

## FROM MODERN RESEARCH IN ASTROPHYSICS TO THE NEXT MILLENNIUM FOR MANKIND

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### *Introduction*

The organizers of this meeting have requested that “the papers should take the form of sets of suggestions rather than academic lectures”. I will, therefore, make two suggestions and support them by a brief review of several areas of research in modern astronomy. Among those areas I will emphasize the search for extra-solar planets and planetary systems.

### *Suggestions*

I would like to suggest that all of our planning for the Plenary Session and other activities of the first year of the new millennium take into account the following two conclusions which can be drawn from the most recent research in astrophysics: (1) there is increasing evidence that we may not be alone in the universe; (2) public opinion to the contrary, our scientific knowledge of the universe is very limited.

We must be very careful in our formulation of the first issue. The question to be addressed is not whether there is extraterrestrial intelligence, since there is no scientific data whereby to even approach an answer. The question is rather: Are there the physical conditions for Earthlike life elsewhere in the universe? In other words, is there any evidence that there are planets like the Earth about stars like the Sun with the macrophysical conditions for life?

As to the matter of our ignorance as regards our scientific understanding of the universe, a brief review will suffice to indicate the limited frontiers of our knowledge. The most significant fields of modern astronomical research extend over a wide range of topics including the physics of the

early universe to the search for extra-solar planetary systems. We shall do that review of selected topics now and subsequently speak in more detail of the search for extra-solar planets.

*Selected Topics in Astrophysics. Frontiers of Ignorance*

By combining elementary particle physics with quantum cosmological models we have a solid understanding of the very early universe, although not its origins. Less well known are the epochs of the formation of structure in the universe: galaxies and clusters of galaxies. Despite intense efforts to determine the ultimate fate of the universe, we do not yet know whether the mass of the universe exceeds the critical mass to close it. More than a decade of attempts to identify the dark matter in the universe have left us still in doubt, although the observational evidence for its existence is overwhelming. Let us review these topics in more detail.

The deep field observations with the Hubble Space Telescope challenge all theories accepted to date for the development of structure. A principal difficulty is that the observations indicate that structure developed much earlier than can be accounted for in any of the expanding universe cosmologies. The detection of non-homogeneity challenges inflationary models. It is not yet known with certainty as to whether galaxies formed from a single massive proto-galactic cloud or whether they formed from mergers of smaller regions where star formation had already begun. This uncertainty is fundamental and is shown graphically in the schematic diagram of the evolution of the universe in Fig. 1. The formation of galaxies at one billion years and of the first stars at five billion years is essentially unknown!

The great success of Big Bang cosmologies during this century may conceal some of the principal problems still remaining. Chief among these is the determination of the distance scale and, therefore, the time scale for the expanding universe. The Hubble law relates the velocity of expansion of the universe, determined by measuring the red-shifts of galaxies and clusters of galaxies, with distance. This is shown in Fig. 2. It is important at this point to note an observational problem associated with the Hubble law. The observational error associated with measuring a red-shift does not depend on distance, whereas the error in measuring distance increases enormously with increasing distance. For large distances we must make many assumptions about the uniformly mean brightness of certain kinds of intrinsically bright objects, for instance, supernovae or globular clusters, and we must apply assumed corrections for the aging of such objects.

