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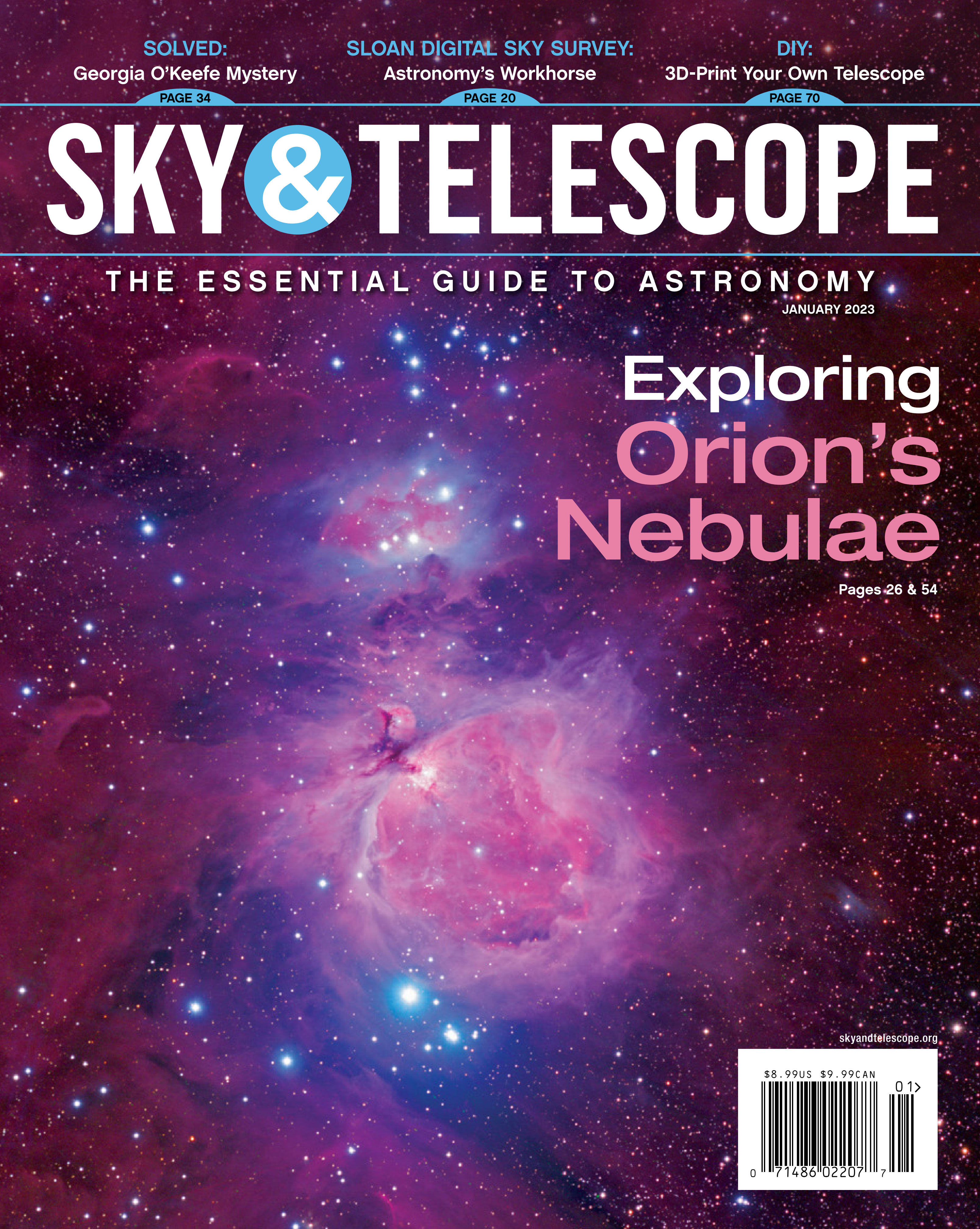
JANUARY 2023



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ASTRONOMY'S WORKHORSE by Karen Masters

The Neverending Survey

The decades-long Sloan Digital Sky Survey project has transformed how astronomers do astronomy.

