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## *FOREWORD*

# The New Economy Model Universe

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**S**OMETIMES NEW IDEAS are quickly accepted—for example, X rays for radiography of opaque objects, such as humans. Others take much longer—for example, using protons for radiography. The article “Proton Radiography” by Edward Hartouni and Christopher Morris points out that the idea of proton radiography has been around for half a century but is only now being seriously developed for routine use, especially for rapidly evolving systems. The key was the realization that standard particle physics techniques could be applied fruitfully. Acceptance of a new concept has to do both with how useful the new idea is and how it impends upon our cherished or familiar notions. People have been remarkably resistant to new models of the Universe—just ask Galileo!

The article “The Stained and Spotty Heavens” by Virginia Trimble reviews some of the long historical development of the idea that the heavens are not ideal. This idea in turn supports the concept that the Universe is made of ordinary materials and that the laws of physics, particularly Newton’s universal gravitation, apply to the heavens. These imperfections and the laws of physics provide much of our key astronomical information.

With emerging confidence in Newtonian gravitation, astronomers came to understand the need for dark matter. The modern beginning dates to a suggestion from Fritz Zwicky in 1932. It strengthened over years as the observational evidence improved. Assuming that stars move in the gravitational potential caused by the accumulated matter of a galaxy, the stars’ kinetic energy matches their gravitational potential energy. However, if the observed stars have roughly the same mass-to-light ratio as our Sun, then the stars’ velocities require about ten times as much matter as observed by their light. Traditional astronomers assumed that matter would be standard and dark in the sense that it did not radiate or reflect significant light. Interloper particle

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physicists, turned astrophysicists and cosmologists, speculated that this dark matter might be new particles. Theorists quickly recognized that weakly interacting particles, if massive, would have roughly the right abundance as relics of the Big Bang to account for the needed dark matter. Hence we have the acronym WIMPs from Weakly Interacting Massive Particles. Kim Griest then produced the counter point acronym MACHOs (Massive Astrophysical Compact Halo Objects) as a baryonic response to WIMPs.

Natural extensions of particle physics techniques provide appropriate means to detect WIMPs. Einsteinian gravitation provides a means to search for MACHOs, provided one is willing, as in high-energy physics, to observe and process millions of events to find the very few that show the MACHOs. In this issue of the *Beam Line* are two articles about experiments exploring for dark matter: “All about MACHOs” by Kim Griest and “Hunting for WIMPs” by Anthony Spadafora.

When these dark matter experiments were launched, the motivations and context were much less developed than at present; ‘modern’ cosmologists thought that the Standard Model of the Universe involved cold dark matter. More traditional astronomers thought that the Universe was WYSIWYG (what you see is what you get)—the Universe needed only known and familiar particles. Many astronomers would have preferred a Universe in which everything was visible, but, if something was going to be dark, then it should be good, old, stable baryons.

The searches for WIMPs and MACHOs were competing experiments and competing world views. Arguments continued as the experiments developed. Studies of large clusters of galaxies—regions large enough to be thought of as a “fair sample” of the Universe—indicate that the total gravitational potential was large but well below the critical value that would produce a geometrically flat Universe, one considered to be the dividing line between a



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Universe that would expand forever and one that would eventually collapse. If the critical density were exceeded, the Universe would eventually stop expanding and recollapse. Arguments went on about whether baryons could not only explain the rotation curves of galaxies but also even the full content of the Universe, which would have an open geometry fated to expand forever and slowing its expansion only moderately. Cosmologists working on the formation of galaxies, clusters, and general large-scale structure found that they needed the cold dark matter (CDM); baryons alone were not sufficient. Though neither model fitted all the data well, the models could be stretched thereby keeping the controversy on the nature of the dominant matter alive.

During the years these dark matter searches developed, our picture of the Universe underwent a significant change, especially recently. We still rely confidently on gravity (specifically general relativity) and the concept that the laws of physics can be applied throughout the Universe. Supernova and cosmic microwave background (CMB) observations have advanced our understanding substantially.

Observations of type Ia Supernovae (see “The Fate of the Universe” by Gerson and Judith Goldhaber in the Fall 1997 issue of the *Beam Line*, Vol. 27, No. 3) have indicated that the universal expansion is accelerating. The Universe is expanding more quickly at present than it was in the past. If the

Universe were dominated by dark matter, then its expansion would be slowing under its relentless gravitational drag. Instead, the rate of expansion is increasing, indicating that the dynamics of the Universe must be dominated by some form of energy that is tied to the structure of space, such as a vacuum energy density.

