Observing the Twenty-First Century Sky and Understanding the Universe

by

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Few, if any, sciences have been pursued for as long as astronomy; yet few, if any, sciences have changed as dramatically in the past few decades.

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The universe we live in is incredibly vast, and equally isolating. While our viewing angle into the universe cycles with the seasons, and planets traverse their orbits around the sun, objects outside our solar system seem to be completely static. Our night sky has remained essentially unchanged since humans first began systematic studies of the sky nearly three millenia ago.[1]

The reason for this constancy is the nature of the universe itself, by both intrinsic and extrinsic mechanics. Intrinsically, astronomical sources do not appear to change because objects like stars and galaxies evolve on timescales of millions to billions of years, much longer than human lifetimes. Extrinsically, even the positions of these long-lived objects appear the same because of their great distances, just as a distant train creeps slowly across the horizon. A typical star orbiting around the center of our Milky Way galaxy has moved just a single degree across the night sky since 1000 B.C.E. Moving at its current rate, Andromeda, the nearest galaxy to the Milky Way, will take 400 billion years to move that same distance across the sky.[2]

Were I an astronomer in the early twentieth century, I may not have given the field a healthy prognosis. After all, there are a finite number of sources – be they planets, stars, or galaxies – on the sky. Astronomers have been observing these same objects for millenia – what more secrets could they hold? Astronomers cannot perform controlled experiments on celestial bodies, we can only study the light they send us, so what new studies could be devised? Astronomers cannot take the same avenues for discovery and experimentation as scientists in other fields. Instead, we push forward the boundaries of technology to learn more from the same light.

[1] Bablyonian star catalogs date to $\lesssim$ 750 B.C.E., see Roughton et al. (2004, Archive for History of Exact Sciences, 58, 6)

[2] The proper motion of Andromeda across the sky was first constrained by Loeb et al. (2005, Astrophysical Journal, 633, 894). They use numerical N-body gravitational simulations to predict that the velocity of Andromeda will change significantly in the next few billion years, as it moves toward a merger with the Milky Way.

Even as the universe itself seems stagnant, astronomy, the study of the universe, is anything but. In this essay I will give an overview of observational astronomy, describing how astronomers do science under the constraints of the laws of nature they are seeking to understand. I will describe the gargantuan telescopes at the forefront of the science and explore how technology is radically changing the work that astronomers do, and the discoveries that we make.

1. Nothing ever changes; the limitations of our universe

What makes the universe a difficult test subject is that it evolves on a timescale millions of times longer than human lives. When the universe formed in the Big Bang 13.8 billion years ago, the universe was a much more exciting place. We know this because we have pieced together a remarkably precise and scientifically-validated cosmology, a history of the universe, over the past century.[3]

In the first instant ($\lesssim 10^{-43}$ seconds) after the Big Bang, all space, time, matter, and energy in the universe was created. Within the next infinitesimal fraction of a second ($\lesssim 10^{-34}$ seconds), the size of the universe expanded by a factor of 10^{43}. To try to imagine this, picture a pencil dot on a piece of paper expanding to the size of the Earth, four times over. At this time, the temperature of the universe was unimaginable, with each particle having energies far beyond what is achieved in the most powerful particle accelerators on Earth today. Before the first second of the universe is over, all the familiar laws of physics are born, in a sense, as expansion cools the universe and the fundamental forces are decoupled. Only then, a few minutes after the Big Bang, are the first atoms formed,

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[3] For a recent introductory level cosmology text, see e.g. "How did the First Stars and Galaxies Form?" by A. Loeb (Princeton University Press, 2010).

limited to only hydrogen, helium, and the slightest traces of heavier elements[4]. It would be hundreds of millions of years before the first stars form from this gas, and begin to form heavier chemical elements such as carbon and oxygen in their cores.

But it wasn't until 10 billion years ago that the universe reached what was, for my tastes, its most interesting phase. There were more stars forming in the universe per second at that time then ever before or after.[5] Next, the universe entered its modern phase, with stars forming at a rate about 20 times slower, and the expansion of the universe slowing down. In the past 10 billion years, the universe has only expanded by factor of a few. The pencil dot is only imperceptibly larger.

What's happened to all the stars formed over these billions of years? The vast majority of them are still chugging along, fusing hydrogen together in their cores as they have since the day they were born. The most massive of these stars lived shorter lives, some as short as a few million years, and ended their lives in spectacular explosions called supernovae.[6] These explosions have become increasingly rare in the universe as the star formation rate has declined. The least massive stars to have ever reached the ends of their lives are a little less massive than our sun, with lifetimes of $\sim$ 13 billion years. These stars don't explode, but rather end their lives by shedding their outermost layers into a cloud of gas like the Ring Nebula, famous in the Northern Summer sky. At the center of this nebula is a newly formed white dwarf, the collapsed remnant of the former star, hundreds of thousands of times as dense as the solids we are familiar with on Earth. But every star ever formed that is significantly less massive than the sun is still living.[7] The most common stars in the

[4] For a more modern review, see Pospelov & Pradler (2010, Annual Review of Nuclear and Particle Science, 60, 539).)

[5] See Reddy et al. (2008, Astrophysical Journal Supplement, 175, 48).

[6] See e.g. Heger et al. (2003, Astrophysical Journal, 591, 288).

[7] An exception to this rule are low-mass stars that have been disrupted by external processes, for example falling into a super massive black hole, see Gezari et al. (2012, Nature, 485, 217).

universe, with masses about one tenth the mass of the sun, will continue fusing hydrogen, virtually unchanged, for trillions of years.[8]

Can we see these stars forming? In the present day universe, about one in five galaxies have essentially no ongoing star formation.[9] These galaxies have produced nearly all the stars they will ever create, and are identifiable by the red color characteristic of old, low-mass stars which emit light in a spectrum like relatively cool flames. Of the remaining galaxies, about four in five are quiescent spiral galaxies like our own Milky Way, forming stars at a rate of about one every decade. Less than one in five galaxies are "starbursts," forming stars at a typical rate of a few per year and as high as hundreds per year.

