ASTRONOMY

BACK

IN TIME

Astronomers have found some of the most distant galaxies in the universe, opening a window on a previously unknown period of cosmic history

By Dan Coe

Illustration by Ron Miller

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WE STAND ON THE VERGE OF

WRITING A NEARLY COMPLETE COSMIC HISTORY. ASTRONOMERS have now observed galaxies going back 97 percent of the way to the big bang, which was 13.8 billion years ago.

The light from one such galaxy, named SPT0615-JD, began its journey toward Earth 13.3 billion years ago. In 2017 it arrived at the Hubble Space Telescope, where we were able to glimpse it for the first time through a project I ran called the Reionization Lensing Cluster Survey (RELICS), which aimed to find some of the cosmos's first galaxies. RELICS ran from October 2015 to October 2017, taking up more than 100 hours of Hubble observing time and more than 900 hours on the Spitzer Space Telescope. The project turned up more than 300 galaxy candidates from the universe's first billion years.

IN BRIEF

A recent experiment called the Reionization Lensing Cluster Survey (RELICS) aimed to find some of the first galaxies to form in cosmic history.

The project used gravitational lenses—areas where massive cosmic objects bend and magnify distant light.

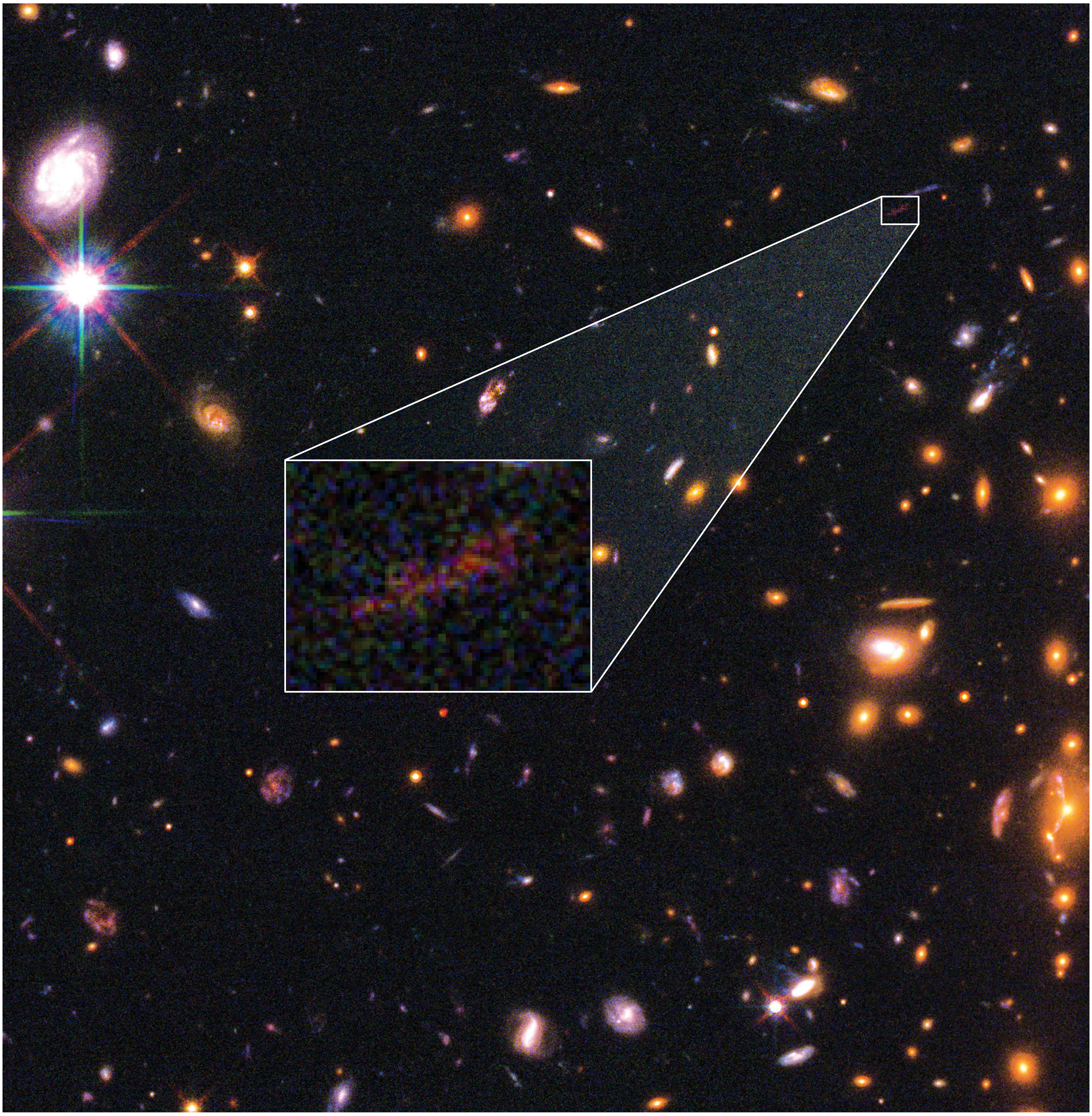
RELICS discovered more than 300 ancient galaxies, including one around 13.3 billion years old.

