The builders of the Sloan Digital Sky Survey have put their careers on hold for as much as a decade. Their reward: a chance to work on the most ambitious astronomical project in history

'Invisible' Astronomers Give Their All to the Sloan

Jim Gunn is by any measure a superb scientist. He's the Eugene Higgins Professor of Astrophysics at Princeton University, a member of science academies, winner of prizes. In the course of a 35-year career he has calculated the composition of the early universe, collected quasars, surveyed distant clusters of galaxies, and cataloged the evolution of stars. He helped invent cosmology as an observational science, and along the way he designed and built the instruments that make the observations possible. But in the last decade, he says, "I basically disappeared from the science scene."

In 1986, Gunn came up with an idea for a digital camera that could conduct the largest, deepest, and most informative survey of the sky yet. Since then, he and a group of colleagues, from grad students to senior professors, have spent a large fraction of their careers turning his brainchild, now called the Sloan Digital Sky Survey, into reality. "I don't say I don't regret it," Gunn says. "But if you undertake something as ambitious as the Sloan, you have to make a decision" about your career.

Astronomers are doing more and more of these surveys of large fractions of the sky in large fractions of the spectrum, each survey resulting in terabytes of data and each requiring years of astronomers' time. The scientific return is magnificent; but the professional return, say participating astronomers, is anything but assured. For example, once the Sloan begins operations, its builders have first crack at authoring papers from the data, but the name of any one builder may get lost among those of co-authors. And as of 5 June, when the data become publicly available, the builders will have no advantage at all. Young builders do not establish the names that certify they'll get or keep jobs. Older builders disappear from the scientific literature and can't compete for grants. When the astronomers on the Sloan were asked how the survey had affected their careers, the first thing they did was laugh.

But astronomers join large surveys anyway, just as high-energy physicists collaborate on multiyear international experiments, biologists spend years mapping and sequencing DNA to decode the human genome, and space scientists take decades to launch giant observatories. In the case of the Sloan, young astronomers say they're willing to gamble that being part of the survey will get them jobs. Older astronomers say such surveys are their field's future, and somebody has to do the work. "Progress requires huge directed projects and lots of time," says Richard Kron of the University of Chicago, "and time is just the cost of admission. But the grand and bold thing is what we wanted to do."

The Sloan is astronomy's grandest and boldest survey yet. Past surveys provided the statistical basis for knowing which of the universe's inhabitants are common, which are rare, what families they fall into, where they prefer to live, and how they are born, age, and die. Until recently, however, most surveys in optical wavelengths have used photographic plates that detect light less sensitively and less accurately than a digital camera's charge-coupled devices (CCDs).

Few regrets. Astronomers Jim Gunn, Michael Strauss, and Jill Knapp say science and people make the Sloan worth the sacrifices.

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The Sloan is astronomers' first large-scale digital survey, and in addition to making higher resolution images of fainter objects over a wider field of view, it finds their distances to boot. And it does all this fast: A 1991 survey by Michael Strauss, now at Princeton University, and his colleagues took 5 years and found the distances to about 5000 galaxies; the Sloan, in the first year of operation, found the distances to 90,000. By the time the Sloan is finished in 2005, it will have measured the shape, brightness, and color of 100 million objects and the distances to a million galaxies and 100,000 quasars. This June, data from the first 18 months will be arranged in a searchable, publicly available archive. And everything—from the telescope to the CCDs, the camera, the two spectrographs, the software for running them, the software for correcting and analyzing the data, and the archive itself—has been designed and built by the Sloan's participants.

Not only have team members committed their time, but depending on their seniority and to varying degrees, they've also changed or deferred their careers. Princeton astronomer Jill Knapp's first job with the Sloan, in 1991, was writing the phone book–sized grant proposal to the National Science Foundation (NSF); her second job was coordinating the software that turns the camera's data into a catalog. "God knows what I do, but it sure takes up time," she says. "You're sort of 100% into it." And her pre-Sloan research on the life cycle of stars? "All gone," she says, "all gone."

