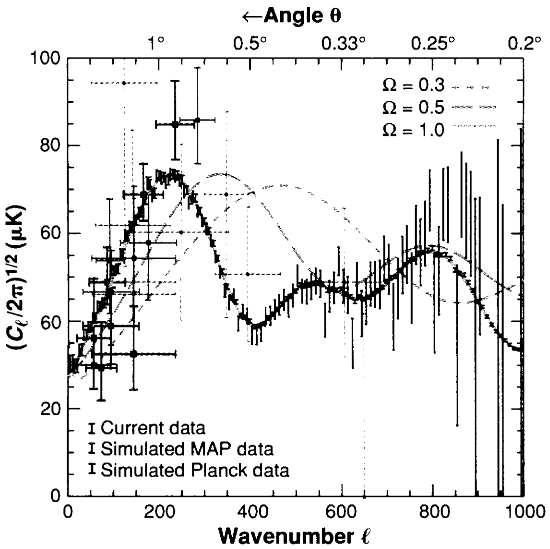

Bumps in the background. Power spectrum of the cosmic microwave background as a function of angle θ or wavenumber ℓ. Curves show spectral behavior expected for different mass densities, Ω. Future MAP data (simulated, red) should permit better constraints on which curve accurately represents the cosmic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

tion 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_ℓ 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_ℓ 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.

If galaxies and clusters grew from gravitational instability of tiny primordial density perturbations, then the cosmic microwave background power spectrum (the C_ℓ) 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*).

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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—ν_e, ν_μ, and ν_τ—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 4×10^8 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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have mass, although the evidence is not yet completely convincing. Yet even a small neutrino mass can affect the distribution of galaxies in the universe.

The relationship between the total neutrino mass $m(\nu)$ and the fraction Ω_ν of critical density that neutrinos contribute is $\Omega_\nu = m(\nu)/(94h^2 \text{ eV})$, where $h = 0.5$ to 0.8 is the expansion rate of the universe (Hubble constant H_0) in units of 100 km s^{-1} Mpc^{-1}. Direct measurements of neutrino masses have given only upper limits. The upper limit on the electron neutrino mass is roughly 10 to 15 eV; the Particle Data Group (*3*) notes that a more precise limit cannot be given because unexplained effects have resulted in substantially negative measurements of $m(\nu_e)^2$ in recent precise tritium beta decay experiments. There is an (90% confidence limit) upper limit on an effective Majorana neutrino mass of 0.45 eV from the Heidelberg-Moscow ^{76}Ge neutrinoless double beta decay experiment (*4*). The upper limits from accelerator experiments on the masses of the other neutrinos are $m(\nu_\mu) < 0.17$ MeV (90% confidence limit) (3) and $m(\nu_\tau) < 24$ MeV (95% confidence limit) (*3, 5*). Because stable neutrinos with such large masses would certainly "overclose the universe" (that is, prevent it from attaining its present age), cosmology implies a much lower upper limit on these neutrino masses. There is a small window for an unstable ν_τ with mass 0.1 to 20 MeV, which could have many astrophysical and cosmological consequences: relaxing the big-bang nucleosynthesis bound on the baryon density and the number of neutrino species, allowing nucleosynthesis to accommodate a wider range of primordial ^{4}He or deuterium abundance, improving the agreement between the cold dark matter theory of structure formation and observations, or helping to explain how type II supernovas explode (*6*).

But there are mounting astrophysical and laboratory data suggesting that neutrinos oscillate from one species to another, which can only happen if they have nonzero mass. The implications if all these experimental results are taken at face value are summarized in the table. Of these experiments, the ones that are most relevant to neutrinos as hot dark matter are the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos and the higher energy Kamiokande and Super-Kamiokande atmospheric (cosmic ray) neutrino experiments. But the experimental results that are probably most secure are those concerning solar neutrinos. The observation by LSND of events that appear to represent $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations followed by $\bar{\nu}_e + p \rightarrow n + e^+$, $n + p \rightarrow D + \gamma$, with coincident detection of e^+ and the 2.2 MeV neutron-capture gamma ray, suggests that $\Delta m^2_{e\mu} = |m(\nu_\mu)^2 - m(\nu_e)^2| > 0$ (*7*). The independent LSND data (*8*) suggesting that $\nu_\mu \rightarrow \nu_e$ oscillations are also occurring are consistent with, but have less statistical weight than, the LSND signal for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. Comparison of the latter with exclusion plots from other experiments allows a range of 10 eV$^2 \gtrsim \Delta m^2_{\mu e} \gtrsim 0.2$ eV^2. The lower limit in turn implies a lower limit $m_\nu \gtrsim 0.45$ eV, or $\Omega_\nu \gtrsim 0.02(0.5/h)^2$. This implies that the contribution of hot dark matter to the cosmological density is larger than that of all the visible stars $\Omega_{ast} \approx 0.004$ (*9*). Such an important conclusion requires independent confirmation. The Karlsruhe Rutherford Medium Energy Neutrino (KARMEN) experiment has added shielding to decrease its background so that it can probe a similar region of $\Delta m^2_{\mu e}$ and neutrino mixing angle, with sensitivity perhaps comparable to that of LSND by the end of 1999 (*10*). The proposed Booster Neutrino Experiment (BOONE) at Fermilab could attain greater sensitivity.