These objects are fascinating because they provide a view into a sliver of our history that is still totally unknown. By studying such objects, we hope to learn how the first galaxies formed and influenced the nascent universe. For instance, we believe galaxies such as SPT0615-JD transformed early space by blasting out ultraviolet light that the gas around them absorbed, turning the universe's first neutral atoms back into the lone protons and electrons that they started out as (a process known as reionization). The details of how and when this process occurred are, however, still unclear. With luck, the ancient galaxies we are observing will change that.

THE FIRST GALAXIES

EARLY GALAXIES were not like those we know today. The first galaxies were more pristine, composed primarily of hydrogen and helium gas. Over time their stars would fuse atoms to form heavier elements, and when these stars died in supernova explosions, the heavy elements dispersed throughout the galaxies, enriching them with "star stuff," including the elements needed to create life. The first galaxies had yet to settle into majestic spiral patterns or puffy elliptical balls like the galaxies we see around us now. They were far more disordered and much smaller (making them even harder to find). The earliest galaxies we have seen were about 1 percent the size of our Milky Way, but they were growing rapidly, forming new stars at prodigious rates. Fuel was plentiful back then; early galaxies were bathed in cool streams of flowing hydrogen gas, lured inward by gravity. The galaxies collided with one another and merged frequently, accelerating their growth and triggering new bursts of star formation. As the universe expanded over time, galaxy growth slowed, significant mergers became less frequent and the gas supply thinned out.

This picture is our basic understanding of cosmic history. We are still working to fill in the details, and many questions remain, especially surrounding the earliest times. When did the first galaxies form? How small were they? What did they look like? Were they "building blocks" of galaxies to come, with single large regions of star formation, or were they more fragmented and clumpy? Were they all bursting with intense star formation, or were some more relaxed, like most galaxies today? Did any early galaxies have time to settle into disks like the Milky Way did, or were they merging too frequently to do so? Will we ever find any filled with pristine hydrogen and helium gas, or did the first supernovae enrich them too quickly with heavier elements? How rapidly did early galaxies build up in mass and numbers? And were they, in fact, responsible for reionizing the universe? With the re-



sults from RELICS, we will take another step toward answering these questions.

COSMIC MAGNIFYING GLASSES

RELICS RELIED on a technique called gravitational lensing to glimpse far back into the past. We took advantage of nature's own magnifying glasses in the form of massive galaxy clusters. These groups of galaxies have so much mass combined that their gravity bends space and time, according to Einstein's general theory of relativity. As light from a more distant object travels through the universe, it follows the bent spacetime around the cluster, becoming magnified along the way. When it reaches Earth, the distant object looks warped and stretched, and sometimes multiple images of it appear. If this effect seems abstract, you can find a similar example as close as your next glass of wine. Look at a lit candle through the base of the wine glass, and you will see multiple images of the flame magnified.

