

Cosmology comes of age

The easy part is over – experimental cosmology has now reached adulthood. That was the message that emerged from a workshop on cosmology and particle physics held at CERN this summer.

While cosmology is one of the oldest of sciences, it is only this century that it has become truly quantitative, with measurements from ground-based detectors extending beyond the traditional visible window and, more recently, with data from an impressive array of space-borne instrumentation. Underlining the new maturity of the science are the emerging values for the basic parameters of the cosmological equations.

A latter-day Copernican revolution came when Edwin Hubble discovered in the 1920s that the universe is still expanding, subsequently understood to be the aftermath of the initial Big Bang. Ever since, observational cosmology has tried to pin down how this expansion has evolved. The “Hubble constant” – the apparent ratio between expansion velocity and distance – has long been controversial. One typical “result” was the paradox that the universe appeared to be younger than its oldest stars – the “old wine in new bottles” dilemma.

Thanks to new data, including parallax measurements from the Hipparcos satellite (May 1997, p20), the Hubble constant and the age of far-flung objects in the universe are now more compatible. The oldest stars are of the same vintage as our universe.

Talks at the CERN meeting, covering observations from the Hubble Space Telescope and other satellites and from systematic supernova searches, showed that the “world average” Hubble constant now looks to be about 67, with a likely age of the universe about 14 gigayears.

Wendy Freedman of the Hubble Space Telescope team showed that the spectrum of the Hubble flow looks remarkably smooth (with the local “infall” drift towards Virgo subtracted). With reliable new data, statistical fluctuations have largely gone away, and the emphasis turns instead to systematic effects.

Observations of distant supernovae, which exploded when the universe was still young, reveal how the universe has since expanded. For the supernova search teams, Saul Perlmutter and Robert Kirshner demonstrated how the subtle effects now being seen at these extreme distances cannot be fitted by a single Hubble constant, and the idea of a “cosmological constant” – an anti-gravity

repulsion – has made a comeback.

According to the basic Big Bang/Hubble picture, the further away an object is, the faster it appears to recede, with the expansion of the universe inexorably slowing as gravity steadily applies the brakes. However, the data from supernovae suggest this is an oversimplified picture, with an anti-gravity effect assisting the expansion, so that the Big Bang can sometimes appear to accelerate.

This reopens the debate on whether the universe is “open”, continuing to expand for ever, or “closed”, ultimately to disappear in a final “Big Crunch”. Neither is yet excluded.

At the CERN workshop, inflation pioneer Andrei Linde showed how an infant universe born in a quantum fluctuation supposedly attained its present proportions due to a brief initial flash of “inflation” which transformed a quantum bubble into a living universe. The incredible rate of this explosion strongly suggests total reconciliation with gravity, so that what we now see should be “flat”, neither continually expanding nor destined to recombine.

Achieving a flat universe with the new cosmological data is not ruled out, but the cosmological constant plays an important role. Flatness is not achieved by conventional gravitational pull alone.

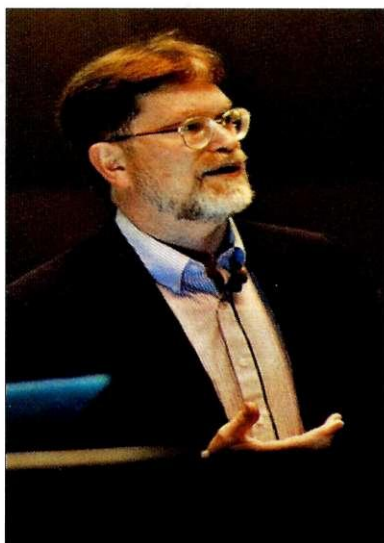
Dark matter

Although inflation practically dictates a flat universe, there is not enough visible matter out there to accomplish the task, and invisible “dark matter” is invoked to provide the extra gravitational pull needed to close the universe. A continuing challenge is to find this missing matter – material we cannot see but which has to be there to explain the gravitational behaviour we do see. However, the arrival of a non-zero cosmological constant provides an additional gravitational effect to help close the universe using less dark matter.

One dark matter candidate is MACHOS – Massive Astrophysical Compact Halo Objects. At the CERN workshop, Michel Spiro summarized the search for MACHOs using gravitational lensing, in which otherwise invisible intervening matter can affect the image of more distant objects as they move across the sky.