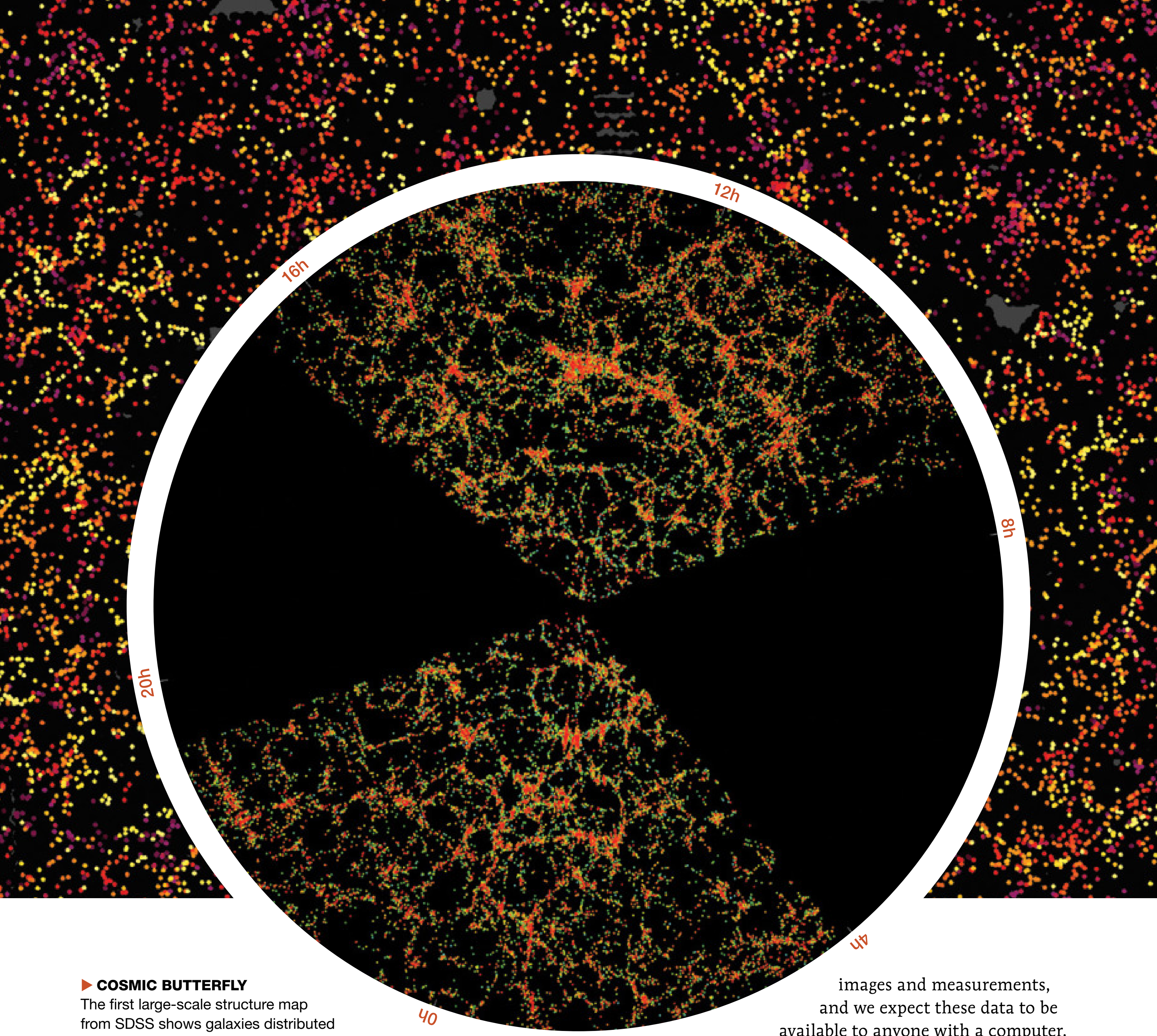
▲ **SLICE THROUGH THE UNIVERSE** Every colored pixel in this picture is a galaxy, mapped by the Baryon Oscillation Spectroscopic Survey (BOSS) out to a distance of 6 billion light-years. The color indicates each galaxy's distance, from near (yellow) to far (purple).

