AstroTalk: Behind the news headlines of October and November 2012

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We live in an expanding Universe

In 1929, the famous American astronomer Edwin Powell Hubble (you may have heard of him in relation to the Hubble Space Telescope, which was named after him) first published what was to become a major yardstick for measurements of cosmological distances, now known as the Hubble law. He combined his own distance determinations to six "extragalactic nebulae" (now known to be galaxies) in the so-called “Local Group” of galaxies—a loose galaxy group containing the Milky Way, the Andromeda and Triangulum galaxies (Messier 31 and Messier 33), as well as a large number of much smaller "dwarf" galaxies, all within approximately 3.26 million lightyears of the Milky Way—with published measurements of the galaxies’ radial motions, which were corrected for the orbit of the Sun through the Milky Way.

Assuming a constant upper limit to the brightness of the “brightest blue stars” (which we now know to be regions of intense star formation) in those galaxies, he expanded his sample of galaxies with 18 additional objects located as far away as the Virgo cluster of galaxies. This data set allowed him to construct the first version of what is now commonly known as a Hubble diagram, a graph relating galaxy distances to their radial velocities. In fact, this result had been anticipated and already published in 1927 by Belgian Roman-catholic priest, physicist and astronomer Monsignor Georges Henri Joseph Édouard Lemaître, based on a mathematical model of an expanding Universe. However, his article was published in French in the rather obscure Annals of the Scientific Society of Brussels, so that it had not attracted much attention from his colleagues at the time. English was—and is—the lingua franca in science, and particularly so in astronomy. Although we have long since realized that Hubble’s result was actually incorrect, his insights provided the basis for the idea that the Universe is not static but has been expanding ever since a cataclysmic event occurred at the dawn of time, which we now usually refer to as the “Big Bang”.

The slope of the linear relationship in the Hubble diagram corresponds to the Hubble constant, H₀. Physically, the Hubble constant corresponds to the current rate of expansion of the Universe. Its inverse, which has units of time, is called the Hubble time. It roughly corresponds to the current age of the Universe. Let me emphasize that the Hubble constant and the Hubble time refer to the current expansion rate and age of the Universe: in a uniformly expanding Universe, the Hubble constant varies over time. Its accurate determination has occupied generations of astrophysicists because of large and lingering systematic uncertainties that affected and continue to hamper the observations. Significant recent research efforts have led to an unprecedented accuracy of H₀ measurements, largely thanks to dedicated programmes using the Hubble Space Telescope, one of whose primary mission goals was determination of H₀ to an
accuracy of better than 10%. The quest to determine $H_0$ to ever higher accuracy continues today.

**Dark energy enters our conscience**

Let us now fast forward to the present. You probably heard that the 2011 Nobel Prize in Physics was awarded to three scientists who first demonstrated that the Universe is not only expanding, but this expansion appears to be accelerating! Saul Perlmutter’s team on the one hand, and Adam Riess, Brian Schmidt and their colleagues on the other, published two important scientific articles towards the end of the 1990s, in which they argued that the idea of simple, uniform expansion of the Universe did not match the results of their observations of distant supernovae (exploding stars). Something caused galaxies at large distances to move away from each other at a faster pace than expected. This “something” was eventually coined **dark energy**, a term inspired by the proposed existence of the invisible “dark matter” as a major mass component in galaxies and galaxy clusters, and the fact that it acts as a source of “outward” pressure (also called “negative” pressure) and hence causes the Universe to expand ever more rapidly.

We don’t know much about this dark energy beyond its effects on the expansion rate of the Universe. It is sometimes identified as Albert Einstein’s “cosmological constant”, but this is physically incorrect. Einstein postulated the existence of a cosmological constant to explain the observed motions of galaxies in the theoretical framework of the Universe of his day, when a majority of scientists thought that the Universe was stuck in a so-called “steady state”. In this, now discarded model of the Universe, new matter would be created continuously so that the Universe would be governed by the perfect cosmological principle. This would imply that the Universe is homogeneous in both space and time, so that it would appear the same no matter in which direction (and at what time) we looked. The fact that we know so little about dark energy is, of course, unsatisfactory, and this realization has spawned a number of large international projects aimed at improving our understanding of its basic properties.

BOSS, the Baryon Oscillation Spectroscopic Survey, is mapping a huge volume of space to measure the role of dark energy in the evolution of the Universe. It is the largest programme of the third Sloan Digital Sky Survey (SDSS-III). It has just announced the first major result of a new mapping technique, based on the spectra of over 48,000 quasars with redshifts up to 3.5. At greater distances, Hubble’s law implies that galaxies will, on average, most away from us at faster speeds. The Doppler effect then causes the radiation we receive from rapidly receding galaxies to shift to longer (“redder”) wavelengths, so that any emission or absorption lines due to the chemical elements that are present in such a galaxy’s spectrum will be “redshifted.” A redshift of 3.5 means that light left these active galaxies up to 11.5 billion years in the past.

