SCIENCE

LIGO Detects Fierce Collision of Neutron Stars for the First Time

By DENNIS OVERBYEOCT. 16, 2017

For the first time, astronomers have seen and heard a pair of neutron stars collide in a crucible of cosmic alchemy. By DENNIS OVERBYE, JONATHAN CORUM and JASON DRAKEFORD on October 16, 2017. Photo by Robin Dienel/Carnegie Institution for Science. Watch in Times Video »

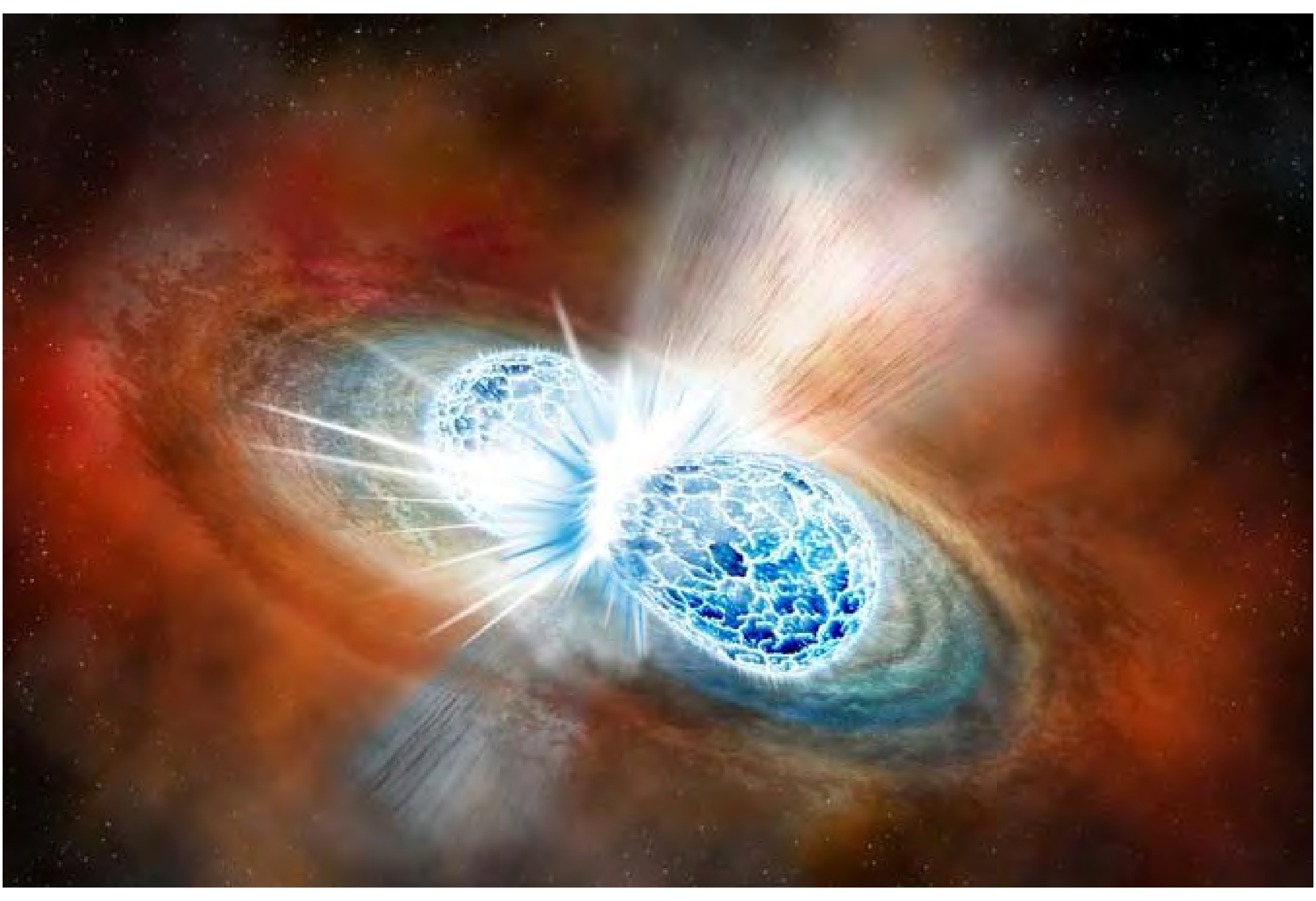
This is the story of a gold rush in the sky.

Astronomers have now seen and heard a pair of dead stars collide, giving them the first glimpse of what they call a "cosmic forge," where the world's jewels were minted billions of years ago.

The collision rattled space-time and sent a wave of fireworks across the universe, setting off sensors in space and on Earth on Aug. 17 as well as producing a long loud chirp in antennas designed to study the Einsteinian ripples in the cosmic fabric known as gravitational waves. It set off a stampede around the world as astronomers scrambled to turn their telescopes in search of a mysterious and long-sought kind of explosion called a kilonova.

After two months of underground and social media rumblings, the first wave of news is being reported Monday about one of the least studied of cosmic phenomena: the merger of dense remnants known as neutron stars, the shrunken cores of stars that have collapsed and burst.

Such collisions are thought to have profoundly influenced the chemistry of the universe, creating many of the heavier elements in the universe, including almost all the precious metals like gold, silver, platinum and uranium. Which is to say that the atoms in your wedding band, in the pharaoh's jewels and the bombs that destroyed Hiroshima and still threaten us all were formed in a cosmic gong show that reverberated across the heavens billions of years ago.



