Dark Energy From the Ground Up: Make Way for BigBOSS

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Ever since the big bang and the epoch of inflation, the universe has been expanding. Now it’s expanding at an accelerating rate, because of a mysterious something called dark energy.

(PhysOrg.com) -- Several ways have been proposed to examine dark energy, in hopes of finding out just what it is. One of them, "supernovae" for short, certainly works: it's how dark energy was discovered in the first place. Other independent techniques, such as weak gravitational lensing and baryon acoustic oscillation, also promise great power but are as yet unproven.

These three techniques all have a share of the proposed Joint Dark

Energy Mission (JDEM), a satellite design managed by NASA with the participation of the U.S. Department of Energy. DOE's JDEM Project Office is headquartered at Lawrence Berkeley National Laboratory and led by Michael Levi of the Physics Division.

During deliberations on JDEM's reference design in the fall and winter of 2008-2009, some members of the JDEM Science Coordination Group (SCG), which included Saul Perlmutter and David Schlegel of Berkeley Lab's Physics Division, questioned whether a satellite was really the best platform for all three of the proposed methods.

"Of the three main things JDEM is supposed to do, the NASA design focuses on baryon acoustic oscillation," says Schlegel. "It's good science, but I wondered whether it could be done just as well, or better, from the ground."

Space is the place - sometimes

The goal of all experiments that seek to determine the nature of dark energy is a detailed expansion history of the universe. For supernova studies, which depend on measuring the redshift and brightness of distant Type Ia supernovae, there's no question that space is the place.

The Mayall 4-meter telescope at Kitt Peak National Observatory can be adjusted to observe a 3-degree field of view with a high-precision spectrograph. A new secondary mirror (top) and a corrector and field flattener will send the light to a flat focal plane (above primary mirror) where the light from each target object is carried to spectrographs by optical fibers.

Beginning in the 1980s, methods for finding Type Ia supernovae "on demand" were developed by the international Supernova Cosmology Project (SCP), based at Berkeley Lab and headed by Perlmutter, and adopted in 1994 by a rival team, the High-Z Supernova Search Team. In the fall of 1997 the SCP concluded that the universe is expanding at an accelerating rate, propelled by a mysterious something soon to be called dark energy. The unexpected acceleration was soon confirmed by the High-Z Team.

Most of the early studies were done from the ground but included a handful of supernova measurements made with the Hubble Space Telescope. To measure expansion rate with enough precision to choose among competing models of dark energy, however, exquisite spectrometry of thousands of distant Type Ia supernovae will be needed. This can only be done by flying a big telescope and an adequate spectrograph in space. That's why the SCP inaugurated a DOE satellite proposal in 1999 called the SuperNova/Acceleration Probe, SNAP, which eventually inspired JDEM.

Early on, SNAP included the capacity to measure weak gravitational lensing, which looks at subtle measures of the distortion of space by both ordinary and dark matter to reveal how the distribution of matter in the universe has changed over time. Weak lensing will also greatly benefit from a space-borne telescope.

Baryon acoustic oscillation (BAO) is distinct from both these methods. "Baryon" is cosmology-speak for ordinary matter, and "acoustic oscillation" is a fancy name for the way galaxies tend to bunch up at roughly 500 million light-year intervals. These density oscillations have their origin in the pressure waves (like sound waves, thus acoustic) that moved through the liquid-like plasma of the early, hot universe.

By the time the universe was 300,000 to 400,000 years old, it had expanded and cooled enough for atoms to form, releasing light to go on its way unimpeded - the era of decoupling. But the density oscillations left their mark as minute temperature differences in the cosmic microwave background (CMB). The denser regions, where matter was clumped more tightly, were the seeds of today's galaxies and groups of galaxies.

The cosmic microwave background provides the starting point for a natural ruler to measure how much, and how smoothly, the universe has expanded since the era of decoupling. The ruler is extended forward in time by measuring variations in the density of galaxies - especially old, bright, red galaxies and quasars - across billions of light-years. The expansion history of the universe emerges when the markings of the ruler, as seen in more recent cosmic structures, are calibrated against the scale frozen in when the universe was less than 400,000 years old.

