carbon capture and storage could be significant in limiting temperature rise, he says.

Although Obama failed to get congressional approval for a carbon cap and trade system early in his administration, Holdren believes that a future president and Congress eventually will agree “in one way or another” to put a price on carbon. “Right now, we’re doing it in effect through regulations of various kinds. That’s not the most efficient way to do it.”

Holdren is the longest-serving science adviser to a US president; his term surpasses that of his predecessor, John Marburger, by several months. Holdren has some advice for his successor. “Keep your priorities straight. Your first responsibility is to the president”—not the federal science and technology agencies, the scientific community, or the media.

The science adviser’s second priority is to run OSTP, which has doubled in size to about 120 staff during the Obama years. That growth, Holdren says, occurred because the president “is more interested in science and technology and why it matters to every aspect of his agenda” than any other president, with one possible exception. “I like to say President Obama is the most science-savvy president since Thomas Jefferson, but there is a lot more science to be savvy about.”

Holdren says his successor also should “stay close to the action; be at the table.” He quotes an unnamed chief of staff to Obama admonishing the science adviser, “If you’re not at the table, you’re on the menu.” It’s one reason Holdren couldn’t be “in all places at all times and all things to all people,” he adds. Finally, the next adviser should partner with, cooperate with, and get to know colleagues throughout the agencies and in the White House, he says. “You will get a lot more done working together than you ever will fighting over territory.”

Although the science adviser position, established after World War II, has been filled by physicists or, less frequently, chemists and engineers, Holdren says “it would be great” if a life scientist were to be chosen next. Precisely because he didn’t want his science advice to come solely from physical scientists, Holdren says, Obama appointed two life scientists, Harold Varmus and Eric Lander, to cochair his President’s Council of Advisors on Science and Technology.

Although Holdren denies looking forward to retirement, the 72-year-old insists he won’t stay on under a new president. “My wife would divorce me; it would end a 50-year marriage.” But when asked, he says his biggest regret is that Obama can’t serve another term, then quickly adds that he also regrets being unable to obtain more funding for federal R&D.

Public support needed

For sustained, large budget increases, he says, the scientific community “will need to get better at telling concrete stories about how investments in research and development have improved the quality of our lives, strengthened our economy, created jobs, and opened new horizons in understanding the world around us and the universe around us. We just have tended to talk too much in abstract terms—how many dollars, what percentage of GDP, and so on.”

Obama’s intent to double the budgets of NSF, NIST, and the Department of Energy’s Office of Science over a 10-year period faltered in the face of budget constraints imposed to reduce deficits. Pointing to basic research investments that serendipitously resulted in inventions such as the laser, Holdren notes that “the folks that sit in Congress and read the titles of NSF research grants and say ‘I don’t see how this makes sense’ are barking up the wrong tree. . . . We know from historical experience the portfolio of investments in basic research yields enormous results, and we have in place at NSF and at our other science-related agencies the sort of gold-standard peer-review process that ensures we are making the best possible bets.”

Holdren says caps on discretionary spending justify Obama’s decision to propose that Congress create a new mandatory account to fund $4.6 billion of R&D in fiscal year 2017 at a half-dozen science agencies, including NASA, NSF, and DOE. Some $1.9 billion of that would pay to establish a network of 45 NIST manufacturing technology centers. But Congress is unlikely to approve new mandatory programs because they cede lawmakers’ control over the budget. Still, he says, “We believe that even if we don’t get everything we want from Congress there is merit in putting out before the public and before Congress the things we believe the government needs to be doing and should be doing in R&D.”