Very nearby, within the Milky Way, we have the ability to observe star formation in some detail.[10] But we immediately encounter challenges with time scales. A star forms when an enormous cloud of cool gas collapses under its own self-gravity. This gravitational potential energy is converted to kinetic energy as material falls, causing the center of the cloud to rise in temperature. This conversion limits the speed of the collapse, because the hot gas radiates light which applies an outward pressure resisting the collapse. The timescale for this process, the "Kelvin-Helmholtz timescale," is tens of millions of years for a typical protostar. Once the temperature reaches about 10 million degrees Celsius, protons have enough energy to fuse together, creating a power source that overcomes the gravitational collapse. These contraction and expansion processes reach equilibrium, yielding a stable star. For human observers, this means that we can find stars undergoing any of the stages of this process, but each individual stage is so slow that we cannot watch it progress.

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[8] For a review, see Bastian, Covey, and Meyer (2010, Annual Review of Astronomy and Astrophysics, 48, 339).

[9] Delgao-Serrano et al. (2009, Astronomy & Astrophysics, 509, 78).

[10] For a recent review, see McKee & Ostriker (2007, Annual Reviews of Astronomy and Astrophysics, 320, 45).

But suppose that a new star pops into existence instantaneously in a nearby galaxy – could we even see this happen? Let's consider a galaxy at a distance of 10 million light years,[11] not far outside the small, Local Group of galaxies which includes the Milky Way. The resolution of the most powerful optical telescopes in the world is about 10 millionths of one degree on the sky (0.04 arcseconds). This means that each pixel in our image would span about 2 light years of space in the galaxy. In a typical starburst galaxy, there will be about 1000 stars in this space. If a single new star were suddenly added to that population, we could only detect this change if we could measure brightness to a precision of one part in a 1000. There is perhaps one instrument in the world capable of such precision, as I will describe in Section 4.

Could we watch stars or entire spiral arms of the galaxy move over time? Stars revolve around the centers of galaxies at speeds of about a hundred miles per second, fantastic on Earth scales, but plodding at Galactic scales. To see a star move from one pixel to the next in our image would take about three-thousand years. Of course, given that ~ 1000 stars are represented on each pixel, it would be very challenging to detect the movement of one star.

The consequence of these considerations is that if you stare continuously at a typical galaxy for a full year with the largest telescope in the world, you are likely to see no change whatsoever. Every few decades you might see a supernova explode in the galaxy, if it has many young, massive stars. You may also see a few variable stars in the galaxy oscillate steadily, predictably, in brightness every few days or weeks. But you will not see new stars form, and you will definitely not see anything move.

It seems that, wherever we look, changes in the universe happen so slowly that we cannot observe them. How is it, then, that astronomers can continue to make progress in

[11] One light year is the distance traveled in one year moving at the speed of light. This is about 6 trillion miles, or 63 thousand times the distance between the Earth and Sun.

understanding the universe? If there are no new things to observe, we need to instead open new spaces for discovery by finding new ways to observe.

2. The state of the art

To understand the technical challenges facing observational astronomers, let's consider a case study. I'll describe research in the one field of astronomy where we actually can observe dramatic changes over human timescales; observations of distant exploding stars.

In my research group at Harvard, we use a telescope in Hawaii to stare at nearly every galaxy in the sky, waiting to catch exploding stars in the act. The telescope, called PanSTARRs1 (PS1), is the most powerful survey telescope operating in the world today. At 1.8 meters, its primary mirror is wider than most people are tall, collecting as much light as possible from these faint and distant galaxies.

Although dozens of large telescopes have been built over the past half-century, PS1 has one piece of technology that makes it absolutely unique. The instrument that records the light collected by the telescope is a 1.4 gigapixel camera. The camera is composed of more than 4000 individual charge-coupled device (CCD) sensors. Every time an image is taken with the camera, it is exposed to the sky for about 30 seconds, building up charge in each pixel as photons from distant galaxies strike silicon atoms and produce electrons. Each individual CCD chip then reads out the charge level on each of its pixels, 1.4 billion in total. Because each chip reads out in parallel, the camera is ready to take another image within seconds; an order of magnitude faster than typical cameras on the previous generation of instruments.

Every aspect of the telescope was built to take advantage of this state-of-the-art CCD chip. The telescope optics are designed to illuminate the entire area of the chip efficiently, providing one of the widest fields of view of any optical telescope in the world. At 7 square degrees, this field is about 10 times the size of the full moon. It's this feature that enables PS1 to survey the entire sky visible on a Hawaiian night in about a week. For comparison, surveying the entire sky with the world's largest telescope, Hawaii's 10 meter Keck, with its 0.02 square degree field of view, would take about six years; that telescope is better suited to deep observations of individual objects.

Each image taken by the PS1 camera will show about 10,000 galaxies, and occupy about 2 gigabytes of hard drive space. Compare this to the digital camera in your cell phone, which uses a consumer-grade version of the same CCDs, but has less than 1/200th as many pixels to record fine details. At about 2 gigabytes per image, PS1 would probably fill up your camera's memory in about 4 minutes of survey operation. In total, PS1 will collect as much data per year as the combined total of all video ever released on DVD.[12] This avalanche of data presents a significant challenge for scientists hoping to make discoveries.

Our group is looking for exploding stars in the PS1 data. These explosions, called supernovae, are so bright that they can be seen from distances of billions of light years, and can outshine the entire galaxy of stars surrounding their progenitor. Their brightness makes them easy to detect, but their short lifespan makes them difficult to catch in the act. A large galaxy like the Milky Way will produce about two supernovae per century, and the explosions only remain bright for a few weeks. This means that to catch a supernova on any given night, you need to observe at least a thousand galaxies simultaneously. PS1, with its enormous field of view, is exactly the instrument to do this.

Detecting supernovae in the PS1 images is a data processing problem on a huge scale, with a tight deadline. To catch as many supernovae as possible, PS1 returns again and again to a few select fields on the sky. This rate of return is called the "cadence" of the

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[12] See the report by the JASON advisory group: www.fas.org/irp/agency/dod/jason/data.pdf

survey, and should be at least once per week to catch supernovae before they fade into obscurity. PS1 actually uses a cadence about five times as high as necessary. Each time PS1 returns to these fields, it observes using one of five different filters. These filters are carefully calibrated to allow only certain frequencies of light, and we compare the explosions intensity in each filter to help classify it.

