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THE CASE FOR THE HOT BIG BANG COSMOLOGY *

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ABSTRACT

The standard relativistic hot big bang model for the expanding universe has developed into a mature physical science, in which the predictions and interpretations substantially outnumber the elements used in devising the theory. Recent successes include the demonstration that the microwave-submillimeter background radiation has a spectrum very close to thermal; the predictions of the light element abundances and the number of neutrino families; the confirmation that distant objects, galaxies as well as quasars, show substantial evolution with light travel ("look back") times; and the explanation of observed gravitational lens systems. There is no well established observation that contradicts the standard model, and no known alternative world picture successfully addresses all the modern data.

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Cosmologists grow used to explaining to their colleagues in other fields why the latest reports of the death of the Big Bang model for the expanding universe are premature to say the least. To the contrary, we explain, in the six decades since the formulation of the model advances in observations and experiments have yielded a considerable body of evidence in support of the Big Bang, and none that convincingly contradicts it.

Reports of the death of the Big Bang, in media and journals (eg. refs. 1,2), often confuse the Big Bang model with free parameters within the model — quantities such as the present mean mass density, and functions such as the fluctuations of the density around the mean. An example is the large structures observed in the distribution of galaxies.[3,4] These structures are one of the serious problems for the set of ideas known as the cold dark matter theory for the formation of galaxies.[5] However, their existence does not contradict the Big Bang model itself, for they are small in size compared to the scales on which the universe is assumed and observed to be close to isotropic. Furthermore, there is no shortage of other ideas within the Big Bang that might account for the large-scale structures in the galaxy distribution.[6,7]

The distinction between a well established theory and the uncertainties in parameters within the theory is familiar to anyone working in an active science. For example, the failure (so far) of our colleagues in particle physics to find the Higgs particle no more vitiates the standard quark-lepton picture than does our failure to explain how galaxies form signify a fatal flaw in the Big Bang model. Perhaps less familiar in some other sciences is the schematic nature of some of the observational evidence in astronomy in general and cosmology in particular — we must work with whatever the physical universe chooses to throw our way. Thus it should be no surprise that the interpretation of evidence in astrononomy can lead to debates that tend to be more intense and longer running than in many other sciences.[1,8] However, as evidence accumulates the range of possible interpretations narrows, and that can lead to a theory that is believable by the standard criteria: the elements that went into the invention of the theory have led to a considerably broader network of successful predictions and interpretations. We will argue that this is what has happened to the Big Bang world model.

A healthy degree of scepticism still is in order, for we are using evidence that sometimes is indirect to arrive at a grand conclusion, that the universe expanded away from a dense hot beginning. But we can assert that the invention of any viable alternative world picture would require a good deal of ingenuity now that the observational tests have become so numerous and apparently convincingly in favour of the Big Bang.

This review is mainly addressed to colleagues in other fields (and was inspired by their questions about the health of the Big Bang). For this purpose there is not much interest or use in a point-by-point rebutal of arguments for alternative cosmologies or against the Big Bang. (For a very incomplete survey see refs. 8 to 14.) Instead, we begin with a statement of what has become the standard model in cosmology, and present our selection of the highlights of the now extensive range of evidence which most cosmologists believe securely establishes the Big Bang model.

The Standard Model

By the standard Big Bang cosmological model we mean a universe that is expanding according to Hubble's law,

$$v = H_o r \, , \tag{1}$$

where v is the recession velocity of a galaxy at distance r. Superimposed on this velocity field are the random motions of the galaxies, typically ~ 500 km s^{-1}. There are relativistic corrections when v is comparable to the velocity of light, c, that is, at distances comparable to the present Hubble length,

$$L = \frac{c}{H_o} \sim 6000/h_{50} \text{ Mpc} \, , \tag{2}$$

where 1 Mpc $\sim 3 \times 10^6$ ly and h_{50} is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}.

The wavelength of radiation from distant objects is stretched toward the red; the redshift factor z is defined by the ratio of the wavelength λ_e at emission (as measured by an observer at rest at the source) to the presently observed wavelength, λ_o,

$$1 + z = \frac{\lambda_o}{\lambda_e}. \tag{3}$$

When v in equation (1) is small this can be considered a Doppler effect, but it is better to note merely that the expansion of the universe stretches the wavelength by the factor by which the universe expands between emission and observation. It is customary to label epochs in the evolving universe by their redshift z even when z is so large that nothing reaches us without absorption and reradiation; then one thinks of z entirely in terms of the expansion factor. Thus since baryons are conserved (at redshifts of interest here) the mean number density of baryons at epoch z is

$$n(z) = n_o(1+z)^3 \ , \tag{4}$$

where n_o is the present value.

In the standard model the universe has expanded from a state dense and hot enough that matter had relaxed to statistical thermal equilibrium. This means space was (and is) filled with black body radiation, the cosmic background radiation, or CBR. As the universe expands radiation is not lost; rather, the number of CBR photons per unit volume drops, as in equation (4), and the photon wavelengths are stretched by the expansion, as in equation (3). The result is that the radiation preserves a blackbody spectrum with a temperature that decreases as the universe expands. The measured present temperature is[15,16]

$$T_o = 2.736 \pm 0.017K. \tag{5}$$

The temperature at the epoch with redshift z is

$$T(z) = T_o(1+z) \ . \tag{6}$$

As will be described, equations (4) to (6) have been tested back to $z \sim 10^{10}$. They of course cannot apply all the way to $z \to \infty$. Ideas on the corrections to these equations associated with the speculative physics of the very early universe[17] are of great research interest but go beyond the standard model we are discussing. In this connection we might note that the name, Big Bang, may be unfortunate because it may be misunderstood as referring to an event at a singular start of expansion of the universe. Whatever started the expansion, perhaps an inflationary epoch, perhaps something even more wild, is not intrinsic to the standard model. Also, any prediction on where the universe is heading, to recollapse, eternal expansion, or something else, is part of the uncertain parameters within the standard model.

The standard model assumes the universe is homogeneous and isotropic in the average over scales comparable to the Hubble length in equation (2), that is, that apart from "small scale" fluctuations the universe looks the same in any direction and would look the same viewed from any other galaxy. This agrees with the precise isotropy of the background radiation fields and the unique temperature of the CBR, and at less precision, with galaxy counts. A useful measure of the scale at which the universe approaches homogeneity is that the rms fluctuation in counts of galaxies found within a randomly placed sphere of radius r is[4,18,19],

$$\delta N/N \sim 0.5 \qquad \text{for} \qquad r = 40 h_{50}^{-1}\ \text{Mpc}\ , \tag{7}$$

and decreases as r increases.