David Kramer

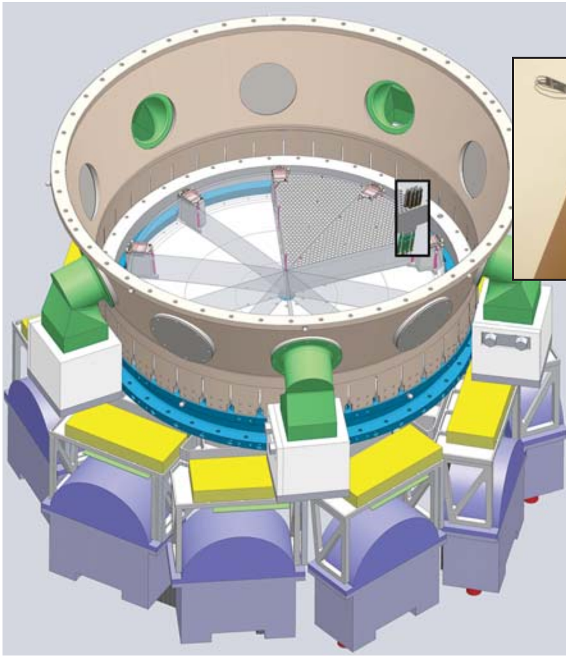
Extragalactic survey aims to shed light on dark energy

Robot-controlled optical fibers will help create 3D map of the cosmos.

It won’t be the “billions and billions” that astrophysicist and science popularizer Carl Sagan famously referred to, but the 35 million galaxies that the Dark Energy Spectroscopic Instrument (DESI) will map in three dimensions will increase by more than an order of magnitude the number of galaxies with precisely known redshifts. DESI will lead the way among several next-generation projects to characterize dark energy; the data may also yield insights about dark matter, general relativity, neutrinos, galaxy formation, and more.

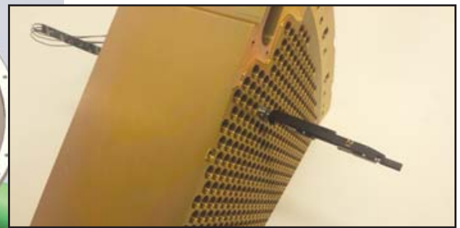
The DESI project will entail reincarnating a 45-year-old, 4 m telescope on Kitt Peak in Arizona. Until now, under the auspices of the NSF-funded National Optical Astronomy Observatory (NOAO), the Mayall telescope has been a workhorse used by the wider astronomy community. But in 2012 NSF, following a review of its budget and priorities, decided to cut purse strings to the telescope, although it retains ownership.

The DESI collaboration saw an opportunity, and next year it will begin reconfiguring the telescope for a roughly $115 million, five-year dedicated extragalactic redshift survey. The Department of Energy is footing the running costs of up to $8 million annually in addition to $56 million of the $75 million conversion. The remaining $19 million comes



R. LAFEVER AND J. MOUSTAKAS, DESI COLLABORATION

DESI COLLABORATION



ONE OF THE ROBOTIC POSITIONERS (above) with which the Dark Energy Spectroscopic Instrument will point optical fibers at preselected targets to measure redshifts. DESI will have 5000 such robots, divided among 10 wedges, like the one shown. The assembly will be located at the focal plane of a 4 m telescope (as in the schematic at left). The fibers can be reconfigured within a couple of minutes. Over five years DESI will map 35 million galaxies.

from international partners and private donors—the Gordon and Betty Moore and the Heising–Simons Foundations provided seed funding. Scientists at Lawrence Berkeley National Laboratory are leading construction on the new instrument. In addition to US institutions, the collaboration includes scientists from Australia, Brazil, Canada, China, Colombia, France, Mexico, South Korea, Spain, Switzerland, and the UK. The survey will begin measuring redshifts in January 2019.

Robotic power

DESI gets its muscle from the speed at which it can gather 3D galaxy positions. The instrument is a follow-on to others, notably BOSS (Baryon Oscillation Spectroscopic Survey, a Sloan Digital Sky Survey project). But it will collect many more spectra at a time than any previous instrument.

At the focal plane of the telescope will be an aluminum plate that is just shy of a meter across and made up of 10 wedge-shaped segments. Each segment has 500 hexagonally arranged circular holes 8.4 mm in diameter. Robotically controlled optical fibers can be positioned over the holes, and because of pivot arms they have 12-mm-diameter patrol areas that slightly overlap those of their neighbors. The 5000 fibers are independently moved around by tiny motors similar to those that make a cell phone vibrate. By contrast, notes David Sprayberry, an NOAO scientist who is overseeing the telescope's transition, the positioning of fibers on BOSS is done painstakingly by hand.