Because our goal is to learn as much as possible about the supernova before it fades away, we need to detect it in the PS1 images as soon as possible so we can conduct follow-up observations using a diverse array of facilities. Each night, our group downloads the data taken by the PS1 telescope in Hawaii and processes them using a special software pipeline developed to detect supernovae.[13] The pipeline's job is simple: to take images taken from PS1 the previous night and subtract an image of the same field taken months earlier (Figure 1). If a new supernova has appeared in any of the galaxies in the field, it should appear as a new bright source in the difference image. Every galaxy without an explosion will be unchanged over the past few weeks, and will not show up at all in the difference. In practice, the images cannot be subtracted until after extensive pre-processing for calibration and normalization.

To perform this complex image processing on hundreds of billions of camera pixels per night requires significant computing horsepower. Even with the fastest desktop computer on the market, it would take more than 24 hours to process each night's images, so you could not keep up with the avalanche data rate of PS1. To solve this problem, we use the Odyssey supercomputing cluster of the Harvard Faculty of Arts and Science to distribute the image processing work across hundreds of computers simultaneously. On the cluster, processing each night's images takes only a few hours.

Once a supernova is discovered with PS1, our work begins. PS1 itself does an excellent

[13] The PS1 supernova pipeline is described by Rest et al. (2005, Astrophysical Journal, 634, 2).

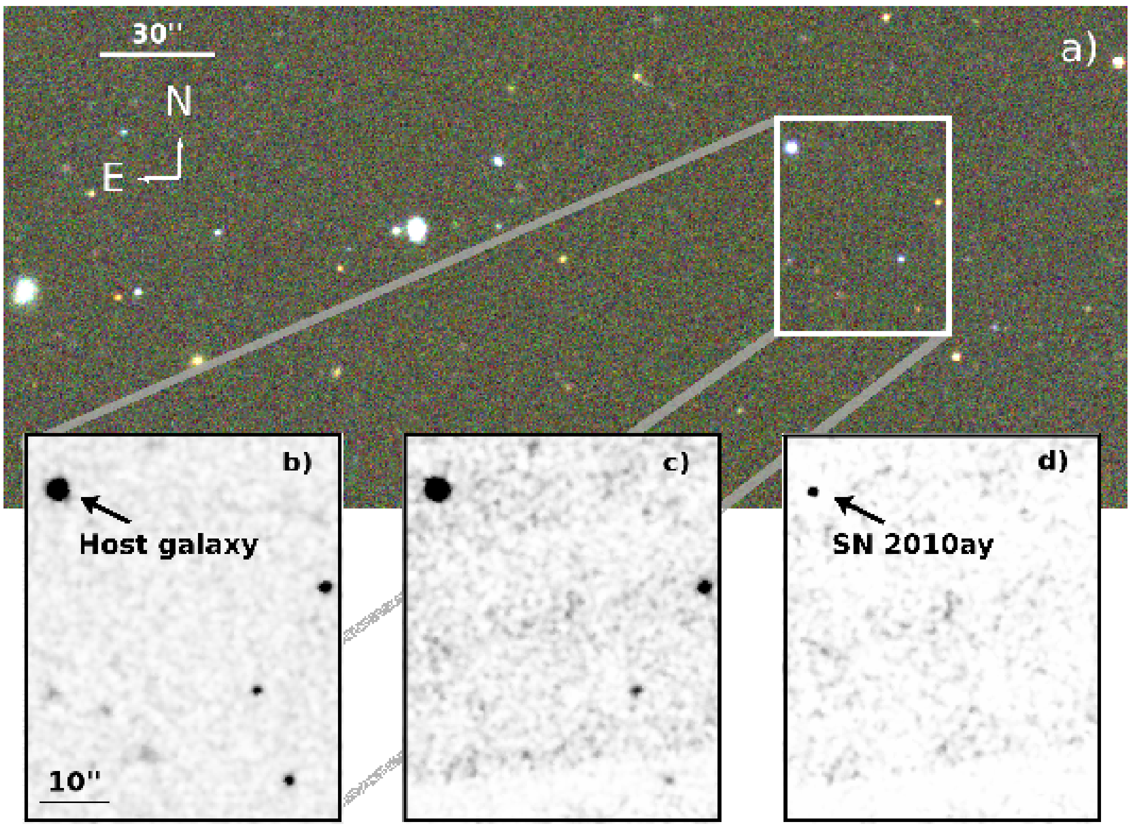

Fig. 1.— Discovery of the supernova SN 2010ay by PS1. Top: Wide-field color composite image. Bottom, left: cutout of the PS1 template image of the field, taken before the explosion. The supernova host galaxy is the bright object at the upper left, at a distance of 970 million light years. Middle: a PS1 image taken during the explosion. Right: The difference of the template and new image, showing the supernova as the lone transient source.

job of monitoring the brightness of the supernova in each of its five filters in the visible regime. We can use spectrographs at other telescopes to disperse visible light into hundreds of channels corresponding to individual wavelengths of light. This is done using a diffractive element similar to a prism. Supernova spectra show strong emission and absorption features at specific spectral wavelengths, which tells us about the abundance of certain chemical elements in the ejecta of the explosion and the velocity at which it travels (Figure 2). Moving to more extreme wavelengths, radio and X-ray wavelengths are produced when electrons in the gas surrounding the star are accelerated to near the speed of light by the blast wave. These observations can tell us about the behavior of the star in the years before its explosion, as it sheds material from its outer layers into its surroundings.

The PS1 supernova group at Harvard is necessarily diverse. To do the science I've just described requires expertise in image processing, parallel computing, optical spectroscopy, radio interferometry, and space-based X-ray observations, not to mention supernova explosion physics. Our group has specialists in each of these fields, and by working together and learning from each other we each broaden our skill set. The specialty I'm developing during my Ph.D. is in the host galaxies of the supernovae. Even after stars explode, information about the properties they had at birth will live on for millions of years. The characteristics of the cloud of gas and population of stars the supernova progenitor came from are unchanged after the supernova, and are clues to the age, mass, and chemical composition of the exploding star.