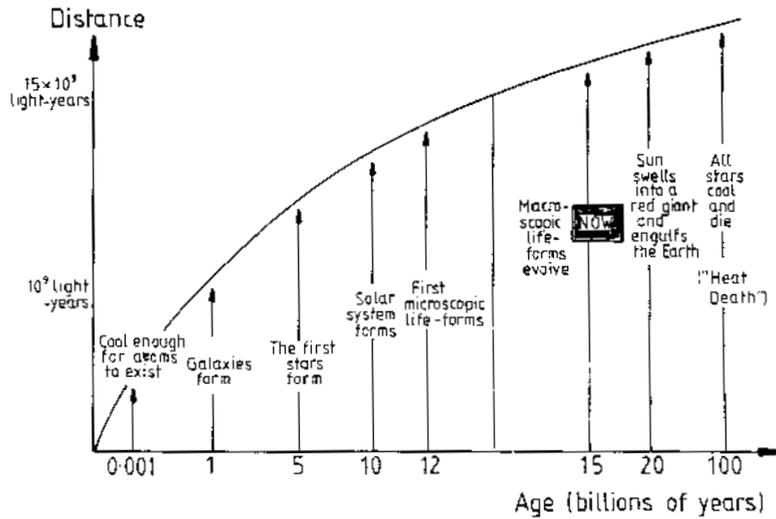


Fig. 1 - A schematic of the expanding universe. As the universe gets older (abscissa) the distances between objects increase (ordinate). The epochs at which various principal events occurred are indicated by arrows. Although shown here, we are not certain about the epochs at which galaxies and the first stars formed.

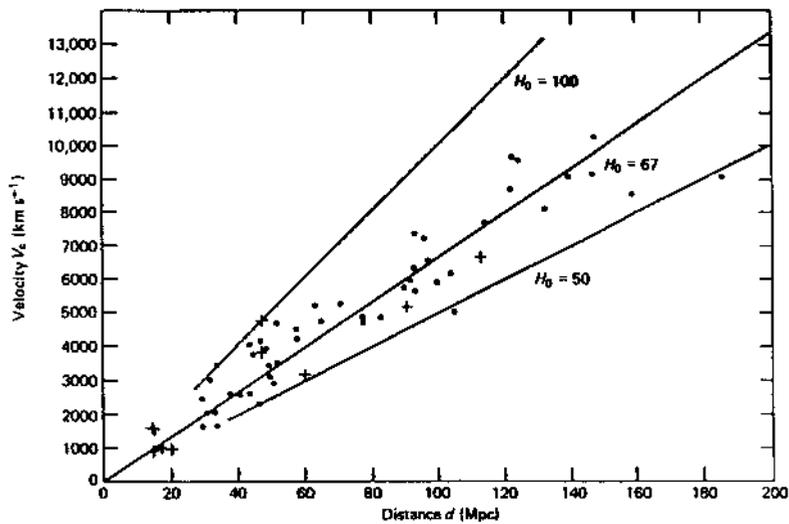


Fig. 2 - The Hubble law shows the velocity at which the universe is expanding at various distances (1 MPC [megaparsec] = 3.3 million light years). The Hubble constant,  $H$ , is the slope of the relationship and is inversely proportional to the age of the universe. The three lines show the extreme values and the mean value to the scattered observations.

The distance limit for the so-called primary methods of measuring cosmological distances is about thirty million ( $3 \times 10^7$ ) light years, only two thousandths of the way back to the Big Bang. For larger distances the observational errors result in an uncertainty in the slope of the Hubble law (the Hubble constant), which is roughly inversely proportional (a specific cosmological model with a given deceleration parameter must be assumed) to the age of the universe. Recent observations with Hubble Space Telescope (HST), for instance, indicate a change in the distance scale which would essentially decrease the currently estimated age of the universe by a factor of two. In that case we would have some globular clusters of stars, whose ages are known by methods completely independent of the Hubble law, with ages about twice that of the universe itself. A problem, indeed! It is of some interest to note the history of the determinations of the Hubble constant. The age of the universe has roughly changed by a factor of five in the course of fifty years!

Two increasingly difficult problems are the quantity and nature of dark matter in the universe and whether the universe is open or closed. The two problems are related. From the observed rotation curves of spiral galaxies and from the gravitational binding of rich clusters of galaxies, it has become increasingly clear that about ninety percent of the gravitating matter in the universe does not radiate. What is the nature of this dark matter which is so predominant?

We know that the universe is tantalizingly close to being either open or closed. There are two approaches to try to resolve which is the case. If we could measure the curvature of the Hubble law at large distances, then with certain reasonable theoretical assumptions, we could resolve whether the universe was open or closed. This is shown schematically in Fig. 3. As we look at large distances, we are looking back in time and we can compare the observed expansion rate then to that in more recent times. We can, therefore, in principle, determine the rate of deceleration of the expanding universe and whether such a rate is sufficient to close the universe. The observational problem is precisely the one which we have discussed previously and is shown by the scatter of the points in Fig. 3. Errors in the measurement of large distances will not allow us to determine accurately enough which of the Hubble curves (A, B, C or D) is the true one.