It is an easy exercise in vector addition to check that the linear redshift distance relation in equation (1) has the property that an observer on any galaxy sees the same recession law. This connection between homogeneity and Hubble's law was the first success of the expanding world model. The considerable subsequent improvements in the tests of homogeneity and Hubble's law (eg. refs. 18 to 20 and Fig. 14 in ref. 21) over what was known when the relation was discovered must be counted as an impressive success for the standard model.

Finally, the dynamics of the expansion of the standard model are described by Einstein's general relativity theory. There is a rich and growing set of tests this theory,[22] but the main justification for its application to cosmology is its successes, as discussed below.

The Cosmic Background Radiation

In the standard model the universe is filled with a uniform sea of thermal blackbody radiation that was produced in the very early universe and cooled by the expansion of the universe. As indicated in Figure 1, there is an isotropic radiation background detected at wavelengths ~ 500 microns to ~ 30 cm with these properties. The boxes in the figure show the COBE satellite measurements, and the solid curve is the best fit thermal Planck spectrum.[15] The boxes represent statistically independent measurements, and the box height is a nominal error bar, at 1% of the peak value of the brightness, that takes account of the uncertainty in a preliminary analysis of the calibration. The small scatter shows that these box heights are quite conservative. As it happened, a rocket measurement[16] just a few weeks after the launch of COBE gave very similar results. Ground-based measurements at longer wavelengths are summarized by Wilkinson.[23] All show that the CBR spectrum is very close to a thermal Planck function.

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Since matter has been hotter than the CBR for a long time, the CBR spectrum could not be exactly thermal. However, the fact that the energy density of the CBR is some nine orders of magnitude larger than the heat capacity of matter (at redshifts $z \lesssim 10^9$) makes it very difficult to think of processes within the standard model that could appreciably perturb the spectrum. Practical evidence of this is to be found in the proceedings of cosmology conferences[24] held just before the recent spectrum measurements, when it was thought that the CBR temperature shortward of the peak might be $\sim 10\%$ higher than in equation (6). Heavy theoretical efforts failed to yield a credible theory that could fit the excess and the other available constraints. That is, given that the CBR effective temperature is about that in equation (6), the standard model says the spectrum has to be very close to thermal, as observed.

The thermal spectrum of the CBR is by now so familiar that we may forget just how specific is the prediction of the standard model, and how dramatic its experimental success. With just one adjustable parameter (the temperature in eq. [6]), this prediction fits the sequence of independent measurements in Figure 1 and the longer wavelength data. Any proposal of an alternative to the standard model must face up to a substantial challenge in accounting for these measurements, as is shown in the example below for the Steady State theory.

Light Element Abundances and Neutrino Counting

In the standard model the universe cools as it expands. The expansion traces back in time to epochs when the universe was hot and dense enough to drive thermonuclear reactions that change the relative abundances of the chemical elements. The values of the abundances left over from this hot epoch depend on the cosmological parameters, but in a reasonably simple way. We assume that the universe did expand from a hot state. Then knowing the present temperature, T_o,[15,16] and assuming a value for the present matter density, we have fixed the thermal history of the universe, including the density, temperature, and expansion rate through the nucleosynthesis epoch. In the standard computation (where matter is uniformly distributed and the lepton numbers are comparable to the baryon number), this is sufficient to fix the final abundances of the light elements.[25,26] (The heavier elements are produced in stars, ejected in supernovae and stellar winds.) As we will describe, this gives a remarkably good and detailed fit to the data.[27–30]

The elements of cosmology and physics that go into the computation need not be discussed here in any detail, but it is worth emphasizing that the computation involves an immense extrapolation of the expansion of the universe back in time, to an epoch when the CBR temperature was some ten orders of magnitude greater than it is now, and the number density of baryons thirty orders of magnitude larger. It is striking that this extrapolation yields a very successful prediction.

Figure 2 shows the abundances produced in the standard model. The free parameter, the present matter density, is expressed in two ways, as the baryon-to-photon ratio, η, or, equivalently, given the measured present CBR temperature, the fraction of the critical density (that density required to make the universe's gravitational binding energy equal to its expansion kinetic energy) in baryons, Ω_b.

The vertical band in Figure 2 is the locus of allowed values of η that are simultaneously consistent with the observed light element abundances of ^{4}He, ^{2}H, ^{3}He, and ^{7}Li extrapolated to their primordial values unassociated with any heavier elements. In particular, as reviewed in references 27 to 30, the primordial mass fraction for ^{4}He is 0.23 ± 0.01 and present abundance ratios are $^2\text{H}/\text{H} \sim 2 \times 10^{-5}$ and $^3\text{He}/\text{H} \sim 2 \times 10^{-5}$. Since ^{2}H cannot be produced significantly in any non-cosmological process,[31] only destroyed, the present abundance of ^{2}H puts an upper limit on the baryon density. Conversely, ^{3}He is made in stars, and since the bulk of the excess cosmological ^{2}H over the present value burns to ^{3}He in stars, the sum of ^{2}H plus ^{3}He provides a lower bound on the baryon density.[31] The allowed range of baryon density that is consistent with these bounds requires ^{7}Li to be near the minimum in its production curve (as shown in Fig. 2). The measurements of the Spites, subsequently verified by others,[32–34] giving $^7\text{Li}/\text{H} \sim 10^{-10}$ in the primitive (Pop II) stars, further substantiates these arguments. Thus, the light elements with abundances ranging from $\sim 24\%$ to one part in 10^{10} of hydrogen all fit with the cosmological predictions, with the one adjustable parameter giving baryon density

$$\Omega_b = (0.06 \pm 0.02) h_{50}^{-2} \ . \qquad (8)$$

Recent attempts to find alternatives to this conclusion by introducing an inhomogeneous baryon distribution at the nucleosynthesis epoch (as might be caused by a first order quark-hadron phase transition at an even earlier epoch) have ended up[35] (once the models are treated in detail) reaching essentially the same constraint on Ω_b as in the standard model.

Added to the impressive agreement of the abundances has been the measurement[36] using high energy colliders of the number of neutrino families, $N_\nu = 2.98 \pm 0.06$. Nucleosynthesis arguments[25,37] show that the cosmological ^{4}He abundance is quantitatively related to N_ν. The current parameter values[28−30] yield the cosmological prediction $N_\nu \lesssim 3.3$, specifically ruling out any light neutrinos beyond e, μ and τ, and consistent with the collider measurements. Thus accelerators as well as telescopes test the standard model.