There are many potential candidates for this dark energy, including scalar fields and frustrated networks of topological defects

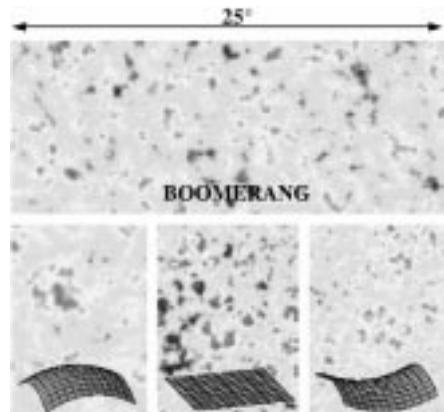
### For Further Information

MAXIMA: <http://cfpa.berkeley.edu/group/cmb/index.html>  
BOOMERANG: <http://www.physics.ucsb.edu/~boomerang/>  
SMOOT: <http://aether.lbl.gov/>  
SUPERNOVA: <http://panisse.lbl.gov:80/public/>  
CDMS: <http://cdms.berkeley.edu/>  
MACHOS: <http://wwwmacho.mcmaster.ca/>  
Connection to all: <http://cfpa.berkeley.edu/>

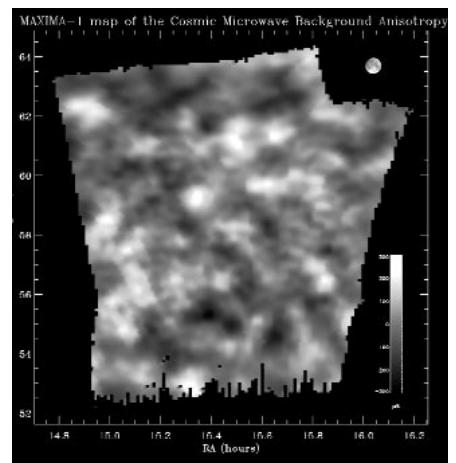
from spontaneous symmetry breaking. Different forms of this energy can have different behavior. The key feature is that the pressure from this dark energy be more negative than one third of its density in order to make the expansion accelerate. The more dark matter contributes to the energy density of the Universe, the more negative the pressure of this dark energy must be to produce accelerating expansion. Vacuum energy, or equivalently a cosmological constant, would have the pressure negative with amplitude equal to its energy density. Currently, cosmologists use the cosmological constant as a convenient parameter to stand for and characterize this spatial energy. The investigation of this dark energy is one of the key questions of cosmology and particle physics. [Editor's Note: for an explanation of the physics and pressure of the vacuum energy density (false vacuum), see the article "Was Cosmic Inflation the 'Bang' of the Big Bang?" by Alan Guth in the Fall 1997 issue of the *Beam Line*, Vol. 27, No. 3.]

After the Griest and Spadafora articles were submitted to the *Beam Line*, new CMB observations were made public. The balloon-borne experiments BOOMERANG and MAXIMA (see the sky maps on the right), combined with the COBE differential microwave radiometer (DMR) data, provide a large step in precision of CMB observations and give strong evidence for a nearly flat geometry for the Universe.

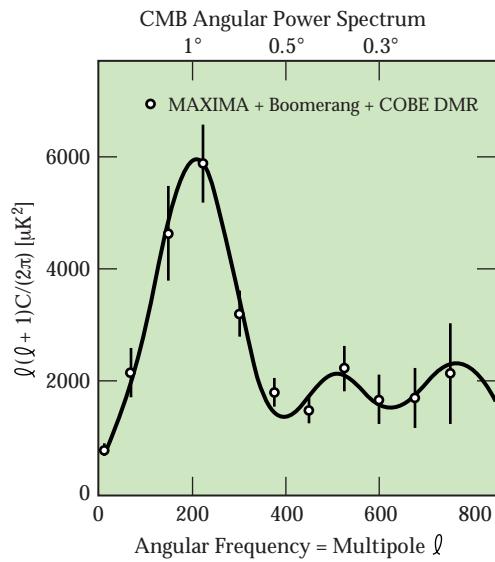
The fluctuation level as a function of angular size is quantified in the CMB angular power spectrum shown on the next page. These CMB data show a convincing, well-defined peak in the angular power spectrum at the expected scale of about one degree ( $\ell \sim 200$ ). This is strong evidence that primordial density perturbations were produced very early and that these perturbations grew, under the influence of gravity, to produce



The upper panel shows a central section of the large BOOMERANG map of the CMB. The lower panels show CMB maps generated from theoretical models of a closed, flat, and open universes. The key point is the angular scale on which the features appear.