The telescope used most across professional astronomy isn't the biggest or the newest, and it isn't in space. It's a modest telescope on a mountain in New Mexico. The images and spectra from this facility, the Sloan Foundation 2.5-meter Telescope at Apache Point Observatory, are so ubiquitous that many astronomers don't even think about where the data come from. But this unassuming telescope and the (so far) five phases of its Sloan Digital Sky Survey (SDSS) have revolutionized how astronomers work.

The original idea behind the SDSS was to make an enormous map of the universe. To do this, the collaboration developed a huge digital camera, which held the record for the largest camera in the world for well over a decade. Before megapixel smartphones became our pocket cameras, this 126-megapixel imager was scanning the night skies from its first light in 1998 until 2009, stitching together a detailed view of a third of the sky visible from New Mexico. Meanwhile, researchers developed computer codes to process these images, calibrate the images' colors, scan them to identify galaxies and stars, and pick some to measure spectra. In all, the first SDSS efforts cataloged more than 1 billion objects.

After the imaging camera's retirement in 2009, SDSS projects refocused on collecting celestial objects' spectra in a series of acronym-titled surveys. Each SDSS observation from these surveys measured hundreds of spectra at once. Decoding these detailed rainbows of light enables us to track how fast galaxies are moving away from us due to the universe's expansion, to measure the types of stars in those galaxies, to find the locations and sizes of supermassive black holes, and to learn more about our own galaxy's stars and their planets.

ALL IMAGES COURTESY OF SDSS UNLESS OTHERWISE NOTED



▶ **COSMIC BUTTERFLY**
The first large-scale structure map from SDSS shows galaxies distributed along bubbles and filaments out to 1.8 billion light-years from Earth (at center). Each point on the map is a galaxy. Parts of the map are missing because those areas are blocked from view by our own Milky Way Galaxy. This map is dwarfed by later phases of SDSS.

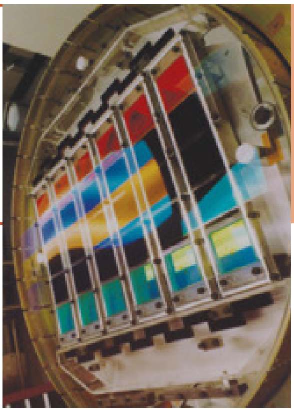
SDSS / MIKE BLANTON

With an alphabet soup of different projects across more than two decades, and now with a second facility in the Southern Hemisphere, the SDSS is arguably one of the most successful and influential astronomy projects in the world.

Astronomy as Data Science

Today, it seems normal that professional astronomers would work together across international borders to create large surveys of the night sky. We're used to collecting and storing images and measurements, and we expect these data to be available to anyone with a computer. But until SDSS became the massive success it is, many astronomers didn't believe this model would work. Astronomers were used to keeping their data private — fair enough, given that building professional telescopes and obtaining observing time on them are costly and difficult endeavors. In fact, when team members in the early 1990s first talked about plans to measure the spectra of hundreds of thousands of objects, other astronomers thought they were joking. It took visionaries to realize that by working together instead of apart, by collaborating to both collect and process the data from telescopes, and (crucially) by releasing these data for the entire community to use, astronomers could map much more of the universe than would ever have been possible if they were working as individuals.

▶ **LEGACY CAMERA** This camera collected all the imaging data of SDSS's first decade. The camera read the CCDs while the sky drifted by the field of view of the telescope in great circles, so images of objects moved along the CCD columns at the same rate that the CCDs were being read.



After being retired, the original SDSS imaging camera was moved to the basement of the Smithsonian in Washington, D.C., where it is stored for its significance to scientific history.

