reference frame

From $\alpha\beta\gamma$ to precision cosmology: The amazing legacy of a wrong paper

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You'd have to be living in a cave in Afghanistan not to know that cosmology is in the midst of an extraordinary period of discovery—perhaps even a golden age. But you might not know that it all started on April Fool's Day 60 years ago. Ralph Alpher, Hans Bethe, and George Gamow published a Letter to the Editor entitled "The Origin of the Chemical Elements" in the April 1 issue of *Physical Review*. Gamow asked Bethe to add his name to the paper he and his student Alpher were writing to create the author list "alpha, beta, gamma"; Bethe agreed. The $\alpha\beta\gamma$ paper marked the birth of the hot Big Bang cosmology and started the march to precision cosmology. It is also exhibit 1 in my case that an interestingly wrong paper can be far more important than a trivially right paper; recall Wolfgang Pauli's famous putdown, "It isn't even wrong."

In 1948 cosmology was practiced by a handful of hardy individuals, mostly astronomers; determinations of the Hubble constant were almost 10 times as large as they are today; the redshifts of less than a hundred relatively nearby galaxies had been measured; and the 200-inch Hale telescope on Mount Palomar was a year away from first light. Cosmology is now center-stage science and attracts a thousand researchers, both physicists and astronomers; two Nobel Prizes have been awarded (1978 and 2006, and more to come); an armada of telescopes, experiments, and even accelerators has been brought to bear on the problems of the universe; and precision cosmology is no longer an oxymoron.

Cosmic nuclear reactor

In the late 1930s, buoyed by the success of solving the riddle of the energy source of stars, nuclear physicists were turning their attention to the origin of the chemical elements. A decade later it was becoming clear that equilibrium nuclear processes in stars (or elsewhere) wouldn't work, for the simple reason that the measured abundances do not correlate with nuclear binding energies.

Gamow took a bold new tack—nonequilibrium physics in the expanding universe. If the universe began in a hot, dense state comprising pure neutrons, the periodic table could be built up by successive neutron captures. Because neutron capture cross sections roughly followed the observed abundances, the idea had the right smell. Gamow's young collaborators, Alpher and Robert Herman, carried out the calculations and broke new ground in cosmology.

As it turns out, the basic idea of nucleosynthesis by neutron capture was wrong, and most of the calculations were irrelevant. The lack of stable nuclei of mass 5 and mass 8 and the rapid incorporation of free neutrons into helium-4 prevent the scheme from working. Interestingly enough, $\alpha\beta\gamma$ did anticipate the so-called r-process, today's paradigm for the production of the heaviest nuclei by rapid neutron capture in stellar explosions.

Sometimes a wrong paper can be very influential and important (*Physical Review Letters* referees take note!). That certainly was the case with $\alpha\beta\gamma$.

Although only the lightest nuclei were made in the Big Bang and not by neutron capture, Big Bang nucleosynthesis (BBN) is a cornerstone of modern cosmology. It led to the prediction of a relic thermal radiation—the cosmic microwave background or CMB—which has turned out to be a cosmic Rosetta stone. Paradoxically, Gamow's Big Bang model spurred Fred Hoyle to think more creatively about the stellar nucleosynthesis to keep his steady-state model competitive and in 1957, with Geoffrey Burbidge, Margaret Burbidge, and William Fowler, he worked out the correct theory of how the bulk of the elements were made in stars.

So what was wrong with $\alpha\beta\gamma$? Although nonequilibrium nuclear processes are an essential ingredient, equilibrium processes are just as important. At very early times, when densities and temperatures in the universe were high, nuclear reaction rates were rapid—so rapid that thermal equilibrium abundances among nuclei and nucleons (so-called nuclear statistical equilibrium, or NSE) were established at temperatures higher than 10^{11} K, corresponding to a time of less than 0.01 s after the bang and thermal energies greater than tens of MeVs. However, at those temperatures, when thermal energies were greater than nuclear binding energies, entropy favored free nucleons and the NSE abundances of nuclei were tiny.