For David Schlegel's doctoral degree, he studied the large-scale motions of galaxies, but for the two and a half years of his postdoc at Princeton he worked on Sloan software; he raises Knapp's estimate of the commitment needed to 200%. Connie Rockosi is still a graduate student at the University of Chicago but has worked on the camera for 10 years: The standing joke, she says, is "that I'm the person with the largest fraction of her life on the Sloan." Kron says he's still doing his pre-Sloan research ("I take a random patch of the sky and study it to death") while helping with Sloan operations strategy, although he admits, "My publication rate has gone down." Alex Szalay of Johns Hopkins University in Baltimore studied the evolution of the structure of the universe until he joined the Sloan in 1992 and began designing the public archive. "It was like a maelstrom, it catches you up and draws you in," he says. "I did write papers, but essentially all my thoughts have been about Sloan."

Among other changes, most Sloan astronomers are newly negotiating a switch to big science. Astronomers traditionally work, and publish papers, in groups of two to four. "The whole reward system in astronomy, the way one's career advances, is by the work that you do in a small group," Strauss says. The Sloan, however, is a collaboration of 11 institutions and 100-plus astronomers. One name hiding among 100 co-authors doesn't stand out: The risk with the Sloan is that an astronomer might invest years in the survey and wind up professionally invisible.

The Sloan collaboration has tried to alleviate this risk by following a complicated set of operating principles. The right to use the data before they become public goes to researchers at any of the participating institutions. The right to list themselves as coauthors on any scientific paper goes to the so-called builders, those who have spent 2 years full-time on the project; their names, currently numbered at 100 or so, are listed in alphabetical order. The right to first authorship goes to those with prime responsibility for a given paper; their names precede the alphabetized list of builders. "I don't think that our authorship system is perfect," says Zeljko Ivezic, a postdoc at Princeton who is first author on one Sloan paper so far, "but I cannot think of any better one."

But despite the operating principles, an astronomer who has neglected, say, galaxy evolution to spend years designing data reduction software still might end up buried in authorial midlist along with dozens of others. In a field in which visibility depends on the names on scientific papers, how do such people get hired or promoted or famous? "It's actually a very difficult question. How can the world know that they did a superb job on the software?" says Strauss. "That's a question we don't have a complete solution to."

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Generations. For Connie Rockosi, Richard Kron, and John Peoples, survey work strikes different balances of risks and rewards.

Scientific invisibility poses different problems for astronomers at different stages of their careers. For younger astronomers, says Szalay, working on the Sloan "is a long shot; it's a calculated risk." The postdocs and untenured faculty members say they must gamble on getting jobs. "What I'm banking on careerwise is just having made a reputation within the survey for being able to get things done," says Schlegel. "To be honest, I don't know how it's going to play out." Ivezic says he's used his early-data rights to mark out his own science: The best bet "for youngish people," he says, "is to define their own science that they will be recognized by. So I hope I'm on the right track with my ideas."

When the astronomers on the Sloan were asked how the survey had affected their careers, the first thing they did was laugh.

Tenured astronomers have more leeway, Szalay says: "We could still blow 5 years of our lives and not destroy our careers." Instead, the main problem facing Sloan's tenured astronomers is funding. Astronomers who launch satellites analyze their data with funding from NASA. High-energy physicists who build colliders analyze their experiments with funding from the Department of Energy (DOE). The Sloan's funding "is patchwork," Kron says—a combination of sponsors that includes the Alfred P. Sloan Foundation, DOE, NASA, NSF, and 13 private and public institutions. And all the funding, says the survey's director, John Peoples of Fermi National Accelerator Laboratory in Batavia, Illinois, "is strictly to get the data into the databases." Princeton's Gunn agrees: "There's no money for science."

In principle, Gunn says, younger astronomers should be able to get grants, but older astronomers who have to support graduate students and postdocs are in a more precarious position: "If you haven't done anything for a long time, it's very hard to get funding." So far, regardless of age or standing, Peoples says, "almost none of the Sloan astronomers have succeeded in obtaining new grants for research."