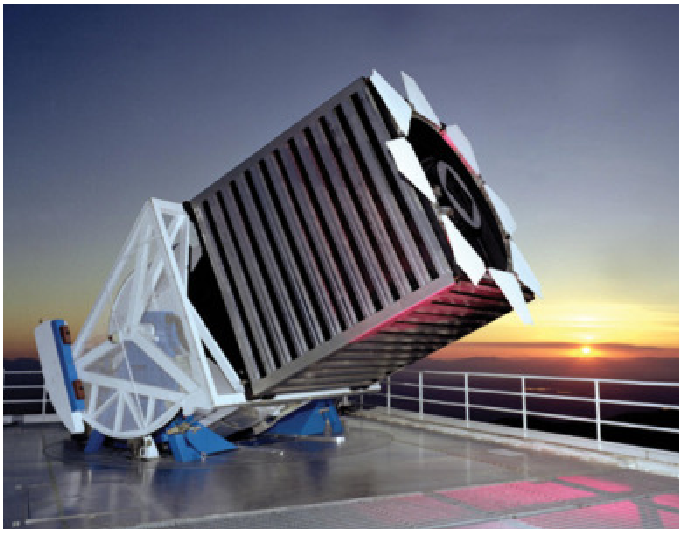
It takes great effort to make "open and accessible data" a reality. Scientists working within the project commit to releasing data regularly, typically about a year after it comes off the telescope. This time gives the team time to do necessary processing, to check and double-check for mistakes, to write supporting documentation — and to benefit from early access before releasing the data to the rest of the world.

Mapping the Universe

SDSS is probably best recognized by its maps of the distant universe. If you've been to a planetarium, you may well have "flown through" one of these. The videos look like how movies imagine jumping to hyperspace, flying past endless galaxies. Eventually, they zoom out to show all that SDSS has surveyed: a butterfly-shape slice of the cosmos.

Across SDSS's first four phases, measuring *cosmological redshifts* was a main goal. Astronomers first calculate how quickly distant galaxies appear to be moving away from us due to the universe's expansion; this *recessional velocity* is proportional to a galaxy's distance from us (*S&T:* Oct. 2022, p. 12). We can then use these distances to map galaxies in 3D.

These first maps of large-scale structure showed galaxies outlining bubbles and filaments in the local universe. Other, smaller surveys had seen evidence for this cosmic web, but SDSS made such a leap in scale that there was no longer any doubt of the web's existence. Later phases of SDSS have dwarfed that first look, measuring galaxy distances out to a redshift of 1.1 (a lookback time of 8.2 billion years). For galaxies with intense beacons powered by supermassive black holes, called quasars, the measurements extend even further, to a redshift of 3.5 (11.9 billion years).



▲ **THE TELESCOPE** Sunset falls at the SDSS 2.5-meter telescope at Apache Point Observatory in New Mexico.

From these maps we learned that as the universe evolves, it becomes clumpier: Gravity pulls matter into a vast network over time. The detailed patterns in the network tell astronomers about the content and expansion history of the universe. We've even identified reliable (albeit very large!) rulers in those patterns. The imprint of ancient soundwaves shows up as a slightly preferred distance between any two pairs of galaxies. SDSS scientists measured this *baryon acoustic oscillation* (BAO) scale for the first time in 2005. The BOSS survey, later extended as eBOSS, improved on this work by obtaining millions of galaxies' and quasars' redshifts.

The BAO scale has enabled astronomers to make some of the most precise measurements of the universe's expansion rate over a wide range of cosmic times. The result favors the lower of two hotly contested values for the universe's *current* expansion rate (*S&T:* Mar. 2022, p. 14). SDSS BAO data haven't yet solved the puzzle of the mysterious dark energy that's accelerating this expansion, but they are an important step toward an answer.

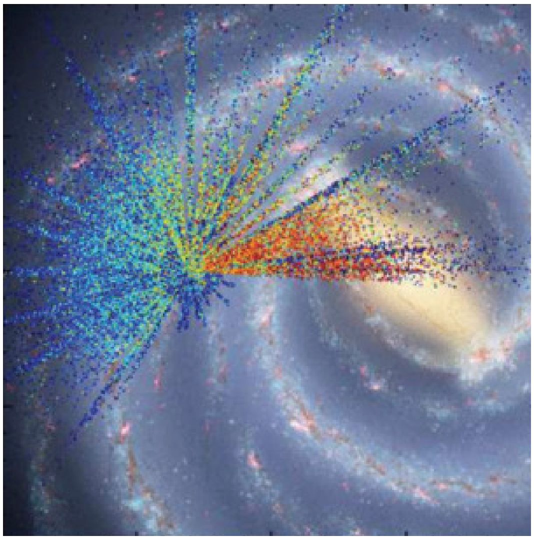
So Many Galaxies, So Little Time

Along the way to creating cosmic maps, SDSS's observations gave astronomers physical information about almost 1 million galaxies. Besides measuring their distances, we can also "weigh" galaxies by probing the motions of their constituent stars, and we can gauge how many baby stars they are forming. Chemical elements leave fingerprints in the detailed spectra that tell us about both the types and ages of stars and about the history of how past stars have enriched the gas with heavy elements. All of this together helps us reconstruct each galaxy's life story.