As the universe expanded and cooled, the binding energies of nuclei became large compared with thermal energies; that condition favored nuclei over free nucleons, and the NSE abundances of nuclei rose. However, nuclear reaction rates also dropped because of lower densities and cross sections that became exponentially suppressed due to Coulomb barriers between nuclei. Eventually, nuclear reactions became rare and the epoch of early nucleosynthesis ended.

Predicting the CMB temperature

The yield of our cosmic reactor involves the interplay between the slowing of nuclear reactions and the rising of NSE abundances and is determined by how hot the Big Bang was, which in turn is quantified by the number of photons per baryon. That number remains constant as both the temperature and baryon density decrease with expansion. More photons per baryon (hotter Big Bang) means a higher CMB temperature today, more dissociating photons per baryon during the epoch of nucleosynthesis, and lower yields of nuclei; conversely, fewer photons per baryon lead to higher yields. Cosmologists prefer the inverse of the photon-to-baryon ratio, the baryon-to-photon ratio ($\equiv\eta$), and its value is now known to be 6×10^{-10}.

Using the simple physics above, it is possible to predict from first principles the acceptable range for η and thereby the CMB temperature. For very small η (very hot Big Bang), there is essentially no nucleosynthesis, while for very large

η (very cold Big Bang), most of the nucleons wind up in the nuclei with the largest binding energies ("iron universe"). The "Goldilocks range" (for those not familiar with the children's bedtime story, see http://en.wikipedia.org/wiki/Goldilocks) is from $\eta = 10^{-11}$ to 10^{-8}. Since the number density of baryons is just the baryon density divided by the mass of a baryon ($n_B = \rho_B/m_B$) and the photon number density is given by a familiar thermodynamic formula, $n_\gamma = aT^3$ (where a is a constant), knowledge of the baryon density today translates into a prediction for the CMB temperature today, $T = (\rho_B/am_B)^{1/3}\eta^{1/3}$. For the Goldilocks range, the prediction is $T \sim 1$ to 10 K, consistent with the value of 2.725 K ± 0.001 K measured by NASA's *Cosmic Background Explorer* (*COBE*) satellite.

The various predictions made by Alpher and Herman were based on the neutron capture model. To produce the observed pattern of abundances, they required that the density of nucleons times the age of the universe ($\equiv f_n$) be about 10^{18} s/cm^3 when the temperature of the universe ($\equiv T_n$) was about 10^{10} K. That requirement leads to a different formula, $T = (T_n/10^{10}\ \mathrm{K})^{1/3}(\rho_B/m_B)^{1/3}f_n^{-1/3}$, and a wrong prediction, 70 K using modern values, reflecting the incorrectness of the underlying physics.

Birth of hot Big Bang cosmology

Computer codes with extensive nuclear reaction networks and precise nuclear data allow the accurate prediction of the yields of BBN. The discovery of the CMB in 1965 and the uncertain knowledge of the baryon density meant that η was between 10^{-10} and 10^{-9}, and for this range only deuterium, helium-3, helium-4, and lithium-7 are produced in significant amounts. By far, the yield of ^{4}He is the greatest, a mass fraction of around 25%. The consistency of that prediction with the unexplained, large primordial abundance measured by astronomers was an early home run for the hot Big Bang cosmology. Together, the CMB and ^{4}He were the last nails in the coffin of the steady-state cosmology. Strangely, no tribute was paid to $\alpha\beta\gamma$, the paper that started it all.

In the 1970s David Schramm and others realized that the rapid fall in the production of deuterium with the baryon density and the fact that subsequent astrophysical processes only destroy deuterium make it a good "baryometer." An upper limit to the baryon density follows directly from any measurement of the present-day deuterium, and a determination of the primordial deuterium abundance accurately pegs the baryon density.