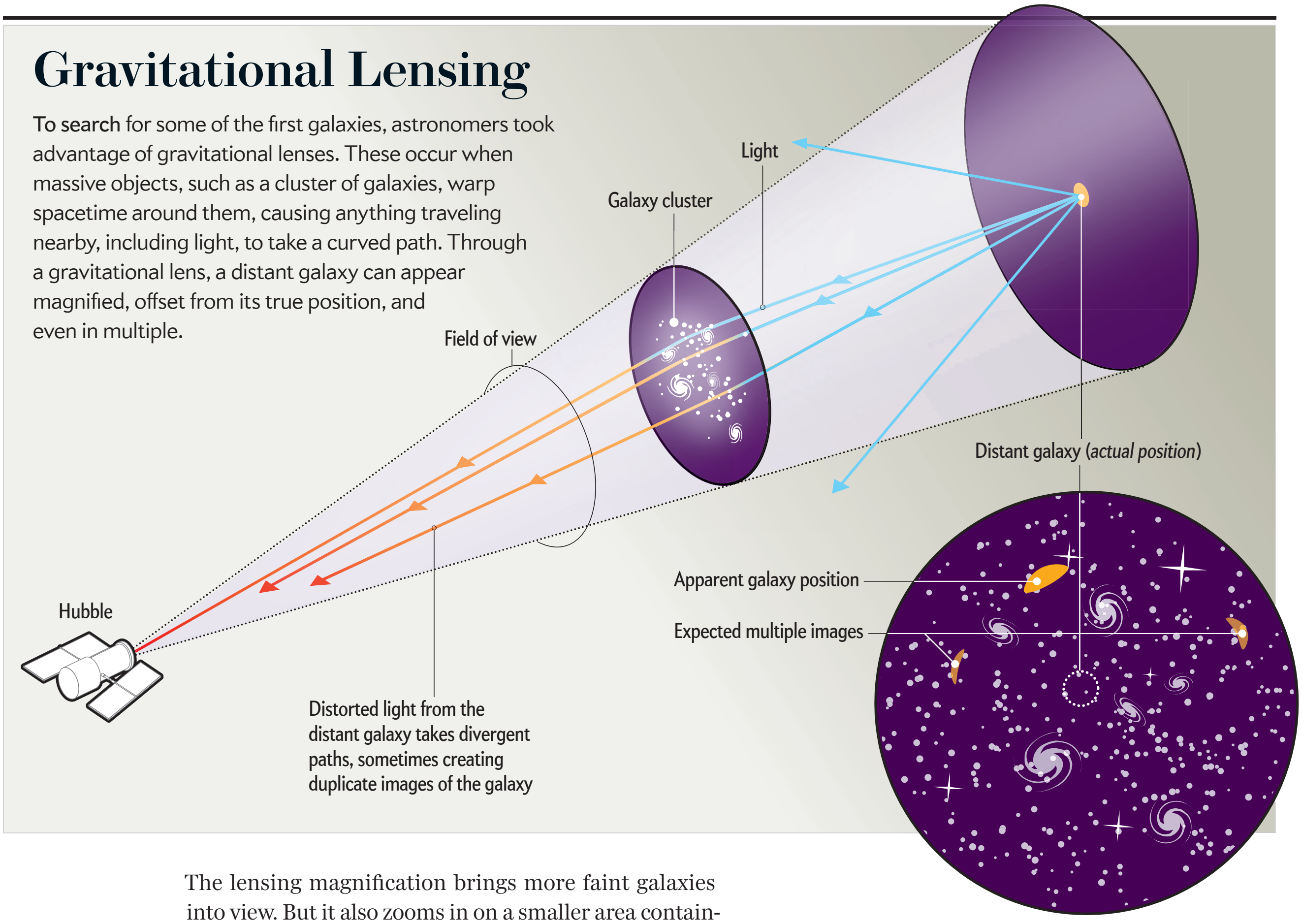
Magnified galaxies are brighter and resolved in more detail than normal, allowing us to better study their properties. Another advantage to observing strongly lensed regions of the sky is that we discover distant galaxies more efficiently than by observing "blank" patches such as the famous Hubble Deep Fields. This outcome is not obvious, and actually there is a trade-off.