It will be noted finally that the predicted baryon density in equation (8) is within the range of estimates of the mean mass density in and around the bright parts of galaxies. However, a more precise test of this point awaits identification of the nature of the dark matter detected through its gravitational effect in the outer parts of galaxies.[17]

To summarize, the standard model makes specific and successful predictions for light element abundances and N_ν. Any proposed alternative cosmology must face up to the particularly difficult questions of what (other than the Big Bang) could have produced the observed abundance of deuterium, an isotope readily destroyed in stars and not easily produced,[31] and the remarkably uniform abundance of helium in galaxies.[30] The successful application of this test has tested the standard cosmological model back to the redshift of last equilibration of the neutron to proton ratio, $z \sim 10^{10}$.

The Evolution of Galaxies and Quasars

Because of the light travel time, galaxies observed at great distances are seen as they were when they and the universe were young. The predicted light travel time is considerable. For example, in the standard model the universe was half its present age at a redshift in the range $z \sim 0.6$ to 1, depending on the mean mass density. Since modern observational techniques allow us to study objects at redshifts in and well above this range, it is naturally expected that there is considerable observable evolution in the properties of the galaxies. As we now discuss, this basic prediction of the standard model has been clearly established for galaxies and quasars.

The counts of galaxies as functions of redshift or brightness in the sky depend on the details of the geometry and evolution of the universe, and also on how the galaxies are evolving — if younger galaxies were brighter, more of them would be counted at a given brightness. There are observed to be more very distant galaxies (that is, those counted to very low brightnesses on the sky) than would be expected for nonevolving galaxies in the standard model (though the numbers are roughly in line with the Steady State model to be discussed below).[19,38] In most cases the observed image parameters are consistent with mild evolution from normal galaxies.[38] The deepest spectroscopic surveys[39,40] show no evidence for either remarkably high luminosity or low luminosity galaxies, nor do they reveal any population of sources that is altogether new. Rather, the observations for even the faintest images have been successfully modeled on the assumption that they are normal distant galaxies undergoing evolution of their stellar populations consistent with their younger ages in the standard model.[41] That is, it is believed that an evolutionary trend has been detected in the average population of galaxies at modest redshifts, $z \sim 0.5$.

The situation for the few percent of galaxies which are members of large clusters can be stated in a simpler way. Compact rich clusters (that have high density and high mass, and contain many galaxies) are such spectacular objects that they are readily identified at redshifts up to $z \sim 1$,[42] and have therefore long been favored cosmological landmarks. It is more than a decade since it was recognized that some such clusters with redshifts $z \gtrsim 0.3$ show a population of anomalously blue galaxies.[43] The significance of this effect for galaxy evolution has now been clearly demonstrated by spectroscopic studies which show that these blue galaxies are indeed in the high redshift clusters, and that they represent types of galaxies which do not occur in low redshift clusters or even do not appear to occur at all at low redshifts.[44] That is, galaxies in clusters show clear evidence of evolution (during the past few billion years in the standard model).

Galaxies which are strong radio sources can be identified to high redshifts and are thus also well suited to studies of evolution. To the largest observed redshifts, $z \sim 3.5$, the redshift continues to appear to be a good measure of distance, judging from radio image angular sizes and infared apparent brightness.[45] The optical-infared morphologies of radio galaxies show a distinct trend with redshift, becoming more elongated and more closely aligned with the major axis of the radio image for $z \gtrsim 0.6$, and there is evidence that some of this extended light originates in stars.[46] Identification of complete samples of radio sources to faint optical limits provides a direct measure of the redshift distribution for radio galaxies, confirming the strong evolution indicated by the source counts.[47] No clear understanding of radio galaxy evolution can be claimed, but it is certain that their morphological forms exhibit distinct changes between high redshifts and low.

Finally, if the redshifts of non-thermal extragalactic sources (quasars and active galactic nuclei) are taken to be of the same nature as ordinary galaxy redshifts and thus indicative of distance (an issue addressed below), they display strong cosmic evolution. At redshifts $z \sim 2$ to 2.5, when the universe was 15 to 35 percent of its present age (depending on the mean mass density), high luminosity quasars were at least a thousand times more numerous than they are at present.[48,49] Moreover, the evidence is that the quasar population again decreases at still higher redshifts, extending out to the limits of observations at $z \sim 5$. That is, there is a rather well defined "quasar epoch" in the history of the universe.[50] Lower luminosity quasars and galaxies showing quasar-like activity in their nuclei are visible only out to $z \lesssim 1$, but they also show clear population evolution over this more recent period.[51]

Our conclusion is that discrete objects show distinct evidence of cosmic evolution. Ordinary galaxies, which have been studied only to fairly small redshifts (corresponding to relatively recent periods in the universe's history), show relatively mild changes, while increasingly more prominent objects visible to higher redshifts (earlier epochs) exhibit increasingly dramatic and extreme evolution. This is a qualitative result, as opposed to the quantitative tests discussed previously, but it is equally important as a major test and success for the standard model.

Quasar Redshifts and Distances and the Lensing of Quasars

In the standard model the expansion of the universe shifts the light from a distant object toward the red. This cosmological redshift increases with increasing distance to the object, so we would expect that high redshift objects lie behind low redshift ones. It sometimes is argued that certain classes of extragalactic objects, quasars in particular, violate this relation.[1,8] If this were true it would not necessarily rule out the standard model, for the model does not exclude other sorts of physical redshifts (indeed some, such as gravitational redshifts, are known to exist), but it certainly would raise the possibility of confusion or systematic error in the vital interpretation of galaxy redshifts as resulting from the expansion of the universe, so it is important to consider the question. It has a long history,[8,52,53] only some highlights of which will be mentioned here.

The most common argument against the cosmological interpretation of quasar redshifts is based on apparent associations in the sky between high redshift quasars and low redshift galaxies. For example, Arp *et al.*[1] point out that among the approximately 4500 quasars so far identified,[54] there are about 20 cases in which a low redshift galaxy brighter than 15th magnitude appears within 2 arc minutes of a high redshift quasar, while less than two such cases would be expected if the quasars and galaxies were unrelated. Although this sounds compelling, it must be understood that the list of 4500 includes all quasars found in any way, from systematic surveys to pure serendipity. Thus, if only a small fraction ($\lesssim 0.005$) of known quasars were discovered *because* they lie near bright galaxies, for example in images taken in order to study a galaxy, then the effect is entirely explained by a tiny selection bias. Such doubts concerning *a posteriori* hypotheses, subjective selection effects, and lack of rigorous control surveys have left us, and we believe the majority of astronomers, unpersuaded by the case for large non-cosmological redshifts.