In the 1980s measurements of the deuterium abundance in the local interstellar medium led to an upper limit to the baryon density of about 10% of the critical density (the energy density that separates the high-density universes that are positively curved from the low-density universes that are negatively curved). A decade later the primordial abundance of deuterium was measured in high-redshift clouds of hydrogen, and the baryon density was determined to be 4.5%. Beginning in the 1980s, measurements of the total matter density indicated a significantly higher number, around 20% of critical density, and a composition that was predominantly dark matter. That BBN-based discrepancy, which grew in size and significance, became the linchpin in the argument that the dark matter is not made of baryons.

The road to precision cosmology

In 1992 *COBE* detected anisotropy in the CMB temperature at the level of about 30 microkelvin (or 1 part in 10^5). Those variations in the temperature between two points on the sky, separated by roughly 10 degrees, provided crucial evidence for the underlying variations in the matter density needed to seed the formation of all the structure in the universe—from galaxies to superclusters of galaxies—and the first evidence for inflation, the best explanation for the origin of the seed inhomogeneities.

The spectrum of anisotropy depends not only on two or three inflationary parameters but also on cosmological ones—curvature of space, total matter density, baryon density, Hubble constant, and age of the universe. In particular, the angular power spectrum takes the form of a series of harmonic or acoustic peaks whose strengths and positions (as a function of angle) encode information about cosmological parameters: The position of the first peak indicates the curvature; the strength of the first peak, the matter density; the ratio of the strengths of the odd to even peaks, the baryon density; and so on (see my article with Charles Bennett and Martin White, PHYSICS TODAY, November 1997, page 32).

The *COBE* discovery triggered a race to measure the wiggles in the CMB angular power spectrum. And a series of ground-based and balloon-borne CMB experiments, mostly in Antarctica, and NASA's *Wilkinson Microwave Anisotropy Probe* have now determined the CMB power spectrum from about 0.1 to 90 degrees. That spectrum, together with maps of the large-scale structure in the universe today, have determined a host of cosmological parameters to percent-level precision. The Hubble constant is now known to be 70 ± 1.3 km/s/Mpc; the age of the universe is fixed at 13.73 ± 0.12 Gyr, its curvature is within 0.6% of the "flat" critical density model, and the values of the various components of mass and energy have been determined with error bars of less than 2% (see below). Finally, measurements of nearby and distant supernovae have directly pinned down the expansion rate today and long ago, revealing that the expansion rate is speeding up and not slowing down.

Today's wealth of cosmological data also permits crosschecks and has paved the way for precision cosmology. The poster child is the baryon density. From measurements of the primordial deuterium abundance, the baryon density is fixed at $4.0 \pm 0.2 \times 10^{-31}$g/cm^3, while CMB anisotropy measurements give $4.2 \pm 0.1 \times 10^{-31}$g/cm^3—an agreement and precision of about 5% (see my Reference Frame in PHYSICS TODAY, December 2001, page 10).

For all its success and precision, cosmology is not yet solved (thank goodness!). Particle dark matter accounts for 23.3% ± 1.3% of the universe, but which particle? The bulk of the universe (about 72% ± 1.5%) is made of a mysterious dark energy whose gravity is repulsive and is causing the expansion of the universe to speed up. The crazy combination of atoms, particle dark matter, and dark energy that is our universe is without explanation. What happened before the Big Bang and the destiny of the universe still elude us. And last but not least, the full extent of the universe is unknown—is it WYSIWYG or a multiverse of disconnected pieces? All of that is why cosmology is so exciting—big questions that seem to be within reach of our powerful instruments and ideas.

The road to precision cosmology started on April Fool's Day 60 years ago with a game-changing idea—that just after the Big Bang the universe was a nuclear reactor. Though Alpher, Bethe, and Gamow didn't get the physics right, they were right about the importance of nuclear physics (and physics in general) in the early universe and the existence of the CMB (though not its temperature), and they broke new ground in cosmology by studying the early radiation-dominated phase that is the focus of much of theoretical cosmology today. Although that groundbreaking paper received little attention when the CMB was discovered in 1965, with hindsight today we can trace the beginning of today's revolution in cosmology to it. ■