“No technique for dark energy research has been able to probe this ancient era before, a time when matter was still dense enough for gravity to slow the expansion of the Universe, and the influence of dark energy hadn’t yet been felt,”
Baryon acoustic oscillations, remnants of the Big Bang itself!

BOSS studies dark energy by mapping baryon acoustic oscillations (BAOs)—the large-scale network of variations in the distribution of visible galaxies and hard-to-see clouds of intergalactic gas, which also reveal impossible-to-see dark matter. BAOs are caused by the excitation of sound-like waves in the hot, dense plasma making up the early Universe, consisting of fluctuating density distributions of electrons and other normal atomic species, which—in the early Universe—were located in the same volume of space as dark-matter density fluctuations. At the “surface of last scattering” (at a redshift of approximately 1100), where matter and radiation decoupled shortly after the Big Bang, gravity counteracted the effects of the “radiation pressure” generated by the heat of photon–matter interactions. In turn, this led to an outward-expanding “acoustic” wave, taking along with it the photons and normal matter. (The dark matter would stay behind because it only interacts through gravity.) This resulted in the presence of regularly spaced peaks in the matter density, whose remnants are visible in the cosmic microwave background radiation. This spacing provides a cosmic ruler for calibrating the rate of expansion wherever BAOs can be measured. Using the Sloan Telescope at the Apache Point Observatory in New Mexico (USA), BOSS has mounted a two-pronged spectroscopic investigation of BAO. The first priority is to survey normal bright galaxies with redshifts up to 0.8, some seven billion years in the past. First results of the galaxy survey, which included over 300,000 galaxies, were announced in March 2012. But collecting enough galaxies at redshifts high enough to map BAO in the very early Universe can’t be done with a 2.5-meter (diameter) telescope. Hence BOSS’s second target: quasars.

“Quasars are the brightest objects in the sky, and therefore the only credible way to measure spectra out to redshifts of 2.0 and beyond,” says Schlegel. “At these redshifts, there are a hundred times more galaxies than quasars, but they’re too faint to use for BAO measurements.” Quasars are distributed too sparsely to measure BAOs directly, but there’s another way in which they reveal BAOs at high redshifts. As the light of a quasar passes through clouds of intergalactic gas on its way to Earth, its spectrum develops a plethora of hydrogen absorption lines known as the Lyman-alpha forest. Ideally, each absorption line in the “forest” reveals where the quasar’s light has passed through an intervening gas cloud. Like a single flashlight seen through the fog, the different prominences and redshifts of the individual absorption lines in a given quasar’s spectrum reveal how the gas density varies with distance along the line of sight. With enough quasars, close enough together and covering a wide expanse of sky, the distribution of intervening gas clouds can be mapped in three dimensions.
SDSS-III’s far more sophisticated spectrograph allows much better coverage and resolution than earlier surveys, but searching for BAOs in the Lyman-alpha forest was still a high-risk proposition for many reasons. Lyman-alpha absorption lines occur in the ultraviolet part of the spectrum, which is absorbed by Earth’s atmosphere; from the ground, only those quasars whose spectra are redshifted the right amount are useful. The lines tag only neutral hydrogen; most hydrogen in the Universe is ionized. Among other uncertainties, irregular heating of hydrogen clouds, or too many quasars too close together, could distort the clustering signal.

The initial Lyman-alpha result—the first map of BAOs at this very early stage of the Universe’s evolution—is based on just a third of the volume of space that BOSS will ultimately map, and includes 60,369 quasars confirmed by visual inspection of their spectra. Schlegel says, “There is no other credible way we could have measured BAOs at redshifts of two or more. Five years ago it was chancy, but it was the only proposal on the table. We could have failed in any number of ways, but Nature was good to us.” Berkeley Lab’s Martin White says, “We are seeing back to the matter-dominated Universe, when expansion was decelerating and dark energy was hard to see. The transition from decelerating to accelerating expansion was a sharp one, and now we live in a Universe dominated by dark energy. The biggest puzzle in cosmology is, why now?” It’s a question BOSS will go far to illuminate as it collects more than a million and a half galaxies and more than 160,000 quasars before SDSS-III is complete. Meanwhile, the Lyman-alpha forest has opened a new view of the ancient Universe, one that may come to full fruition with future, more powerful surveys like the proposed BigBOSS, which just received a significant cash injection to take it to the next stage of development.

