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Abstract

Reasons for suspecting that fundamental constants might change with time are reviewed. Possible consequences of such variations are examined. The present status of experimental tests of these ideas is discussed.

I. INTRODUCTION

Introductory courses in classical and modern physics acquaint students with the notion that there are a limited number of so-called "fundamental constants" which set the basic scales for the rich variety of physical and astronomical phenomena that we observe. A list of such constants would certainly include Newton's gravitational constant, G, the speed of light, c, Planck's constant, h, the charge of the electron, e, and the masses of the electron and proton, m_e and m_p. These quantities have been measured to ever-increasing precision and are now known to impressive levels of accuracy. A curious student might ask , however, if these "constants" have always had their present values or whether they might have changed over the course of time? In this paper, some reasons for taking this question seriously are reviewed. Possible consequences of the time variation of physical constants are examined. Finally, a discussion is presented of a number of clever and sensitive tests that have been carried out to search for such effects.

While the question of the time variation of fundamental constants may at first appear to be wild speculation, over the years it has attracted the attention of a number of well-known physicists and astronomers. This is in large part due to the following observations made in 1937 by Dirac[1] . From the constants e, m_e , and c it is possible to construct a quantity which has the dimensions of time:

$$\frac{e^2}{m_e c^3} \approx 10^{-23} \quad \text{seconds} \qquad (1).$$

This extremely short interval is roughly the time required for light to traverse the diameter of an atomic nucleus. If one now expresses the approximately 20-billion-year age of the universe in these "natural" units of time, one obtains a dimensionless number,

$N_1 \approx 10^{40}$. Dirac found that two other large dimensionless numbers could be formed. In the hydrogen atom, an electron and a proton are held together by their mutual electromagnetic force of attraction. In addition, however, there is a very much weaker gravitational attractive force. In fact, if we calculate the ratio of the electromagnetic force to the gravitational force one finds another dimensionless number,

$$N_2 = \frac{e^2}{G\, m_e\, m_p} \approx 10^{39} \qquad (2).$$

Finally, if one takes the ratio of the estimated mass of the visible universe to that of the proton one obtains the number of baryons in the universe, N_3 , a number of roughly 10^{78} .

Is it merely an accident that these three numbers are all approximately integral powers of 10^{39} ? Dirac suggested that this is not just a passing coincidence that happens to be true at the present time, but instead represents a set of relationships which are preserved as the universe evolves. Furthermore, because N_1 varies linearly with time, Dirac argued that in order to maintain these relationships, all such large dimensionless numbers must be simple functions of time. This idea has subsequently come to be known as Dirac's Large Numbers Hypothesis or LNH. To make these dimensionless numbers time dependent, at least one of the above-mentioned constants must vary with time. In Dirac's original model it was proposed that in order to maintain the near equality between N_1 and N_2 , the gravitational constant, G, should decrease as 1/t. From the fact that N_3 is approximately equal to the squares of N_1 and N_2 , Dirac made another remarkable prediction, namely that the number of baryons in the universe should increase as t^2 . Subsequently, Brans and Dicke[2] and Hoyle and Narlikar[3] have developed theories of gravity in which it is also expected that G decreases with time, but at a rate different from that suggested by Dirac. Somewhat later, Gamow[4] proposed that G remains constant, but that instead the electron charge, e, varies with time. More recently, there has been some discussion of the possibility that G actually increases with time[5,6] .

II. CONSEQUENCES OF A TIME-VARYING G

About ten years after Dirac's original proposal, Teller[7] produced an argument which seemed to rule out the possibility of a variation in G as large as that required by the LNH. He derived the relationship between the luminosity of a star, L, its mass, M, and G:

$$L \propto G^7 M^5 \qquad (3).$$

From this it was argued that if G had in fact varied at the rate expected from the LNH, then the Sun's luminosity would have been so much larger in the past that life on Earth would have been impossible two billion years ago. The discrepancy between this result and the evidence provided by the fossil record led to the conclusion that G could not have varied appreciably over this period of time. Similarly, Pochoda and Schwarzschild[8] argued that a larger value of G in the past would have produced a faster rate of evolution for the Sun. From their calculations, it was concluded that if G varied as $1/t$, the Sun should already be a red-giant star unless the age of the universe were at least 15 billion years. While in 1964 this was considered to be an unreasonably large value for the age of the universe (and hence a strong argument against the LNH), it is not in disagreement with estimates currently obtained from studies of globular cluster ages and from nuclear cosmochronometers. More recently, Canuto and Hsieh[9] have shown that the product GM must be constant, and that as a result, L should be essentially constant in time. Furthermore, as discussed by Wesson[10], when one includes the effects of the variation in the Earth's orbital size expected from the LNH, the objections of both Teller and Pochoda and Schwarzschild to Dirac's model appear to be removed.