An artist's rendering of the merger of two neutron stars from Aug. 17. Robin Dienel/The Carnegie Institution for Science

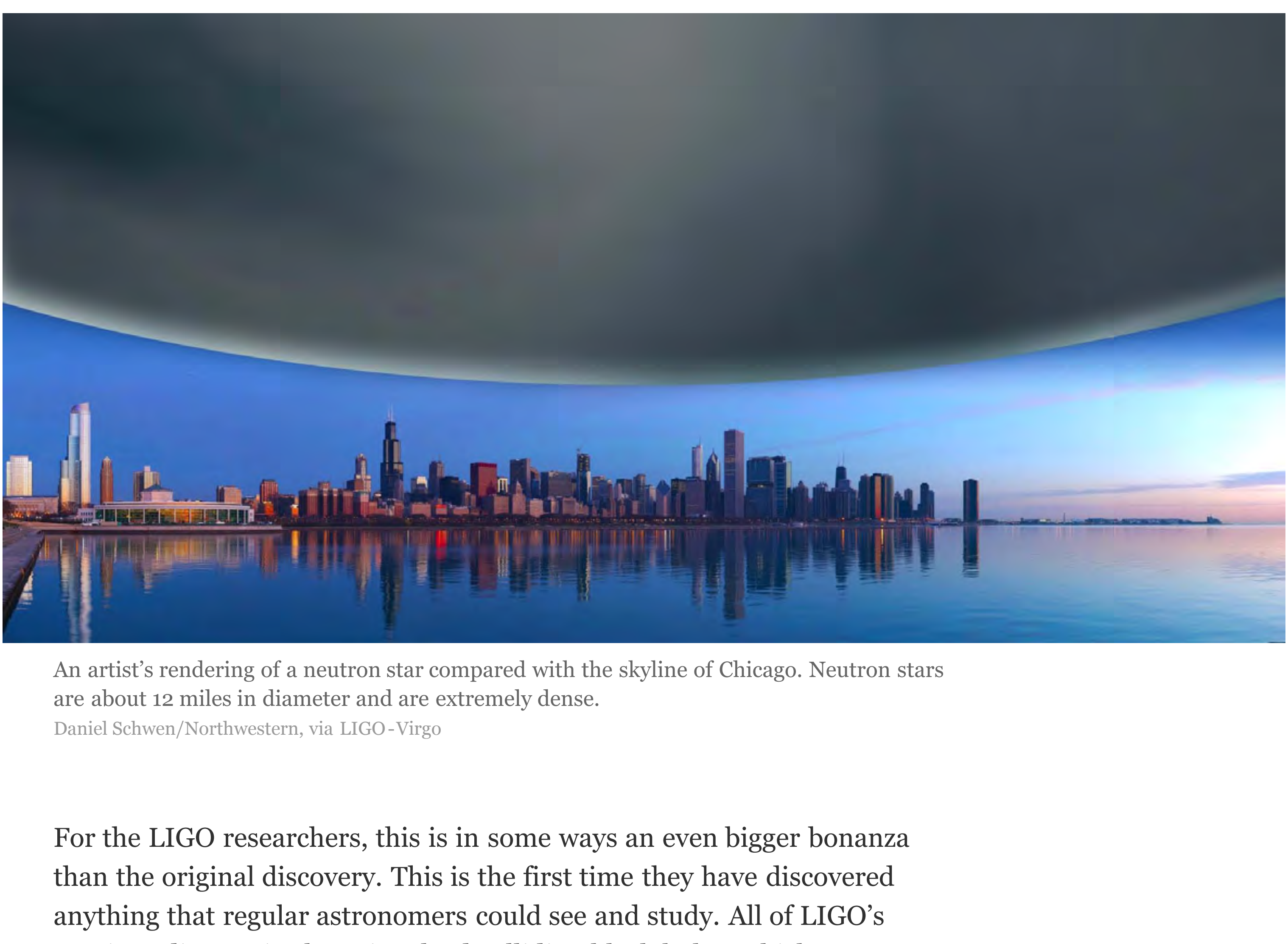
As astronomers gather for news conferences in several cities around the world, a blizzard of papers are being published, including one in The Astrophysical Journal Letters that has 3,500 authors — a third of all the professional astronomers in the world — from 910 institutions. "That paper almost killed the paperwriting team," said Vicky Kalogera, a Northwestern University astrophysicist who was one of 10 people who did the actual writing.

More papers are appearing in Nature and in Science, on topics including nuclear physics and cosmology.

"It's the greatest fireworks show in the universe," said David Reitze of the California Institute of Technology and the executive director of the Laser Interferometer Gravitational-Wave Observatory, or LIGO.

Daniel Holz, an astrophysicist at the University of Chicago and a member of the LIGO Scientific Collaboration, a larger group that studies gravitational waves, said, "I can't think of a similar situation in the field of science in my lifetime, where a single event provides so many staggering insights about our universe."

It was a century ago that Albert Einstein predicted that space and time could shake like a bowl of jelly when massive things like black holes moved around. But such waves were finally confirmed only in 2016, when LIGO recorded the sound of two giant black holes colliding, causing a sensation that eventually led this month to a Nobel Prize.