EXPERIMENTAL SOURCE	NATURE OF DATA
Solar ν_e deficit	$\Delta m^2_{ex} \sim 10^{-5}$ eV^2 $\sin^2 2\theta_{ex} << 1$
Atmospheric ν_μ deficit	$\Delta m^2_{\mu\tau} \sim 10^{-3}$ to 10^{-2} eV^2 $\sin^2 2\theta_{\mu\tau} \sim 1$ excludes $x = \tau$
LSND	$\Delta m^2_{\mu e} \sim 0.2$ to 10 eV^2 $\sin^2 2\theta_{\mu e} << 1$ excludes $x = \mu$, so solar $\nu_e \rightarrow \nu_s$
Cold + hot dark matter	$\Sigma m_\nu \sim 5$ eV for $h \sim 0.5$

Table: Data suggesting that neutrinos have mass

Older Kamiokande data (*11*) show that, for events attributable to atmospheric neutrinos with visible energy $E > 1.3$ GeV, the deficit of ν_μ increases with zenith angle. The much larger Super-Kamiokande detector has confirmed the results of its smaller predecessor (*12*). These data suggest that $\nu_\mu \rightarrow \nu_\tau$ oscillations occur with an oscillation length comparable to the height of the atmosphere, which implies that $\Delta m^2_{\mu\tau} \sim 10^{-3}$ to 10^{-2} eV^2. This in turn implies that if either ν_μ or ν_τ have large enough mass (~1 eV) to be a hot dark matter particle, then they must be nearly equal in mass (that is, the hot dark matter mass would be shared between these two neutrino species). Both the new Super-Kamiokande atmospheric ν_e data and the lack of a deficit of $\bar{\nu}_e$ in the CHOOZ reactor experiment (*13*) make it quite unlikely that the atmospheric neutrino oscillation is $\nu_\mu \rightarrow \nu_e$. It may be possible to verify that $\nu_\mu \rightarrow \nu_\tau$ oscillations occur through a long-baseline neutrino oscillation experiment to look for missing ν_μ due to $\nu_\mu \rightarrow \nu_\tau$ oscillations with a beam of ν_μ from the Japanese KEK accelerator directed at the Super-Kamiokande detector, with more powerful Fermilab-Soudan and possibly CERN–Gran Sasso long-baseline experiments later. However, the lower range of $\Delta m^2_{\mu\tau}$ favored by the Super-Kamiokande data will make such experiments more difficult than initially hoped.

The observed deficit of solar electron neutrinos in three different types of experiments suggests that some of the ν_e undergo Mikheyev-Smirnov-Wolfenstein matter-enhanced oscillations $\nu_e \rightarrow \nu_x$ to another species of neutrino ν_x with $\Delta m^2_{ex} \approx 10^{-5}$ eV^2 as they travel through the sun (*14*), although a recently proposed "astrophysical" explanation (*15*) of the solar neutrino deficit has not been ruled out (*16*). But the LSND $\nu_\mu \rightarrow \nu_e$ signal with a much larger $\Delta m^2_{e\mu}$ is inconsistent with $x = \mu$, and the Super-Kamiokande atmospheric neutrino oscillation data are inconsistent with $x = \tau$. Thus, a fourth neutrino species ν_s is required if all these neutrino oscillations are actually occurring. Because the neutral weak boson Z^0 decays only to three species of neutrinos, any additional neutrino species ν_s could not couple to the Z^0 and is called "sterile." This is perhaps distasteful, although many modern theories of particle physics beyond the standard model include the possibility of such sterile neutrinos. The resulting pattern of neutrino masses would have ν_e and ν_s very light and $m(\nu_\mu) \approx m(\nu_\tau) \approx (\Delta m^2_{e\mu})^{1/2}$, with the ν_μ and ν_τ playing the role of the hot dark matter particles if their masses are high enough (*17, 18*). This neutrino spectrum could also explain how heavy elements are synthesized in core-collapse supernova explosions (*19*).