Grounded cosmology

But does one need a telescope in space to measure baryon acoustic oscillations? David Schlegel didn't think so. In 2006 he and his colleague Nikhil Padmanabhan, both members of the Sloan Digital Sky Survey (SDSS), completed the largest three-dimensional map of the universe ever made until then, in which they first detected the 500-million-light-year scale of baryon oscillations. Now Schlegel leads the SDSS's Baryon Oscillation Spectroscopic Survey, BOSS, whose goal is to map one and a half million galaxies and quasars and measure the varying densities of hydrogen gas in the universe. It will be the first survey with a chance at using BAO to measure the universe's expansion history.

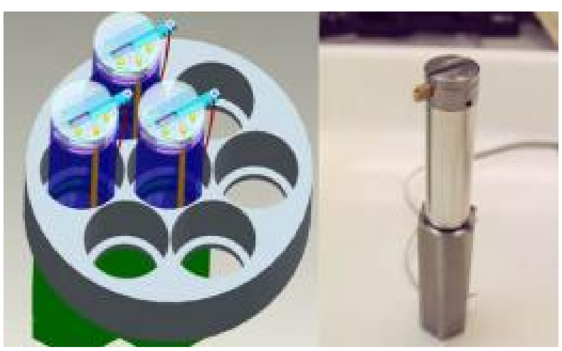
As a member of JDEM's Science Coordination Group, however, Schlegel was taken aback by NASA's emphasis on baryon acoustic oscillation. "I was surprised that JDEM, a $600-million mission, was going down what seemed a risky scientific pathway," he says.

"Last winter, I was scheduled to give a talk at an SCG meeting the next day in Washington with no idea what I was going to say," Schlegel recalls. "On my way down from New Haven on the train I just decided to work out the numbers to see if what JDEM wanted to do with BAO could be done from the ground. Remarkably, no one had done that. Instead of asking what kind of instrument we needed to do the science, the approach had been, 'here's the instrument we're giving you, what can you do with it?'"

Schlegel's back-of-the-envelope BAO calculations looked "encouraging," as he put it, and his presentation to the SCG raised a few eyebrows. But he realized existing programs were no threat to JDEM's "figure of merit" for BAO - a more or less abstract number based on the 2006 DOE-NASA-National Science Foundation Dark Energy Task Force's calculation of how useful a given experimental result would be for measuring dark energy. JDEM's figure of merit is 313. The figure of merit for BOSS, the biggest ground-based BAO search underway so far, is 107.

Nevertheless, Schlegel couldn't shake the idea, and in February of 2009, once NASA had finalized their design ideas, he started thinking about it more seriously.

"To match what JDEM proposes to do, we would need a bigger telescope than the SDSS telescope in New Mexico we're using for BOSS. Optimum would be a 4-meter telescope that could accommodate a spectrograph with a wide field of view, covering three degrees of the sky," Schlegel says. (For comparison, the full moon is half a degree in diameter.) "There are only 14 4-meter telescopes in the world, seven of them U.S.-operated. And whether any of them had three-degree field-of-view imaging capability, I wasn't sure."



Robot actuators individually position each optical fiber precisely where it needs to be to collect the light from a specific astronomical object programmed by computer. The light is analyzed by blue, visible, and infrared spectrographs. For videos of the prototype actuators, see "Additional Information" below.

Two of the candidate telescopes are operated by the National Science Foundation's National Optical Astronomical Observatory (NOAO), which oversees the Kitt Peak National Observatory in Arizona with its 4-meter Mayall Telescope, and the Cerro Tololo Inter-American Observatory in Chile, which also has a 4-meter telescope. Schlegel's inquiries indicated that the NOAO astronomers would indeed be interested in exploring the possibility of BAO studies.

Says Schlegel, "So I asked Michael Sholl, the optical designer in the JDEM project office here, whether the 4-meter Mayall could be adapted for a spectrograph with a three-degree field of view. He said, 'I'll look into it and get back to you.'"

A string of luck

Schlegel fully expected Sholl to tell him it couldn't be done. And when Sholl knocked on his office door and said, "I'm really sorry, I can't get to three degrees." Schlegel thought that was the end of it - until Sholl added, "The best I can do is 2.94."

Says Schlegel, "I dropped everything. We were in business." It turned out that the telescope design which would allow a three-degree (oh all right, a 2.94-degree) spectrograph was common to only three of the world's 4-meter telescopes. NOAO's Kitt Peak and Cerro Tololo had two of them.