Most large astronomical research projects today operate something like our group. To solve the biggest problems left in astrophysics requires broad capabilities and enormous time commitments. This is no different than the model for research in most fields of science, where, for example, high energy physics experiments are performed by international

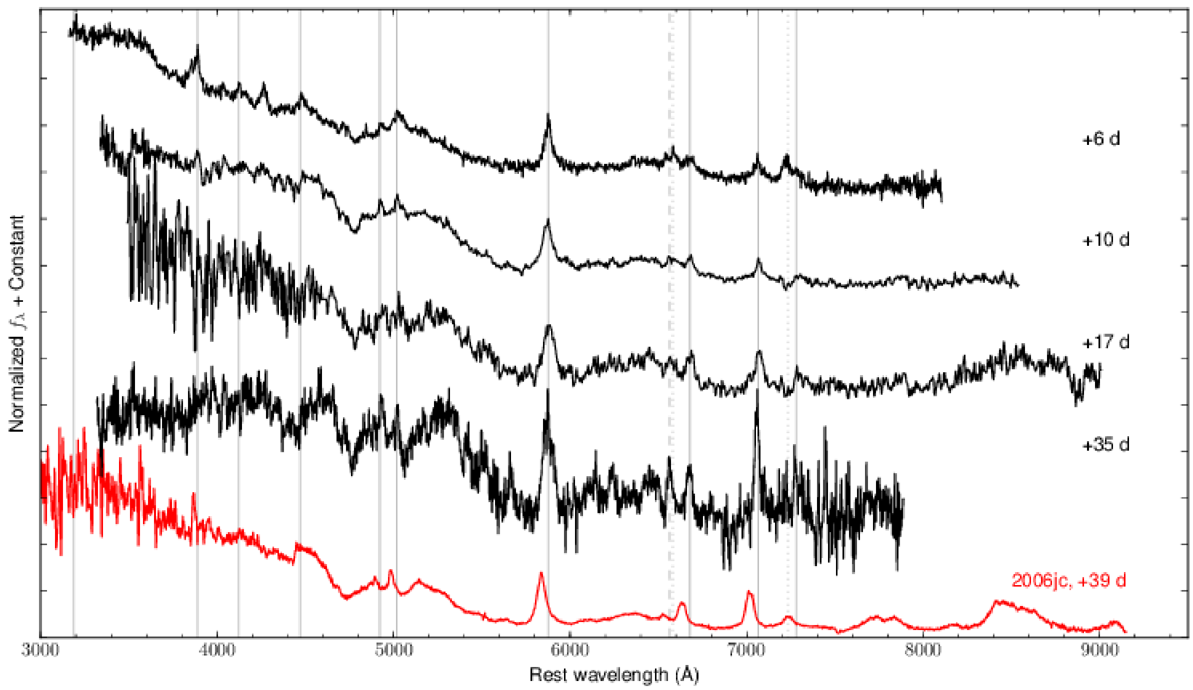

Fig. 2.— Spectra of a peculiar supernova discovered by PS1 at various times since maximum supernova brightness (black), with the spectrum of a similar supernova for comparison (red). The emission features marked by the vertical lines help us to interpret the chemical composition of the outer layers and surroundings of the progenitor star at the time of explosion.

collaborations of thousands of scientists[14] and pharmaceutical companies employ armies of chemists, physicians, and epidemiologists, to develop and test new drugs. But in astronomy, massive collaborations were not, until recently, the norm.

3. The lonely science

Astronomy is a field immersed in a time of transition. There is an iconic image of the astronomer: a loner on a hilltop, using a telescope in silence, searching for a vantage on the universe that no one has found before. While this is not the modus vivendi for astronomers practicing today, Harvard's Department of Astronomy has a rich history of this style of observation.

A tribute to the lonely astronomy, the Great Refractor, sits above my office in the Harvard-Smithsonian Center for Astrophysics. The Great Refractor, with a 15 inch objective lens, was the largest telescope in the United States at the time of its construction shortly before the American Civil War. Walking into the dome of the Great Refractor, it's hard not to imagine a 19th century astronomer sitting in the burgundy velvet observer's seat, peering through the eyepiece and recording measurements (sketches, often) on paper in his lap.

Now the Great Refractor serves as an exquisite standard-bearer for an outmoded optical design, with its 20 foot mahogany tube mounted on an 11 ton granite pillar buried deep into the ground on Observatory Hill in Cambridge (Figure 3). I walk into the dome of the Great Refractor about once a month, leading public tour groups through it on their way to observing sessions out on the roof. There they will use telescopes every bit as powerful,

[14] See for example the ATLAS particle detector experiment at CERN's Large Hadron Collider in Switzerland, a collaboration of $\sim$ 3000 scientists from 38 countries worldwide, http://atlas.ch.