The cosmological interpretation of quasar redshifts is based on the same well established standard model that allows us to interpret such phenomena as the CBR spectrum in Figure 1, the element abundances in Figure 2, and the cosmic evolution discussed in the last section. This interpretation therefore should be explored before we resort to new physics for which we have no independently established evidence or indication. Furthermore, in many specific cases there is evidence that quasar distances are of the order implied by the cosmological interpretation of their redshifts. We review only the most recently studied and striking line of argument, the gravitational lensing of quasars by foreground galaxies. Not discussed here are other lines of evidence that support the cosmological interpretation. (The list includes the following: Quasars at low redshifts, $z \lesssim 0.5$, are close enough on the cosmological interpretation of their redshifts that galaxies associated with the quasar should be visible. Consistent with this, low redshift quasars have fuzz comparable to what would be expected from light from a normal host galaxy,[55] and they have normal looking companion galaxies in about the same abundance observed for radio galaxies.[49,53] High redshift quasars on lines of sight that happen to pass near low redshift galaxies are observed to produce absorption features in the quasar spectra,[53] showing that the quasars really are behind the galaxies. And the statistical properties of quasar absorption lines are independent of the line of sight to the quasar, indicating that the lines arise from intervening intergalactic material.[56])

The lensing of a distant high redshift quasar by a low redshift galaxy or cluster of galaxies occurs when the two are closely enough aligned in the sky that the deflection of light rays by the mass in the foreground galaxy "lens" is large enough to produce multiple images of the background quasar.[57] As discussed below, identification of a lensed quasar requires evidence that the quasar images are indeed multiple views of the same object. One finds that in such cases the masses known to be associated with galaxies or clusters of galaxies would produce multiple images with angular separations like those observed if the quasars lie far behind the lensing galaxies (so the bending angles required for the lensing are those expected for reasonable galaxy masses). That is, the lensing phenomena give us examples where the high redshift quasar certainly is well behind the low redshift galaxy, as implied by the cosmological interpretation of quasar redshifts.

In the few best instances, the case for a gravitational lens model of specific systems is detailed, extensive, and compelling. This includes the quasar Q0957+561, in which high angular resolution VLBI radio maps of the two source images display a mirror symmetry[58] predicted by the lens model, and the two images display identical flux variations (in the optical and radio) with a time delay corresponding well to that expected from the geometry.[59,60] In an "Einstein ring" lens the alignment of quasar and galaxy is so close and the mass distribution in the lensing galaxy close enough to axisymmetric that the galaxy images a region in the quasar as a ring centered on the galaxy. This is observed in the quasar MG1654+1346, where a galaxy at redshift 0.254 produces a classic "Einstein ring" lens image of the radio lobe of a redshift 1.74 quasar.[61] A third example is the system Q2237+0305, for which a lens model fits a remarkably detailed set of the observations. We now discuss this case in some detail.

The object Q2237+0305 has been offered as an example of evidence for non-cosmological quasar redshifts,[1] on the basis of the small probability of such precise alignment of a quasar with a low redshift galaxy. Values of this probability in the range of $\sim 2 \times 10^{-6}$ to $\sim 9 \times 10^{-3}$ have been quoted, depending on details of the lens model and exactly what *a posteriori* characterization of the alignment is chosen[62,63]. One has to be cautious of such statistics, for a specific real event may be exceedingly unlikely when compared to all the things that might have happened. If one accepts that such an alignment exists, then the system matches the expected lensing event to an extraordinary degree. Although Arp *et al.*[1] characterize its morphology as a "blobby" QSO, high resolution images obtained from the ground,[64] and more recently from HST (Fig. 3), show four distinct unresolved images superimposed on an ordinary barred spiral galaxy. All four of these images show apparently identical emission line spectra,[65] and their separations are those expected given a conventional dynamical mass for the nucleus of the observed galaxy.[66] Moreover, the relative positions of the galactic nucleus and the four images are just those predicted if it is assumed the mass that causes the lens is distributed like the observed starlight in the galaxy's nucleus.[66] Finally, this lens model predicts independent flux variations in the four images due to "micro-lensing" events in which a star in the lensing galaxy passes just across the path of one of the lines of sight to the quasar. Such an effect now has been observed.[66–69].

If this system were not a lens but instead consisted of four separate quasars physically associated with the galaxy,[1] the nearly perfect resemblance to the lens system which would have resulted from a single quasar at its cosmological redshift distance behind the galaxy is an extraordinary coincidence!

In addition to the best understood cases cited here there are a substantial number of less dramatic instances which are plausibly understood as quasar lensing by galaxies,[70] and the frequency of lens candidates among quasar samples is consistent with that expected within the standard cosmology,[71,72] if all observed quasars are at their inferred redshift distances.

To summarize, there is strong observational evidence of the gravitational lensing of quasars by foreground galaxies. Well before quasars were known it was predicted that, within the standard cosmological model, low redshift galaxies would lens high redshift objects.[73–75] If lensing were not observed in quasars, it would have been a serious problem for the standard model. By the same token, the positive observation is an important success. In particular, lensing give us examples where high redshift quasars manifestly are far behind low redshift galaxies along nearly the same line of sight, consistent with the cosmological interpretation of the redshifts.

Challenges to the Hot Big Bang Model

As we have discussed, the more common of the reports of the death of the Big Bang mistakenly confuse the standard hot expanding universe model outlined in equations (1) to (6) above with some specific version or extension of the picture. For example, the

Einstein-de Sitter model (in which space curvature, Einstein's cosmological constant Λ, and pressure all have a negligible influence on the expansion rate compared to the mean mass density) is attractive because it is particularly simple. Also, this case is indicated in some interpretations of the physics of the very early universe.[17] Indeed, at least 50% of the authours of this report agree that the Einstein-de Sitter model is the strong sentimental favourite. As indicated below, the model does have some possible observational problems. If observations should eventually rule out the Einstein-de Sitter case it would show that the universe is even more complicated than some of us thought, but it certainly would not be a problem for the standard model.

An example of the situation is the timescale problem. The age t_o of the universe, reckoned from a very high redshift to the present, and the Hubble parameter H_o in equation (1), yield a dimensionless number $H_o t_o$. In the Einstein-de Sitter model, $H_o t_o = 2/3$. If space curvature is significant but Λ is negligible, $H_o t_o < 1$. If Λ is significant, $H_o t_o$ may exceed unity. Thus if H_o and the ages of the oldest stars, which have to be $\lesssim t_o$, were known with enough accuracy, we would have an exceedingly valuable constraint on the cosmological parameters.

