100 YEARS OF THE IAU

Cosmology's early days

After George Gamow first proposed the idea of a hot Big Bang in 1948, it took 15 years for the burgeoning cosmology community to recognize his contribution for what it was.

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In the 30 October 1948 issue of *Nature*, George Gamow[1] discussed his idea that the Universe expanded from a state dense and hot enough that thermonuclear reactions had converted matter to comparable amounts of hydrogen and helium. In the 13 November 1948 issue, Gamow's former graduate student Ralph Alpher, with their colleague Robert Herman[2], concluded that the thermal radiation left from Gamow's hot early Universe would have cooled with the expansion of the Universe to a present temperature of "about 5° K". The large abundance of helium, and the thermal radiation, are central to our established relativistic theory of the expansion of the Universe from a hot dense initial condition. But recognition took time.

Astronomers had indications of more helium than might be expected to have come from stars. The case became strong enough that Fred Hoyle and Roger Tayler[3] published a paper entitled 'The mystery of the cosmic helium abundance'. They suggested that "little bangs" in massive objects in the young Galaxy might have been energetic enough to have produced the helium. But their main point was that this helium could be from Gamow's hot Big Bang. That was notable because Hoyle preferred the steady-state cosmology. It postulates continual creation of matter that collects to form young galaxies to replace the older ones that are moving apart with the expansion of the Universe, maintaining a steady state with no Big Bang. Hoyle certainly was not persuaded by this indication of a Big Bang. But the paper, with an author who was a prominent sceptic, could have shown the community that the hot Big Bang cosmology is worth a closer look. It happened another way, however, by identification of a sea of radiation at temperature close to the Alpher and Herman prediction.

Figure 1 is derived from a Bell Telephone Laboratories study[4,5] of communication by microwave radiation — a technology that led to cellular phones, for better or for worse. It shows contributions to the noise, microwave radiation, detected by a receiver system. This noise originates in components of the system and it enters from the environment. The noise produced by the atmosphere was measured by tilting the antenna — the longer the path through the atmosphere the greater the noise from that source. To make the sum of contributions to the system noise agree with the measured total the Bell engineers assigned a noise temperature of 2 K to microwave radiation leaking from the ground into the horn antenna. But the antenna was designed to reject ground radiation better than that; they had an unexpected noise source. The same problem with other Bell microwave receivers was a 'dirty little secret' at the lab. That changed in 1964 when Arno Penzias and Robert Wilson, both new to the Bell Radio Research Lab at Crawford Hill, New Jersey, made a thorough search for the source of the excess noise. They could not find it in the instrument or surroundings, and to their credit they did not give up. They complained about it until someone heard and pointed them to an experiment in progress at Princeton University, also in New Jersey, that was seeking to detect radiation left from a hot early Universe. The Bell receivers had detected what the Princeton group was looking for, a sea of radiation[6,7].

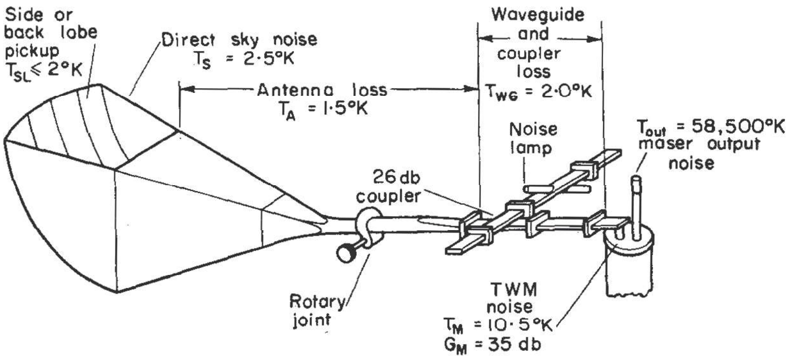

Fig. 1 | The noise budget in a Bell study for microwave communication. The diagram of the original apparatus for measuring antenna noise temperature was first published in 1959[4] and later modified[5]. The travelling-wave maser amplifier, TWM, inserts little noise that is well measured. The antenna loss refers to absorption of incoming radiation that is balanced by microwave emission by the antenna and waveguide walls and joints. The 2.5 K sky noise is radiation from the atmosphere at zenith. The 2 K entering the horn antenna through side or back lobes is a fudge factor. Credit: Adapted from ref. [5], Elsevier.