While we can only ever see an instantaneous snapshot in the life of an individual galaxy, from data on hundreds of thousands, or even millions, of galaxies, we can piece together how they change over time. That wasn't possible before SDSS: "Big samples" of galaxies had previously numbered up to a couple thousand.

The advance to much larger samples meant astronomers had to become data scientists: Instead of examining a handful of galaxies, they started looking for big-picture correlations. For example, SDSS data showed that larger galaxies tend to be redder. Their ruddy hue reveals that they are past their peak of star formation, because all the young, massive bluish stars have died. These larger and redder galaxies are more likely to be elliptical in shape (rather than spiral), and they're richer in heavy elements from past starbirth and -death. Such galaxies also tend to crowd more closely with their neighbors.

Such studies showcase the connections between galaxies, and that many galaxies' properties depend on their location within the cosmic web. Astronomers had seen a lot of these trends earlier on, but SDSS data confirmed the relations with a clarity and precision that revolutionized extragalactic astronomy.



◀ **STAR BY STAR** The APOGEE survey targets individual stars, taking spectra to determine how chemically enriched each one is. Stars marked blue have fewer heavier elements and are likely older; stars marked red have more heavier elements and are likely younger. Data are overlaid on an artist's illustration of the Milky Way.

This immense success from the first phase guaranteed that galaxy science would continue to be a big theme in SDSS. The original Main Galaxy Survey measured just a single spectrum per galaxy, but in SDSS IV the Mapping Nearby Galaxies at Apache Point Observatory (MANGA) survey used a technique called *integral field spectroscopy* to measure tens to hundreds of spectra per galaxy, for a total of 10,000 galaxies. These spectra enabled MANGA to map star formation across different parts of a galaxy, revealing beautiful complexity. Internal structures like bars and spirals mix things up and change how stars and gas move. We see that galaxies stop forming stars from the inside out, and we are beginning to put together how internal processes combine with a galaxy's environment to impact its evolution.

Stars in Our Galaxy

Another unexpected side benefit of SDSS's early days was spectral observations of a large number of individual stars. These images and spectra resulted in a number of serendipitous findings. For example, astronomers discovered numerous stellar streams littering the Milky Way's halo. We now know these are the drawn-out remains of smaller galaxies that our own gobbled up.

This initial serendipity led to planned surveys targeting our galaxy's stars, first using the telescope's optical spectroscope but then moving to near-infrared with the Apache Point Observatory Galactic Evolution Experiment (APOGEE). Observing infrared wavelengths has several benefits for stellar astrophysicists. For one, it allows them to observe during bright moonlit nights, opening up the amount of time available on the telescope. But it also helps them peer deeper through the interstellar dust that obscures the Milky Way's central parts.

APOGEE has given us a more complete picture of the galactic ecosystem, revealing patterns in the ages, motions, and chemical compositions of its stars, including the amount of carbon, iron, and other elements important to life as we know it. When combined with stellar distances, such as those provided by the European Space Agency's Gaia mission, APOGEE spectra help us pick apart the substructures of the Milky Way, revealing details about how our galaxy came together over cosmic time.

However, this analysis is complicated by the fact that our galaxy stretches into a giant circle all around the sky from our perspective, and not all of it is visible from New Mexico. Inspired by a wish to observe stars at the galactic center, the APOGEE team led the charge to bring SDSS to the Southern Hemisphere. The group built a twin spectrograph to send to

Why *Sloan* Digital Sky Survey?