Another interesting consequence of a time-varying G has been noted by Bishop and Landsberg[11]. Within the context of Newtonian mechanics, if G changes with time, then the law of energy conservation is no longer valid! This can easily be seen by considering the situation shown in Fig. 1. A ring-shaped object and a small-sized particle approach each other from infinity under the influence of their mutual gravitational attraction. They pass through one another and then again separate to infinity. If G monotonically decreases with time, then, for the same separation, the force of attraction between these objects is less while they are receding from each other than while they are approaching each other. Their final relative velocity, and hence kinetic energy, is therefore greater than the initial value. Since the initial and final potential energies are both zero, the total energy of the system is not conserved.

III. EXPERIMENTAL TESTS OF DIRAC'S LNH

What about direct experimental searches for time variations in G? On the basis of the LNH, such changes are expected to be on the order of one part in 10^{10} per year. Thus, needless to say, experimental tests for these effects are extremely difficult. Nevertheless, experiments have been performed which set quite stringent limits on any possible variation in G. Since the sizes of planetary and lunar orbits depend critically on the value of G, time variations in these distances could provide evidence for variations in G itself. Modern radar ranging and timing techniques now allow the distances to the Moon and to other planets to be accurately determined. By repeating such measurements over long periods of time, variations in G can be searched for. By 1971, Shapiro and his colleagues[12] had used such a technique with Mercury and Venus and found that, within the accuracy of their experiment, G appeared to remain constant. From their data, it could be established that G varies by less than 4 parts in 10^{10} per year. Similarly, one can use the orbit of the Moon around the Earth to search for variations in G. From studies of lunar occultations of distant stars, Van Flandern[13] reported in 1981 that G does in fact decrease by about 5 parts in 10^{11} per year. However, uncertainties in the influences of tidal forces on the Earth-Moon system cast some doubt upon this result.

More recently, Hellings and his collaborators[14] used the Viking landers on Mars to determine the distance to this planet. Between 1976 and 1982, the separation between the Earth and Mars was measured 1136 times. Each such measurement was accomplished by sending a radio signal to a lander which then transmitted it back to Earth. By measuring the round-trip transit time for the signal, the distance to a particular point on the surface of Mars could be determined to an accuracy of about 10 meters. Many factors influence planetary orbital parameters. Thus, in order to use this data to search for time-variations in G, thousands of other measurements of the positions and distances of the Sun, and of the planets Mercury, Venus, and Mars were used to provide additional constraints in the data analysis. From this investigation, it has now been shown that G varies by less than one part in 10^{11} per year. Thus it appears that if G does vary at all, it does so at a rate substantially lower than that originally proposed by Dirac.

What about the other prediction of the LNH, namely that the number of baryons in the universe increases as t^2 ? Two general creation schemes have been suggested. In "additive" creation[15] , new matter is supposed to continuously appear uniformly throughout the universe. Dirac suggested that the most likely form for this new matter might be that of hydrogen atoms. Alternatively, in "multiplicative" creation[15], new matter is created in the vicinity of existing matter and at a rate proportional to the amount already present. Presumably this new matter would be of the same type as that already existing. These processes would represent a new type of "radioactivity" and would violate a number of conservation laws. Nevertheless, it is necessary to look to experiments to decide if such phenomena occur.

While it might at first be thought that the sudden appearance of new matter should be easily observable, the additive creation process will be extremely difficult (if not impossible) to detect. From the observed average density of the universe of about 10^{-30} grams per cubic centimeter and the rate of creation predicted by the LNH of roughly 10^{-10} new baryons per existing baryon per year, one new particle would be expected to appear per year inside a volume of about 2 cubic miles! This creation rate is orders of magnitude below the sensitivity of any past or planned experimental search.