We would have another test if we had other ways to measure the parameters of the standard model (including the mean mass density, the radius of curvature of space, and Λ), and check for consistency with the constraint from the timescale. Deep galaxy counts are sensitive to these parameters, and there are indications that they may yield a useful measure,[76] although untangling the cosmological effects from evolution of the galaxies remains a vexed problem. Applications of these and other cosmological tests based on observations of distant objects may become one of the major themes of cosmology in the 1990s. This is because there have been dramatic advances in the ability to observe galaxies at redshifts $\gtrsim 1$, where the observational measures are considerably more sensitive to the cosmological parameters than when z is well below unity. But the way will not be easy, as the following numbers for the timescale part of the test indicate.

In a recent review, van den Bergh[77] finds

$$H_o = 67 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1} = 1/(15 \pm 2 \text{ Gyr}) . \tag{9}$$

The main uncertainties in this very difficult measurement are systematic errors; other recent studies have yielded values in the range $H_o^{-1} \sim$ 10 to 20 Gyr. The oldest reliably established ages of globular star clusters, based on stellar evolution theory, are $t_{GC} = 15 \pm 3$ Gyr.[78] Radioactive decay ages give $t_N > 10$ Gyr, independent of galactic evolutionary models, and when combined with evolution models indicate $t_N \sim 15 \pm 4$ Gyr.[78]

It is impressive that the products $H_o t_{GC}$ and $H_o t_N$ are on the order of unity, for this unites the astronomical measurement of H_o with the physics and astrophysics of stellar evolution and of the production and decay of the heavy elements. It is also interesting that the Einstein-de Sitter case, $H_o t_o = 2/3$, is within the realistic ranges of uncertainty quoted. Some astronomers are starting to suspect that $H_o t_o$ will be turn out to be larger than 2/3. This "time-scale problem" is very relevant to the Einstein-de Sitter model universe, but easily resolved in the standard model: it would say that the mean mass density is lower than the Einstein-de Sitter case. The possible result $H_o t_o > 1$ would be particularly interesting, indicating a positive cosmological constant, Λ.[79] However, all that awaits improved accuracy in two extremely difficult measurements, of Hubble's constant and the ages of the oldest objects.

An important ongoing research topic in physical cosmology is the search for a theory of the origin of galaxies and the large-scale structure of the universe.[80] News reports tend to emphasize the failed attempts, which is right and proper, but we feel misses the main point. Directions of research are changing because the numbers of observational and possible theoretical pieces to the puzzle are growing at a rapid rate, perhaps approaching the critical value where we might hope to hit on a believable solution. We are not aware of any pieces of the puzzle that contradict the Big Bang. For example, the sizes of connected structures revealed by galaxy redshift surveys are one of the serious challenges for the cold dark matter theory of galaxy formation. (It should be noted that this theory involves a set of assumptions,[5] some of which are in trouble. But it remains quite possible that some of the dark matter needed to account for observed motions in the outer parts of galaxies and in groups and cluters of galaxies is in the form of nonbaryonic slowly moving particles.) As we have emphasized, the structures certainly fit in the standard cosmological model. Given the complexity of the problem we do not consider it surprising that our attempts to find a believable theory for the origin of the galaxies so far have not met with success. We also don't know how to predict tornados, but we don't doubt that the Earth's atmosphere is governed by standard hydrodynamic and thermodynamic laws.

Alternatives to the Standard Model

As we have described, the standard model passes all believable tests to date. But one can also ask whether there is an alternative cosmology that can do as well or even better. This is important not only because we should be alert to new ideas but also because it gives us an indication of how seriously to take the successes of the standard model: if alternative cosmologies also were consistent with the data it would suggest that available observations are inadequate to critically test world models. That is the case for some of the tests. For example, the linearity of Hubbles's law in equation (1) follows from the homogeneity assumption and local Lorentz invariance, independent of any further elements of general relativity theory. However, we will argue that no other cosmological model proposed so far fits the full suite of observational constraints.

The classic alternative cosmology, the Steady State model,[9,10] assumes a homogeneous expanding universe which is not evolving because matter is continuously created so as to preserve a steady mean density. This model provides a useful foil for the discussion of the significance of the CBR spectrum measurements.

In the Steady State theory it would be reasonable to suppose radiation is created along with the continuous creation of baryons, but absurd to suppose the spectrum of the created radiation is just such that the integrated background, taking account of the varying redshifts of radiation created at different distances from us, adds up to a thermal form. To make an alternative theory for the spectrum of the CBR within the Steady State theory, let us postulate that the created energy is absorbed by intergalactic dust and reradiated by the dust with a thermal spectrum at constant temperature T. (This is a version of the picture proposed by Arp *et al.*[1]) The optical depth for this process, measured in units of reciprocal light travel time, is κ. For simplicity we will suppose κ is independent of wavelength in the range of COBE measurements in Figure 1. Then in the classical Steady State model the integrated surface brightness (energy flux per steradian and unit frequency interval) due to the thermal emission of the dust is

$$i(\nu) = \int_0^\infty \kappa d\tau \, e^{-(3H_o+\kappa)\tau} P(e^{H_o\tau}\nu) \,. \tag{10}$$

Here τ is the lookback time, $t_o - t$, the Hubble parameter H_o is independent of time, and $P(\nu)$ is the thermal Planck spectrum at the constant dust temperature T. The absorption of the dust would reduce the observed flux density f_o from a radio source at redshift z from the value f in the absence of the dust, by the relation

$$f_o = f(1+z)^{-\kappa/H_o} . \tag{11}$$

Equation (10) says that if $\kappa \gg H_o$ then $i(\nu)$ is close to a Planck spectrum. This corresponds to a case in which the universe becomes black (opaque) at a distance corresponding to a low redshift, so the radiation we detect has not been appreciably affected by the redshift.

The dashed line in Figure 1 shows the predicted spectrum for $H_o = 0.3\kappa$ and the dust temperature adjusted to get the best fit to the data. Here the universe reaches unit optical depth at redshift $z \sim 0.3$. The radiation coming from dust grains at redshift z has its temperature lowered by the factor $(1+z)^{-1}$ (eq. [6]), so we see an admixture of temperatures, which add up to the distinctly nonthermal spectrum shown as the dashed line. This case manifestly is ruled out by the observations.