So why do they sign on with the Sloan, let alone stick it out for years? The most obvious reason is that, with data from a volume of the universe 100 times larger than that of any previous survey, Sloan's science leaves its astronomical predecessors in the dust. "We can answer questions people have been puzzling over for years," says Strauss. "We already have more data than [they] ever did." The data should finally answer astronomy's broadest question: how the universe grew up. That is, how the featureless gas of the infant universe evolved into the lacy network of galaxies observable today, and within that network, how the galaxies themselves evolved. "The relationship between galaxy evolution and large-scale structure," says Strauss, was "purely in the realm of speculation 5 years ago."

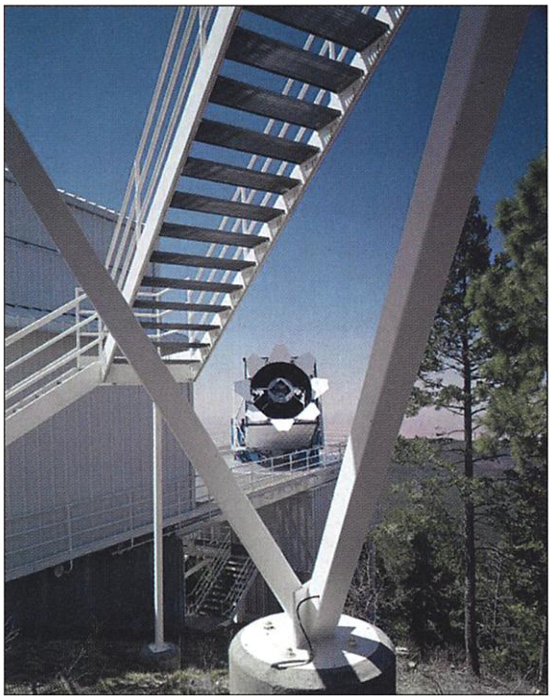
Moreover, the Sloan's laboriously ho-

Funding the Sloan

Astronomers around the world will get their first look at the Sloan Digital Sky Survey's treasure trove of information next month, when the survey opens up its database for the first time. Even the highly focused group of scientists who put their careers on hold to see the venture through (see main text) must have wondered if this day would ever come. The financial "ups and downs of the survey have been tortuous," says Jim Gunn of Princeton University. "We've nearly lost it so many times." It survived thanks to an extraordinary patchwork of funding. The Sloan survey may look like the epitome of big science, but it was stitched together with small-science funds.

The project began in 1988, when Gunn, Steve Kent of Harvard University, and Richard Kron and Don York of the University of Chicago wanted to survey the sky using a small, dedicated telescope mounted with two spectrographs that together take 640 spectra simultaneously, and the largest-yet digital camera that makes images in five colors. "We didn't have any money," says Gunn, "and so Don and I tried to drum up support at our respective universities." Gunn's department chair, Jerry Ostriker, told him, "You build it and I'll pay for it." (Ostriker, Gunn says, "is a mastermind at finding money.") Not long after, says Gunn, a Princeton alumnus with a career on Wall Street "walked into Jerry's office and said, 'I've always been interested in astronomy and I want to give some money. Do you want any?' And that was the seed money that got us going."

Shortly thereafter, Ostriker happened to hear that the Alfred P. Sloan Foundation was looking for a bigger-than-usual project to fund. "And boy," says Gunn, "did we have a deal for them." The survey group sent in a proposal, and the foundation wrote a check for $8 million, Gunn says, "which we confidently said would be over half the capital cost." The foundation's support, says Gunn, "is why it's the Sloan Digital Sky Survey."



Vision thing. The Sloan Survey's 2.5-meter telescope in New Mexico went to work after years of planning—and much creative fund raising.