Multiplicative creation, on the other hand, lends itself more readily to experimental study. Because the expected rate of such creation is proportional to the amount of matter already present, it is natural to look for such a process to occur where matter is quite dense. However, to perform experiments, one has to know what to look for. Thus, an assumption must be made about the form in which the new matter will appear. On the basis of the steady-state cosmology, which also required the continuous creation of matter, Cohen and King[16] in 1969 searched for the appearance of hydrogen gas in mercury metal. No such effect was observed, but an upper limit of about one new hydrogen atom per 10^{15} baryons per year was established. Dirac[15] and others[17,18,19] have discussed the possibility of the creation of new atoms within solid materials. Although there are problems associated with incorporating these new atoms in ancient rocks without altering their crystal structure, this possibility cannot be absolutely ruled out.

Despite the fact that these investigations cast some doubt on the possibility of multiplicative creation, the theory has not suffered a mortal blow. It just might be that Nature is more imaginative in the form it chooses for this new matter. An interesting idea that was recently suggested by Shenkin[20] is that new matter might instead appear where matter is at its densest, namely inside atomic nuclei. In this scheme, it is expected that the new matter would appear in the form of neutrons and/or protons. As a result of this "accretion" process, the isotopic and elemental composition of ordinary matter would change with time. However, from the investigations of Shenkin and subsequent studies by Norman[21] , it seems that if this particular type of creation did occur at the rate predicted by the LNH it would have produced isotopic abundances in both terrestrial and meteoritic samples very different from what is actually observed. Thus, while little can be said about additive creation, it appears that multiplicative creation (at least in the forms searched for to date) if it occurs at all, must do so at a rate much lower than that expected from the LNH.

IV. DO OTHER CONSTANTS VARY ?

Although Dirac originally suggested that G alone varies with time, as mentioned above, one can imagine that other "constants" might also change. During the 1950's and 1960's, investigations were been made regarding the questions of the time variations of the electron charge[22] , the fine-structure constant[23,24] , and the strength of the weak interaction coupling constant[25] . The status of these studies was reviewed by Dyson[26] in 1972. From a variety of astronomical, geological, and nuclear physics techniques it was concluded that there was no evidence for the variation in any of these quantities at levels as great as one part in 10^{11} per year. More recent and sensitive searches for time variations in the fine structure constant[27-30] , Planck's constant[31,32] and both the weak and strong interaction coupling constants[28] have also failed to show any positive evidence.

The experiments of Baum and Florentin-Nielsen[31] and of Solheim, Barnes, and Smith[32] illustrate how the techniques of modern astronomy can be used to look for such time variations. It is well known that photons satisfy the energy-wavelength relation

$$E \lambda = h c \qquad (4).$$

Thus by measuring both the energy and wavelength of a photon, the product hc can be determined. If one could perform such measurements on both "young" and "old" photons, time variations in h could be looked for (assuming c does not change). Fortunately, Nature provides us with photons with a variety of ages. Using the observed redshifts of galaxies and quasars, together with the Hubble redshift-distance relation, the distance and hence light-travel time to these objects can be determined. For instance, a photon reaching us today from a quasar whose redshift is $z = 0.1$ was actually emitted about 2 billion years ago. Such photons thus allow us to "look back" into the very distant past.

A schematic drawing of the apparatus used in both of the these investigations is shown in Fig. 2. Light from astronomical sources was collected with a telescope. Photon wavelengths were selected with a filter or scanner, and their energies were measured with the use of a photomultiplier tube. The results of Solheim, Barnes, and Smith are shown in Fig. 3. It can be seen that within the experimental uncertainties the values of h inferred from both "young" and "old" photons are equal. From analysis of this data, it has been established that if h varies at all, it does so by less than 4 parts in 10^{13} per year.