With

$$\kappa/H_o = 10 , \tag{12}$$

the predicted spectrum from equation (10) is below the error boxes in Figure 1 at wave numbers 3 to 6 cm^{-1}, and above the error boxes at at wave numbers 11 to 16 cm^{-1}. Since the error boxes are very conservative, this case also is ruled out; still higher opacity is needed. But according to equations (11) and (12) the radio flux from a source at redshift $z = 2$ would be attenuated by a factor of 10^5. That certainly does not agree with the observation of high redshift radio galaxies at wavelengths ~ 2 cm that show no indication of absorption extrinsic to the source.[81]

The conclusion is that, even with the freedom to adjust the amount of intergalactic dust, the classical steady state model cannot account for the distinctive thermal spectrum of the CBR: if the opacity of the dust is low enough to agree with the observations of radio galaxies at high redshifts then the theory predicts that the CBR is an admixture of thermal spectra at different redshifted temperatures, which is not observed. And of course this model leaves unexplained other observations discussed above: the systematics of light element abundances, and the cosmic evolution of extragalactic objects.

Hoyle has consistently emphasized that the perfect cosmological principle of the Steady State theory (which says that the universe is invariant under translations in time as well as space) might apply only in the average over long times, just as the homogeneity condition in the standard model ignores local fluctuations in the mass distribution. Even before the discovery of the CBR, Hoyle and Narlikar[82] considered a model in which creation occurs in bursts between which the universe evolves as in the standard model. If the bursts are dense, hot and rare enough the results can be indistinguishable from the standard model (and can be considered a forerunner of the inflation picture).

In a cold Big Bang model the CBR would be produced and thermalized by dust at some fairly recent epoch, labeled by redshift $z \sim z_t$. If $z_t \gtrsim 5$, beyond the most distant observed quasars, the dust would not violate the observed transparency of the universe. Wright[83] showed that one can find physically realizable models for the dust (graphite or iron needles) and the source of radiation (neutron stars or black holes accreting much of the mass of the universe and reradiating the energy at the theoretical Eddington upper limit) at $z_t \sim 200$ that fit the spectrum measurements then available. This model requires highly special conditions, and of course it fails to account for the light element abundances, but still it would be interesting to see whether the model could be arranged to fit the new spectrum measurements.[15,16]

In Alfven's[11] "Plasma Universe" we are part of a finite cloud of material expanding into empty asymptotically flat space. If the CBR were present in the otherwise empty space into which the galaxies are moving, it would be an extreme coincidence that we are moving at the observed low velocity ~ 600 km s^{-1} relative to the CBR,[23] since most galaxies are moving away from us at relativistic speeds. In the version discussed by Lerner,[84] the CBR is radiated from material in the expanding cloud. Here the above mentioned problem of making the opacity high enough to get a thermal spectrum without obscuring distant radio galaxies is exacerbated by the fact that the cloud would hardly be expected to be spherically symmetric to the degree required to account for the isotropy of the CBR[23] (isotropic to better than one part in 10^4 on angular scales ~ 15 arc minutes to 180°). The anisotropic expansion of the plasma cloud would cause anisotropic dimming of the CBR due to the redshift, in violation of the observations. In this model, rifts in the emitting clouds could permit observations of high redshift radio galaxies, but that would imply extreme variability in the mean redshift of the CBR in different directions, causing strong anisotropy, again in violation of the observations.

The Chronometric theory of Segal,[12] which gives a quadratic redshift distance relation, would have been a useful spur to discussion if introduced in the late 1920s, when the linear relation was proposed on limited observational grounds. However, the modern tests of the redshift distance relation[20,21] convincingly rule out the chronometric relation, so it perhaps is not surprising that discussions of this model have not even reached the stage of addressing the problems of the CBR spectrum and the light element abundances.

Finally, in a pure fractal model, the galaxy distrbution is a scale invariant clustering hierarchy.[13,14] On small scales the observed galaxy distribution is well approximated as a fractal with dimension $D = 1.23 \pm 0.04$.[85] However, as Mandelbrot's[13] dramatic examples show, a pure fractal (with a single dimension) has the same appearance under a change of scale. That is, in a pure fractal universe the galaxy distribution would be as clumpy in deep samples as in shallow ones, quite contrary to the observations.[4,19,85]

Summary

The standard model was proposed in the late 1920s on the slightest of theoretical grounds (consistency with Mach's principle, and the simplest and most analytically tractable model compatible with general relativity theory) and observational evidence (marginally significant indications of large-scale uniformity in the galaxy space distribution, and of a linear redshift distance relation for nearby galaxies).[86] It would have been natural to expect that this naïve model would have to be heavily modified or even abandoned as more data became available, but that is not what has happened. The model has been extended in a natural way to include the CBR and light element nucleosynthesis, and it has led to the search for new physics, in connection with the puzzle of the very early universe and the nature of the dark matter.[17] But the basic picture has survived the great advances in astronomy and physics in the six decades since its conception. Major successes include the enormous extensions of the homogeneity and redshift tests; the consistency of timescales from cosmology, stellar evolution theory, and radioactive decay ages; the thermal spectrum of the CBR; the observational and experimental tests of the theory of light element production; the observation of cosmic evolution; and the interpretation of galaxy-quasar gravitational lensing.

A good scientific theory is falsifiable. In view of its above enumerated "escapes" from falsification, it is worth emphasizing that the standard hot Big Bang model satisfies this criterion; it is not so vague and flexible, nor our observational characterization of the universe so slight, that that the standard model could survive a wide variety of possible outcomes of observations or experiments. Here are some examples. If the galaxy distribution had been observed to follow a pure scale-invariant fractal, a possibility that would have been quite difficult to rule out in the late 1920s, the closely thermal spectrum and isotropy of the CBR in this highly inhomogeneous universe would have been a deep puzzle. Whatever the baryon distribution at light element nucleosynthesis, the match of theory to observation indicates that the primordial ^{4}He mass fraction should be near 24% . The discovery of an extragalactic object with a well established mass fraction in ^{4}He of, say, 0.15 would be another serious, if not fatal, problem. The same would have been true if experiments at LEP had found $N_\nu = 5$ light neutrino families, instead of the predicted and observed values close to three. Astronomers could have discovered a class of distant objects with large blue shifts. That would have shown that the fundamental kinematics of the Big Bang model are seriously incomplete. And, for a final example, the discovery of a star cluster with a stellar evolutionary age of, say, 10^{11} years would put the product $H_o t_o$ well outside the range allowed by the uncertainty in the cosmological parameters.

Physical cosmology today is in an exciting state. Research is being driven by a large and growing flow of observations, and in turn is driving new investigations, from the theorists' search for the physics of the very early universe to the experimentalists' searches for nonbaryonic dark matter. The standard model has incorporated this flow of new results in a remarkably clean way. That is what has caused us to conclude that there is a strong case for the Big Bang as a useful approximation to reality. To our colleagues who retain a healthy degree of scepticism about the possibility of deducing the nature of the universe from what little we can observe of it, we will grant that the evidence conceivably could have been misread, but we emphasize that the error would have to be subtle indeed to have been hidden within the broad suite of evidence we now have.