With DESI, the fibers will collect data for 20–30 minutes, and then the telescope will be repointed and the fibers positioned for a new set of targets; that automated process will take a minute or two. DESI's targets are being selected from three ongoing surveys: two based on Kitt Peak and the third in Chile.

The galaxy light will be bundled into 10 cables and run down the telescope to a spectrograph room. That, Sprayberry says, is the part that keeps him up at night. "The cables are long and stiff and the optics on the free end of them are delicate," he says. "We are still figuring out how to install the cables on the telescope without damaging them."

Looking for hints

Observational evidence indicates that the universe will expand forever and is made up of about 5% ordinary matter, 25% dark matter, and 70% dark energy. "But we know only about ordinary matter, not about the other 95% of the universe," says project member Ofer Lahav of University College London.

Dark energy was originally discovered through its apparent influence on the increase in acceleration of expansion that started 7 billion years ago. Going from discovering dark energy to finding out what it is requires more detailed data on the cosmic expansion. "It's not like the Higgs particle, that you know when you have it," says project scientist Brenna Flaugher of Fermilab. "With dark energy, we don't know what we have to measure to understand what it is. We are looking for hints."

That's where DESI comes in. By analyzing the galaxy map data in two distinct ways—through baryon acoustic oscillations (BAO) and redshift-space distortions—scientists hope to learn how dark energy behaves, if not exactly what it is.

In the hot plasma of the very early universe, oscillations resembling sound waves—the BAO—were produced by the opposing forces of gravity and gas pressure. Where local perturbations in density existed, matter coalesced and enhanced the BAO signal. The density waves propagated spherically until 400 000 years after the Big Bang, when the universe had cooled sufficiently for free electrons and protons to bind together into neutral hydrogen. Galaxies formed preferentially at the sites of the initial perturbations and where the propagation stopped; their separations constitute a physical length scale that has expanded with the universe.

A convenient way to characterize the distribution of galaxies is to calculate the distance between pairs of them. By computing vast numbers of pairwise distances, investigators can identify BAO signatures and then follow how those separations evolve over cosmological time scales.

The same DESI data can also be plumbed for distortions in redshift space. Gravity pulls galaxies into regions of higher mass, increasing the galaxies' velocities so that, along our line of sight, the redshifts of closer galaxies are stretched while the redshifts of more distant ones are squished. The redshift-space distortion can provide information about both the expansion rate of the universe and the growth of structure due to gravity.

Comparing the BAO and redshift-space distortion measurements with theoretical models could yield insights into whether the cosmological constant is in fact constant and into the physical phenomena ultimately responsible for the expansion of the universe. "The combination of methods is very powerful," says Lahav. "DESI will test current models of dark energy. And it will also test Einstein's theory of general relativity."