Another approach to determine the closure or not of the universe is to measure the mean density of the universe. If the mean density is greater than a critical value, estimated to be about five H atoms per cubic meter, then the universe is closed. This is a very sound approach, based on the

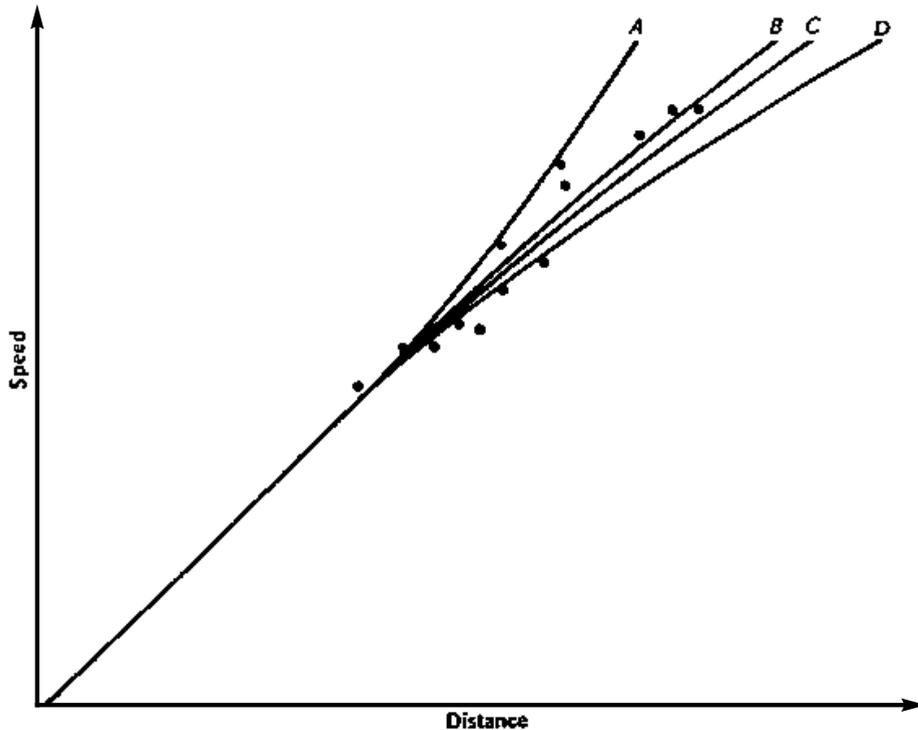


Fig. 3 – Because of the uncertainty of the Hubble law at large distances, due to increasing errors in the distance measurements, it is difficult to decide which of the curves, A, B, C or D describes the real universe. Thus, we do not know whether the universe is open or closed.

simple working of gravity, but how are we to measure this mean density when it is estimated that ninety percent of the matter in the universe is not radiating? We are left with the uncertainty as to whether the universe will end at all and, if so, whether with a crunch or a whimper.

#### *Extrasolar Planets. Theory and Observations*

The best model we have for the formation of planets about solar-like stars is shown in Fig. 4. A large interstellar cloud, typically containing  $10^3$  masses of the sun, fragments due to an interplay of kinetic, gravitational and magnetic energy. Each fragment that is sufficiently compact and sta-

