forms in the present epoch and at modest redshifts in the recent past. There is also good observational evidence for the presence of noncosmological redshifts. The observations fit into our theory very well.

But those who have adopted the standard cosmological model simply ignore them. On the other hand, they have to make many assumptions that have no basis in direct observation. There is, for example, no *primary* observational evidence for initial density fluctuations, for nonbaryonic matter of the kind they invoke for large-scale structure scenarios, for biasing in galaxy formation or for their assumption that clusters of galaxies must always obey the virial condition. These are all *ex post facto* theoretical postulates that allow the standard model makers to build what may well turn out to be a make-believe universe.

References

1. R. Wagoner, W. Fowler, F. Hoyle, Ap. J. **148**, 3 (1967).
2. R. Alpher, R. Herman, Rev. Mod. Phys. **22**, 153 (1950).
3. F. Hoyle, G. Burbidge, J. Narlikar, Astrophys. J. **410**, 437 (1993); Mon. Not. R. Astron. Soc. **267**, 1007 (1994); Astron. Astrophys. **289**, 729 (1994); Proc. R. Soc. London Sec. A **448**, 191 (1995).
4. G. Sears, Ann. NY Acad. Sci. **65**, 388 (1957). F. Nabarro, P. Jackson, in *Growth and Perfection in Crystals,* R. Daramus, B. Roberts, D. Turnbull, eds., Wiley, New York (1958).
5. E. M. Burbidge, G. Burbidge, W. Fowler, F. Hoyle, Rev. Mod. Phys. 29, 547 (1957). A. Cameron, Chalk River Nuclear Labs. Report CRL-41, Chalk River, Ontario (1957).
6. G. Burbidge, F. Hoyle, Astrphys. J. Lett. **509**, L1 (1998).
7. A. McKellar, Publ. Astron. Soc. Pac. **52**, 407 (1940).
8. A. Cameron, W. Fowler, Astrophys. J. **104**, 111 (1971).
9. W. Sargent, J. Jugaku, Astrophys. J. **134**, 777 (1961).
10. E. Chupp, D. Forrest, P. Higbie, A. Suri, C. Tsai, P. Dunphy, Nature **241**, 333 (1973).
11. *A Life in Astrophysics—Selected Papers of V. A. Ambartsumian*, Allerton, New York (1998).
12. V. A. Ambartsumian, in *Solvay Conf. Reports*, R. Stoops, ed., Brussels (1958); Trans. IAU **11B**, 145 (1962); in Proc. 13th Solvay Conf. on Physics, U. Brussels, P. Prigogine, ed.,Wiley Intersciences, New York (1965), p. 1.
13. G. Burbidge, E. M. Burbidge, A. Sandage,, Rev. Mod. Phys. **35**, 947 (1963).
14. J. Ostriker, J. Peebles, A. Yahil, Astrophys. J. **193**, L1, (1974). J. Einasto, A. Kansik, E. Saar, Nature **250**, 319, (1974). G. Burbidge, Astrophys. J. **196**, L7 (1975).
15. W. A. Fowler, F. Hoyle, Mon. Not. R. Astron. Soc. **125**, 169 (1963). F. Hoyle, W. A. Fowler, G. Burbidge, E. M. Burbidge, Astrophys J. **139**, 909 (1964).
16 G. Burbidge, in *Proc. 13th Solvay Conf. on Physics,* P. Prigogine, ed. Wiley Intersciences, New York (1965), p. 137. M. Rees, Annu. Rev. Astron. Astrophys. **22**, 471 (1984).
17. E. M. Burbidge, G. Burbidge, P. Solomon, P. Strittmatter, Astrophys. J. **270**, 233 (1971). H. C. Arp, *Quasars, Redshifts and Controversies*, Interstellar Media, Berkeley, Calif. (1987). Y. Chu *et al.*, Astron. Astrophys. **138**, 408 (1984). X. F. Zhu, Y. Q. Chu, Astron. Astrophys. **297**, 300 (1995). M. Bartelmann, P. Schneider, Astron. Astrophys. **271**, 421 (1993); **284**, 1 (1994). G. Burbidge, Astron. Astrophys. **309**, 9 (1996). This last paper lists all known associations of bright galaxies and quasars separated by less than 3 arcminutes.
18. W. Pietsch, A. Vogler, P. Kahabka, A. Jain, V. Klein, Astron. Astrophys. **284**, 386 (1994). E. M. Burbidge, Astron. and Astrophys. **298**, L1 (1995); Astrophys. J. Lett. **484**, L99 (1997). Y. Chu *et al.*, Astrophys. J. Lett. **500**, L596 (1998). H. Radecke, Astron. Astrophys. **319**, 18 (1997). H. Arp, Astron. Astrophys. **319**, 33 (1997). ■