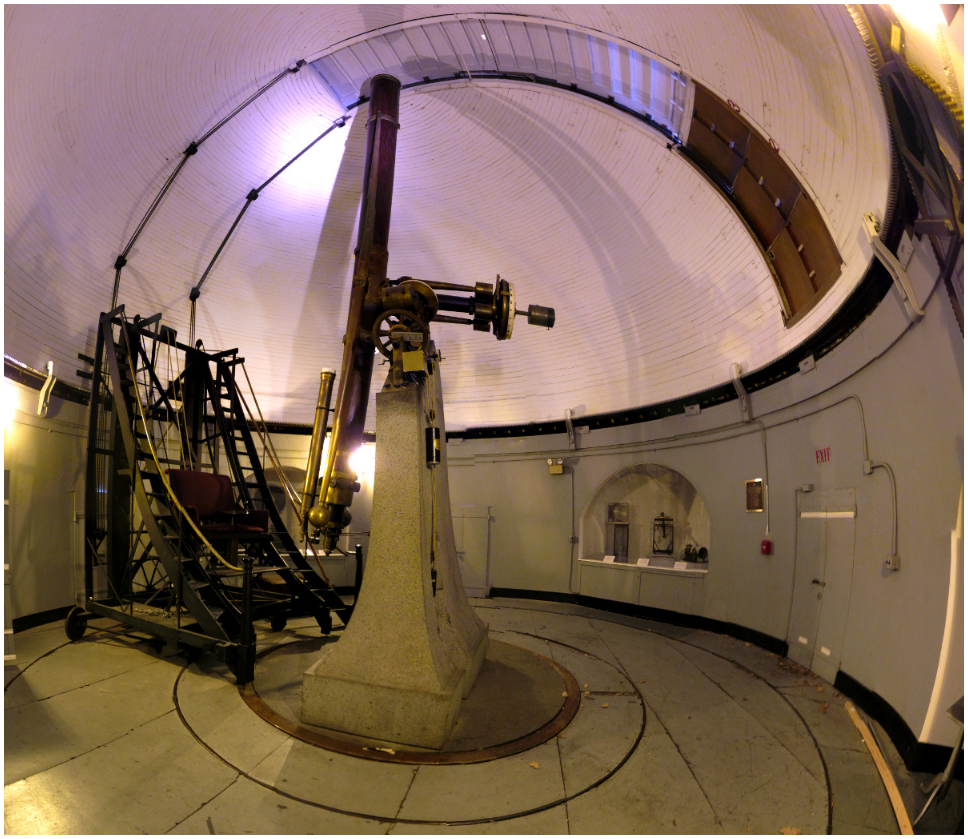

Fig. 3.— The Great Refractor, a 15" telescope built at the Harvard College Observatory in 1847. Photograph by the author, 2010.

but about 10 times smaller.

Modern telescopes are built with reflecting mirrors, rather than refracting lenses. One of the primary advantages of the reflector design is that they don't require mahogany tubes 16 times longer than their mirrors are wide to focus the light – the telescopes are much more compact. For amateur astronomers, this means that the telescopes are more portable and can be thrown in a car trunk; for professionals, this means that the majority of a telescope's construction budget need not be spent on a dome big enough to enclose it.

But when I think of the lone astronomer, I don't think as far back as the 19th century.

I think of my first academic advisor at Harvard, Professor John Huchra. John is a legend in our field, responsible for much of the work which unveiled the large scale structure of the universe. He logged perhaps as many hours behind an eyepiece as any twentieth century astronomer. While many senior astronomers leave the observing to their students, John was famous for relishing every moment at any telescope. John died in 2010, just a few months after I started my Ph.D., but reminders of his love for the science are scattered throughout observatories around the world like breadcrumbs. I learned this when I first traveled to the Fred Lawrence Whipple Observatory at Mount Hopkins in Arizona. I took a tour of five or six of the buildings at the observatory, each housing one of its telescopes and also a bookshelf full of trade paperback science fiction; late night reading for John as he sat by the telescope.

I can't help but think that I'm one of the last generation of astronomers who will experience observing in the way that John Huchra did. Just this semester, our group stopped sending observers to the Whipple Observatory in Arizona. Now when we are awarded time on this telescope, one of us sits in our office in Cambridge and controls the instruments remotely over the Internet. The alternative, what Harvard astronomy graduate students have been doing for generations, is traveling halfway across the country – if not the world – for those few nights that your lucky number is called and you have the opportunity to collect data for your thesis work.

I took one such trip in January, 2012, but not everything went as planned. I boarded a plane in Boston heading to the Las Campanas Observatory in Chile. Harvard is a member of a consortium that operates the twin 6.5 meter Magellan telescopes at the Observatory. These behemoths have seen more than their fair share of the most exciting discoveries in astronomy since their first light in 2000. I was traveling with my advisor and I wondered where she was sitting on the huge Boeing 737 commuter jet. I hoped we would get a chance to discuss our observing strategy for the following nights while we rushed to catch our connecting flight in New York. The connection was for a thirteen hour flight to Santiago, Chile. That would be a chance to sleep before the short, but sometimes-harrowing flight through the Andes to La Sarena and the long and always-harrowing drive up the mountain to the observatory that completed the 24 hour journey. I was familiar with this trip, as it was my third in as many months. That's an unusually dense schedule for any astronomer, but it promised to secure me the data I needed for my project.

The surprise came when I landed in New York and turned on my cell phone as the plane taxied. I tend to communicate with my friends and family by email, and I couldn't remember the last time I had more than half a dozen phone messages in an hour, as I did while my cell phone was off during that flight. All of them were letting me know that my advisor was not on the plane, having fallen victim to an airline scheduling error. I would be making the rest of the trip to Chile on my own.

I sat for a moment on the plane, evaluating my situation. I had enough observing experience that I felt fairly confident doing a solo run, and I had studied the instrument manuals before leaving. I was more concerned about how I would get to the mountain, as almost all the Observatory staff spoke a language that is foreign to me (Spanish) and I would not have Internet or telephone access until I got to Las Campanas. Fortunately, I made it to the mountain top observatory with no problems. I was fortunate that the Observatory staff are so experienced and professional in dealing with the hordes of American observers who compete for the opportunity to spend a day looking at the night sky in their country.

Walking around the observatory during the day is a surreal experience (Figure 4). Ranges of red mountains stretch into the distance in every direction. On my first morning I chose a direction and set out, walking about two miles up and down steep terrain, careful

Fig. 4.— Panorama of the mountains of the Atacama desert at the Las Campanas Observatory in Chile, taken by the author. The domes of the twin Magellan telescopes are visible at the upper right.

not to lose sight of Magellan's dome. It was the only viable landmark for finding my way back. Packing light for the hike, I brought nothing but my camera and two bottles of water. I was walking in the outskirts of the Atacama desert, just about the driest on Earth, and there was very little wildlife. The only flora were a few cacti and shrubs that, although found everywhere throughout the mountains, seemed too dried out to survive. I found almost no insects, except for occasional swarms of red fire ants that seem to build camps near the buildings, where food might be found. Large animals, though, are surprisingly common, including small herds of donkeys and wild horses that tackled the mountain climbs with much more grace than I could manage.

The only signs of human development are the Observatory itself; the long, winding road that leads to it; and the telescope domes of other observatories dotting mountains far on the horizon. If this seems desolate, I find it vastly preferable to the conditions at Mount Hopkins in Arizona, where beds need to be checked every night for scorpions and poisonous spiders.