An artist's rendering of a neutron star compared with the skyline of Chicago. Neutron stars are about 12 miles in diameter and are extremely dense.
Daniel Schwen/Northwestern, via LIGO–Virgo

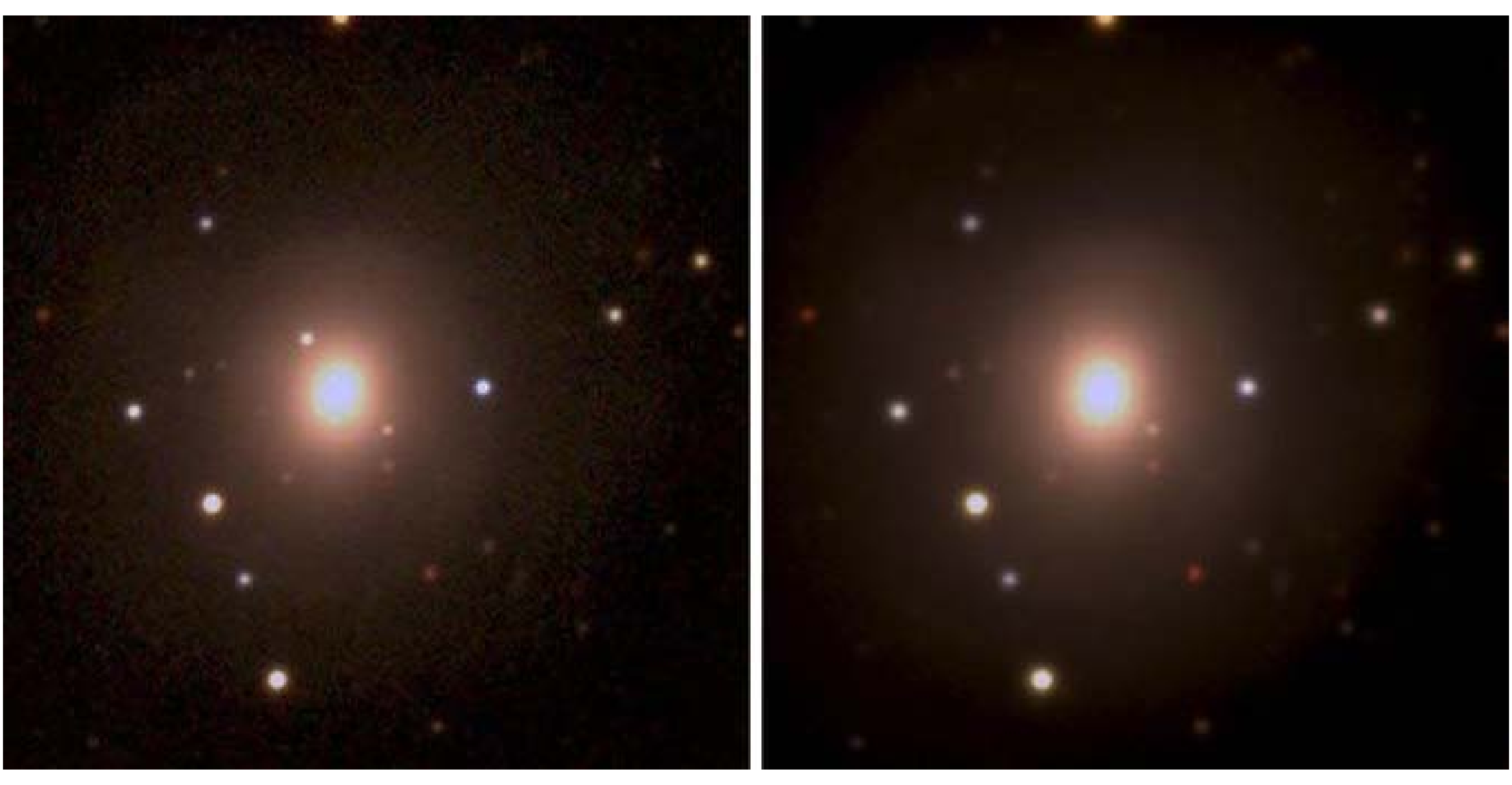
For the LIGO researchers, this is in some ways an even bigger bonanza than the original discovery. This is the first time they have discovered anything that regular astronomers could see and study. All of LIGO's previous discoveries have involved colliding black holes, which are composed of empty tortured space-time — there is nothing for the eye or the telescope to see.

But neutron stars are full of stuff, matter packed at the density of Mount Everest in a teaspoon. When neutron stars slam together, all kinds of things burst out: gamma rays, X-rays, radio waves. Something for everyone who has a window on the sky.

"Joy for all," said David Shoemaker, a physicist at the Massachusetts Institute of Technology who is the spokesman for the LIGO Scientific Collaboration.

It began on the morning of Aug. 17, Eastern time. Dr. Shoemaker was on a Skype call when alarms went off. One of the LIGO antennas, in Hanford, Wash., had recorded an auspicious signal and sent out an automatic alert. Twin antennas, in Washington and Louisiana, monitor the distance between a pair of mirrors to detect the submicroscopic stretching and squeezing of space caused by a passing gravitational wave. Transformed into sound, the Hanford signal was a long 100-second chirp, that ended in a sudden whoop to 1,000 cycles per second, two octaves above middle C. Such a high frequency indicated that whatever was zooming around was lighter than a black hole.

Checking the data from Livingston to find out why it had not also phoned in an alert, Dr. Shoemaker and his colleagues found a big glitch partly obscuring the same chirp.



National Optical Astronomy Observatory

Meanwhile, the Fermi Gamma-Ray Space Telescope, which orbits Earth looking at the highest-energy radiation in the universe, recorded a brief flash of gamma rays just two seconds after the LIGO chirp. Fermi sent out its own alert. The gamma-ray burst lasted about two seconds, which put it in a category of short gamma ray bursts associated with the formation of black holes perhaps as a result of neutron stars colliding.

“When we saw that,” Dr. Shoemaker said, “the adrenaline hit.”

Dr. Kalogera, who was in Utah hiking and getting ready for August’s total solar eclipse when she got the alarm, recalled thinking: “Oh my God, this is it. This 50-year-old mystery, the holy grail, is solved.”