Reply to "A Different Approach to Cosmology"

Expanding surveys of galaxy redshifts and fluctuations in the microwave background continue to rein in the cosmologist's freedom to invent.

Andreas Albrecht

As physicists confront the unknown, a crucial part of the job is choosing a set of assumptions that will guide their efforts in productive directions. The only certainty is that only a small fraction of the many conceivable outcomes of the inquiry process will remain viable as the field continues to progress—assuming it does indeed progress. Along the way, choices must be made: Which results should be taken as important hints to be used as the foundations of future work, and which results should be viewed with skepticism, needing further confirmation before being allowed to influence the field significantly? Those who wind up making good choices (either through wisdom or good luck) will eventually be recognized as pioneers.

The same body of data can produce different interpretations, depending on what prejudice the researcher starts out with. (This idea is formalized in the "priors" of Bayesian inference.) As data on a given question become more conclusive, the broader will be the range of prior prejudices that converge on a consensus. Geoffrey Burbidge, Fred Hoyle and Jayant Narkilar, the authors of the preceeding article, "A Different Approach to Cosmology," approach cosmology with a set of prior prejudices that take them far afield from the mainstream community of cosmologists.[1] They hold on to views that, I must say, look pretty unreasonable to most of us working in the field. Nonetheless, I believe convergence will eventually be possible.

First, let me briefly discuss some of the key points of departure:

▷ **Primordial nucleosynthesis**. One important issue is the origin of the light elements. It is commonly understood that the lightest nuclear species (in particular, deuterium, ^{3}He, ^{4}He and ^{7}Li) were produced in the immediate aftermath of the Big Bang, after temperatures and densities had became low enough to allow net production to go forward.[2] All this was long before there were any stars around to change the nuclear abundances. The fact that this primordial nucleosynthesis can be calculated and successfully fit to the observed light-element abundances with only one free parameter (the baryon-to-photon ratio) is widely held as a great success of standard Big Bang cosmology. (See PHYSICS TODAY, August 1996, page 17.) Otherwise, such a good fit would have to be an extraordinary coincidence, because most conceivable sets of abundance data would fail to fit the

ANDREAS ALBRECHT *is a professor of physics at the University of California, Davis.*

model for *any* value of the baryon-to-photon ratio.

Burbidge and company are more impressed with a different coincidence: If one assumes that all the ^{4}He in the cosmos was produced in stars, the resulting radiation turns out to have about the same energy density as that of the observed microwave-background radiation. Their line of reasoning also embraces an exotic stellar alternative for the origins of ^{3}He and ^{7}Li. While acknowledging that there is no known way of generating a net deuterium increase in stellar processes, they appeal to a combination of remaining uncertainties in the observations and what they feel is an inherently compelling belief that a stellar origin for deuterium is *better*, to hold out hope that some future insight will allow them to build models that do not require cosmic deuterium production.

▷ **Dark matter** is another issue on which Burbidge *et al.* diverge from the mainstream.[3] While conceding that there is clear evidence for dark matter in the universe, they insist that there are some situations in which the dark matter presumed in the standard model is, in reality, absent. That would imply gravitationally unbound galaxy clusters where others expect dark matter to provide the necessary binding force. They regard the fact that the dark matter has not yet been found and the diverse speculations about its exact nature as significant weaknesses of the standard Big Bang cosmology. At the same time, they purport to improve the situation by inventing the purpose-built energy injection mechanism their model requires—all this while admitting that they also need *some* dark matter.