Even on this trip, I was not alone on the mountain. I ate meals and slept in a common area shared by about a dozen observers, most of whom had made the long trip to Chile for the opportunity to use one of the Observatory's telescopes for just one or two nights. I shared my own nights on the Clay Telescope with an observer from Arizona; time on these telescopes is so valuable[15] that nights are often split in half in this way to hedge against potential losses to each observing program if the weather turns bad.

Our job as observers was not to operate the telescope, but rather a science instrument. I used a spectrograph to disperse light from distant galaxies which hosted supernovae (see Figure 5). I never once touched a button or pulled a level that affected the operation of the telescope in any way. This responsibility fell to the telescope operator on duty, a Chilean man sitting on the other side of the observing room who expertly monitored the telescope's movements, optical configuration, and weather conditions, from a bank of about a dozen computer monitors.

The observing room itself is a comfortable space, warm and well-lit with soft music playing from yet another computer in the back. Passing through the thick doors and up the stairs into the telescope dome (Figure 6) feels like walking through a spaceship's portal. Like turning on a stereo, the sound of whirring motors and cooling fans overwhelms you. Liquid nitrogen leaks to the ground like weighty smoke from a six-foot dewar cooling one of the infrared detectors. The dewar feels impossibly frigid on an already cold Chilean night.

But the dominating sensory perception in the telescope room is darkness. The slightest bit of ambient light in the room could drown out the precious few photons the telescope is collecting from the observer's target on the other side of the universe. The only light in the room comes from the stars, confined to the narrow slit in the dome open for the telescope.

My observing run at Magellan was a success. I sent about 30 gigabytes of data

[15] The National Optical Astronomy Observatory estimates the cost of operating Magellan for one night at $18,000, ¡http://ast.noao.edu/system/tsip/more-info/time-calc-mmt-magellan¿

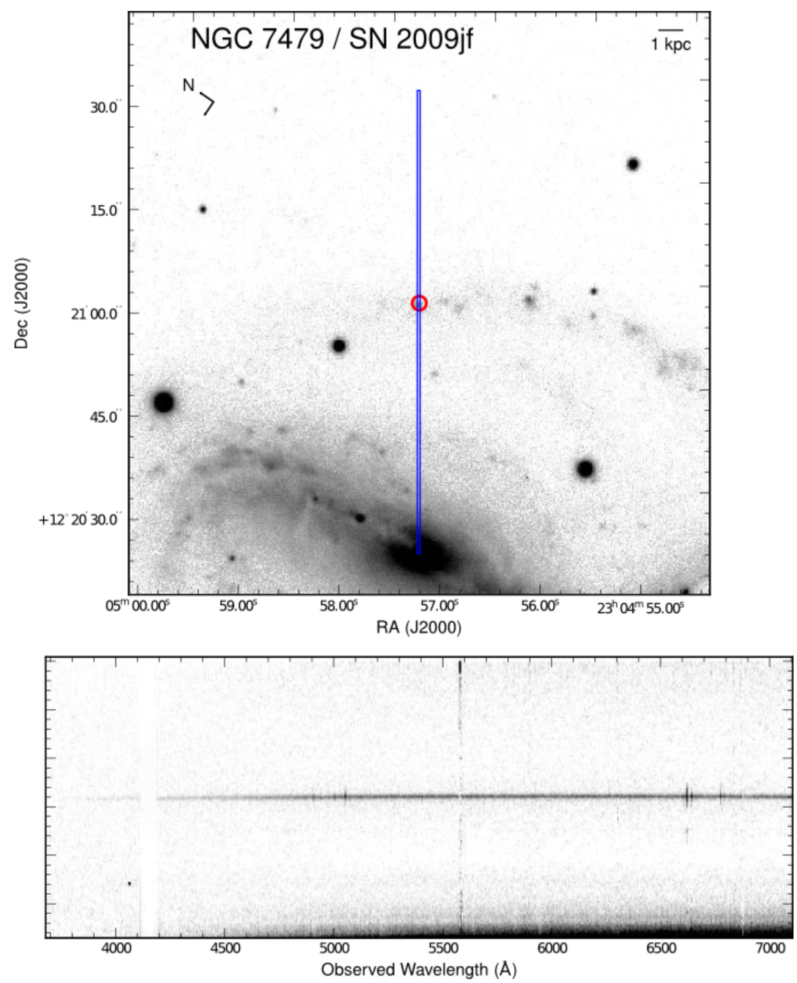

Fig. 5.— Image and spectrum of NGC 7479, a spiral galaxy like the Milky Way about 110 million light years distant from us, from the Magellan-Baade telescope. This galaxy hosted a supernova (exploding star) at the position of the red circle in 2009, called SN 2009jf. I used a spectroscopic slit (illustrated with the blue rectangle) to disperse the light of the galaxy and record the spectrum (below). Characteristic emission features of particular ions determine the characteristics of the galaxy's stars and the chemical composition of its interstellar medium. The scalebar at the top shows 1 kiloparsec, a distance about 200,000 times the distance from the Earth to the Sun.

Fig. 6.— Photograph of the Magellan-Clay telescope at Las Campanas Observatory in Chile, taken by the author. The 6.5 meter telescope itself sits within the silver dome. The door to the observing room is to its left, on the second floor.

(equivalent to $\sim$ 30 thousand smart phone photos) back to Cambridge over the Internet and packed my suitcase for the long return journey. I spent about ten hours in the Santiago airport, an extreme layover that we always book in case the connecting flight from the observatory gets canceled. I had plenty of time to begin analyzing the data from the previous few nights on my laptop, doing "quicklook" reductions that I would improve upon later at home. When I arrived in New York I was still thinking about my experience at the telescope and wondering what I would find buried in my data upon a closer inspection.

But as soon as I checked my phone messages, astronomy left my mind entirely. My wife was sick, our car had been towed from a parking spot just outside our apartment, and all flights to Boston were canceled for the next 24 hours due to a snowstorm. As I ventured out toward a train station in the unfamiliar streets of New York, it was clear to me why remote observing was such an attractive proposition. It is difficult to leave your life behind for a week to travel to a remote corner of the world for a few hours behind six-and-a-half meters of glass. There are other ways to do astronomy.