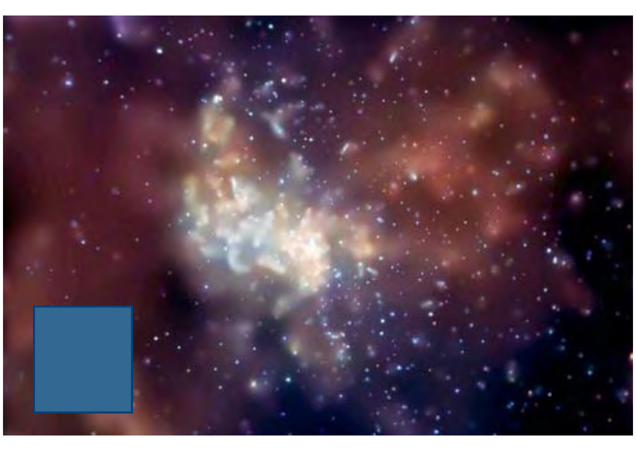
Together the two signals told a tale of a pair of neutron stars — dense balls about as massive as the sun but only about the size of Manhattan — spiraling around each other like the blades of a kitchen blender.

The stars were each the survivors of cosmic violence: All that was left of a pair of stars whose explosions had once lit up their galaxy, circling each other and merging in a cataclysm never before seen by human eyes.

And it was loud, meaning that it was relatively close to Earth, said Zsuzsa Marka, a Columbia astrophysicist, showing off the chirp on a laptop in her office recently. But where?

An Earthling’s Guide to Black Holes

Welcome to the place of no return — a region in space where the gravitational pull is so strong that not even light can escape it. This is a black hole.



Luckily the European Virgo antenna had joined the gravitational wave network only two weeks before, and it also showed a faint chirp at the same time. The fact that it was so weak allowed the group to localize the signal to a small region of the sky in the southern constellation Hydra that was in Virgo’s blind spot.

The hunt was on. By then Hydra was setting in the southern sky. It would be 11 hours before astronomers in Chile could take up the chase.

One of them was Ryan Foley, who was working with a team on the Swope telescope run by the Carnegie Institution on Cerro Las Campanas in Chile. Figuring the burst had come from a galaxy, they made a list of the biggest galaxies in that region and set off to photograph them all systematically, the biggest ones first. “Just mow the lawn,” as Dr. Foley, a professor at the University of California, Santa Cruz, put it in a phone interview.

The fireball showed up in the ninth galaxy photographed, as a new bluish pinprick of light in the outer regions of NGC 4993, a swirl of stars about 130 million light years from here. “These are the first optical photons from a kilonova humankind has ever collected,” Dr. Foley said.

Within 10 minutes, another group of astronomers, led by Marcelle Soares-Santos of Brandeis University and using the Dark Energy Camera, which could photograph large parts of the sky with a telescope at the nearby Cerro Tololo Interamerican Observatory, had also spotted the same speck of light.

From left, France A. Córdova, the director of the National Science Foundation; David Reitze, executive director of the LIGO Laboratory; David Shoemaker, an M.I.T. physicist and spokesman for the LIGO Scientific Collaboration; Jo van den Brand, spokesman of the Virgo Collaboration; and Vicky Kalogera, a Northwestern University astrophysicist, held a news conference to discuss developments in gravitational-wave astronomy at the National Press Club in Washington on Monday. Alex Wroblewski for The New York Times

Emails went flying about in the Chilean night. Within hours four more groups had found the fireball.

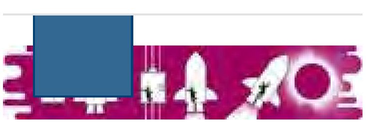
When the Hubble Space Telescope swung over to the galaxy, it was inadvertently announced on Twitter, which led J. Craig Wheeler, an astronomer at the University of Texas, to respond with his own tweet: “New LIGO. Source with optical counterpart. Blow your sox off!”

Dr. Wheeler quickly deleted his tweet, but the discovery was creating a social media buzz among astronomers and stargazers.

When it was first identified, the fireball of 8,000-degree gas was about the size of Neptune’s orbit and radiating about 100 million times as much energy as the sun.

Nine days later, the orbiting Chandra X-ray Observatory detected X-rays coming from the location of the burst, and a week after that, the Very Large Array in New Mexico recorded radio emissions. Over the course of a few days, meanwhile, the visible fireball faded and went from blue to red.

From all this, scientists have begun patching together a tentative story of what happened in the NGC 4993 galaxy.



Graphic: What Is General Relativity?

