change the past without jeopardizing their subsequent existence in the present? Barrow argues that the causal significance of a time traveler should not be presumed. He holds that if the traveler were to have an impact, the effects would render history "different" but not "changed," since the latter expression implies a necessary course to history that contradicts the possibility of genuine action of any sort, be it by a native or an alien of a given time.

The conundra surrounding time travel arise if the past exerts an asymmetrical control over the present comparable to an imperial power over a distant colony. But what if the past is no more than a sphere of influence in the present? Even without eliminating the foreign presence, the natives can nevertheless substantially contain its influence. Take that favorite destination of time travelers, the moment Lincoln was shot by John Wilkes Booth. If future historians were to agree that prolonging Lincoln's life would have made little difference to the overall course of history, then little would be gained by replaying what happened on April 14, 1865. Indeed, if the "turning point" came to be seen as a motif in popular historical writing, rather than an important joint at which reality is cut, then the fascination with time travel might simply evaporate. Of course, Booth's murder of Lincoln would remain, but who ever said that altering an event is either necessary or sufficient for altering its significance?

Those who think they understand what is and is not possible should envisage what would happen if scientists succeeded in creating a workable time machine just when the idea of time travel came to be seen as old-fashioned. It would be like discovering limitless supplies of coal and petroleum on neighboring planets, just when we shift to more economical sources of fuel or simply learn to economize on fuel altogether. These are examples of what Hegel called the "cunning of reason," whereby knowledge and desire interact in ways that guarantee that all putative limits on human achievement will eventually become obsolete. Hopefully, in the second edition of his provocative book, Barrow will include a section entitled: "History: Is the universe safe for physicists?"

**RESEARCH: COSMOLOGY**

# The Case of the Curved Universe: Open, Closed, or Flat?

Marc Kamionkowski

Determination of the geometry of the universe has been a central goal of cosmology ever since Hubble discovered its expansion 75 years ago. Is it a multidimensional equivalent of the two-dimensional surface of a sheet of paper ("flat"), a sphere ("closed"), or a saddle ("open")? The geometry determines whether the universe will expand forever or eventually recollapse, and it may also shed light on its origin. Particle theories suggest that in the extreme temperatures prevalent in the very early universe, gravity may have briefly become a repulsive, rather than attractive, force. If so, the ensuing period of "inflation" (*1*) could account for some of the most fundamental features of the universe, such as the remarkable smoothness of the cosmic microwave background, the afterglow of the big bang (see schematic timeline).

Until now, most astronomers have pursued the geometry by attempting to measure the mass density of the universe. According to general relativity, if the density is equal to, larger than, or smaller than a "critical density" fixed by the expansion rate, then the universe is flat, open, or closed, respectively. Several measurements currently seem to suggest a density only a fraction $\Omega \cong 0.3$ of the critical density (as opposed to $\Omega = 1$ predicted by inflation). However, most of these measurements probe only the mass that clusters with galaxies. If a substantial amount of some more diffuse component of matter exists, such as neutrinos or "vacuum energy" (Einstein's cosmological constant), then the measurements do not necessarily tell us the geometry of the universe. The research article by Gawiser and Silk (*2*) on page 1405 of this issue and an accompanying commentary on page 1398 by Primack tell this side of the story (*3*).

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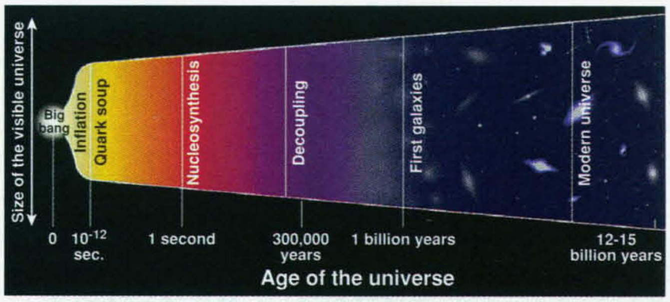
Another possibility is to look directly for the effects of a curved universe. As an analogy, consider geometry on a two-dimensional surface. On a flat surface, the interior angles of a triangle sum to 180° and the circumference of a circle is $2\pi$ times its radius. However, when drawn on the surface of a sphere, the interior angles of a triangle sum to more than 180°, and the circumference of a circle is less than $2\pi$ times the radius. Similar lines of reasoning show that in an open (closed) universe, objects of some fixed size will appear to be smaller (larger) than they would in a flat universe.