▷ **Redshifts** are another area of the authors' divergence from the mainstream. In an expanding universe, light from distant objects is Doppler shifted to longer wavelengths by the relative motion of source and observer. The model that Burbidge and company prefer presumes an oscillatory cosmos in which the present epoch finds itself quite far along in a cyclic expansionary phase. Their model yields objects with redshifts as high as $z = 5$, essentially the same value as the largest redshifts observed to date. Still, they prefer to interpret some high quasar redshifts to high ejection velocities and "intrinsic" redshifts of unknown provenance, rather than to great distance and correspondingly great Hubble velocity. While emphasizing apparent associations between quasars and galaxies at much lower redshifts, which most of us think are not clearly statistically significant,[1] they do not even mention the modern studies that link high-redshift quasars with host galaxies at the *same* redshift.[4]

The main reason, it would seem, that the "steady-state cosmology" became the *quasi*-steady-state cosmology, with its hundred-billion-year oscillation period, was the problem of turning the highly nonthermal radiation from the ^{4}He-producing stars into the thermal microwave background observed by the COBE satellite. The thermalization couldn't have happened at the low cosmic density. Even at the higher densities earlier in the present oscillatory cycle, the quasi-steady-state scenario requires the authors to postulate the existence of exotic dust grains to achieve thermal equilibrium.

▷ **Active galactic nuclei** are widely understood to be driven by the release of gravitational energy, possibly through very efficient hydromagnetic processes. But Burbidge *et al.* invoke a dissident, *ad hoc* energy injection mechanism instead. They refer to a 1966 paper of theirs to claim that the release of gravitational energy is known to be inefficient, but they simply dismiss work during the last 35 years that leads to the opposite conclusion.[5]

Metaphysics

In the process of articulating their particular set of choices and directions, Burbidge, Hoyle and Narlikar often resort

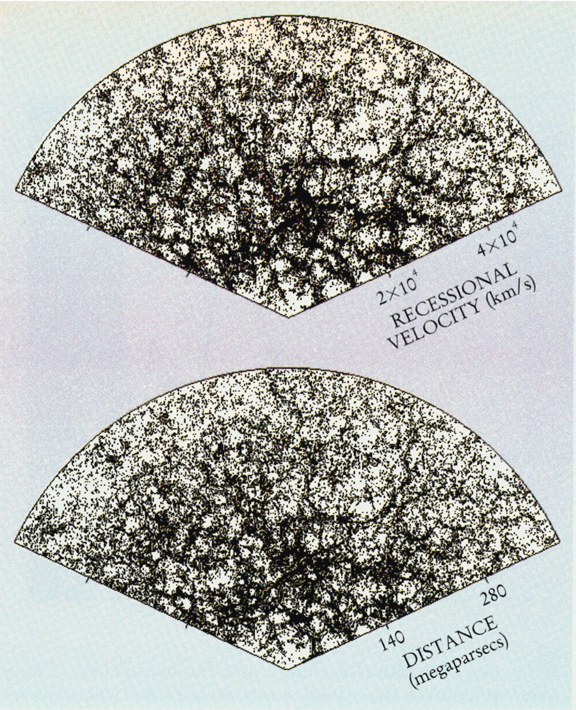

FIGURE 1. SIMULATED REDSHIFT SURVEY shows the depth and detail of galaxy clustering that the Sloan Digital Sky Survey expects to see in a wedge of 65 000 galaxies, each represented by a dot on these scatter plots of redshift against celestial longitude. The survey expects to measure about 20 such wedges. Both plots are for the same strip of sky, 130° wide and 6° thick. The only difference is that the radial coordinate in the lower figure is labeled in distance rather than recessional velocity (assuming a Hubble constant of 70 megaparsecs per km/s), and that the lower plot has been corrected for "fingers of God," artifacts that exaggerate filaments and appear to point back to us. They are due to large non-Hubble internal velocities in big clusters.

to philosophical arguments to bolster their positions. They are concerned, for example, that the Big Bang model does not start with initial conditions that are "known from observation or experiment." Apparently they feel that their particular package of assumptions and extrapolations does better on this score. Sometimes, they appeal to aesthetic arguments.