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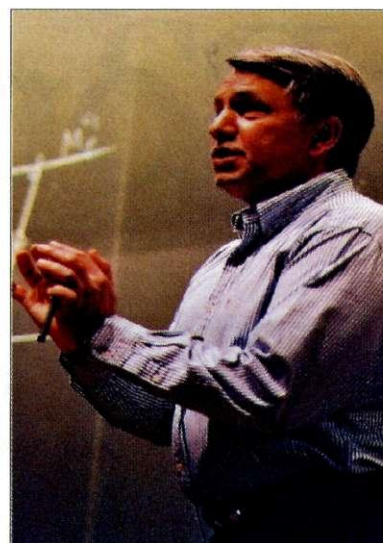
One MACHO-seeking collaboration, itself called MACHO, now has 14 candidates in the direction of the Large Magellanic Cloud (LMC), whose durations range from 15 to 90 days. Another collaboration – EROS – has two, each lasting about four weeks. MACHO cov-



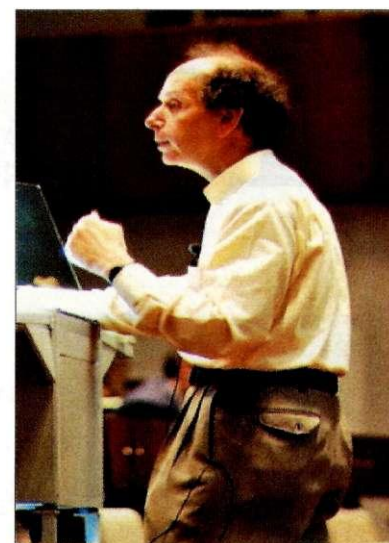
George Smoot, whose COBE team discovered in 1992 that the cosmic microwave background contains tiny temperature fluctuations, a template from which gravity subsequently shaped the large matter structures in our universe.



Wendy Freedman – a smooth Hubble flow from the Hubble Space Telescope.



Andrei Linde – showing how an infant universe born in a quantum fluctuation attained its present proportions due to a brief initial flash of “inflation”.



Michel Spiro – looking for dark matter via gravitational lensing.

ers most of the LMC, but with low efficiency, while the complementary EROS search covers a restricted area containing some 150,000 stars with high efficiency. Taken together, these results imply that planetary mass objects account for less than 10% of the halo. Their attention is now also extended to the Small Magellanic Cloud, while other dark-matter searches have also joined the hunt.

Microwave background

The feeble cosmic microwave background radiation is the vestigial rumble of the Big Bang. Even when this radiation was released, the infant universe should have contained some seeds of its present form. After the discovery of this radiation in 1965, theorists were convinced that its superficially smooth envelope would ultimately reveal small irregularities.

In 1992 the COBE satellite team discovered that the cosmic microwave background does contain tiny temperature anisotropies (variations in angle), a template from which gravity subsequently shaped the large matter structures – galaxies and clusters of galaxies – in our universe.

Ever since, COBE and other experiments have sought to enlarge this window. The gravitational “seeds” initially seen by COBE correspond to far larger structures than are visible today. So the aim is to tighten the angular coverage and look for smaller seeds which could have produced visible galaxies and galactic clusters.

At CERN, COBE pioneer George Smoot sketched the ongoing programme of ground-based, balloon-borne and satellite studies, and Dick Bond described the business of extracting meaningful microwave background data from the mess of surrounding effects. The results now cover much smaller patches of sky than the 1992 COBE results. Charles Lineweaver demonstrated how cosmological measurements

from microwave background, supernovae and other effects could be combined. The cosmological constant looks to be here to stay.

However, the definitive determination of the cosmological parameters, to better than 1% accuracy, will come from the future satellite missions MAP (due to be launched in 2001) and PLANCK (due 2007).

Making light nuclei

With protons and neutrons available, light nuclei such as deuterium, helium and lithium were formed in the first 1000 seconds or so after the Big Bang. The relative abundances of these nuclei in the universe at large provide another lever to prise apart the Big Bang mechanism.

A researcher who made a major impact on this area was David Schramm, who died in a flying accident last December. He continually emphasized the importance of deuterium as a cosmological mirror, a technique he called “deuteronomy”. The nucleosynthesis session at the CERN meeting was dedicated to Schramm’s memory.

Speaking in this session was longtime Schramm collaborator Gary Steigman, who pointed out the current “crisis” in the measurements of light nuclear abundances. Fitting these to the standard Big Bang picture requires some ingenuity. The discrepancies could be simply observational, or due to additional physics effects, like an unstable tau neutrino with a mass less than about 20 MeV.

As well as displaying new confidence in observational data, the CERN meeting showed how the veil of cosmological mystery is slowly being pulled aside. The very creation of the universe is being parametrized and processes which only a few years ago were on the theoretical drawing board have become phenomenology.

Gordon Fraser, CERN.