SDSS as an overarching project has always been eponymously linked to the Alfred P. Sloan Foundation. This organization, which leverages the wealth generated by industrialist Alfred P. Sloan, Jr., during the early part of the 20th century, seeks to support innovative scientific research and the diversification of the scientific workforce. Across five phases of SDSS, the Sloan Foundation has provided essential seed funding, contributing more than $70 million across three decades. However, each phase of SDSS has also been strongly supported by institutional buy-in: Academic institutions pay a "joining fee" for early access to data and the right to direct the surveys' scientific priorities. In the fourth phase, a cosmological analogy was somettimes used to talk about the funding sources: The Sloan Foundation was the dark matter (around a quarter of the total funds), institutions provided the dark energy (most of the rest), while grants from government agencies like the Department of Energy provided the baryons (less than 5%). All parts were essential to make the survey work.

Las Campanas Observatory in Chile, which hosts a telescope that to astronomers is almost identical to the Sloan Foundation Telescope. Now, we enjoy a full-sky view of stars in the Milky Way. SDSS V continues this work with the Milky Way Mapper, which is measuring spectra using either the infrared spectrograph from APOGEE or the optical one from BOSS — or both — for more than 4 million stars.

The Changing Universe

Over the years, SDSS has sometimes surveyed the same regions of sky again and again. In these data, astronomers can look for sources that change with time, either because they move or because their brightness changes. Repeated measurements thus turned out to be crucial to studying the changing universe.

Even individual SDSS images are carried out over a period of time: During imaging, the telescope is fixed, purposefully letting the sky drift by while its set of five filters consecutively transmit a specific part of the spectrum, from the ultraviolet to the infrared. These monochrome images are stitched together to make color images, but they're actually taken at slightly different times. Anything that's moving across the frame ends up looking like a little traffic light in the composite image, with blue, green, and red light slightly spread out. Astronomers have used this signature to discover more than 100,000 asteroids as they move across the sky.

SDSS began making more deliberate movies of the sky by repeatedly imaging narrow stripes of sky in an effort to discover and measure the light from Type Ia supernovae, which astronomers can use to measure large distances. SDSS has also run programs that take multiple spectra of objects, such as a *reverberation mapping* survey of distant quasars. Astronomers gauge how quickly these spectra vary — and, thus, how long it takes light to travel across the quasar's domain — to reveal the mass of the supermassive black hole and the size of the gaseous disk around it. This technique powers another core component of SDSS V, Black Hole Mapper, which will make this kind of measurement for 300,000 quasars (a big leap over the not-quite-1,000 done to date).

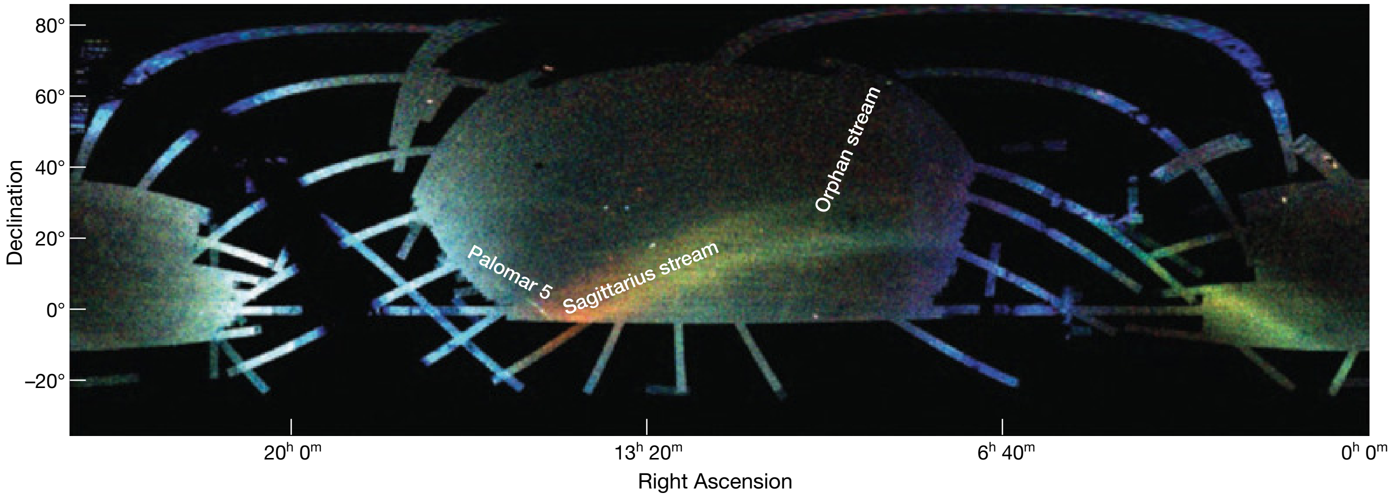
Are you a teacher interested in incorporating SDSS into your astronomy curriculum? Check out **sdss.org/education.** In addition to providing various activity ideas, SDSS distributes its old plug plates for free (while supplies last) for use in education.