RED BLUR: A faint streak in a Hubble Space Telescope image represents SPT0615-JD, one of the most distant known galaxies.

NASA, ESA, STScI AND B. SALMON

Gravitational Lensing

To search for some of the first galaxies, astronomers took advantage of gravitational lenses. These occur when massive objects, such as a cluster of galaxies, warp spacetime around them, causing anything traveling nearby, including light, to take a curved path. Through a gravitational lens, a distant galaxy can appear magnified, offset from its true position, and even in multiple.



The lensing magnification brings more faint galaxies into view. But it also zooms in on a smaller area containing fewer galaxies. Which effect wins out? Lensing does when there are many faint galaxies brought into view by magnification, compensating for the loss of area. In the early universe small, faint galaxies were plentiful, meaning we detect many more distant galaxies by searching in images strongly lensed by galaxy clusters.

Three of the largest Hubble programs carried out in the past seven years have used galaxy-cluster gravitational lensing to search for distant galaxies. These programs also partnered with Spitzer, which observes in infrared light at longer wavelengths than Hubble. The first, the Cluster Lensing and Supernova Survey with Hubble (CLASH), was a three-year program led by Marc Postman of the Space Telescope Science Institute (STScI) in Baltimore to observe 25 galaxy clusters. I helped write the proposal and analyze the images, and in 2012 I discovered MACS0647-JD, a galaxy observed at just 420 million years after the big bang. This is a strong candidate for the most distant galaxy known, surpassed only in 2016, when Pascal Oesch of Yale University discovered a galaxy from 20 million years earlier, this time with the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS), a large Hubble scan of relatively blank patches of sky, unaided by strong lensing.

After the successes of CLASH, I helped to convince Hubble's director at the time, Matt Mountain, to include galaxy clusters in the next big Hubble program: the Frontier Fields, led by Jennifer Lotz of STScI. This project followed in the footsteps of the previous Hubble Deep Fields programs, which stared at small patches of sky for many days. These earlier projects targeted the emptiest areas of sky scientists could find, devoid of relatively bright "close" galaxies (within mere billions of light-years away) that would block our views of the more distant universe. The first Hubble Deep Field image, which combined 342 exposures taken over 10 days in 1995, was a revelation: in a blank bit of sky the size of a grain of sand held at arm's length, some 3,000 galaxies appeared. The subsequent Hubble Deep Field South and Ultra Deep Field were similarly careful to avoid nearby galaxies. The Frontier Fields boldly broke from that tradition by obtaining deep images of six regions containing some of the densest concentrations of galaxies three billion to five billion light-years away. The project also observed six relatively blank areas nearby, more in the tradition of the previous deep-field programs. By boosting the power of Hubble and Spitzer with gravitational lensing, the Frontier Fields revealed the smallest and faintest distant galaxies ever observed.

RELICS FROM THE PAST

AFTER CLASH and with the Frontier Fields under way, it was not clear that astronomers would approve another large Hubble proposal to observe galaxy clusters. But I

Illustrations by Nigel Hawtin

found that many massive clusters had never been observed by Hubble at near-infrared wavelengths, in which distant galaxies would appear. (As the universe expands, light from faraway objects gets stretched and shifted toward longer, redder wavelengths—an effect called redshift.) I had uncovered a set of natural telescopes that we had yet to look through in our search for galaxies in the first billion years.

