental side by the lack of accelerators of high enough capability. The best that can be achieved today is energy in the range approaching ~1000 GeV, which falls short of the energy required to verify a grand unified theory (GUT) by some 13 orders of magnitude! Evidently, if there is no experimental verification possible a theory remains just a speculation.

Cosmology provided a way out of this apparently insoluble difficulty. The models of the universe, based on the application of general relativity lead to the conclusion that the universe originated from a gigantic explosion, a *big bang* a finite time ago. Applications of thermodynamics to the early universe lead to the conclusion that it was a *hot big bang*. The big bang epoch itself was of course a singular one when the density and temperature of the universe were infinite. However, in the early moments after the singular event, the temperature T of the universe was related to its age t by a relation of the kind:

$$T \approx [t_{\text{second}}]^{1/2} \cdot 10^{10}\text{K} \qquad (11)$$

where K stands for the absolute (Kelvin) scale of temperature.

It is assumed that the universe was in thermodynamic equilibrium and so the typical energy E per particle at temperature T is around kT, where k is the Boltzmann constant. So, we can work out that an energy of the order of 10^{16} GeV per particle existed at the very early epoch of $t \sim 10^{-36}$ second. So at such early epochs the grand unified theory operated.

In short, the one and the only occasion when the GUT played any role in the universe, was in the very early epoch mentioned below. Thereafter it ceased to operate, as the particle energies were not high enough. This circumstance is responsible for the statement that *the early universe is the poor man's high energy accelerator*.

Theoreticians from the two interested fields of big bang cosmology and high energy particle physics have therefore combined their efforts to explore these very early epochs under the joint subject of astroparticle physics. The 1980s and 1990s have seen a spurt of activity in this field. Some of the important conclusions of this field are summarized below. (Narlikar, 2002).

[A] The phase transition that takes place in the universe around the GUT energy, leads to inflation, i.e., a rapid expansion of the universe with an exponential scale factor exp (at), with $a \sim 10^{36}$ second^{-1}. This rapid expansion wipes out any curvature of the expanding 3-space, so that it is almost flat. This is the reason why we used the flatness criterion (equation 10) for the cosmological models.

[B] One consequence of inflation is that it specifies the spectrum of primordial inhomogeneities in the universe, which are believed to grow into galaxies and clusters of galaxies. The formation and evolution of large scale structure is perhaps the largest effort area in today's theoretical cosmology. The aim of the exercise is to understand the present large scale structure observed in the universe starting from stipulated initial conditions.

[C] The inflationary epoch is characterized by a cosmological vacuum-driven force that formally is identical to the cosmological term of Einstein. However, its magnitude is some 108 orders above that proposed by Einstein and observationally expected today. So one major question that inflationary models have to answer is how did the initially so high inflationary λ get converted to a fraction $\sim 10^{-108}$ of itself by the present epoch. This is known as the *cosmological constant problem*. There are some ideas generally known under the title of *quintessence* which undertake to achieve this. However, any such exercise is open to the objection that it involves fine-tuning and *post-dicting*.

[D] Astronomical observations suggest that if we assume that the gravitational laws of Newton and Einstein continue to be valid at the galactic and cluster scale distances, then the observed dynamical activity in these objects demands a large quantity of unseen or *dark* matter. What could be the composition of dark matter? It could be made of small planet-scale objects that are not self-luminous, or it could be in the form of black holes, or at a more esoteric level, it could be in the form of particles that have no interaction or very very weak interaction with light. For reasons too technical to go into here, the big bang cosmology requires the last alternative, and it is here that new particles hypothesized by grand unified theories offer attractive possibilities. Collectively these are called *weakly interacting massive particles* (*WIMP*s). No WIMP has yet been found in any laboratory accelerator.

Alternative cosmologies

The big bang picture has many adherents. It has the merit of explaining some observed features of the universe, such as the radiation background in microwaves, its Planckian spectrum and extremely tiny but non-trivial inhomogeneties, the existence and abundance of light nuclei, etc. Still it has some weaknesses too, such as its singular beginning, the fine-tuning required for many of its parameters, the important role of highly speculative initial conditions, etc. Its adherents point to its merits and argue that the weaknesses will eventually go away after we have a more sophisticated theoretical framework. Its critics (-now there are very few die hard ones left!) say that the merits are overstated and the weaknesses are now becoming serious enough to warrant looking for alternative scenarios for the basic cosmological model.

It should be admitted that most rivals to the big bang have had poor track record of longevity. The only possible exception has been the steady state theory which was proposed in 1948 by Hermann Bondi, Tommy Gold and Fred Hoyle (see: Bondi and Gold, 1948, Hoyle, 1948). This cosmology has a universe without a beginning and without an end; and its expanson is driven by a steady creation of new matter at an admittedly very small rate of $\sim 10^{-46}$ g cm^{-3} sec^{-1}. There were several attractive features in this theory, including the fact that it did not have a singular event like the big bang, which lies beyond the scope of science. As mentioned before, the steady state cosmology had an accelerating universe and as such, it would have passed with flying colours today's test of the (z, D) relation for

3)

supernovae. However, this cosmology lost its viability in the mid-sixties when the microwave background was discovered and when it was felt that stars alone could not generate all the observed abundance of light elements. Neither of these observations could be explained by the steady state theory. Notice that, by contrast, these are the strong points of the big bang model.