Of course, it is not uncommon to invoke philosophical arguments when one is trying to chart a way through unfamiliar territory. That is as true of the mainstream cosmology community as it is of our detractors. The key to progress is that the philosophical arguments matter less and less as the data accumulate. A good example is the issue of the cosmological constant. It was not too long ago that any cosmologist worth his salt could rattle off several reasons why the cosmological constant had to be zero today. But now the data strongly favor a nonvanishing cosmological constant, and the discussion has moved on to how our theories might accommodate it. (See PHYSICS TODAY, June 1998, page 17.)

One of the great things about modern cosmology is that many more such successes can be expected in the near future. We are on the verge of acquiring an extraordinary wealth of new data that promise to lay many open questions to rest. In fact, the flow of new data has already had an enormous impact. Many ideas that were popular not long ago have fallen by the wayside.[6] This abundance of observations has affected everyone who works in cos-

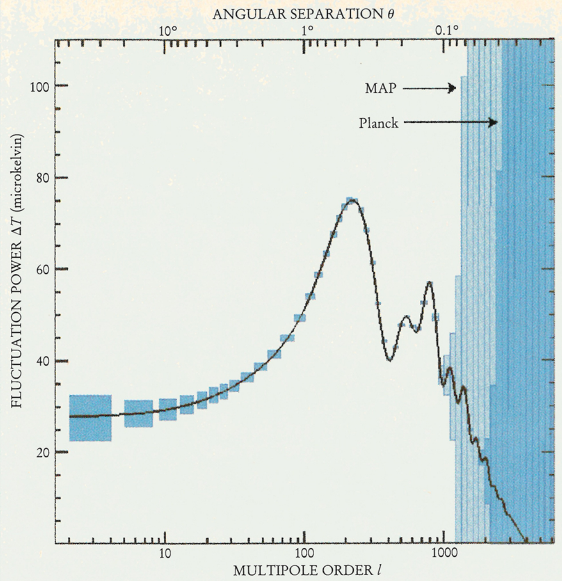

FIGURE 2. ANTICIPATED UNCERTAINTIES in the measurement of cosmic microwave background fluctuations by the MAP and Planck satellite missions, scheduled for 2001 and 2007, respectively. The microwave background's departure from isotropy is represented by the spherical-harmonic power spectrum of point-to-point fluctuations from the mean temperature (≈ 2.73 K). The abscissae indicate multipole order and corresponding angular separation of the points being compared. Predicted positions of the peaks, which depends on cosmological parameters, are shown here for critical mass density ($\Omega_m = 1$) with no cosmological constant. For $l < 1000$, both missions will have about the same resolution. For higher multipoles, however, Planck should do better. (Figure courtesy of W. Hu.[9])

mology, not excluding Burbidge and his coauthors. There is every hope that the steady confrontation between theory and new observations will, before too long, bring us to convergence.

Challenges

In the interest of encouraging this convergence, I would like to pose two challenges to Burbidge *et al.* First, they should bring their model up to current standards, in terms of comparison with data. Specifically, a huge body of information now exists on the distribution of matter and radiation in the universe. (See, for example the PHYSICS TODAY articles by H. Ferguson, R. Williams and L. Cowie, April 1997, page 24, and by C. Bennett, M. Turner and M. White, November 1997, page 32.) Already, several popular models have failed when confronted by the new data. Some key points of confrontation have been the two-point and higher-order correlation functions of the matter and radiation distributions. What predictions do do Burbidge and company make for these correlations? Even if their model is currently too phenomenological to predict all these quantities, it must be possible to say something. For example, given the two-point function of galaxies, exactly what is their prediction for the COBE background fluctuation measurements?