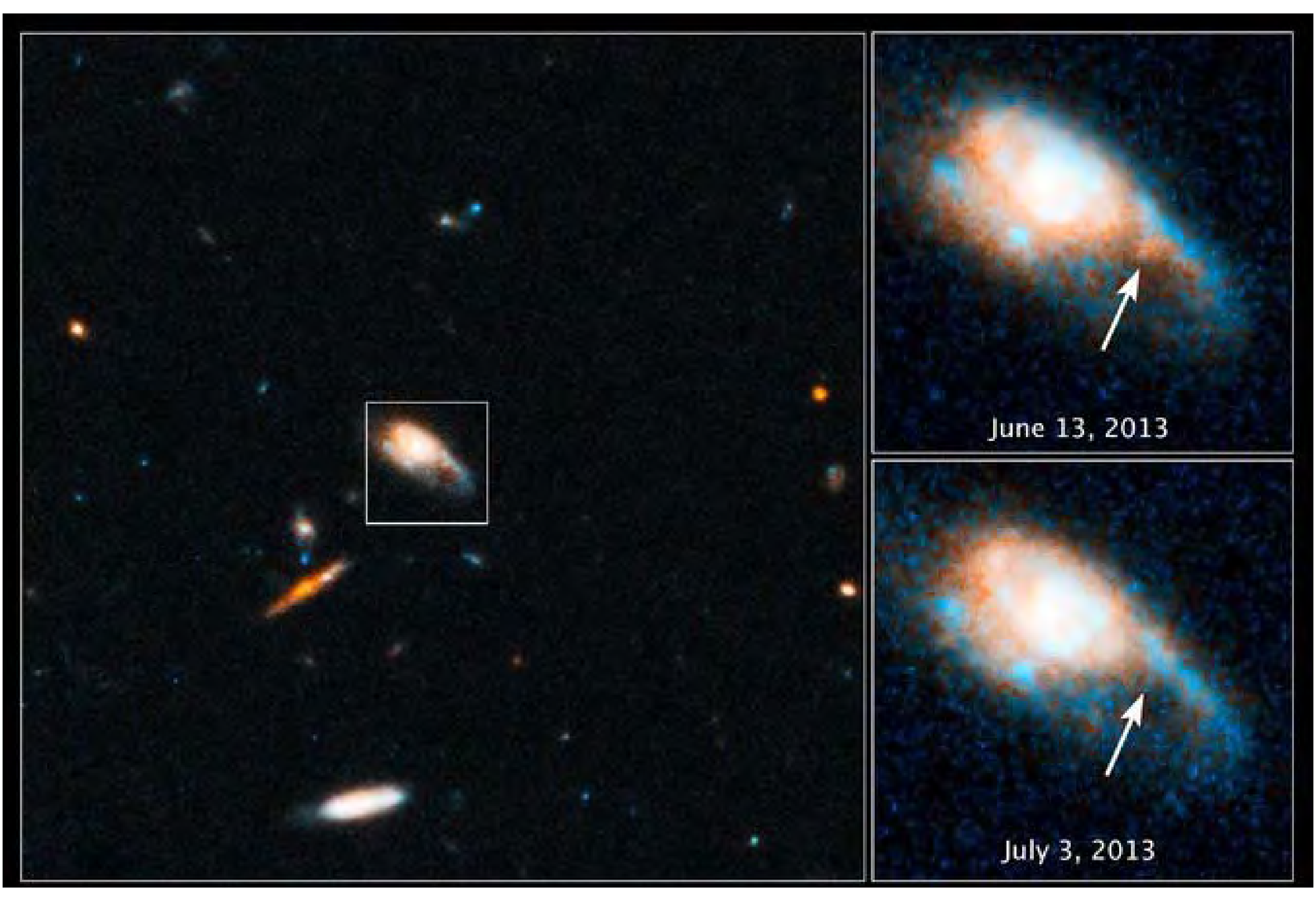
“It’s actually surprising how well we were able to anticipate what we’re seeing,” said Brian David Metzger, a theorist at Columbia University who coined the term kilonova back in 2010. But Dr. Kalogera cautioned that this was not a “vanilla gamma ray burst, being way fainter and closer than any previously observed.”

As they tell it, the merging objects were probably survivors of stars that had been orbiting each other and had each puffed up and then died in the spectacular supernova explosions in which massive stars end their luminous lives. Making reasonable assumptions about their spins, these neutron stars were about 1.1 and 1.6 times as massive as the sun, smack in the known range of neutron stars.

As they approached each other swirling a thousand times a second, tidal forces bulged their surfaces outward. Quite a bit of what Dr. Metzger called "neutron star guts" were ejected and formed a fat doughnut around the merging stars.

At the moment they touched each other, a shock wave squeezed more material out of their polar regions, but the doughnut and extreme magnetic fields confined the material into an ultra-high-speed jet emitting a blitzkrieg of radiation. Those were the gamma rays, carrying news of the catastrophe to the outside universe.

As the jet slowed down and widened, encountering interstellar gas in the galaxy, it began to glow in X-rays and then radio waves.



Images taken by the Hubble telescope showing the fireball emitted from a gamma ray burst in 2013. NASA/ESA

The subatomic nuggets known as neutrons meanwhile were working their cosmic alchemy. The atoms in normal matter are mostly empty space: a teeny tiny nucleus of positively charged protons and electrically neutral neutrons enveloped in a fluffy ephemeral cloud of negatively charged electrons. Under the enormous pressures of a supernova explosion, however, the electrons get squeezed back into the protons turning them into neutrons packed into a ball denser than an atomic nucleus.

The big splat liberates these neutrons into space where they inundate the surrounding atoms, transmuting them into heavy elements. The radioactivity of these newly created elements keeps the fireball hot and glowing.

Dr. Metzger estimated that an amount of gold equal to 40 to 100 times the mass of the Earth could have been produced over a few days and blown into space. For uranium the number is 10 to 30 times the mass of the Earth. In the coming eons, those metals could be incorporated into new stars and planets and in some far, far day become the material for an alien generation's jewels or weapons.

The discovery filled a long-known chink in the accepted explanation of how the chemistry of the universe evolved from pure hydrogen and helium into the diverse place it is today. Stars and supernovas could manufacture the elements up to iron or so, according to classic papers in the 1950s by Margaret and Geoffrey Burbidge, Fred Hoyle and William A. Fowler, but heavier elements required a different thermonuclear chemistry called r-process and lots of free neutrons floating around. Where would they have come from?

One idea was neutron star collisions, or kilonovas, which now seem destined to take their place on the laundry list of cosmic catastrophes along with the supernova explosions and black hole collisions that have shaped the history of the universe.

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October 22 The Orionids meteor shower will peak

November 1 Events we're watching starting in November

November 18 The Leonids meteor shower will peak

By Michael Roston. Produced by Gray Beltran, Sherman Hewitt and Britt Binler. Video by NASA, ESA, and M. Estacion (STScI).