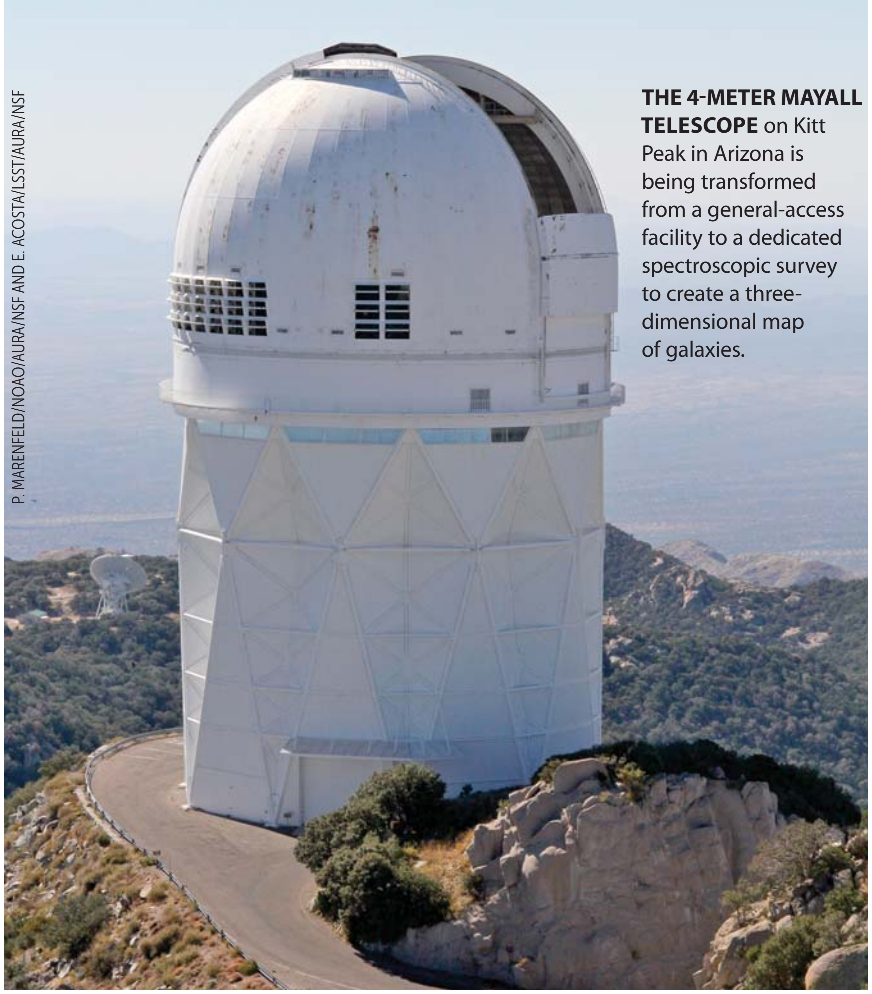
"A gold mine"

About 700 000 of DESI's targets will be bright, high-redshift quasars. They can be used as beacons to measure the absorption of hydrogen along the line of sight and map the distribution of hydrogen gas, thus providing another window onto cosmological structure and its evolution. The quasars' brightness makes them DESI's most distant tracers and allows cosmologists to measure the influence of dark energy back 12 billion years.

DESI's science will go beyond the primary goal of studying dark energy. The quasar spectra, for example, can also be used to probe the structure of intervening galaxies. And DESI's fibers could be trained on targets—transient objects, say, such as supernovae or gravitational-wave sources—identified by other telescopes.

When the night sky is too bright to take spectra of distant galaxies (out to redshift 1.6), DESI will survey closer galaxies (below redshift 0.6) and measure the redshifts of millions of stars in our galaxy. "Mapping out stars in the Milky Way gives you a way to figure out how clumpy the dark matter is," says DESI cospokesperson Risa Wechsler of Stanford University.

DESI will also be sensitive to neutrino mass. "Without massive neutrinos, the universe would be more blobby; with neutrinos, it is smoother," says Lahav. "One dream we have with DESI is to measure the mass of neutrinos" by looking at the clustering patterns of galaxies.



P. MARENFELD/NOAO/AURA/NSF AND E. ACOSTA/LSST/AURA/NSF

THE 4-METER MAYALL TELESCOPE on Kitt Peak in Arizona is being transformed from a general-access facility to a dedicated spectroscopic survey to create a three-dimensional map of galaxies.

After a yet-to-be-determined proprietary period, the DESI data will be released to the wider astronomy community. Says project member Will Percival of the UK's University of Portsmouth, "Once you have such a survey, it's a gold mine of data for lots of science. A whole range of physics is encoded into the distribution of galaxies."

DESI is not the only new experiment to characterize dark energy's influence on the cosmos. The other main ground-based projects in the works are the prime focus spectrograph planned for Japan's Subaru Telescope in Hawaii, scheduled to begin science operations in mid-2019; a wide-field spectrograph on the William Herschel Telescope on La Palma in the Canary Islands, set to start up in June 2018; and studies with the Large Synoptic Survey Telescope in Chile, which is slated to start collecting data in 2022. Two space missions to be launched in the 2020s will also have strong dark-energy components: the European Space Agency's *Euclid* and NASA's *Wide Field Infrared Survey Telescope*.

Toni Feder PT