Meanwhile, astronomers at the University of Chicago talked John Peoples, the director of the Department of Energy's Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, into joining the survey and writing a letter to the president of the University of Chicago. The university's president wrote back, "If Fermilab is in, it must be OK," Peoples says; so both Chicago and Fermilab joined. A little later, Ostriker was on a site visit at Johns Hopkins University in Baltimore, which had a reputation for building spectrographs. "Jerry realized that we could be of help to Sloan," says Hopkins's Alex Szalay. Hopkins joined and built two spectrographs. About the same time, astronomer Bruce Margon urged his school, the University of Washington, Seattle, to join; their engineering group built the 2.5-meter telescope in Apache Point, New Mexico. Chicago's eventual responsibility was the software—the "pipeline"—that got the data from the spectrographs into a database at Fermilab. Princeton's responsibility was the camera, which Gunn designed and built, and the pipeline that got data from the camera into the same Fermilab database. Fermilab's responsibility was to integrate the pipelines and feed them into a common archive, which was designed and built by Hopkins, and which becomes public in June. Technologically, Gunn says, "we were really pushing the envelope."

"Now, it is a sad thing about us," Gunn adds, "that from the very beginning we have always been tremendously behind schedule and tremendously over budget." The initial budget was low, Szalay says, "because the expectation was that faculty members at the different institutions would all chip in 50% of their time." The reality proved much less rosy, Gunn recalls: "If you think we were 3-year-olds, you're right."

A second expectation was that the pipelines and archive could be built with off-the-shelf astronomical software. Unfortunately, says Jill Knapp of Princeton, that software "was never intended to handle anything remotely as big as the Sloan." The Sloan software had to be written from scratch, Szalay says—more than a million lines of code in all. And since "we didn't have volunteers flocking in to write difficult code," Gunn says, "we had to pay people."

With the equipment built and programmers paid for, after management crises, several near-bankruptcies, and a broken secondary mirror, a completed Sloan will have cost $84.1 million, Peoples says—not including the "incalculable but tangible value" of faculty and administrators' time. The Sloan Foundation has contributed about $20 million; Fermilab, Los Alamos National Laboratory, and the Navy together, over $28 million. The National Science Foundation and NASA have each put in about $5 million; the universities together, $9.8 million; and international partners, over $9 million. The survey still needs another $6.5 million. Peoples, who is now the survey's director, says, "Trying to keep this afloat has been interesting."

The upshot of Sloan's tight budget, Gunn says, is that it has no funds earmarked for research. When NASA budgets its big observatories, by contrast, it includes a few percent for the costs of research using the data. "We felt the budget should be to produce data, not to analyze it," says Kron. "Otherwise it would drive costs to the unaffordable." Gunn would like an institute set up to disburse research funds, "but I've been banging my tiny feet about it for a long time without any success." Peoples says that raising money for research "is on my mind, but first we have to finish the survey and pay the bills."

In the end, the Sloan survey's troubles may be the inevitable price of a unique, ambitious (Peoples prefers the word "pioneering") project run by professional astronomers who are amateur managers. Since a management overhaul 3 years ago, however, the survey has stayed on schedule, financially and technically. Hirsh Cohen was vice president of the Sloan Foundation and has been the survey's program officer. "The winds were strong and the waves were high," he says, "but I'd go through the adventure again. It's setting a new mode of study: reaching out and grabbing in data by the gigabyte. We're proud of it."

–A.F.

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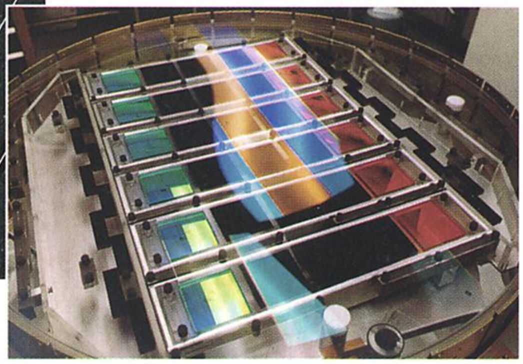
mogenized database allows astronomers to do the first real statistical studies of the sky, enabling them to define the typical and identify the weird. Astronomers plot 100,000 stars, say, by the brightness of their light in specific colors (ultraviolet, blue, green, red, and infrared), trace how they line up, and then look for the objects that fall off the line. "Going after objects of unusual colors has been a lot of fun," says Strauss. "It's basically shooting fish in a barrel." So far, Sloan astronomers have snagged eight of the 10 most distant quasars known. Close by, they've found stars that are barely stars at all, small and dim and so cool that their atmospheres contain molecules of water and methane. On the day of "the methane stars news" in May 1999, Princeton's Knapp says, "the grapevine—well, I came in and there were 200 e-mails from all over the world—'Jill,' 'Jill,' 'Jill, what's going on?' I've never seen a thing like that before or since."