I tracked down these clusters in a catalog produced in 2015 by the European Space Agency's Planck space telescope. Planck is more famous for its detailed all-sky images of the cosmic microwave background (CMB)—the earliest observed radiation in the universe. But it was also able to catalog more than 1,000 massive galaxy clusters by noting their distortion effect on the CMB light. Most of these clusters were well known, but many were new discoveries. I found that the most massive cluster in the catalog, Abell 2163, had been observed by Hubble only in visible wavelengths, not near-infrared wavelengths. The second most massive cluster—PLCK G287.0+32.9, one of Planck's recent finds—had shown itself to be an excellent lens in ground-based imaging, but Hubble had yet to take a peek at it.

I compiled a list of 41 massive clusters lacking Hubble near-infrared imaging and assembled a team of astronomers to help write a large proposal to observe them. We requested the use of Hubble during 190 of its orbits around Earth—roughly 5 percent of the observing time available for proposals that year, amounting to more than 100 hours of observations. Once all the Hubble proposals were submitted, astronomers from around the world convened in Baltimore to deliberate over them. Our team was fortunate to learn in June 2015 that our proposal was accepted as the largest General Observer program in Hubble's 23rd full year of science operations.

RELICS observed all 41 clusters with Hubble's Wide Field Camera 3 infrared channel (WFC3/IR). We also observed them at red, green and blue visible wavelengths (if they had not been observed already) with the telescope's Advanced Camera for Surveys (ACS). The higher-resolution ACS images help us to measure the lensing properties of the cluster and to estimate the magnifications of the distant galaxies discovered in the WFC3/IR images. We observed at seven different wavelengths spanning 0.4 to 1.7 microns, enabling us to separate the light from each galaxy into its constituent colors. By looking at known light features, such as the specific wavelength that neutral hydrogen absorbs, we can estimate how much the galaxy's light has been redshifted and therefore how distant it is.

We have also been awarded 945 hours of observing time with Spitzer in proposals led by Maruša Bradač of the University of California, Davis, with important contributions from Spitzer's director, Tom Soifer. Spitzer's wavelengths deliver a more complete census of the stars in early galaxies, enabling us to measure their stellar mass and whether they are truly as far as they appear in the Hubble images.