“BigBOSS is the next big thing in cosmology,” says Uroš Seljak, director of the Berkeley Center for Cosmological Physics (BCCP). “It would map millions and millions of galaxies, allowing us to measure dark energy to high precision—and would yield other important scientific results as well, including determining the neutrino mass and the number of neutrino families.” “After we won the Nobel Prize, the question we all heard most was, ‘Now that you’ve discovered dark energy, what comes next?’” says Saul Perlmutter. “The answer is pretty clear: we have to find out what dark energy is. There’s no end of theories. To know which are possible, what we need most is the kind of accurate observational evidence that only BigBOSS and other advanced experiments can give us.”

“If we tasked all the telescopes in the world on this project, we wouldn’t be able to make such a comprehensive map of the Universe in less than 10 years, with existing instruments,” says David Schlegel. “We’ve figured out how to make such a map with a single telescope, the Mayall Telescope, with the right kind of clever instrument.” Installing that right kind of clever instrument will require modifying the existing 4-meter (diameter) Mayall Telescope on Kitt Peak in Arizona (USA), which currently covers just half a degree of sky (roughly the diameter of the full moon). The Mayall’s field of view will be enlarged to encompass three degrees, and its focal plane will be populated by robotic actuators capable of precisely positioning 5,000 optical fibres simultaneously, so
that each single exposure can rapidly capture the light of 5,000 individually focused galaxies or other astronomical objects. During every exposure, the light from each object is carried by its individual fibre to one of 10 spectrographs.

It seems, therefore, that the conditions are right to make significant gains in our understanding of the properties and nature of dark energy in decades to come. Watch this space!

**Figures** (in no particular order)

**Figure 1:** The BigBOSS proposal adds a new wide-field, prime-focus corrector to the Mayall 4-meter telescope. A focal array with 5,000 optical fibres, individually positioned by robotic actuators, delivers light to a set of 10 three-arm spectrometers. (*Credit: Lawrence Berkeley National Laboratory. Background photo Mark Duggan.*)
Figure 2: Light from distant quasars (dots at left) is partially absorbed as it passes through clouds of hydrogen gas. A “forest” of hydrogen absorption lines in an individual quasar’s spectrum (inset) pinpoints denser clumps of gas along the line of sight, and the spectra are collected by the telescope’s spectrograph (square at right). Before BOSS, the Sloan Digital Sky Survey had collected spectra from 10 times fewer quasars (yellow dots) per square degree of sky in the accessible redshift range, which corresponds on average to some 10 billion years ago. By measuring the spectra from many more quasars in this range (red dots), BOSS can reconstruct a three-dimensional map of the otherwise invisible gas, revealing the large-scale structure of the early Universe. (Illustration by Zosia Rostomian, Lawrence Berkeley National Laboratory; Nic Ross, BOSS Lyman-alpha team, Berkeley Lab; and Springel et al., Virgo Consortium and Max Planck Institute for Astrophysics.)

Figure 3: Until recently, three-dimensional maps by BOSS (red dot, right of centre) and other surveys were able to measure the regular distribution of galaxies back to an average of only approximately five and a half billion years ago, a time when the expansion of the Universe was already accelerating. BOSS’s quasar measurements (red dot, left), by measuring the distribution of intergalactic gas, have now probed the structure of the early Universe at a time when expansion was still slowing under the influence of gravity. The quasar data gives new access to the transition from deceleration to acceleration caused by dark energy. (Graph by Zosia Rostomian, Lawrence Berkeley National Laboratory, and Nic Ross, BOSS Lyman-alpha team, Berkeley Lab.)
**Figure 4:** The record of BAOs (white circles) in galaxy maps helps astronomers retrace the history of the expanding Universe. These schematic images show the Universe at three different times. The representative-colour image on the right shows the “cosmic microwave background,” a record of what the very young Universe looked like 13.7 billion years ago. The small density variations present then have grown into the clusters, walls, and filaments of galaxies that we see today. These variations included the signal of the original BAOs (white circle, right). As the Universe has expanded (middle and left), evidence of the BAOs has remained, visible in a “peak separation” between galaxies (the larger white circles). The SDSS-III results announced in March 2012 (middle) are for galaxies 5.5 billion lightyears distant, at the time when dark energy turned on. Comparing them with previous results from galaxies 3.8 billion lightyears away (left) measures how the Universe has expanded with time. (*Credit: E. M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian.*)
Figure 5: BOSS is capturing accurate spectra for millions of astronomical objects by using 2,000 plug plates that are placed at the Sloan Telescope’s focal plane. Each of the 1,000 holes drilled in a single plug plate captures the light from a specific galaxy, quasar, or other target, and conveys its light to a sensitive spectrograph through an optical fibre. The plates are marked to indicate which holes belong to which bundles of the thousand optical fibers that carry the object’s light. (Credit: Lawrence Berkeley National Laboratory and Sloan Digital Sky Survey III.)