The measured temperature of the sea of thermal radiation that nearly uniformly fills space is 2.725 ± 0.001 K. Alpher and Herman had put the present temperature in the Big Bang theory at about 5 K. The Bell engineers had excess noise of about 2 K. Both are close enough considering the uncertainties. Gamow's impression in 1948 was that the cosmic mass fraction in hydrogen is about $X = 0.5$. Since he put the mass fraction in elements heavier than helium well below that it would mean, if he thought about it, that he expected the mass fraction in helium left from the hot Big Bang to be roughly $Y = 0.45$. The astronomical evidence available to Hoyle and Tayler suggested about $Y = 0.3$. Recent measures, after a small correction for helium produced in stars, are in the neighbourhood of $Y = 0.25 \pm 0.01$. This amount is less than what Gamow seems to have had in mind, but again close enough. The key point in 1965, when the Bell and Princeton groups got together, was that the presence of the sea of radiation agrees with the Big Bang theory and a considerable abundance of helium.

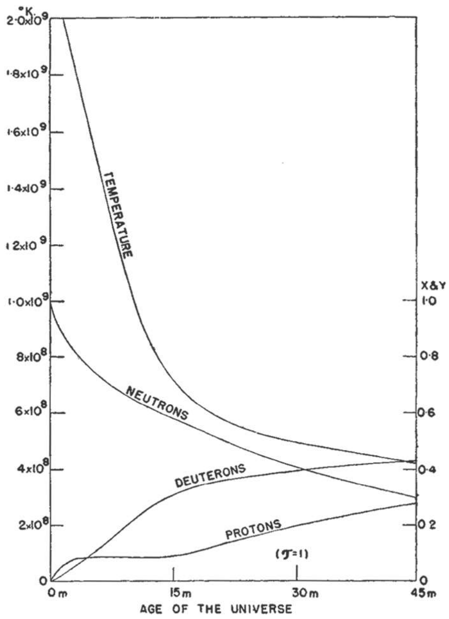

Fig. 2 | Gamow's picture for cosmic evolution in the early stages of expansion of the Universe in his hot Big Bang theory. The left-hand axis is the scale for the radiation temperature, which drops as the Universe expands. The right-hand axis shows mass fractions in three kinds of atomic nuclei. Credit: Reproduced from ref. [1], Springer Nature Ltd.

The nature of the relation between radiation and helium is illustrated in Fig. 2 (from Gamow's 1948 *Nature* paper). He assumed matter started out as neutrons. As neutrons decayed to protons they would be captured by other neutrons to form deuterons. The right-hand panel shows the evolution of the fractions X and Y of nucleons that are neutrons and protons, with the rest bound in deuterons. Gamow's example has it that, at 45 minutes after expansion from much larger densities, about 30% of the nucleons are neutrons and 30% protons with the rest in deuterons. Deuterons are far less abundant than that, but we recognize now, and I expect Gamow understood then, that deuterons can fuse to form the nuclei of helium. One path is d+d→^{3}He+n and ^{3}He+d→^{4}He+p. Alpher recognized that element formation beyond helium is suppressed by the absence of a reasonably stable ion at atomic mass five, so we may expect a considerable build-up of helium. A present temperature of several kelvin with the baryon density seen in galaxies is about right to extrapolate back to a matter density in the early Universe large enough that most of the deuterons would fuse to helium while leaving at least 50% of the mass in hydrogen. Gamow chose the present conditions in his illustration to make this so.

Details were to be added. Hayashi showed that the ratio of numbers of neutrons to protons is set by relaxation to thermal equilibrium by reactions with thermal electrons and neutrinos at radiation temperatures greater than about 10^{10} K. And at temperatures above about 10^9 K, deuteron build-up is suppressed by thermal dissociation. Gamow knew that but doesn't seem to have taken it into account in Fig. 1. But he made the following point: reasonable-looking values of the present density and radiation temperature extrapolate back to a hot Big Bang that produces an interesting helium abundance and leaves a substantial amount of hydrogen.