The spectroscopic instrument that would fit these telescopes had already been developed at Berkeley Lab using Laboratory Directed Research and

Development funds, but wasn't completed in time to be installed on BOSS. BOSS's spectrograph uses optical fibers fitted into holes in metal "plug plate" masks, drilled in the precise position of galaxies mapped from previous photos. To obtain redshift and other spectral information, each fiber conducts the light of a single galaxy to a sensitive CCD. Each plate is limited to 1,000 fibers. BOSS will use some 1,500 virtually hand-made plates to gather the light of 1.5 million quasars and galaxies.

The new spectrograph does away with plug plates altogether. Target galaxy positions are stored in a computer, which directs the positioning of an array of thousands of optical fibers for each exposure. A single aluminum block machined to the curvature of the modified telescope's 1 meter focal plane is divided into 5,000 cells, each perforated by a cylindrical hole.

"In each hole live a couple of robots," says Schlegel, "actuators that can position the fibers to an accuracy of 15 microns" - 15 millionths of a meter. The robots put the tip of the fiber right where the light from the distant galaxy falls - even, if necessary, outside the hole - and positions the fibers in the focal plane with no dead space, gathering the light of some 4,000 galaxies at a time.

To accommodate the spectrograph, the existing telescopes would need to be modified with a 2-meter secondary mirror. It so happened that a glass blank for just such a mirror, intended for the SNAP satellite, had already been bought and paid for by DOE. DOE offered it to NASA for JDEM, but NASA wasn't interested. It was available.

Schlegel realized that he and his colleagues were looking at the possibility of mounting a three-degree spectrograph on existing telescopes that could gather millions of galaxies with extraordinary spectral resolution - precision that would allow the study not just of density variations of galaxies but in the hydrogen gas that fills the universe, something JDEM could not do, covering a much wider range of redshifts than JDEM, and looking much farther back in time.

Because the new approach had evolved from the existing BOSS, it was tagged BigBOSS.

Into the fray

"In a March 3 phone call to Kitt Peak we decided to go for broke," Schlegel says. "Every 10 years the National Academy of Science's Decadal Survey lays out a roadmap for future astronomy and astrophysics research. White papers describing proposals were due April 1. Most people work for years on these proposals; we did it in four weeks."

The joint DOE-NSF BigBOSS white paper was submitted to the Decadal Survey on time and has since gathered a string of approvals from government committees; the Decadal Survey report is due at year's end. "We made a Hail Mary pass and hit every committee," says Schlegel. "Our case is strong."

BigBOSS proposes to advance in two stages, the first at Kitt Peak covering the northern sky, the second at Cerro Tololo. BigBOSS North would look at the distribution of 30 million galaxies and a million quasars. After this survey is complete the project would move to Chile, where BigBOSS South would add another 20 million galaxies and quasars. Both surveys would measure distortions in hydrogen gas.

The construction of the spectrograph and telescope modifications are estimated to take three years, beginning in 2011, at a cost of $71 million, with operations costing $2.5 million a year for 10 years.

Compared to JDEM's figure of merit, 313, BigBOSS North alone would achieve 240, and North and South together would achieve 338. At three years to build and 10 years to cover the whole sky, assuming five million targets a year, BigBOSS could take longer than JDEM, which might launch in 2016 at the earliest. The cost is less than a sixth JDEM's, however, and the risk of failure is minimal - BigBOSS uses existing facilities and proven technology.

"BOSS will be the first survey to produce a 3-D map of red galaxies and quasars and clouds of hydrogen gas in the universe, and BOSS is the first BAO survey from which it may be possible to measure the expansion history of the universe. BigBOSS's map will be far bigger and more detailed," says Schlegel.

"But BigBOSS offers more. One of the most interesting questions in cosmology is the relationship between dark energy and the early inflationary epoch of rapid expansion. Something was happening then, and we wonder if it's repeating in some way. BigBOSS will have the best sensitivity to the inflationary epoch. In some ways this could be the best argument for BigBOSS of them all."

More information: "BigBOSS: The Ground-Based Stage IV Dark Energy Experiment," by David J. Schlegel, Chris Bebek, Henry Heetderks, Shirley Ho, Michael Lampton, Michael Levi, Nick Mostek, Nikhil Padmanabhan, Saul Perlmutter, Natalie Roe, Michael Sholl, George Smoot, and Martin White of Lawrence Berkeley National Laboratory, and Arjun Dey, Tony Abraham, Buell Jannuzi, Dick Joyce, Ming Liang, Mike Merrill, Knut Olsen, and Samir Salim of the National Optical Astronomy Observatory, is posted at arXiv:0904.0468v3.

Source: Lawrence Berkeley National Laboratory (news : web)