4. Observing in the future

Before he died, John Huchra helped ring in a new era for astronomy, one where science is done within massive collaborations and only a handful of specially trained astronomers will ever touch a rarefied set of billion-dollar telescopes. A detailed plan for this future was laid out in the 2010 report by the Decadal Survey Committee of the National Academy of Sciences, on which John was Vice Chair. The report prescribes that funding agencies such as the National Science Foundation focus their efforts on a few new key facilities. These include the Wide-Field Infrared Survey Telescope, a space telescope that is to be the successor of the successor of the Hubble Space Telescope, and the Large Synoptic Survey Telescope, a next generation version of PanSTARRs1 to be built in Chile.

All the facilities described in the Decadal Survey, share a few operational characteristics that separate them completely from the style of observation John represented. Their sophistication is overwhelming. No one individual could understand, much less execute, all aspects of both the instrumentation and the scientific applications of the data. As a result, the projects are operated by collaborations of hundreds or thousands of scientists, and much of the observing is automated. If this describes the future of observational astronomy, it also describes many aspects of its present.

The Sloan Digital Sky Survey[16] is a stunningly successful example of the automation paradigm. Its dedicated 2.5 meter telescope has been staring into the New Mexico sky nearly every night since 2000, collecting images that have been used to discover hundreds of millions of distant galaxies and stars within our own Milky Way. Each night the survey uses software to select thousands of promising targets among these objects for follow-up study, using algorithms designed to meet the goals set by the hundreds of astronomers from around the world who participate in the Sloan collaboration. A robot drills 1000 tiny holes into each of several metal plates, corresponding precisely to the positions of 1000 target objects in one field of the sky. Optical fibers are then plugged into these holes, and will carry the light received from these stars and galaxies to a spectrograph that will disperse the light so that the objects can be studied in detail.

This is exactly what I traveled to Las Campanas Observatory to do, one object at a time (Figure 5). All of the Sloan data – the countless nights of imaging and millions of spectra – are made freely available to the astronomical community over the Internet. The Sloan collaboration does their own analysis of the data, yielding some of the most impactful work in recent decades.[17] For example, they have produced the most detailed map of the

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[16] http://sdss3.org/

[17] See Eisenstein et al. (2005, Astrophysical Journal, 633, 560)

three-dimensional large scale structure of the universe, which places crucial constraints on our cosmological theory. Like thousands of other astronomers, I have used this data to do my own science, unrelated to and independent of the goals of the Sloan survey itself. Few of us have ever seen the Sloan telescope, or understand in detail how it is operated.

For many of my classmates at Harvard, the situation is even more extreme. They rely on data from one of the most celebrated instruments in astronomy today, NASA's Kepler space telescope.[18] Kepler stares at the same exact field of stars for years on end, recording the slight variations of brightness exhibited by each star with unprecedented precision. What it's looking for is the signature of planets that may be orbiting those stars. When a planet's orbit takes it between the telescope and the star, it blocks a small fraction of light from the star, casting a shadow on Kepler. Kepler records this as a small dip in the star's brightness – very small. For a planet the size of Earth orbiting a star the size of the Sun, exactly the sort of planet Kepler is looking for, the change in brightness is about one hundredth of one percent.

Kepler is the first instrument built by humans capable of measuring a change in brightness that small. The engineering prowess responsible for fabricating, calibrating, and operating this spacecraft – not to mention launching it into space – is incredible, and a world apart from the science of planet formation and habitability that interests astronomers. This division necessitates a dichotomy between the individuals who work on the telescope and those who do science with its data products.

And it's not only facilities like Sloan and Kepler, purpose-built for survey missions, that foster a disconnect between the technicians who perform observations and the "observational astronomers" who do science with the data. Even general purpose facilities like Magellan, the telescope I used in Chile, are moving towards observing models where institutional

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[18] http://kepler.nasa.gov/

experts take care of the actual observing and astronomers just interpret the data. The best illustration of this new reality is the Atacama Large Millimeter Array (ALMA)[19], one of the highest ranked projects in the Decadal Survey, which came online this past year.

ALMA is located about 600 miles north of Magellan, deep within the Atacama desert. ALMA is an array of 43 115-ton radio antennas (with 19 more to be installed), each twice as big as the Magellan telescope's mirror at 12 meters in diameter. The antennas are dispersed over an area as great as 10 miles long, but can be reconfigured to suit the needs of the observers by using specially-built trucks that lift and precisely relocate the antennas.

ALMA is an interferometer, meaning that radio waves received by each antenna are compared with each other in such a way that the array acts as a single, enormous telescope. Combining (or "correlating") the observations from each antenna is a massive signal processing challenge performed by an on-site supercomputer, which outputs about 1 gigabyte of data per second. ALMA is in many ways the successor to the Very Large Array, a facility that was operated for three decades in the New Mexico Desert and made famous by the movie "Contact." ALMA produces as much data output in four hours as the Very Large Array did in its 30 year lifetime.

The $\sim$ 10 mile effective diameter of ALMA means one thing to astronomers: high resolution. Bigger telescopes achieve better resolution because they reduce the diffraction effect. Light waves bouncing off different points on the telescope's mirror interfere with each other, causing the image of a point source to look smoothed out, or blurred (Figure 7). This diffraction effect is weaker the farther apart the reflecting light waves are, so telescope with a larger mirror will produce higher-resolution, less blurry images. However, diffraction is stronger at longer wavelengths of light. Radio waves are about 100,000 times longer than visible wavelengths of light, so the effect of diffraction is 100,000 times stronger. As a

[19]For a visual and technical tour of ALMA, see: http://astrobites.com/2012/05/11/it-takes-a-village-to-raise-the-alma-observatory/