Until now there was only indirect evidence of kilonovas. Astronomers found a fireball from a gamma-ray burst in 2013, but there was no proof that neutron stars were involved. At least some of the mysterious flashes in the sky known as short gamma-ray bursts, astronomers now know, are caused by mating neutron stars. Dr. Kalogera said this had been expected for decades: "For the first time ever, we have proof."

One burning question is what happened to the remnant of this collision. According to the LIGO measurements, it was about as massive as 2.6 suns. Scientists say that for now they are unable to tell whether it collapsed straight into a black hole, formed a fat neutron star that hung around in this universe for a few seconds before vanishing, or remained as a neutron star. They may never know, Dr. Kalogera said.

Neutron stars are the densest form of stable matter known. Adding any more mass over a certain limit will cause one to collapse into a black hole, but nobody knows what that limit is.

Future observations of more kilonovas could help physicists understand where the line of no return actually is.

Back when LIGO was being designed, in the 1970s, few astronomers knew there would be black hole collisions to see, but everybody knew there were binary star systems containing neutron stars, that should collide. And so LIGO was designed and sold to see these. And now it has.

Dr. Holz, the University of Chicago astrophysicist, said, "I still can't believe how lucky we all are," reciting a list of fortuitous circumstances. They had three detectors running for only a few weeks, and it was the closest gamma-ray burst ever recorded and the loudest gravitational wave yet recorded. "It's all just too good to be true. But as far as we can tell it's really true. We're living the dream."

Correction: October 16, 2017

An earlier version of this article misstated the number of authors of a paper published in an astronomy journal. It is 3,500 authors, not 4,500.

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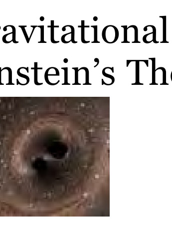

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Multi-messenger Observations of a Binary Neutron Star Merger

B. P. Abbott *et al.* 2017 *ApJL* 848 L12

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On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~ 1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg ^{2} at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_{\odot}$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at ~ 40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over ~10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position ~ 9 and ~ 16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.

https://doi.org/10.3847/2041-8213/aa91c9 Cited by References

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. III. Optical and UV Spectra of a Blue Kilonova from Fast Polar Ejecta

M. Nicholl *et al.* 2017 *ApJL* 848 L18

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We present optical and ultraviolet spectra of the first electromagnetic counterpart to a gravitational-wave (GW) source, the binary neutron star merger GW170817. Spectra were obtained nightly between 1.5 and 9.5 days post-merger, using the Southern Astrophysical Research and Magellan telescopes; the UV spectrum was obtained with the *Hubble Space Telescope* at 5.5 days. Our data reveal a rapidly fading blue component ($T \approx 5500$ K at 1.5 days) that quickly reddens; spectra later than $\gtrsim 4.5$ days peak beyond the optical regime. The spectra are mostly featureless, although we identify a possible weak emission line at ~7900 Å at $t \lesssim 4.5$ days. The colors, rapid evolution, and featureless spectrum are consistent with a "blue" kilonova from polar ejecta comprised mainly of light *r*-process nuclei with atomic mass number $A \lesssim 140$. This indicates a sightline within $\theta_{\rm obs} \lesssim 45°$ of the orbital axis. Comparison to models suggests ~0.03 M of blue ejecta, with a velocity of $\sim 0.3c$. The required lanthanide fraction is $\sim 10^{-4}$, but this drops to $< 10^{-5}$ in the outermost ejecta. The large velocities point to a dynamical origin, rather than a disk wind, for this blue component, suggesting that both binary constituents are neutron stars (as opposed to a binary consisting of a neutron star and a black hole). For dynamical ejecta, the high mass favors a small neutron star radius of $\lesssim 12$ km. This mass also supports the idea that neutron star mergers are a major contributor to *r*-process nucleosynthesis.

https://doi.org/10.3847/2041-8213/aa9029 References

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. II. UV, Optical, and Near-infrared Light Curves and Comparison to Kilonova Models

P. S. Cowperthwaite *et al.* 2017 *ApJL* 848 L17

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We present UV, optical, and near-infrared (NIR) photometry of the first electromagnetic counterpart to a gravitational wave source from Advanced Laser Interferometer Gravitational-wave Observatory (LIGO)/Virgo, the binary neutron star merger GW170817. Our data set extends from the discovery of the optical counterpart at 0.47–18.5 days post-merger, and includes observations with the Dark Energy Camera (DECam), Gemini-South/FLAMINGOS-2 (GS/F2), and the *Hubble Space Telescope* (*HST*). The spectral energy distribution (SED) inferred from this photometry at 0.6 days is well described by a blackbody model with $T \approx 8300$ K, a radius of $R \approx 4.5 \times 10^{14}$ cm (corresponding to an expansion velocity of $v \approx 0.3c$), and a bolometric luminosity of $L_{\rm bol} \approx 5 \times 10^{41}$ erg s $^{-1}$. At 1.5 days we find a multi-component SED across the optical and NIR, and subsequently we observe rapid fading in the UV and blue optical bands and significant reddening of the optical/NIR colors. Modeling the entire data set, we find that models with heating from radioactive decay of ^{56}Ni, or those with only a single component of opacity from *r*-process elements, fail to capture the rapid optical decline and red optical/NIR colors. Instead, models with two components consistent with lanthanide-poor and lanthanide-rich ejecta provide a good fit to the data; the resulting "blue" component has $M_{\rm ej}^{\rm blue} \approx 0.01\,M_{\odot}$ and $v_{\rm ej}^{\rm blue} \approx 0.3$ c, and the "red" component has $M_{\rm ej}^{\rm red} \approx 0.04\,M_{\odot}$ and $v_{\rm ej}^{\rm red} \approx 0.1$ c. These ejecta masses are broadly consistent with the estimated *r*-process production rate required to explain the Milky Way *r*-process abundances, providing the first evidence that binary neutron star (BNS) mergers can be a dominant site of *r*-process enrichment.