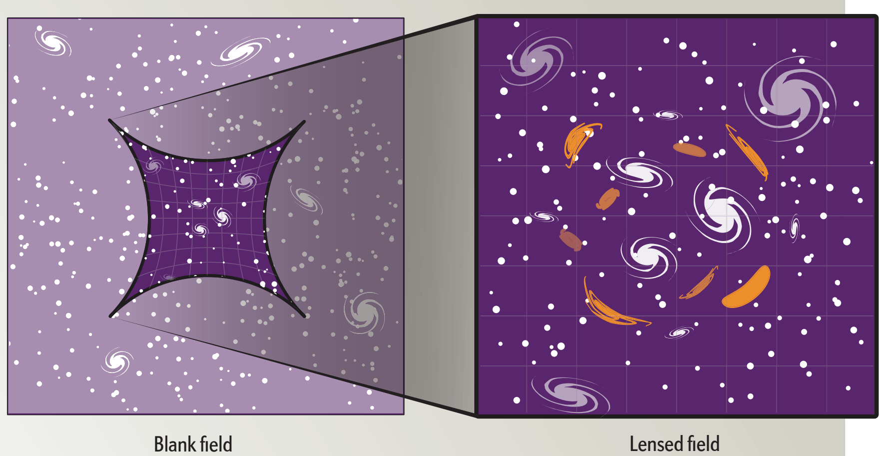
DISCOVERY

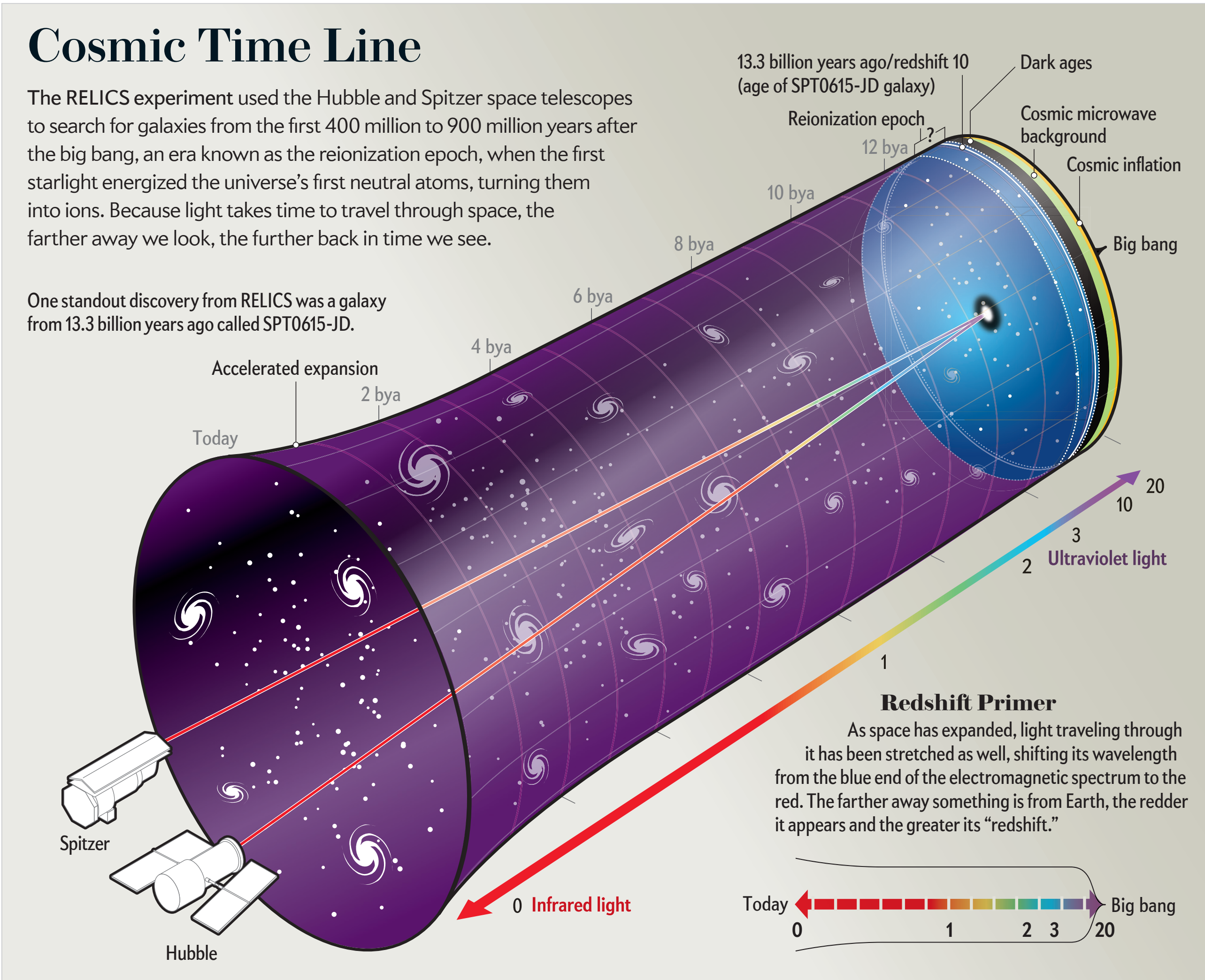
SPT0615-JD REVEALED itself in 2017 to a postdoctoral astronomer named Brett Salmon hired by myself with RELICS deputy principal investigator Larry Bradley of STScI. It did not pop out of the Hubble images right away as the unique object that it is. Galaxies can appear red to us for different reasons. Some are highly redshifted, such as SPT0615-JD. Others are enshrouded in dust, which absorbs bluer light and then reemits it as infrared light, making the galaxies appear redder than they are. Still other red galaxies are simply older—they have not formed many new stars in a while, and the stars that remain are longer-lived redder ones. Red galaxies may also be any combination of these: redshifted, dusty and old.