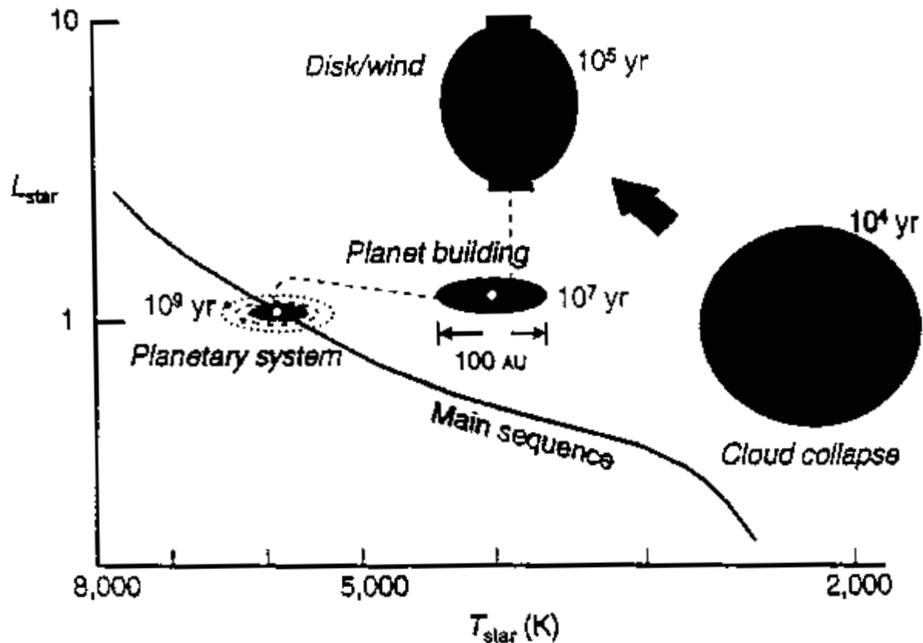


Fig. 4 - The scenario for the birth of stars and planets. See text for explanation.

ble begins to collapse by self-gravity and, like any normal gas, as it collapses it heats up. If it is sufficiently massive (more than about 0.1 the mass of the sun), it will raise the temperature in its interior sufficiently high, so that thermonuclear burning begins. At this point a star is born. (This is called a pre-main sequence star, since it is not yet completely stable.) For a star with a mass equal to that of the sun this process takes about  $10^7$  years. For more massive stars it is shorter, for less massive stars longer. The sun will keep shining as it does today for about  $10^{10}$  years and then it will explode and become a white dwarf. Note, therefore, that a star like the sun is born relatively (relating "gestation" to "lifetime") fast, some ten times faster than the birth of a human being! In the course of the cloud collapse there are stages which are important for the formation of a planetary system. As the star collapses, in order to conserve angular momentum, it rotates and this rotation causes a continuous flattening of the cloud until at the end of  $10^7$  years a disk has formed. There is also an intermediate stage after about  $10^5$  years at which a wind of high energy particles

sweeps through the cloud and carries away much of the material left over from the collapse.

So, we have a solar-like star with a rotating disk of hydrogen gas and dust about it. How do planets form within this disk? As the disk continues to rotate the material in it begins to separate out into rings according to the mass distribution. Within each ring conglomerates begin to form due to elastic collisions, gravity and electrostatic binding. Eventually larger conglomerates, called planetesimals, of the order of 100 kms in extent are formed and then from these the planets are formed. During these processes the lighter elements are preferentially driven to the outer parts of the disk due to temperature of the parent star and the stellar wind. This explains why the outer planets in the solar system are more gaseous than the inner planets. Thus, for a star like the sun we have after about  $10^9$  years a stable star with a planetary system about it.

Patient and painstaking research over the past decade has led to the discovery of more than fifty planets about other stars. These planets have been discovered by analyzing the systematic oscillations in the motion of the parent star or, in rare cases, by the direct measurement of the displacement of the star on the sky. Examples of such measurements are shown in Fig. 5. Only massive planets near to their parent star can be discovered in this way. Jupiter, for instance, could not be detected in this way from the nearest star to the Sun. So, the method is very limited. In no case, do we have an Earth-like planet in a habitable zone. A sample of planets discovered thus far is shown in Fig. 6.

At times there is an ambiguity as to whether the object discovered is a "brown dwarf" or a true planet. If a collapsing cloud has less than about 0.1 solar masses it cannot raise the internal temperature high enough to start a thermonuclear furnace; so, no star is formed. The object still shines but not by thermonuclear energy. It has short-lived residual gravitational energy and is called a "brown dwarf". The division between "brown dwarfs" and planets is ambiguous and it is difficult to separate out these objects. Planets form by the accretion of planetesimals; "brown stars" form like stars do by the collapse of a cloud fragment. So, the formation processes are very different; but the resultant object may lie on the observational borderline.