Another reason everyone cited for sticking it out is a spirit of community. "I just find it incredibly satisfying to bat ideas around with other people," Gunn says. Szalay says it was a "thrill to work [with] the people you really admire through your whole career." Knapp agrees: "These are fantastically good people. It's just a privilege to be in the same room with them." In particular, Ivezic says, "it's wonderful for someone young"—a judgment that 29-year-old Rockosi confirms. "I've got 200 people asking me when I'm going to finish my thesis," she says. "I think they even care."

The deepest reason for sticking with the Sloan is that it's the shape of things to come. Eventually, astronomers hope to merge the Sloan's database with the databases of surveys in other wavelengths, from x-ray through optical to infrared and radio, and create a full-spectrum digital sky. "Once we figured out where the Sloan is leading," says Szalay, "it was obvious that the problem we are facing is much bigger than the Sloan." Szalay, along with astronomers around the world, is putting together the so-called Virtual Observatory, a group of linked databases in 15 different wavebands, all searchable by the same yet-to-be-created methods (*Science*, 14 July 2000, p. 238). Everyone calls this era of grand integration the new astronomy. In the new astronomy, says Gunn, "you no longer have to go to a telescope to answer your questions. You can just look it up in the database."



Ribbons of stars. Sweeping the sky, the Sloan's five-color digital camera *(right)* records everything in sight.

CREDITS: (TOP TO BOTTOM) SDSS; MICHAEL A. CARR/SDSS CAMERA PROJECT

Sloan's younger astronomers in particular are betting their careers on the new astronomy. "Once you finish Sloan and cross-correlate with all the other catalogs," says Eric Peng, a graduate student at Johns Hopkins University, "astronomy's going to be different. Partly I want to learn how to do science in that mode, with statistics, having large databases." Ivezic wants to compare 10 million stars from the Sloan with another 10 million from an infrared survey, the Two Micron All Sky Survey: "It is impossible that there would be no good results." Peter Kunszt, who spent his postdoc at Johns Hopkins working on the software to run Sloan's archive, was hired at CERN, the European particle physics laboratory near Geneva, to help create the archives for its next big experiment, the Large Hadron Collider. "All this working on the Sloan paid off," he says. "CERN's job description fit my person 100%." Szalay thinks that by giving young scientists the experience of writing scientific software, "we will see in 10 years from now that we actually trained a whole generation of people who are much better adapted for this new world. I think we gave them skills which they could not have otherwise."

In the end, the payback on such a large investment is intangible; it's the reward of working on something truly important, and it looks surprisingly like altruism. "I know what the potential of this thing is," says Gunn. "I'm old enough and there are enough technical problems left that I'm not going to have time to do much science with it. So I've managed to work that around in my head in a way that I can just feel fatherly about this. These are my children doing this wonderful thing with this project that I've worked on for some substantial fraction of my life. And I'm happy to have had my part in making it happen."

"Your own papers have legacy value of 2 to 3 years," says Szalay. "But you'd like to leave a legacy that's hardwired. It's so rare that you can be part of something that really changes the field. And you know, to be able just to say, 'I worked on this thing, I was one of the 100 who did this.' "

Rockosi says she has heard science called a tapestry woven by multitudes of hands. "Sloan will be used by many, many people for many, many years. Sometimes I wake up at 3 a.m. and think, 'What am I doing?' But even if I do no other astronomy, I've contributed a lot. And it's not just a thread I'm contributing to, it's the warp."

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Ann Finkbeiner is a science writer in Baltimore, Maryland.

Acknowledgement

This article necessarily but unfortunately leaves out many of the people and institutions who have contributed to the creation and operation of the Sloan Digital Sky Survey.

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