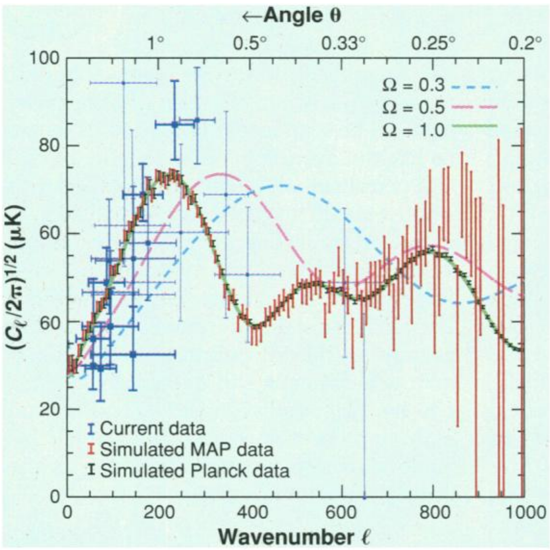



**From smooth to structured.** Schematic history of the universe. The big bang may have been followed by a period of rapid inflation, with the resulting "soup" of particles coalescing into nucleons and lighter elements. Matter and radiation eventually became decoupled, the former gravitationally clumping into the structure of the modern universe and the latter yielding the microwave background we see today. The seeds from which galaxies grew should be apparent in the variations in the radiation background.

ADAPTED FROM ILLUSTRATION BY B. SANDERS, THE NATIONAL CENTER FOR SUPERCOMPUTING APPLICATIONS, UNIVERSITY OF ILLINOIS

The problem, then, is to find distant objects in the universe of known size ("standard rulers"). It was recently proposed that features at the cosmic microwave background surface of last scatter could provide such standard rulers (*4*). The photons that make up the cosmic microwave background last scattered roughly 10 to 15 billion years ago, when the universe was only 300,000 years old. Therefore, when we look at the cosmic microwave background, we see a spherical surface in the early universe 10 to 15 billion light-years away. Although galaxies and clusters of galaxies had not yet formed, the seeds that later grew into these structures existed, and we know the distribution of their intrinsic sizes. By measuring the distribution of their apparent sizes on the sky, we can determine the geometry of the universe.

More precisely, one must measure the angular power spectrum of the cosmic microwave background: Suppose we measure the temperature $T(\theta)$ as a function of direction θ on the sky over some approximately square region of the sky. We may then compute the Fourier transform $\tilde{T}(\vec{\ell})$ of this temperature map. The power spectrum is then given by the set of multipole moments $C_\ell = \langle\tilde{T}(\vec{\ell})\tilde{T}^*(\vec{\ell})\rangle$ where the angle brackets denote an average over all wavevectors $\vec{\ell}$ of magnitude $|\vec{\ell}| = \ell$. Roughly speaking, each $C_\ell$ measures the mean-square temperature difference between two points separated by an angle $\theta \cong (200/\ell)$, so larger-$\vec{\ell}$ modes measure temperature fluctuations on smaller angular scales. Increasingly accurate measurements of the $C_\ell$ values require mapping larger portions of the sky to reduce the sampling error. Precise temperature measurements are also required. Good angular resolution is needed to determine the larger-$\vec{\ell}$ moments.




**Bumps in the background.** Power spectrum of the cosmic microwave background as a function of angle θ or wavenumber ℓ. Curves show spectral behavior expected for different mass densities, Ω. Future MAP data (simulated, red) should permit better constraints on which curve accurately represents the cosmic microwave background. Even better constraints should be produced by the future Planck Surveyor mission (simulated, black).

If galaxies and clusters grew from gravitational instability of tiny primordial density perturbations, then the cosmic microwave background power spectrum (the $C_\ell$) should look like the curves shown in the graph. The bumps in the curves are due to physical processes that lead to large-scale structures. If Ω is smaller than unity, then the universe is open and the structure in the cosmic microwave background is shifted to smaller angular scales, or equivalently, larger $\vec{\ell}$ values. Therefore, the location of the peaks (primarily the first peak) in the cosmic microwave background spectrum determines Ω and thus the geometry of the universe (*4*).