https://doi.org/10.3847/2041-8213/aa8fc7 References

INTEGRAL Detection of the First Prompt Gamma-Ray Signal Coincident with the Gravitational-wave Event GW170817

V. Savchenko *et al.* 2017 *ApJL* 848 L15

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We report the *INTernational Gamma-ray Astrophysics Laboratory* (*INTEGRAL*) detection of the short gamma-ray burst GRB 170817A (discovered by *Fermi*-GBM) with a signal-to-noise ratio of 4.6, and, for the first time, its association with the gravitational waves (GWs) from binary neutron star (BNS) merging event GW170817 detected by the LIGO and Virgo observatories. The significance of association between the gamma-ray burst observed by *INTEGRAL* and GW170817 is 3.2σ, while the association between the *Fermi*-GBM and *INTEGRAL* detections is 4.2σ. GRB 170817A was detected by the SPI-ACS instrument about 2 s after the end of the GW event. We measure a fluence of $(1.4 \pm 0.4 \pm 0.6) \times 10^{-7}$ erg cm $^{-2}$ (75–2000 keV), where, respectively, the statistical error is given at the 1σ confidence level, and the systematic error corresponds to the uncertainty in the spectral model and instrument response. We also report on the pointed follow-up observations carried out by *INTEGRAL*, starting 19.5 hr after the event, and lasting for 5.4 days. We provide a stringent upper limit on any electromagnetic signal in a very broad energy range, from 3 keV to 8 MeV, constraining the soft gamma-ray afterglow flux to $<7.1 \times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$ (80–300 keV). Exploiting the unique capabilities of *INTEGRAL*, we constrained the gamma-ray line emission from radioactive decays that are expected to be the principal source of the energy behind a kilonova event following a BNS coalescence. Finally, we put a stringent upper limit on any delayed bursting activity, for example, from a newly formed magnetar.

https://doi.org/10.3847/2041-8213/aa8f94 Cited by References

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Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A

B. P. Abbott *et al.* 2017 *ApJL* 848 L13

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On 2017 August 17, the gravitational-wave event GW170817 was observed by the Advanced LIGO and Virgo detectors, and the gamma-ray burst (GRB) GRB 170817A was observed independently by the *Fermi* Gamma-ray Burst Monitor, and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory*. The probability of the near-simultaneous temporal and spatial observation of GRB 170817A and GW170817 occurring by chance is 5.0×10^{-8}. We therefore confirm binary neutron star mergers as a progenitor of short GRBs. The association of GW170817 and GRB 170817A provides new insight into fundamental physics and the origin of short GRBs. We use the observed time delay of $(+1.74 \pm 0.05)$ s between GRB 170817A and GW170817 to: (i) constrain the difference between the speed of gravity and the speed of light to be between -3×10^{-15} and $+7 \times 10^{-16}$ times the speed of light, (ii) place new bounds on the violation of Lorentz invariance, (iii) present a new test of the equivalence principle by constraining the Shapiro delay between gravitational and electromagnetic radiation. We also use the time delay to constrain the size and bulk Lorentz factor of the region emitting the gamma-rays. GRB 170817A is the closest short GRB with a known distance, but is between 2 and 6 orders of magnitude less energetic than other bursts with measured redshift. A new generation of gamma-ray detectors, and subthreshold searches in existing detectors, will be essential to detect similar short bursts at greater distances. Finally, we predict a joint detection rate for the *Fermi* Gamma-ray Burst Monitor and the Advanced LIGO and Virgo detectors of 0.1–1.4 per year during the 2018–2019 observing run and 0.3–1.7 per year at design sensitivity.

https://doi.org/10.3847/2041-8213/aa920c References

SCIENCE

2017 Nobel Prize in Physics Awarded to LIGO Black Hole Researchers

By **DENNIS OVERBYE**OCT. 3, 2017

About a hundred years ago, Einstein predicted the existence of gravitational waves, but until now, they were undetectable. By DENNIS OVERBYE, JONATHAN CORUM and JASON DRAKEFORD on February 11, 2016. Photo by Artist's rendering/Simulating eXtreme Spacetimes. Watch in Times Video »

Rainer Weiss, a professor at the Massachusetts Institute of Technology, and Kip Thorne and Barry Barish, both of the California Institute of Technology, were awarded the Nobel Prize in Physics on Tuesday for the discovery of ripples in space-time known as gravitational waves, which were predicted by Albert Einstein a century ago but had never been directly seen.

In announcing the award, the Royal Swedish Academy called it "a discovery that shook the world."

That shaking happened in February 2016, when an international collaboration of physicists and astronomers announced that they had recorded gravitational waves emanating from the collision of a pair of massive black holes a billion light years away, it mesmerized the world. The work validated Einstein's longstanding prediction that space-time can shake like a bowlful of jelly when massive objects swing their weight around, and it has put astronomers on intimate terms with the deepest levels of physical reality, of a void booming and rocking with invisible cataclysms.

Why Did They Win?

Dr. Weiss, 85, Dr. Thorne, 77, and Dr. Barish, 81, were the architects and leaders of LIGO, the Laser Interferometer Gravitational-wave Observatory, the instrument that detected the gravitational waves, and of a sister organization, the LIGO Scientific Collaboration, of more than a thousand scientists who analyzed the data.