Why did community recognition take so long? Gamow was a master of imaginative intuitive physics, but not pesky details. In the first paper by Gamow and Alpher, before they had all of the elements of the hot Big Bang, Hans Bethe was added to the author list to approximate the first three letters of the Greek alphabet. The computation in the α, β, γ paper is numerically inconsistent — by ten orders of magnitude[8]. Through the mid-1960s this wrong paper was more frequently cited than Gamow's 1948 papers that pointed in the correct direction, which no one but Gamow seems to have understood. People were not paying much attention. It cannot have helped that in the 1950s Gamow stopped writing about the physical considerations in his 1948 picture and instead implicitly postulated that there was a time in the evolution of the expanding Universe when the mass density in baryons, the density in the sea of thermal radiation, and space curvature made three equal contributions to the rate of expansion of the Universe. That implied sensible present values of these quantities, but the postulate makes no sense otherwise. It cannot have inspired confidence for anyone paying attention.

Some did remember Gamow's hot Big Bang and knew about the problem with helium. The report of a conference on 'The Problem of Stellar Populations' held in Vatican City on 20–28 May 1957, includes this recorded discussion:

> Fred Hoyle: The difficulty about helium still remains, however.
>
> Martin Schwarzschild: The evidence for the increase in heavy elements with the age of the galaxy supports [element formation in stars]. However, it does not necessarily mean that He production occurs mainly in stars. Gamow's mechanism may work up to mass 4.
>
> Hoyle: That is why a knowledge of the He concentration in extreme population II is so important.

Hoyle was referring to the old stars in the Milky Way that contain low abundances of elements heavier than helium. They would have formed when there had been little production of heavier elements in stars. It was already known[9] that the abundance of helium in planetary nebulae is large, $Y \approx 0.3$. (This is the plasma around a hot star as it is exhausting its supply of nuclear fuel. The plasma recombination lines offer a measure of the helium abundance.)

The Hoyle–Schwarzschild exchange was in the literature. But to my knowledge it did not inspire anyone to argue that the large helium abundance could be evidence against the steady-state model and for the idea that the Universe expanded from a hot dense state. Osterbrock and Rogerson[10] had better data on helium, and in 1961 they pointed out that the helium could be from Gamow's hot Big Bang, but again no one seems to have turned this into an argument for the Big Bang. The tipping point for Hoyle in 1964 was the observation of a large helium abundance in a planetary nebula in an old globular cluster of stars with low abundances of heavier elements[11]. As there had not been much heavy element production when the stars in this cluster formed, one might suppose there had been little production of helium. So where did all the helium in that planetary nebula come from? Maybe the Big Bang, Hoyle and Tayler pointed out.

The sea of microwave radiation at a temperature of a few kelvin could have been detected before 1959, if someone who understood microwave physics had thought to look. In 1964 Bob Dicke suggested that two young members of his gravity research group, Peter Roll and David Wilkinson, build a Dicke microwave radiometer — which he invented as part of war research — to check the idea that the early Universe was hot and dense, leaving a sea of thermal radiation. He had a different idea about why the Universe might have been hot; if he ever knew about Gamow he had forgotten. Bob suggested that I "look into the theoretical implications" of finding or not finding the radiation. I didn't know about Gamow; I learned that I had been reinventing the wheel at about the time the Hoyle and Tayler article appeared in *Nature*. But that left a lot to look into in cosmology. Roll went on to education, introducing computers in classrooms. Wilkinson and I continued to follow Dicke's suggestion for the rest of our careers.

Cosmology in the 1950s was a real physical science, with theories and observations and research in progress aimed at improving both, but progress was sluggish compared to what was happening in laboratory physics. Recognition of the sea of radiation and its possible relation to the large abundance of helium was a considerable addition to the empirical basis for cosmology and a major stimulus for seeking more. The great advances since then have made a compelling case for the relativistic hot Big Bang cosmology with its helium and radiation along with the hypothetical nonbaryonic dark matter and dark energy. Much of the story traces back to 1948. ❒

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Published online: 25 November 2019
https://doi.org/10.1038/s41550-019-0960-3

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