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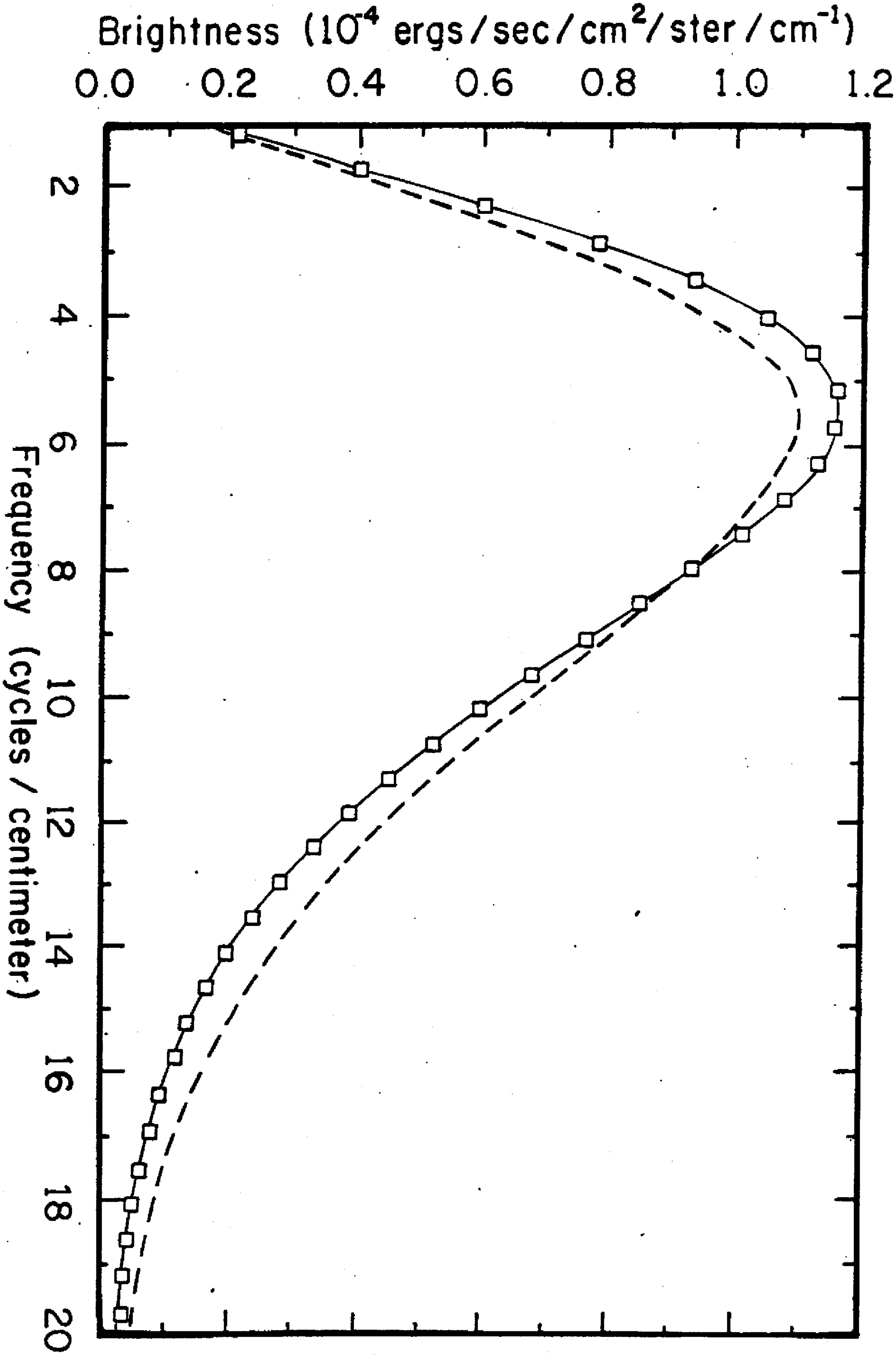
Figure 1. Spectrum of the cosmic microwave background from COBE.[15] The boxes are statistically independent measurements. The solid line is the best fit for the thermal spectrum predicted by the standard model. The dashed line shows the predicted spectrum in a Steady State cosmology in which the optical depth in dust reaches unity at redshift $z \sim 0.3$.

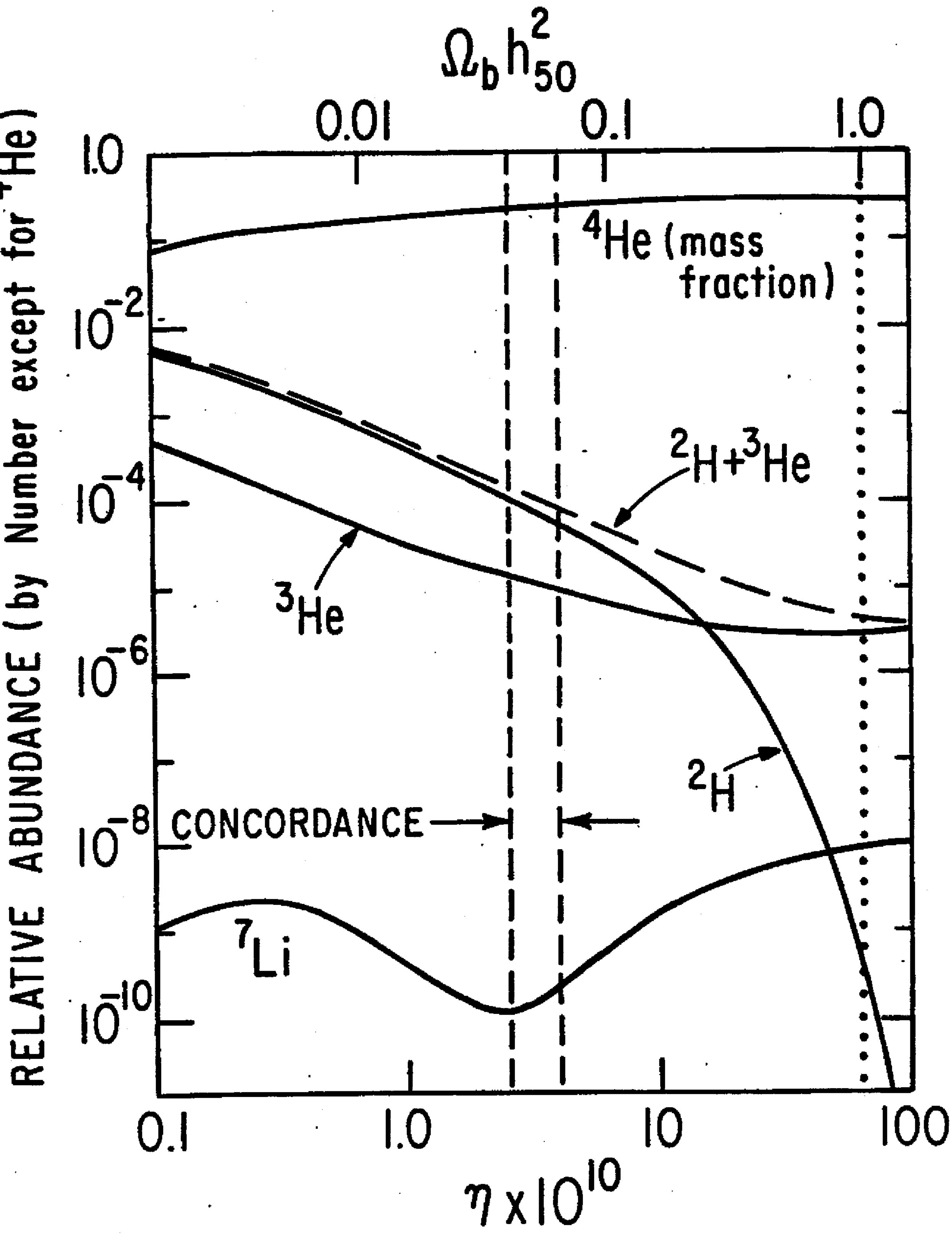
Figure 2. Abundances predicted in the homogeneous standard model as functions of the baryon to photon ratio, η, or, equivalently, the fraction of the critical density, Ω_b. (This figure is based on ref. 26.)