In 1993, however, the steady state theory was revived in a modified form known as the *quasi-steady state cosmology* (QSSC) by Fred Hoyle, Geoffrey Burbidge and this author (Hoyle, et al., 2000). In this cosmology, the scale factor of the universe has the form

$$S(t) = \exp\,(t / P)\,([\,1 + \eta \cos \{2\pi\tau(t) / Q\}], \qquad (12)$$

where, $P >> Q$, $0 < \eta < 1$ and the function $\tau(t)$ is very close to t. Typical values for P and Q are 1,000 and 50 billion years respectively. The parameter η may be close to 0.8. Thus there is no singularity (i.e., an epoch when the scale factor vanishes), and the universe has a long term expansion superposed with short term oscillations. We are at present in the expanding phase, with the last oscillatory minimum of the scale factor occuring at redshift of $\sim$ 5 - 6. Hoyle, et al (op. cit.) have shown that this model can explain all the presently observed features of the universe. We illustrate this statement with the example of how the QSSC solves the problem of the microwave background.

Notice first that each QSSC cycle of expansion and contraction takes the time period Q, which can be as high as 50 billion years. Normally this time period is sufficient for the evolutionary life of all but the very low mass stars (say with masses less than half the solar mass). What happens to the radiation of all such burnt out stars from previous cycles? This can be estimated, and assuming that it gets thermalized, its temperature at this epoch can be determined. This exercise leads to a present day temperature of 2.7 K, very close to that observed for the microwave background.

How is the relic radiation thermalized? This has been extensively discussed, (see for example, Narlikar et al, 1997) and the likely thermalizing agents are seen as whiskers of carbon and iron which are produced when the carbon and iron created in supernovae and ejected in vapour form condense. Laboratory experiments show that metallic vapours cool and condense not in spherical shapes, but in cylindrical forms like whiskers. Typical whisker is around 0.5 to 1 mm in length and around 10^{-6} cm in radius of cross-section. These whiskers are blown out into the intergalactic space. There they act as thermalizers of relic starlight, that is, they absorb the starlight and re-emit it in microwaves. The extinction properties of such cylinders show that they can indeed fulfill this role.

As the sources of relic starlight will be in clusters of galaxies, we may expect to see some inhomogeneities in the temperature of the background in different directions. This can be estimated by taking into consideration cluster luminosities and averaging over the number of clusters in any beamwidth out to the distance to the last minimum of oscillation. The pattern of inhomogeneities does indeed match the present data at different spherical harmonics quite well.

This alternative way of looking at the origin of the microwave background has the advantage over the conventional big bang explanation in that it *predicts the magnitude of its present temperature, which the latter is not able to do.* Moreover, by linking the radiation to the starlight of previous generations, the explanation connects it to important observed astrophysical phenomena in the universe.

This explanation also has a bearing on the (z, D) test. In the QSSC, we can similarly estimate the theoretical (z, D) curve and compare with the supernova data. In doing so, we have to now include the extinction of light by dust made of whiskers. The resultant curve gives a very satisfactory agreement with the observations. Indeed, the dust density required to explain the supernova data agrees very well with that needed to explain the Planckian spectrum of the microwave background.

Clearly, in order to gain recognition as a serious contender on the cosmological scene, the QSSC must match or improve on the performance of the standard big bang model in understanding the universe as we find it today. It therefore needs more such achievements in the observational field.

Concluding remarks

The main thrust of astronomy till the end of the eighteenth century was on the Solar System. The next two centuries saw a remarkable progress in the observations and theoretical understanding of stars. Now, although exciting challenges exist in finding extra-solar planets, and in understanding some of the details of stellar evolution, the central stage has shifted to extragalactic astronomy and cosmology. This article reflects this trend. The menu for the twenty-first century includes as the main course the understanding of the large scale structure of the universe. How and when did galaxies come into existence and how did they acquire their current shapes and hierarchy of structure in the form

$$\text{Galaxies} \rightarrow \text{groups} \rightarrow \text{clusters} \rightarrow \text{superclusters} \rightarrow ?$$

with the question mark denoting our ignorance of whether any higher structure than superclusters exists. Other items on the menu include dark matter, how much of it and in what form; why does the universe seem dominated by matter over antimatter; the question of what is the ultimate structure of matter; the issue of how old the universe has to be in order to accommodate all its observed constituents; etc., etc....

And another problem which we have not touched on in this brief review, relates to astrobiology. With millimetre-wave astronomy showing the existence of complex organic molecules in the vast interstellar clouds, the question naturally arises, as to whether there is life elsewhere in the universe. Perhaps this century will mark progress in understanding the answer to this question also.

References

H. Bondi and **T. Gold,** 1948, The steady state theory of the expanding universe, Mon. Not. R. astron. Soc. 109, 252.

F. Hoyle, 1948, A new model for the expanding universe, Mon. Not. R. astron. Soc. 109, 372.

F. Hoyle, G. Burbidge, and **J.V. Narlikar,** 2000, A Different Approach to Cosmology, Cambridge .

E.P. Hubble, 1929, A relation between distance and radial velocity among extragalactic nebulac, Proc. Nat. Acad. Sci. (USA), 15, 168.

M.R. Matzger et al., 1997, Spectral constraints on the redshift of the optical counterpart to the γ-ray burst of 8 May 1997, Nature, 387, 878-880.

J.V. Narlikar, N..C. Wickramasinghe, R. Sachs and **F. Hoyle,** 1997 Cosmic iron whiskers: their origin, length distribution and astrophysical consequences, Int. J. Mod. Phys. D6, 125-142.

S. Perlmutter, et al., 1999, Measurements of Ω and Λ from 42 high-redshift supernovae, Astrophys. J., 517, 565-586.

A. Sandage, 1972, The redshift-distance relation. II. the Hubble diagram and its scatter for first ranked cluster galaxies : A formal value for q_0 Astrophys. J., 178, 1-24.

(Manuscript received 9th Nov., 2001)