Of course, if one or more of the indications of neutrino oscillations in the table are wrong, then a sterile neutrino would not be needed and other patterns of neutrino masses are possible. But, in any case, the possibility remains of neutrinos having large enough mass to be hot dark matter. How can a little hot dark matter have such a dramatic effect on the predicted distribution of galaxies (*20*)? In the early universe, the free streaming of the fast-moving neutrinos washes out any inhomogeneities in their spatial distribution on the scales that will later become galaxies. If these neutrinos are a substantial fraction of the total mass of the universe, then although the density inhomogeneities will be preserved in the cold dark matter, their growth rates will be slowed. As a result, the amplitude of the galaxy-scale inhomogeneities today is less with a little hot dark matter than if the dark matter is only cold. Because the main problem with $\Omega = 1$ cosmologies containing only cold dark matter is that the amplitude of the galaxy-scale inhomogeneities is too large compared with those on larger scales, the presence of a little hot dark matter could be just what is needed.

If the new data (*21*) from high-redshift supernovas suggesting that $\Omega \approx 0.4$ are confirmed, then the amount of neutrino mass allowed is decreased, because there will be less cold dark matter (*18*). But the success (*1*) of the cold + hot dark matter model in fitting the cosmic microwave background and galaxy distribution data certainly suggests that low-Ω cosmologies with mostly cold and a little hot dark matter should be investigated in more detail (*22*).

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DEVELOPMENTAL BIOLOGY

Cloning for Profit

Gary B. Anderson and George E. Seidel

The genetic "parent" of Dolly—the cloned sheep that captured the imagination of the scientific community and the general public last year—was the nucleus from a single adult mammary gland cell (*1*). This nucleus was substituted for the chromosomes normally provided by the sperm and egg at fertilization. The resulting embryo, transferred to the oviduct of a surrogate mother, grew to be Dolly. While the media concentrated on the potential benefits and pitfalls of cloning in humans, after Dolly, embryologists have been using cloning procedures to efficiently generate transgenic farm animals with defined—and commercially useful—genotypes (*2*). A report in last week's issue highlighted this progress in the biology of cloning. Cibelli *et al.* (*3*) reported the birth of normal, genetically identical calves whose genetic "parents" were a line of transgenic fibroblasts derived from a 55-day bovine fetus.

To many people, cloning was invented with the birth of Dolly. In fact, cloning has been practiced for millennia in plants and for decades in mammals, and Dolly's birth followed an orderly progression of experiments that started with cloning mammalian embryos. Broadly defined, cloning is asexual reproduction that results in a genetically identical organism. For example, when a plant cutting is rooted, a new clone is produced, completely identical to the parent. Cloning of mammalian embryos first became a useful laboratory technique in the 1970s when procedures were developed for the culture of individual blastomeres. This allowed commercialization of procedures in cattle in which single embryos were split into several pieces (usually two), each giving rise to a complete embryo. Such efforts have produced many thousands of cloned calves that are routinely used for cattle breeding. Because such split embryos (as well as embryos in which the nucleus has been replaced) can be cryopreserved, researchers with sufficient foresight could freeze some members of genetically identical sets. Thus, it already was possible, even before Dolly, to copy an adult from a cryopreserved, genetically identical embryo (*4*).

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The first successful mammalian cloning by nuclear transfer, in which cells from cleavage-stage sheep embryos were fused with unfertilized sheep eggs, was reported in 1986 (*5*). The reconstituted embryo contained not only the nucleus of the donor (parent) cell, but its cytoplasm as well. This procedure, therefore, results in two sources of mitochondria, producing a mitochondrial mosaic if the donor and recipient cells are from different maternal lines. Subsequent experiments defined the conditions that were needed for survival and development of nuclear-transfer embryos, and also extended nuclear donation to cells from older and older embryos (*6*). Successful cloning from older embryos (and ultimately from an adult cell, in the case of Dolly) challenged conclusions from work on amphibia and mammals that indicated that, as cells become more differentiated, they become unable to support normal development. Re-

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