Spitzer's observations at three to five microns are critical in helping us to distinguish distant redshifted galaxies from less distant galaxies that are intrinsically red and would appear even brighter in Spitzer's

Two Strategies

Astronomers can take two approaches to search for galaxies. One is to look at an apparently "blank" patch of sky. Another option, employed by the Reionization Lensing Cluster Survey (RELICS), is to observe areas that include a massive galaxy cluster to capitalize on its gravitational lensing. This strategy takes in a smaller, oddly shaped field of view (because lensing magnifies the sky), but it reveals galaxies that would otherwise be too faint to see.





Cosmic Time Line

The RELICS experiment used the Hubble and Spitzer space telescopes to search for galaxies from the first 400 million to 900 million years after the big bang, an era known as the reionization epoch, when the first starlight energized the universe's first neutral atoms, turning them into ions. Because light takes time to travel through space, the farther away we look, the further back in time we see.

One standout discovery from RELICS was a galaxy from 13.3 billion years ago called SPT0615-JD.

Redshift Primer

As space has expanded, light traveling through it has been stretched as well, shifting its wavelength from the blue end of the electromagnetic spectrum to the red. The farther away something is from Earth, the redder it appears and the greater its "redshift."

wavelengths. In fact, we originally discovered three candidate galaxies (including SPT0615-JD) in our Hubble images that appeared to be at a redshift, or "*z*," of about 10, dating from when the universe was less than 500 million years old, more than 13 billion years ago. Analysis of the Spitzer observations, however, revealed that two of them were more likely to lie at a redshift of around two, when the universe was "only" 10 billion years old (nearly three quarters of its current age). SPT0615-JD survived the Spitzer analysis as a more likely redshift 10 candidate.

Combining Salmon's Hubble analysis with a Spitzer analysis by Victoria Strait of U.C. Davis, we found the light from SPT0615-JD drops off at around 1.34 microns, with all the light of smaller wavelengths missing. This light was absorbed as it excited hydrogen gas in the infant universe, or reionized it, turning atoms back into ions. The hard break in SPT0615-JD's spectrum is very useful because it allows us to measure its distance. Although we see the break at around 1.34 microns, we know that neutral hydrogen absorbs extreme ultraviolet light at wavelengths of less than 0.1216 micron. The ratio between the original and observed breaks in SPT0615-JD's spectrum reveals just how much the universe has expanded and its light has been redshifted and therefore just how far away it is.

We are seeing SPT0615-JD at a redshift of 10, when the universe was just 3.5 percent of its present age. This dating makes SPT0615-JD one of the oldest galaxies we are aware of. Two other galaxies are known to be a bit more distant, at a redshift of 11, observed when the universe was 400 million years old. But Hubble reveals those galaxies as simply infrared dots, too small for us to discern any details about their inner structure. SPT0615-JD is special. Its light has been stretched and magnified by gravitational lensing, giving us our most detailed look at such an early galaxy.

It may not look like much in our current observations, but we hope to take deeper Hubble images to reveal more details and uncover the fainter lensed multiple images of this galaxy predicted by Rachel Paterno-Mahler of the University of California, Irvine.

Illustration by Nigel Hawtin

We also have an accepted observing program with the Atacama Large Millimeter Array (ALMA), which we expect to confirm our distance measurement and to reveal oxygen, which would be the earliest detection yet of such a heavy element. And we will propose observations with NASA's next flagship observatory, the James Webb Space Telescope (JWST), which could provide detailed images of the galaxy's inner workings, measure its contribution to reionization, and reveal its chemical makeup, whether it be of pristine hydrogen and helium or enriched heavier elements.

SPT0615-JD was RELICS's most noteworthy discovery, but we also found more than 300 ancient-galaxy candidates (still to be confirmed) in the universe's first billion years. Among them are the brightest galaxies known dating back to these early times, which will allow us to study them in great detail. At first, I found this surprising because ground-based telescopes had observed many times more of the sky's area. But after crunching the numbers, the results are as expected. By using Hubble, Spitzer and the advantage of lensing, RELICS was able to uncover brighter galaxies at these distances.