An increasingly fruitful area of research is the detection of proto-planetary disks about young stars. Very high resolution imaging is required and thus far only Hubble Space Telescope has succeeded. In some of the disks detected we have indications that the formation of planets has

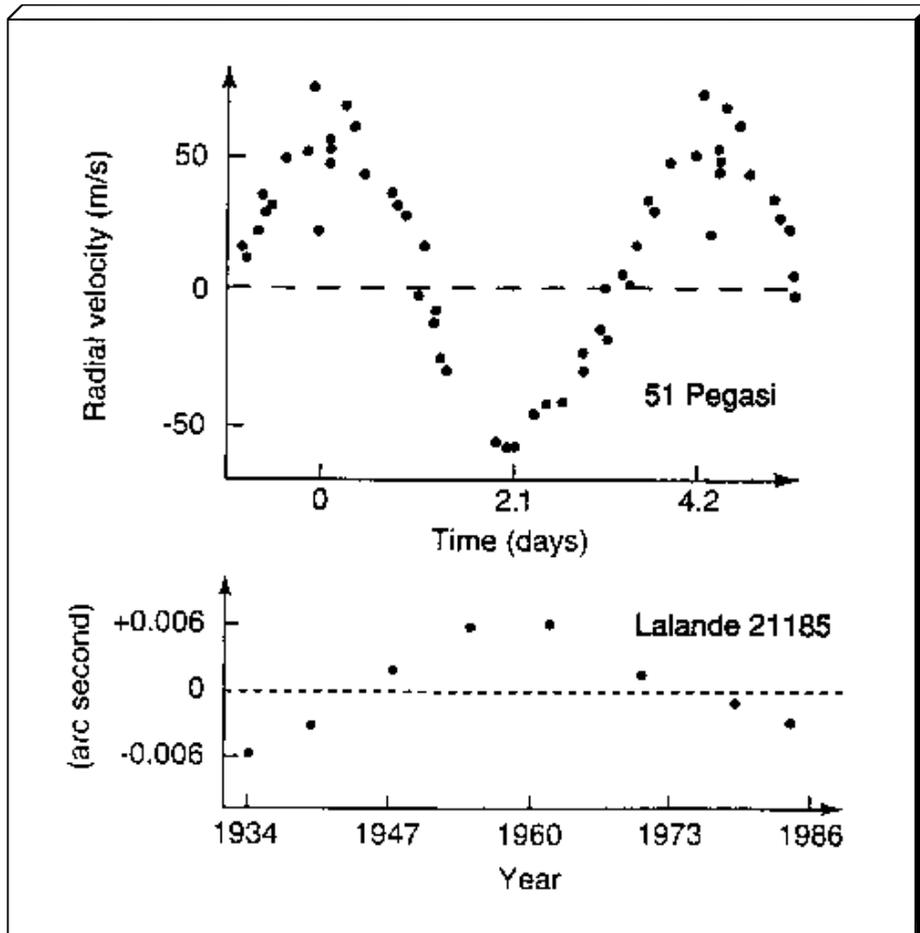


Fig. 5 - The oscillations in the line of sight motion of the star 51 Pegasi reveal the presence of a planetary object in orbit about the star. The periodic variation in the position of the star Lalande 21185 likewise reveals the presence of a planet.

already begun. There is a well-founded hope that in the near future we will not only discover many planets but also planets in formation. This, of course, will provide an immense leap forward in our search for the physical conditions for extraterrestrial life.

The conclusions to be drawn from the observations to date are: (1) the discovery of extra-solar planets by studying the motion of the parent star is