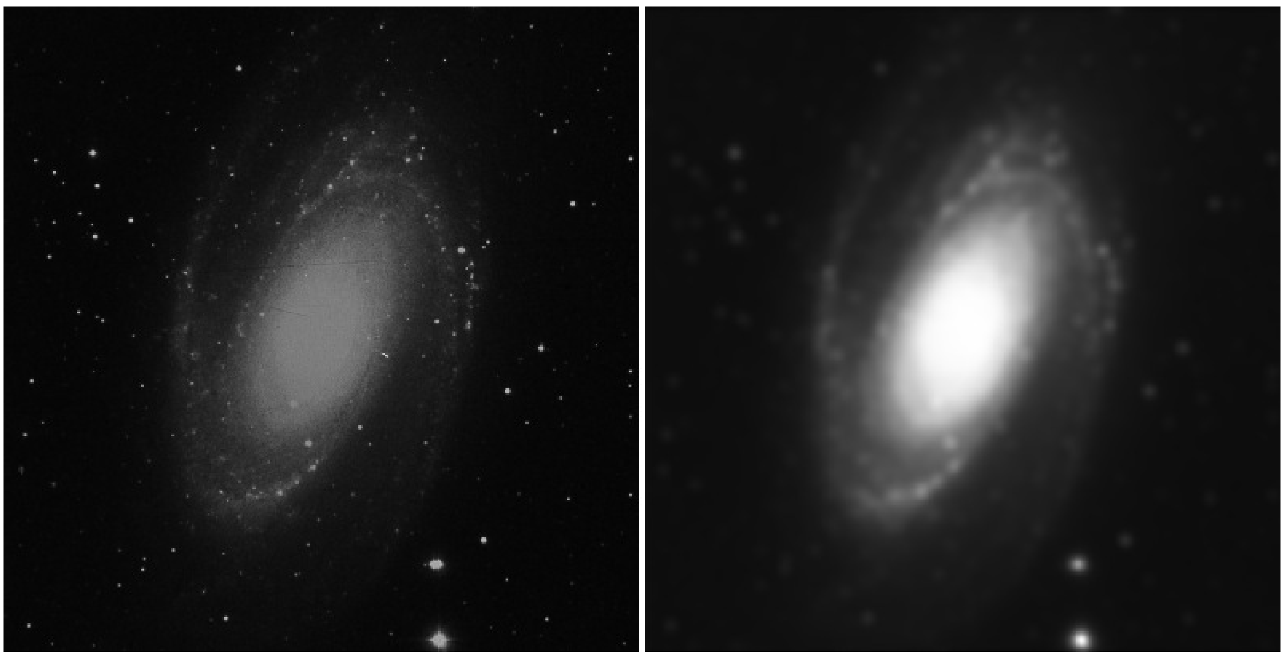

Fig. 7.— Left: Image of the nearby galaxy M81, from the Digitized Sky Survey. Right: The same image, blurred to simulate the effect of diffraction for a telescope with mirror diameter ten times smaller.

result, if you looked at the moon with a great single-dish radio telescope like the 305 meter Arecibo antenna in Puerto Rico, the resolution would be so poor that you could not even tell that it has craters. Even your naked eye can easily resolve craters on the moon at visible wavelengths.

The ALMA array is so large ($\sim$ 10 miles) that it overcomes this diffraction, and has resolution that rivals the greatest visible light telescopes in the world. Despite the diffraction effects at radio wavelengths, ALMA could resolve a football field on the moon. This capability is providing astronomers with the most detailed view yet of the radio sky, including the internal structure of gas in distant galaxies and the protoplanetary disks around young stars in the Milky Way.[20]

At 5000 meters above sea level, ALMA is at about twice the elevation of Magellan and the Las Campanas Observatory. ALMA's location makes it much more difficult to travel to than Magellan (remarkable to me, given my own experiences), but it has to be located there. This is the best observing site in the world for radio astronomy: far from any sources of human radio emission that would produce interference, and above much of the Earth's atmosphere rich in water molecules that would absorb radio waves from astronomical sources.[21]

But few of the astronomers who use ALMA will need to visit its site at the Chajnantor Plateau in the Atacama desert. ALMA's operation follows a service observing model. Scientists propose observing programs to a committee of ALMA scientists, who will select the most interesting projects that make the best use of ALMA's unique capabilities. Each project will then be scheduled during a time when the ALMA array is arranged in the

[20] The first science results from ALMA were published by Boley et al. (Astrophysical Journal Letters, 2012, 750, 1) and Herrera et al. (Astronomy & Astrophysics, 2012, 538, 9).

[21] Water, and other small molecules in the atmosphere, absorbs radio waves because they excite characteristic rotational transitions in the molecules. This is the same principal on which microwave ovens work.

optimal antenna configuration for those observations. On the scheduled date, the ALMA operators at base camp, a mile below the antennas on the Plateau, will point the array towards the target and execute the observations. ALMA's supercomputer will then correlate the signals from each antenna, and the finished data product will be made available via the Internet to the scientists who proposed the observations.

The advantage to the service observing model is that it helps make a broader range of observing capabilities available to every astronomer. This is integral to my own research on supernovae. Because the energetics involved in stellar explosions are so great, light is emitted at all wavelengths from low-energy radio waves to extremely high-energy gamma rays. A different physical process is responsible for producing light at each regime, so we learn about a different aspect of the explosion by observing with Magellan as we would with, say, ALMA. But the practical barrier to this kind of multi-wavelength research is clear to me, after spending the better part of a Ph.D. program becoming an expert in optical spectroscopy. The skillset needed to perform and analyze observations in all these different regimes is too vast for any one scientist to develop. With the service observing model, you only need to understand the implications of the data, not the workings of the telescope. Individual astronomers will be empowered by the next generation of service observing facilities to do more broad-ranging and comprehensive research projects than ever before – so long as they can secure the observing time they need amongst an ever-more-competitive pool of applicants.

This is how progress is made in astronomy. While the universe stays the same, we get a better view of it each time a technological advance makes a new kind of observation possible. PanSTARRs1, Kepler and ALMA are revolutionizing instrumentation today, just as Galileo and Newton did five and four centuries ago, respectively.[22] We cannot yet say

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[22] Galileo made the first astronomical observations with a telescope and Newton introduced the reflecting telescope, which superseded refracting

what the next generation projects such as the Wide-Field Infrared Survey Telescope and the Large Synoptic Survey Telescope will bring, but the recent track record in astronomy is clear. When new windows are opened to the universe, remarkable discoveries are made.

(lens) designs.