Two Theorists Never in Doubt

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Cosmologists are often in error, but never in doubt.
—LEV LANDAU

One of Lev Landau's most colorful quotes is about cosmology. It is often applied to astrophysics as well. Because of the historic paucity of quality data in both fields, there used to be more than a little truth in the quote. The other day, a colleague said to me, "It must be great to work in a field where you don't need to worry about your theories being ruled out by data." I told him I'm not a string theorist (just kidding).

With the tremendous growth in the quantity and quality of data, astrophysics and cosmology are undergoing a sea change. And being a theorist is becoming more dangerous. But there are also opportunities for great success. I devote my inaugural column to celebrating two recent triumphs. While there are many notable examples of persistence in physics and astrophysics, I have singled out two longstanding theoretical predictions in astrophysics. First, because I am a theorist and I want to dispel the belief that the term "persistent theorist" is an oxymoron. Second, because both triumphs illustrate deep connections between astrophysics and particle physics, an especially important theme in physics today. In future columns, I will return to the connections between quarks and the cosmos.

Two astrophysicists were never in doubt—John N. Bahcall about solar neutrinos and the late David N. Schramm about the density of baryons in the universe. (At times, Schramm had his doubts about solar neutrinos and Bahcall had his about the baryon density.) Their steadfastness has recently paid off: Results from the Sudbury Neutrino Observatory[1] have confirmed Bahcall's more than three-decade-old calculations of the solar neutrino flux, and new measurements of the anisotropy of the cosmic microwave background[2] have confirmed Schramm's long-standing claim that baryons are a minor component of the cosmic mix. Sadly, Schramm cannot enjoy his triumph. He died in a plane crash in 1997.

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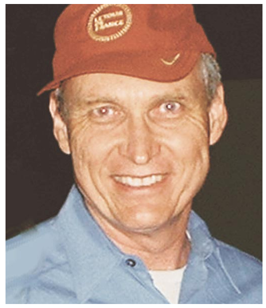

Solar certainty

Bahcall's solar neutrino calculations[3] provided the theoretical foundation for the first solar neutrino experiment in the Homestake Mine in South Dakota. When Ray Davis proposed the experiment to the Brookhaven National Laboratory management, he and Bahcall worried that it might be viewed as, God forbid, astronomy. Director Maurice Goldhaber had the good sense to recognize that whatever solar neutrinos were, they were great science. In 1968, Davis announced the first results: Neutrinos are coming from the Sun, but the rate is three times smaller than Bahcall had predicted.

The Davis experiment is remarkable: In the 100 000 gallon tank of cleaning fluid, a solar neutrino transforms a chlorine atom to an argon atom every other day. The 30 or so Ar atoms produced over two months are flushed out of the more than 10^{30} atoms in the detector with an efficiency of greater than 90%. If I hadn't restricted my column to the persistence of theorists, I would have included Davis.

The neutrinos detected by the Davis experiment are high-energy neutrinos from a side reaction responsible for very little of the Sun's nuclear energy production. This side reaction is very temperature dependent, in essence, providing a solar thermometer. Decreasing the central temperature in Bahcall's solar model by about 7% would accommodate Davis's result. Calculating the central temperature of the Sun to 7% is pretty good—after all, it's astrophysics where it was said the errors are in the exponents!

But 7% was not good enough for Bahcall. He was certain that his calculations were more accurate than that. He backed up that belief by answering every criticism and addressing every alternative explanation for the discrepancy. Bahcall refined his predictions, incorporating improved nuclear cross-section data and updating the physics in his solar model. As the theoretical error bars shrunk, the stakes became higher.

His persistence and calculations convinced particle and nuclear physicists—even hard-nosed experimentalists—that the neutrino deficit might involve neutrino physics. More experiments were built. First came the Kamiokande II experiment in Japan. It directly detected solar neutrinos by their elastic scattering off electrons in a 3000-ton water Čerenkov detector. It too saw a neutrino deficit. Two new radiochemical experiments involving 100 tons of gallium followed. With their lower energy thresholds the gallium detectors were able to observe the neutrinos produced by the main reaction that powers the Sun, $p + p \rightarrow D + e^+ + \nu_e$. More neutrino deficits.

If Bahcall was right, something funny was going on with neutrinos. Oscillation of electron neutrinos to another flavor (μ or τ) was the leading explanation. The Sudbury Neutrino Observatory and its 1000 tons of ultrapure D_2O could settle the question by detecting neutrinos three different ways. The charged current reaction $\nu_e + D \rightarrow p + p + e^-$ records only electron-type neutrinos; electron scattering $\nu_x + e^- \rightarrow \nu_x + e^-$ is sensitive to all three neutrino types, with cross section ratios of 1:1/6:1/6 and the neutral current reaction $\nu_x + D \rightarrow p + n + \nu_x$ is equally sensitive to all three types. SNO began operating in 1999, and Bahcall began living very dangerously.

On 18 June 2001, after collecting 240 days worth of data—some 1000 events—SNO scientists announced their result: The flux of electron neutrinos from the Sun (above 6.75 MeV) is $(1.75 \pm 0.14) \times 10^6\ \mathrm{cm^{-2}\,s^{-1}}$, or about 35% of the standard solar model prediction. Once again, a neutrino deficit.[1] (Where's the politician offering neutrino surpluses?) The SNO neutral-current data are not yet good enough to infer the total number of neutrinos reaching Earth. However, the SNO team used the high-precision Superkamiokande electron-scattering result to the same end. (Superkamiokande is the larger successor to the Kamiokande II experiment.) The team inferred a total neutrino flux of $\nu_{TOT} = (5.44 \pm 1) \times 10^6\ cm^{-2}s^{-1}$, bang on the Bahcall prediction of $5 \times 10^6\ cm^{-2}s^{-1}$. Never in doubt and right on the money.