V. CONCLUSIONS

What can be deduced from all of this work? Experiments have now ruled out time variations in fundamental constants as large as those first suggested by Dirac. How are we then to understand the near equality of N_1 and N_2 ? Dicke[33] has produced a natural explanation for this seeming coincidence. His argument is based on the idea that the present age of the universe is roughly the time required for the development of intelligent life. While the time required for such evolution is not well determined, we do know that life (at least as we understand it) depends upon the existence of chemical elements such as carbon, nitrogen, oxygen, and phosphorus. These elements are produced via nuclear reactions that occur in stars. Thus this time interval must be at least as long as the luminous lifetime of an upper-main-sequence star, t_L . From the luminosity of such stars and from nuclear energetics, Dicke found

$$t_L \approx \frac{\hbar^2}{G\, m_p\, c^3} \qquad (5).$$

If one now computes N_1 using this value of time one finds (apart from "small" numerical factors)

$$N_1 = t_L \Big/ \left(\frac{e^2}{m_e\, c^3}\right) \approx \frac{e^2}{G\, m_e\, m_p} = N_2 \qquad (6).$$

From this it can be seen that N_1 and N_2 will be approximatly equal even in the absence of a variation in G. Thus the apparent need for time variations in physical constants seems to have been removed. Nevertheless the question of the "constancy" of fundamental constants remains intriguing and will undoubtedly continue to attract the interest of curious physicists and astronomers.

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FIGURE CAPTIONS

1. Two objects approach, pass through, and recede from one another as a result of their mutual gravitational attraction. If G decreases monotonically with time, then their final relative velocity, and hence kinetic energy, is greater than the initial value. Since the initial and final potential energies are both zero, the total energy of the system is not conserved.

2. Schematic drawing of the apparatus used to search for time variations in Planck's constant (Ref. 31,32). Light from astronomical sources is collected by the telescope; photon wavelengths are selected with the filter (scanner) , and their energies are measured with the use of the photomultiplier tube. By comparing the results obtained for photons from both nearby and distant sources, the wavelength-energy relation for both "young" and "old" photons could be examined.

3. Relative value of h (compared to its laboratory value) as a function of the redshift of the photon source (Ref. 32). The redshift is proportional to the source's distance and thus to the photon's transit time. The apparent equality between the value of h inferred for both "young" and "old" photons provides stringent limits on any possible time variation in this quantity.