The blue points in the graph are current measurements from balloon-borne and ground-based experiments. Several groups (*5*) have recently found a value of Ω consistent with unity by fitting these data to the theoretical curves. Although these results are intriguing and perhaps suggestive, even a cursory glance demonstrates that the current data cannot robustly support a flat universe.

However, a new generation of experiments will soon provide substantial advances. As indicated by the red points in the graph, the Microwave Anisotropy Probe (MAP), a NASA satellite mission scheduled for launch in the year 2000, should confirm the peak structure suggested by the gravitational-instability paradigm (if it is correct) and make a precise determination of the geometry. The Planck Surveyor, a European Space Agency mission scheduled for launch in 2005, should improve on MAP's precision and may also illuminate the nature of the missing mass.

If the peak structure of gravitational instability is confirmed and the measurements are precisely consistent with the inflationary prediction of a flat universe, then new avenues of inquiry will be opened to provide clues to the new particle physics responsible for inflation. As one example, the polarization of the cosmic microwave background may probe a stochastic background of gravitational waves predicted by inflation (*6*).

### References


1. A. H. Guth, *Phys. Rev. D* **28**, 347 (1981); A. D. Linde, *Phys. Lett.* **108B**, 389 (1982); A. Albrecht and P. J. Steinhardt, *Phys. Rev. Lett.* **48**, 1220 (1982).
2. E. Gawiser and J. Silk, *Science* **280**, 1405 (1998).
3. J. Primack, *ibid.*, p. 1398.
4. M. Kamionkowski, D. N. Spergel, N. Sugiyama, *Astrophys. J. Lett.* **426**, L57 (1994).
5. C. H. Lineweaver and D. Barbosa, *Astrophys. J.* **496**, 624 (1998); S. Hancock *et al.*, *Mon. Not. R. Astron. Soc.* **294**, L1 (1998).
6. M. Kamionkowski, A. Kosowsky, A. Stebbins, *Phys. Rev. Lett.* **78**, 2058 (1997); U. Seljak and M. Zaldarriaga, *ibid.*, p. 2054.


**COSMOLOGY**

# A Little Hot Dark Matter Matters


Joel R. Primack


One of the fundamental issues facing cosmologists is: what is the matter? We know that observable matter only makes up a fraction of what is needed to have a universe with the properties observed. A large portion of the matter in the universe must therefore be unobserved or dark matter. But what is the nature of this unseen mass? Gawiser and Silk conclude in an article on page 1405 of this issue (*1*) that, of all the currently popular cosmological models, the only one whose predictions agree with the data on the cosmic microwave background anisotropies and the large-scale distribution of galaxies is the cold + hot dark matter model. [See also the related Research Commentary by Kamionkowski on page 1397 (*2*) for a discussion of the how this relates to the geometry of the universe and efforts to understand the microwave background.]

Gawiser and Silk settle on a critical-density (that is, Ω = 1) model in which most of the matter (70% of the total) is cold dark matter, 20% is hot dark matter, and 10% is ordinary baryonic matter. Hot dark matter is defined as particles that were still moving at nearly the speed of light at about a year after the big bang, when gravity first had time to encompass the amount of matter in a galaxy like the Milky Way; cold dark matter is defined as particles that were moving sluggishly then. Neutrinos are the standard example of hot dark matter, although other more exotic possibilities such as "majorons" have been discussed in the literature. Three species of neutrinos—$\nu_e$, $\nu_\mu$, and $\nu_\tau$—are known to exist. The thermodynamics of the early universe implies that, just as there are today about 400 microwave background photons per cubic centimeter left over from the Big Bang, there are about 100 per cubic centimeter of each of the three species of light neutrinos (including the corresponding anti-neutrinos). There are thus about $4 \times 10^8$ times as many of each species of neutrino as there are electrons or protons, and as a result a neutrino mass (in equivalent energy) of only 4.7 eV, a mere $10^{-5}$ of the electron's mass, corresponds to 20% of critical density in the cold + hot dark matter model. There is experimental evidence that at least some of the three neutrino species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