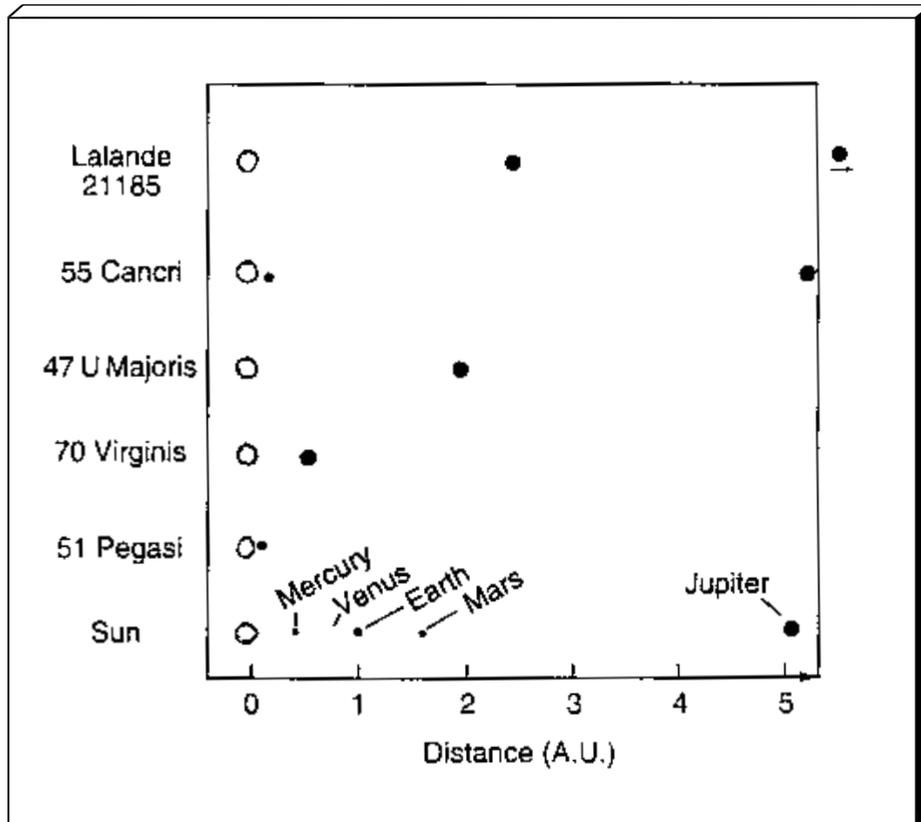


Fig. 6 - A sampling of planets (filled circles) recently discovered about nearby stars (open circles)

promising, but the results thus far are few; (2) some of the objects discovered thus far may actually be "brown dwarfs"; (3) no Earth-like planets in a habitable zone have been discovered.

Other techniques, such as high-resolution imaging in space and from the Earth, spectroscopic detection of extra-solar planetary atmospheres etc., are being developed. Ambitious programs are being developed to search by spectroscopy for biotic or pre-biotic conditions in extra-solar planets. Within the next decade we will undoubtedly discover hundreds of candidates as extra-solar planets. In 2004 the NASA will launch the Full-sky Astrometric Mapping Explorer (FAME), a space telescope designed to

obtain highly precise position and brightness measurements of 40 million stars. This rich database will allow astronomers to determine with unprecedented accuracy the distance to all stars on this side of the Milky Way galaxy and to detect large planets and planetary systems around stars within 1,000 light years of the Sun. While that will be a sampling of only one percent of the distance across the Galaxy, it will increase by a factor of at least 100 the distances thus far sampled. It appears, therefore, from an observational point of view, that we will soon know whether the existence of planetary systems is a common phenomenon.

#### *Questions for the Future*

The convergence of many fields of research in modern astrophysics allows us to pose some scientific questions about the origins and evolution of the universe as a matrix from which life has evolved. We are intimately related to the energy and the matter in the universe of which we are a part. We are constantly exchanging atoms with the total reservoir of atoms in the universe. Each year 98% of the atoms in our bodies are renewed. Each time we breathe we take in billions and billions of atoms recycled by the rest of breathing organisms during the past few weeks. Nothing in my genes was present a year ago. It is all new, regenerated from the available energy and matter in the universe. My skin is renewed each month and my liver each six weeks. In brief, human beings are among the most recycled beings in the universe. Life has made a relatively late appearance considering the total age of the universe (see Fig. 1) and there are three intriguing questions which it poses in terms of the evolution of the universe itself: (1) in the evolving physical universe was it inevitable that life come to be; was it by chance; can it be understood; (2) is life unique to our planet; (3) is life at the level of intelligence and self-reflection an important factor in the future evolution of the universe?