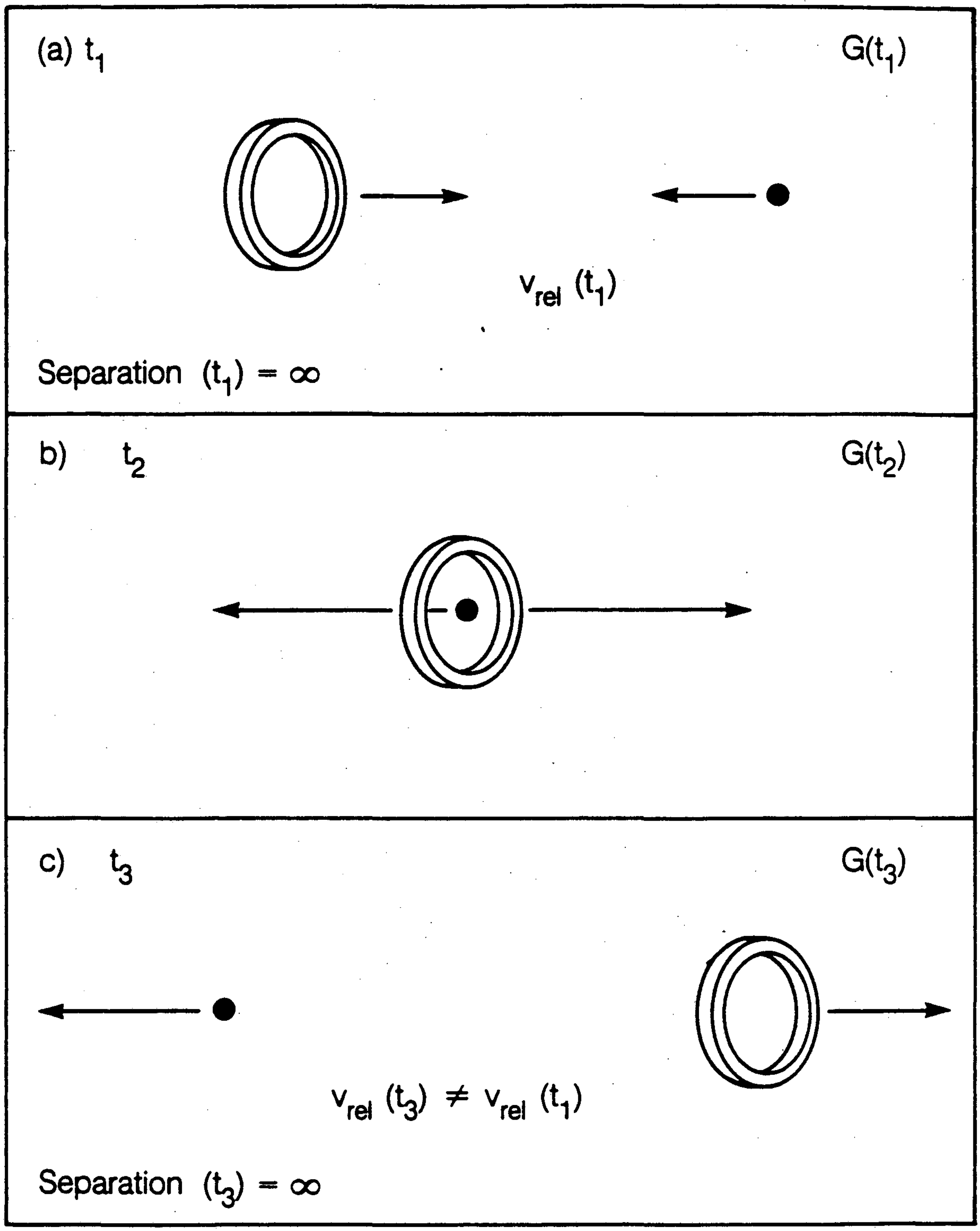

Fig. 1

XBL 851-713

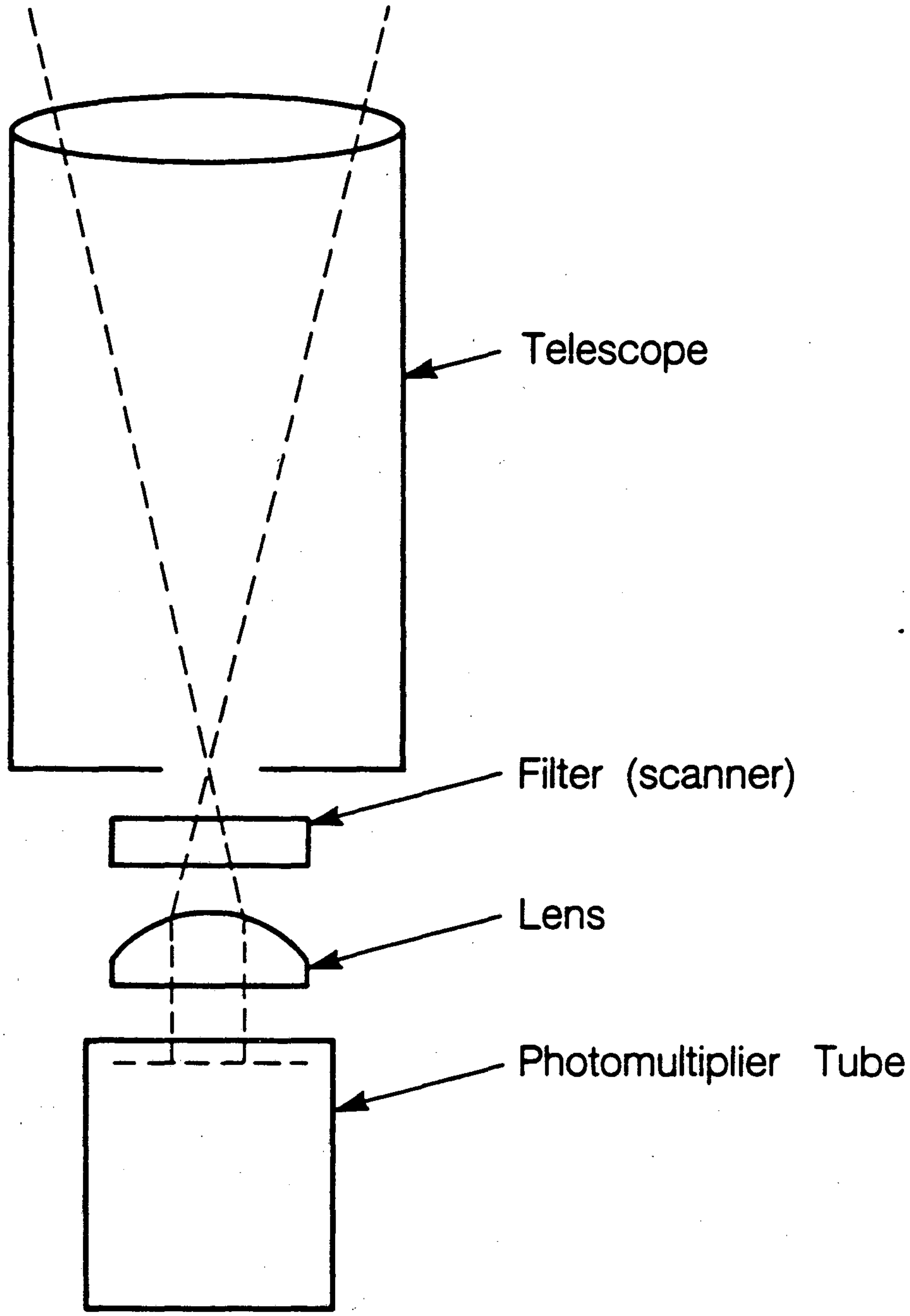

Fig. 2