The Robots Are Taking Over

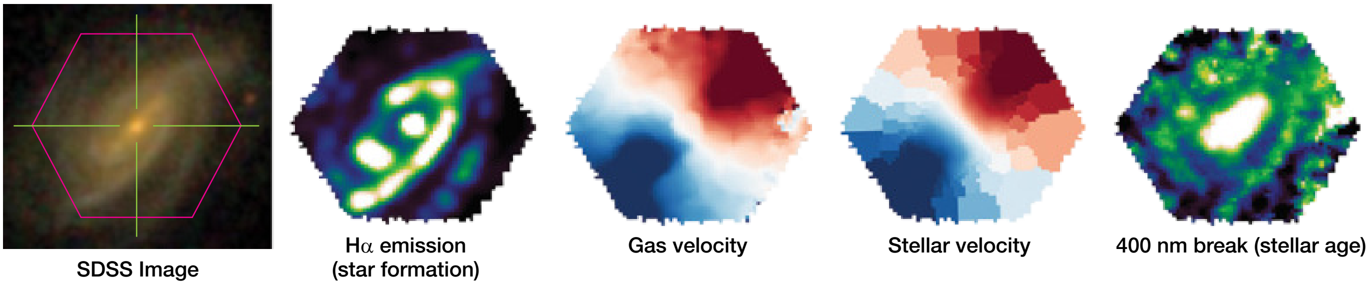
I've been working within the SDSS collaboration for more than a decade now, and one of my pet peeves has been incorrect descriptions of SDSS as a "robotic" or "automated" telescope. I presume this idea comes from thinking that SDSS data are so vast and perfect that only an automaton could have produced them. It's flattering in that way. But I also feel it diminishes the vast scale of the human effort that went into SDSS.

Two human observers have run every single night of spectroscopic data-taking: one "warm" in the control room and one "cold," venturing outside periodically to change over the *plug plates*. Those plates are flat metal circles about the size of a coffee table, each of which is custom-drilled with holes to hold up to about 1,000 fiber-optic cables. Celestial light travels through each cable to the spectroscopes. To prepare for a night's observing, multiple people throughout a dayshift load these plates into cartridges and then plug in the hundreds of fiber optics by hand. The all-time record was nine plates in a single night, representing 10,000 fiber optics plugged during the day — ouch. I once tried to plug just one plate by myself, and it wasn't an easy job!

The funny thing about my pet peeve is that the future of SDSS actually *is* robots, and the future is now. The last observation with a plug plate at Apache Point Observatory



▲ **FIELD OF STREAMS** In this all-sky image, which contains SDSS data through 2011, the brightness indicates the density of certain types of stars. Color indicates distance, with blue marking stars out to 50,000 light-years away, green for stars out to 60,000 light-years, and red for stars out to 88,000 light-years. The several stellar streams visible were once dwarf galaxies or globular clusters but were torn apart by the Milky Way's gravity.


SDSS Image

Hα emission (star formation)

Gas velocity

Stellar velocity

400 nm break (stellar age)

▲ **PICKED APART** MANGA spectra across the face of this spiral galaxy reveal (from left to right) ongoing star formation, gas motions, star motions, and the size of a characteristic break in the spectrum at 400 nanometers, an indicator of stellar age. In this classical spiral galaxy, the stars and gas are rotating in an orderly way about a central bulge of older stars. New stars are forming in clumps along the spiral arms.

happened on June 26, 2021. SDSS V has graduated to using robotic positioners: 500 little robots now guide fiber-optic cables to their positions. But learning to control hundreds of robots to move in sync — and never collide — has been a significant challenge. The transition was made all the more impressive by happening during a global pandemic, with some engineers even building cardboard mockups at home. It was worth it, though: This technological shift enables much higher efficiency, and the number of spectra SDSS V anticipates measuring will dwarf the rest of SDSS.