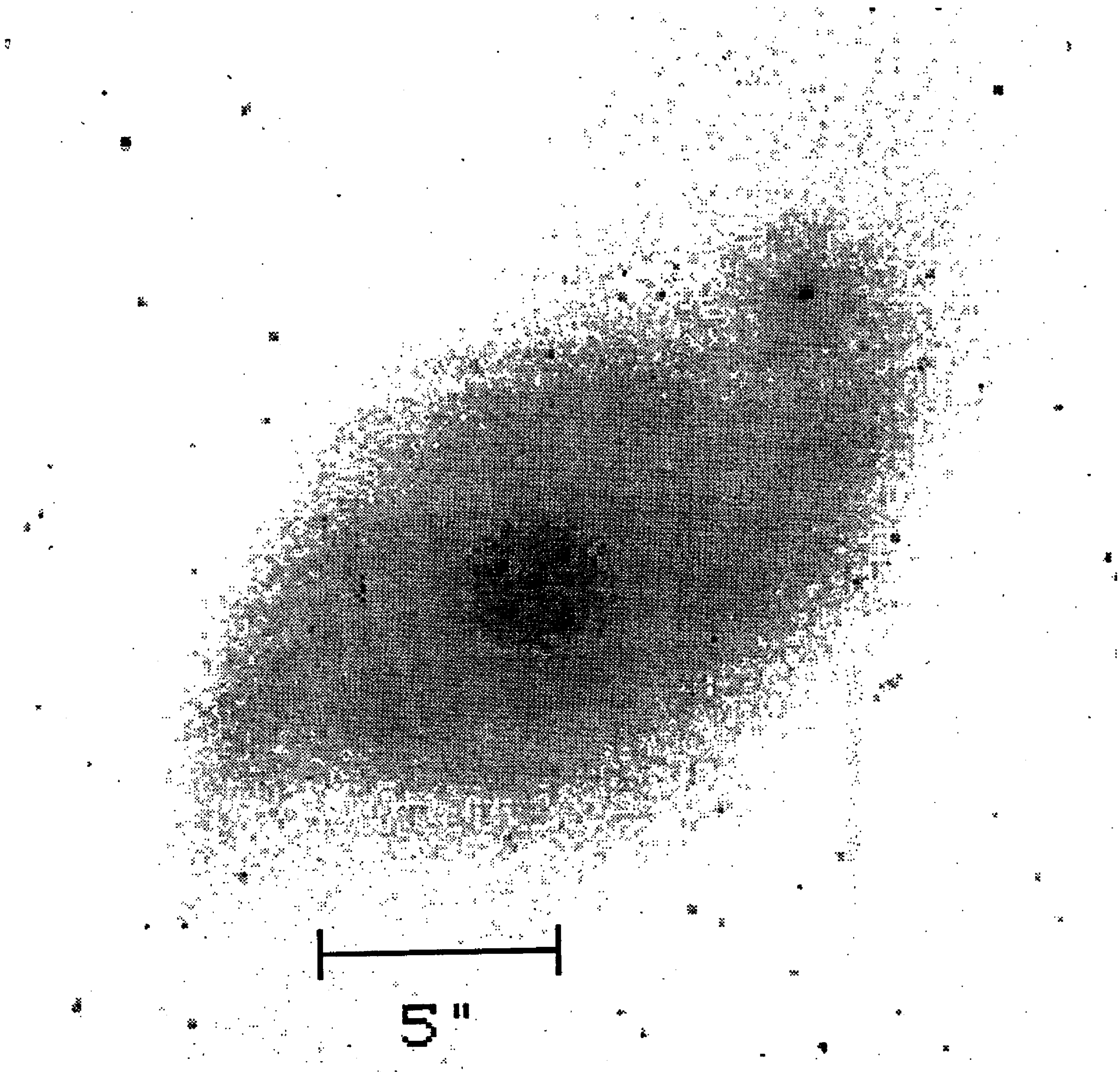
Figure 3. This F702W (near infrared) band image of Q2237+0305 obtained with the Hubble Space Telescope (HST) shows four distinct quasistellar images of the redshift 1.695 quasar (the source). The ordinary barred spiral galaxy at redshift 0.0394 (the lens) is seen as the diffuse light centered on the four quasar images. (Photograph courtesy of NASA. Image taken with the JPL Wide Field Camera.)



Brightness (10^{-4} ergs / sec / cm^{2} / ster / cm^{-1})
0.0 0.2 0.4 0.6 0.8 1.0 1.2
Frequency (cycles / centimeter)
2 4 6 8 10 12 14 16 18 20

BIG BANG NUCLEOSYNTHESIS





X1: 1 Y1: 1