XBL 851-714

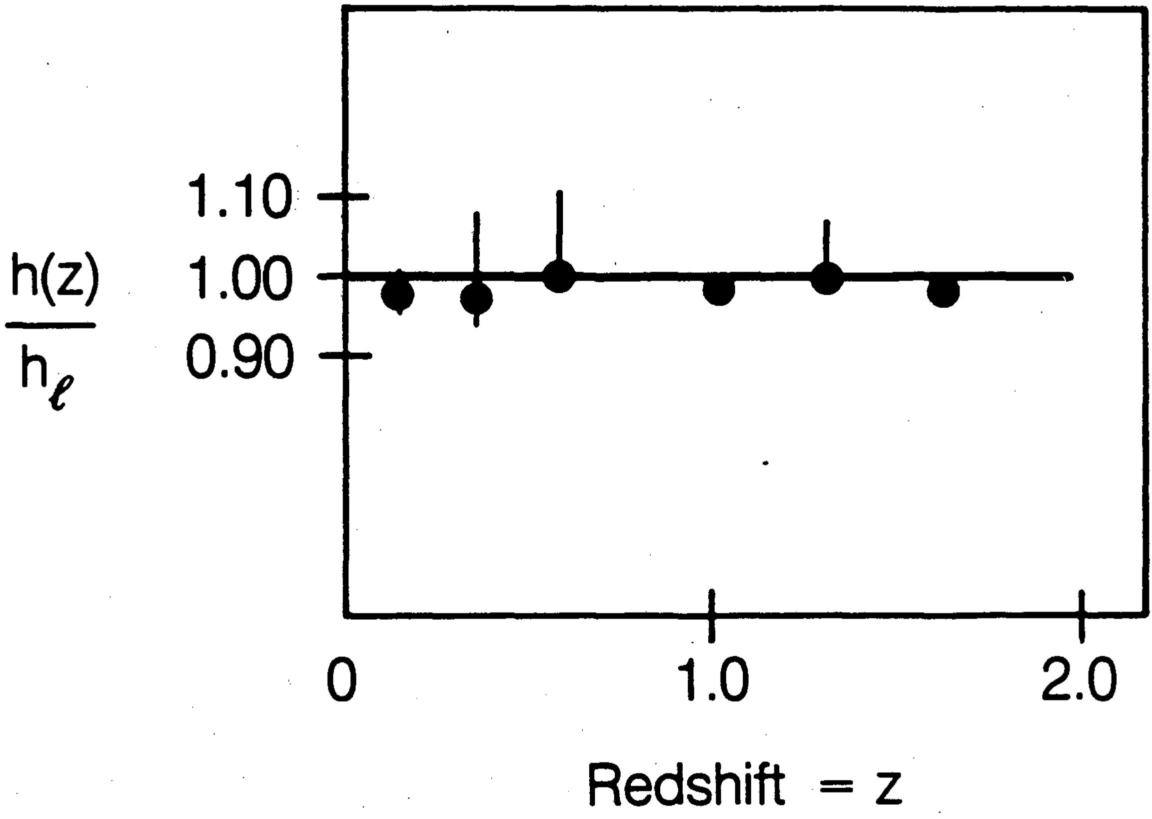

Fig. 3

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