THE GAP IN OUR STORY

THE ANCIENT GALAXIES we are finding through RELICS are helping to fill in a missing chunk of the cosmology history books. Scientists have a basic theory about the first moments of time, when the big bang initiated the universe, and space ballooned rapidly in a period called inflation. Around 380,000 years after the birth of space and time, the universe had cooled enough for the first atoms to form and for light to stream free. We see that afterglow today as the CMB.

After that snapshot, what follows is a 400-million-year gap in our story. We have yet to observe a single object as it existed during that time. That 3 percent of cosmic history is unknown to us. But we do know it was eventful. The first stars formed perhaps 100 million years after the big bang. Then, we think, stars began to cluster, eventually forming the first galaxies. Light from these galaxies streamed out and scattered off hydrogen atoms, ionizing them and liberating their electrons.

Understanding how this process happened by studying these galaxies is crucial for filling in the missing pages in our origin story. RELICS and projects that came before it—such as CLASH, CANDELS and the Frontier Fields—are taking big strides, but we expect an even bigger leap when JWST launches. This observatory, due to fly in 2021, will be humanity's most powerful tool ever for looking back at the earliest times. Observing with a larger mirror at longer wavelengths than previous telescopes, it will be able to see fainter, more distant galaxies with better resolution than any observatory before it. And it should be able to determine those galaxies' masses and compositions and how they contributed to reionization.

As much as gravitational lensing has helped us discover distant galaxies with current telescopes, I expect this advantage to be even greater at higher redshifts with JWST. As we look back in time, we find that smaller galaxies make up more and more of the overall census. If this trend continues into the first 400 million years, the lensing advantage will multiply further. Based on the current estimates, I predict that lensing will be the key to discovering the very first galaxies with JWST.

JWST will almost certainly see galaxies 300 million years after the big bang, and I strongly suspect that lensing will allow us to see galaxies within the first 200 million years, shrinking our historical gap in half—that is, if galaxies even formed that early.

We need to hit the ground running as soon as JWST launches because we may have a mere five to 10 years to work with it. Although Hubble is operating strongly 28 years after its launch, JWST will have only enough fuel to maintain its orbit for a decade. It is due to fly about a million miles from Earth, much too far for astronauts to service, repair or add new instruments to it, as they did several times for Hubble. RELICS is crucial to making the most use of JWST while we have it because it has already identified some of the best ancient galaxies for the new telescope to observe in detail, as well as the most gravitationally lensed areas of sky in which JWST can search for new galaxies.

LOOKING BACK

OUR MILKY WAY is probably as old as SPT0615-JD. The difference is that we see our galaxy as it is now and have no insight into how it looked in the very early universe. Because SPT0615-JD's light has taken so long to get here, we are seeing a fossilized version of its younger self.

But SPT0615-JD and our galaxy may have had similar histories, building up in size over the past 13 billion years. Planets probably formed around stars in the SPT0615-JD galaxy. Perhaps on some of those planets, life formed. And just maybe some of that life developed intelligence, culture, technology and telescopes in space. If so, they may be looking back at us now, through the same galaxy cluster, seeing a similarly magnified image of our galaxy as a pale red dot, the Milky Way as it was shortly after it was born.

Such possibilities are why we explore the frontiers of our universe: to discover our origins and, ultimately, to find ourselves. SA

MORE TO EXPLORE

RELICS: A Candidate z~10 Galaxy Strongly Lensed into a Spatially Resolved Arc. Brett Salmon et al. in *Astrophysical Journal Letters,* Vol. 864, No. 1, Article No. L22; September 1, 2018. **http://iopscience.iop.org/article/10.3847/2041-8213/aadc10**

RELICS Web site: **https://relics.stsci.edu**

FROM OUR ARCHIVES

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