Also, exactly what claims are the quasi-steady-staters making about redshifts? Their model appears to require that, in the present cyclic expansion phase, genuine cosmological Hubble redshifts be present in the range observed. What part of the multitude of modern redshift observations do they suggest is attributable the ejection processes they favor, or to "intrinsic" non-Doppler spectral shifts? For many quasars, host galaxies have now been observed at the *same* high redshift. How do those results fit into the quasi-steady-state picture?

The second challenge I would pose to Burbidge and company is to prepare for the future data sets. A new generation of experiments, such as the Sloan Digital Sky Survey (figure 1) and the MAP and Planck microwave-background observer satellites (figure 2), will make dramatic new demands on theoretical models. For example, in preparation for these new data sets, it is important to calculate the microwave-background anisotropies to within better than 1%. The cosmic microwave background appears to be a particularly promising avenue. The quasi-steady-state adherents propose an origin for this background that differs radically from the various mainstream models. It is extremely unlikely that their predictions would duplicate any of the others at the 1% level.[7]

Burbidge *et al.* make a point of their inability to get time on the big telescopes to pursue their ideas, but those facilities are so oversubscribed that even many highly rated mainstream proposals must be turned away. Still, they have enormous resources at their disposal. Almost all of the current data is in the public domain, and the new data will also be made public after a short proprietary period.

As extreme as the ideas of the quasi-steady-state cosmology may appear to those of us more in the mainstream, we freely admit that there are also domains of mainstream cosmology that are far from being settled. Within such domains, different groups have emerged, each regarding the others as extreme. In fact, proposals have emerged in the context of inflation that bear some superficial resemblance to the steady-state models.[8]

The thing that keeps us all going is the conviction that the wealth of new data will intervene to let us make genuine progress. We have every reason to expect that the new observations will also enlighten the debate between the proponents of the "different approach" and the rest of us.

References

1. J. Peebles, D. Schramm, M. Turner, R. Kron, Nature **352**, 769 (1991) clearly spells out the case for the standard Big Bang model. For a more current picture, see M. Turner, J. A. Tyson, astro-ph/9901113, to be published in the centennial volume of Rev. Mod. Phys.
2. K. A. Olive, astro-ph99/01231, to be published in *Proc. Of the Theoretical and Observational Summer School, Cargese, Corsica, 1998*, M. Lachieze-Ray, ed. NATO Science Series, Kluwer, Dordrecht, The Netherlands. G. Steigman, to appear in *Proc. of the 2nd Oak Ridge Symp. on Atomic and Nuclear Astrophys., 1997*, A. Mezzacappa, ed., Institute of Physics, Bristol, England.
3. M. Turner, astro-ph/9901109, in *Proc. of the Nobel Symp. on Particle Physics and the Universe, Enkoping, Sweden, August 1998*, to be published in Physica Scripta.
4. See, for example, C. Kochanek, in *After the Dark Ages: When Galaxies Were Young*, (proc. oOf the 9th Annual Astrophysics Conference in Maryland), S. Holt, E. Smith, eds., American Institute if Physics, New York (1998).
5. M. Rees, Annu. Rev. Astron. Astrophys. **22**, 471 (1984). J. Frank, A. King, D. Raine, *Accretion Power in Astrophysics*, Cambridge U. P., Cambridge, England (1996).
6. M. Tegmark, Astrophys. J. Lett., in press. U.-L. Pen, U. Seljak, N. Turok, Phys. Rev. Lett. 79, 1611 (1997). A. Albrecht, R. Battye, J. Robinson, Phys. Rev. Lett. **79**, 4735 (1997). B. Allen *et al.*, Phys. Rev. Lett. **79**, 2624 (1997).
7. A. Albrecht, D. Coulson, P. Ferriera, J. Magueijo, Phys. Rev Lett. **76**, 1413 (1996). M. White, W. Hu, in *Proc. Of the XXXIst Moriond Meeting: Microwave Background Anisotropies*, F. Bouchet *et al.*, eds., Editions Frontiers, Singapore (1997), p. 339.
8. A. Linde, D. Linde, A. Mezhlumian, Phys. Rev. D **49**, 1783 (1994).
9. W. Hu, N. Sugiyama, J. Silk, Nature **386**, 37 (1997). ■