The Impact of SDSS

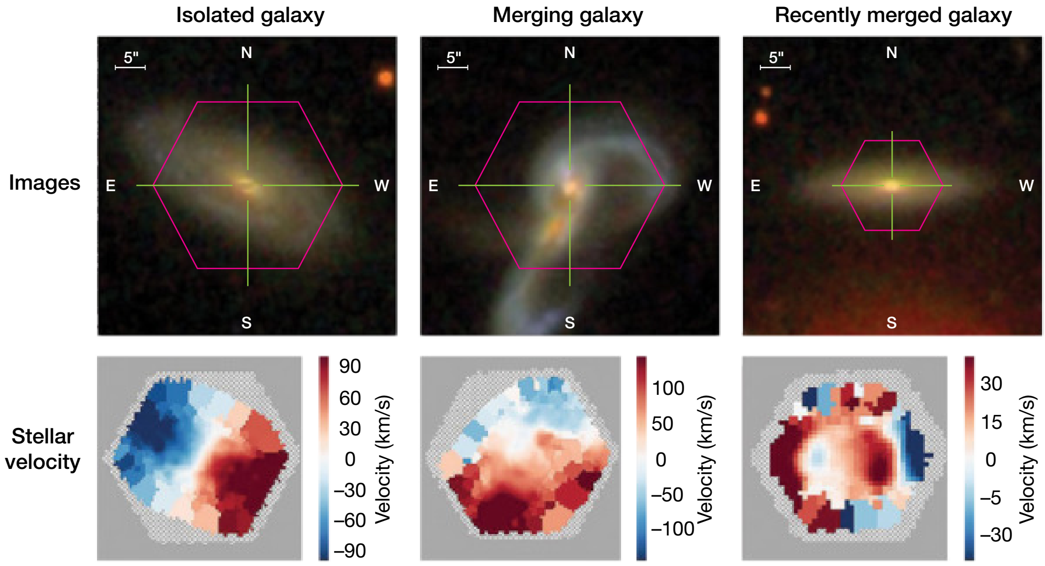
Summarizing SDSS's impacts on science is a neverending task. While I have been writing this article, even more papers have come out using SDSS data, and more astronomers are figuring out more ways to get more science out of our vast archive. That SDSS has impacted science in areas as diverse as understanding asteroids in our own solar system to the overall scale of the universe is simply astonishing.

If I had to pick one important impact, though, it would be the change in how astronomers work and share data. Open data have fueled the huge volume of science results. They have also enabled highly successful spin-off projects such as Galaxy Zoo (**galaxyzoo.org**), which invites members of the public to help classify the galaxies in SDSS images by shape and type. Galaxy Zoo inspired a massive expansion of citizen science, with a "Zooniverse" of similarly designed projects (see **zooniverse.org**). Open and accessible data also make SDSS available for use in teaching, or as a check for other observations. As one astronomer I talked to about this article said, "If I want to know about the optical properties of my object of interest, I check the SDSS first."

Ironically, this is the greatest evidence of the transformation wrought by SDSS: The data it has collected are now so ubiquitous that they have become part of the background of how we do astronomy.

■ **KAREN MASTERS** is an astronomer at Haverford College near Philadelphia but originally comes from the UK. She has worked with SDSS data since she was a graduate student and serves as the spokesperson for SDSS IV, as well as Principal Investigator for Galaxy Zoo.

SDSS MOVIES: Fly through the universe, see SDSS-discovered asteroids of the solar system, and watch a night of observing at **https://is.gd/sdssmovies**.



▶ **ROTATION REVEALS** MANGA spectra across the face of these spiral galaxies show the disturbance another galaxy can cause. The leftmost image shows an isolated spiral galaxy. Half of its stars are moving toward us (blue) and half away (red) due to its rotation. When two galaxies merge, as in the second panel, chaos ensues, mixing up the rotational motions. MANGA can reveal such disturbances to stars' orbits long after the merger has happened, as in the case of the third panel. The image shows an isolated galaxy, but the spectra reveal the effects of a recent merger.