This MAXIMA sky map represents a slice of the sky some 22 times the size of the moon or about 500 times its area. What is most evident are the structures roughly twice the size of the moon or about 1 degree in linear extent. The moon, which is 1/2 degree on our sky, is included for scale. Astrophysicists were surprised at the paucity of moon and smaller-sized structures.



The combined MAXIMA, BOOMERANG, and COBE differential microwave radiometer cosmic microwave background anisotropy angular power spectrum shown as data points and error estimates. The smooth curve is the best fitted inflationary model flat Universe power spectrum.

the large scale structure present in the Universe today. Augmenting the Big Bang model with inflation is the only model that is supported by these data.

The CMB data also show more—a relatively high first peak in the angular power spectrum and a relatively low second peak. A universe with significant dark energy (for example, cosmological constant) and a lesser amount of cold dark matter has a much higher first peak to second peak ratio than one with only cold dark matter. A more effective way to lower the second peak is to add in extra baryons (uh-oh, here we go again?) over the

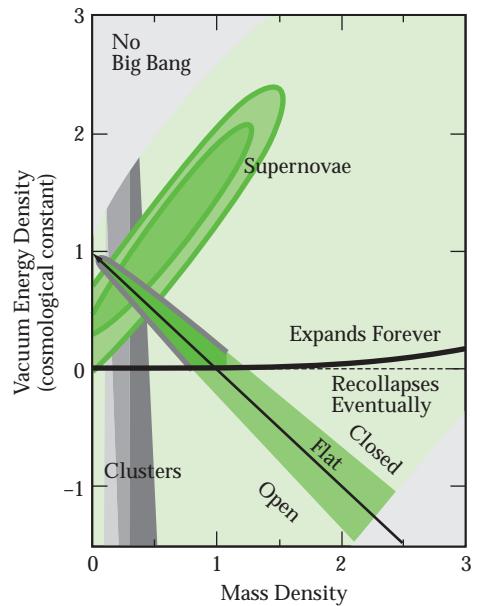
Big Bang light element nucleosynthesis estimate of about 4 percent of the critical density. Fits to the CMB data give numbers of order  $6 \pm 2$  percent with a 95 percent confidence level of the critical density. This potential disagreement is very interesting but should not obscure the remarkable point that two very independent methods and underlying physics effects give roughly the same answer for the baryon density in the Universe.

The illustration on the next page shows the likelihood contours in the vacuum energy density versus matter energy density plane for the clusters, supernova Ia, and CMB data. Note the area of overlap with a matter component around 30 percent, a cosmological constant or dark energy about 70 percent, and a baryon density of around 5 percent. The other cosmological parameters, such as baryon density, are suppressed in this figure. If the plot were three dimensional, the overlap would produce likelihood ellipsoids to its energy density, total matter, and baryon densities.

We have thus extended the idea that there can be not only non-baryonic matter but also that there can be significant energy in the Universe that is

not matter or relativistic particles, such as photons and neutrinos. We have extended the Copernican Principle—not only are we not the center of the solar system nor are we made of the dominant form of matter, but even that matter is not the dominant form of energy. We have resurrected the “Flat Universe Society.” Thus the context, but not the significance of dark matter searches and their results, have changed substantially over time. The discovery of MACHOs is a major accomplishment as is the determination of their abundance. There are tantalizing results from the WIMP searches, and we eagerly await new results.

While we have begun to answer some questions, new ones have arisen to take their place. Some were questions we did not know to ask, and others have risen in import. These new questions and results underline the merging of cosmology and particle physics and the connections between them.



*Likelihood contours in the vacuum energy density versus matter density plane for the cluster, supernova, and cosmic microwave background data sets. Note that there is a region of agreement.*