Cosmic certainty

After the discovery of the cosmic microwave background, the first success of the hot Big Bang cosmology was the correct prediction of a large (about 24%) primordial abundance of helium. This He was cooked by nuclear reactions when the universe was seconds old. The basic theory of Big Bang nucleosynthesis (BBN) was worked out in the late 1960s, just as Schramm got to graduate school. Only the lightest elements (and their isotopes)—H, D, ^{3}He, ^{4}He and Li—are made in significant amounts in the Big Bang. The rest of the periodic table is produced billions of years later in stars.

To make He from neutrons and protons, you have to first make D; because BBN occurs out of thermal equilibrium, a small amount (a few parts in 10^5 relative to H) remains unburned. The amount of unburned D is very sensitive to the baryon density: Higher density of baryons leads to more complete burning and less unburned D. Schramm recognized that deuterium is the "baryometer."

The 14-billion-year gap between the production of deuterium and today makes understanding the post–Big Bang history of deuterium critical. The deuteron is only loosely bound and when D goes through stars, it is burned to He. Schramm showed that astrophysical processes since the Big Bang are net destroyers of D. This means that the Big Bang must have produced at least as much D as is seen anywhere in the universe today. And any measurement of D is a lower limit to the Big Bang production and can be used to set an upper limit to the baryon density, because Big Bang D production decreases with baryon density.

In 1973, using NASA's Copernicus ultraviolet satellite, John Rogerson and Donald York measured the D abundance in the local interstellar medium (ISM). Neutral H and D are seen by their UV absorption along the line of sight to nearby, hot, young stars. By comparing the hydrogen Ly-α feature at around 1216 Å with the deuterium feature, which is isotopically shifted by about 0.33 Å, they deduced an ISM abundance of $(D/H) \approx 1.5 \times 10^{-5}$. This lower limit to Big Bang D production corresponds to a baryon density of 10% or less of the critical density.

By 1980, it was becoming clear that the total amount of matter, the majority of it existing in a form other than stars, amounted to more than 10% of the critical density. This much "dark matter" was needed to hold galaxies, clusters of galaxies, and other cosmic structures together. The BBN upper limit became the linchpin in Schramm's argument for a new form of matter that holds the universe together. His influential first prize Gravity Research Foundation essay on the subject (with Gary Steigman) in 1980 awakened the astrophysics community to a remarkable possibility: While we are made of star stuff, the universe is not. If true, it really puts us in our place. We are not at the center of the universe, and we are not even made of the primary stuff of the cosmos.

The case for exotic dark matter hinged on D. Just as mechanisms were proposed to lower the central temperature of the Sun to solve the solar-neutrino problem, ways around the BBN limit to the baryon density were put forth. Some suggested that exotic post–Big Bang processes could make enough deuterium to mask the low D signature of a high-baryon-density universe. Others suggested a new inhomogeneous version of BBN to evade the standard bound to the baryon density. Like Bahcall, Schramm led the charge in addressing each challenge. He was never in doubt and stood steadfast.

Because it is believed that about half the material in the local ISM has been through stars and has lost its D, the Rogerson–York abundance pointed to a Big Bang production of around 3×10^{-5} (relative to H). A few months before his death, Schramm's goal of using D as a baryometer was realized. David Tytler and his graduate student Scott Burles measured the D/H ratio in primeval samples of the universe, using the same technique as Rogerson and York. The UV light came from distant quasars and the absorbers were pregalactic gas clouds. The abundance they found, $(D/H) = (3.0 \pm 0.1) \times 10^{-5}$, pinned down the baryon density at $(4 \pm 0.8)\%$ of the critical density, far below the amount of dark matter needed to hold structures in the universe together.

Schramm's last paper was written just after the Burles–Tytler deuterium measurement.[4] In it, he and I discussed how the BBN prediction could soon be tested by an independent determination of the baryon density involving measurements of cosmic microwave background (CMB) anisotropy. The physics underlying this determination is very different—gravitational rather than nuclear. When the universe was 30 000 years old, dark matter began collapsing into cosmic structures; baryons tried to follow. However, their collapse was resisted by the pressure force of photons. The net result was gravity-driven acoustic oscillations. These oscillations, whose amplitude depends on the baryon density, left their signature in the anisotropy of the CMB.

In April 2000, two teams (BOOMERanG and MAXIMA) reported that they had detected the CMB signature of acoustic oscillations. Their determination of the baryon density was 1.5 times the BBN prediction, but had a large uncertainty. The discrepancy was about 2.5 σ. This result, like the Davis detection of solar neutrinos, was a stunning success. It confirmed that baryons contribute only a small part of the dark matter. I am certain that Schramm, like Bahcall, would not have been satisfied. In April 2001, at the Washington meeting of the American Physical Society, John Carlstrom and his DASI team announced the first results from their more precise South Pole CMB experiment: Baryons account for $(4.4 \pm 1)\%$ of critical density (PHYSICS TODAY, July 2001, page 16). Right on Schramm's Big Bang number. New results from BOOMERanG announced at the same meeting now also agreed with the BBN number. In addition, the results from all three experiments indicated that the ratio of the total amount of matter to baryonic matter is about 8 to 1, solidifying the case for exotic dark matter that Schramm began 20 years earlier.

Never in doubt, these two towering nuclear astrotheorists mastered the nuclear ovens of the Sun and of the Big Bang. Their triumphs and other results are signaling a new era in astrophysics and cosmology. Five years ago, in a moment of irrational exuberance, I coined the phrase precision cosmology. Time will tell how true this rings. I am certain that it is time to retire Landau's quote.

References

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