Dr. Weiss will receive half of the prize of 9 million Swedish Krona, or more than $1.1 million, and Dr. Thorne and Dr. Barish will split the other half.

The prize announcement at the Royal Swedish Academy of Sciences in Stockholm, on Tuesday. The detection of gravitational waves was described as "a discovery that shook the world."
Jonathan Nackstrand/Agence France-Presse — Getty Images

Einstein's General Theory of Relativity, pronounced in 1916, suggested that matter and energy would warp the geometry of space-time the way a heavy sleeper sags a mattress, producing the effect we call gravity. His equations described a universe in which space and time were dynamic. Space-time could stretch and expand, tear and collapse into black holes — objects so dense that not even light could escape them. The equations predicted, somewhat to his displeasure, that the universe was expanding from what we now call the Big Bang, and it also predicted that the motions of massive objects like black holes or other dense remnants of dead stars would ripple space-time with gravitational waves.

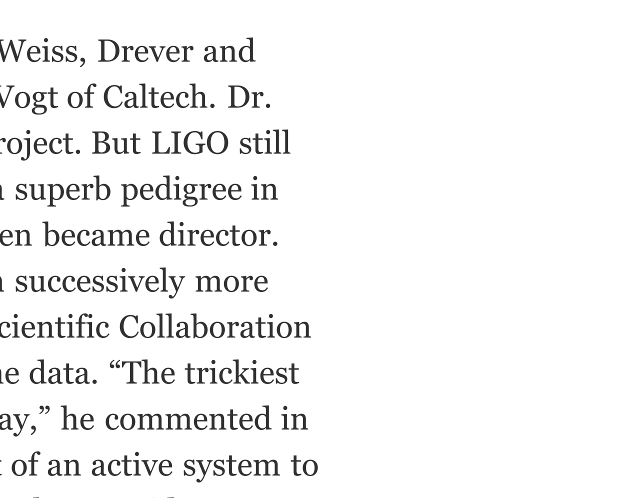
These waves would stretch and compress space in orthogonal directions as they went by, the same way that sound waves compress air. They had never been directly seen when Dr. Weiss and, independently, Ron Drever, then at the University of Glasgow, following work by others, suggested detecting the waves by using lasers to monitor the distance between a pair of mirrors. In 1975, Dr. Weiss and Dr. Thorne, then a well-known gravitational theorist, stayed up all night in a hotel room brainstorming gravitational wave experiments during a meeting in Washington.

Dr. Thorne went home and hired Dr. Drever to help develop and build a laser-based gravitational-wave detector at Caltech. Meanwhile, Dr. Weiss was doing the same thing at M.I.T.

The technological odds were against both of them. The researchers calculated that a typical gravitational wave from out in space would change the distance between the mirrors by an almost imperceptible amount: one part in a billion trillion, less than the diameter of a proton. Dr. Weiss recalled that when he explained the experiment to his potential funders at the National Science Foundation, "everybody thought we were out of our minds."

Nobel Prize Winning Scientists Reflect on Nearly Sleeping Through the Life-Changing Call

How eight winners got the word.



The foundation, which would wind up spending $1 billion over the next 40 years on the project, ordered the two groups to merge, with a troika of two experimentalists, Drs. Weiss and Drever, and one theorist Dr. Thorne, running things. The plan that emerged was to build a pair of L-shaped antennas, one in Hanford, Wash., and the other in Livingston, La., with laser light bouncing along 2.5-mile-long arms in the world's biggest vacuum tunnels to monitor the shape of space.

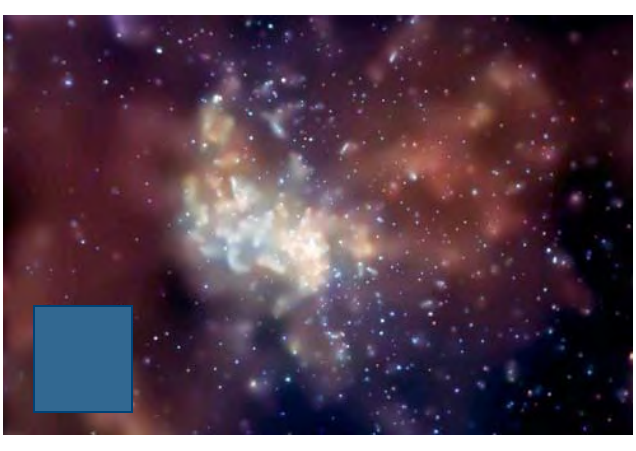
In 1987, the original three-headed leadership of Drs. Weiss, Drever and Thorne was abandoned for a single director, Rochus Vogt of Caltech. Dr. Drever was subsequently forced out of the detector project. But LIGO still foundered until Dr. Barish, a Caltech professor with a superb pedigree in managing Big Science projects, joined in 1994 and then became director. He reorganized the project so that it would be built in successively more sensitive phases, and he created a worldwide LIGO Scientific Collaboration of astronomers and physicists to study and analyze the data. "The trickiest part is that we had no idea how to do what we do today," he commented in an interview, giving special credit to the development of an active system to isolate the laser beams and mirrors from seismic and other outside disturbances.

"Without him there would have been no discovery," said Sheldon Glashow, a Nobel Prize-winning theorist now at Boston University.

The most advanced version of LIGO had just started up in September 2015 when the vibrations from a pair of colliding black holes slammed the detectors in Louisiana and Washington with a rising tone, or "chirp," for a fifth of a second.

An Earthling's Guide to Black Holes

Welcome to the place of no return — a region in space where the gravitational pull is so strong that not even light can escape it. This is a black hole.



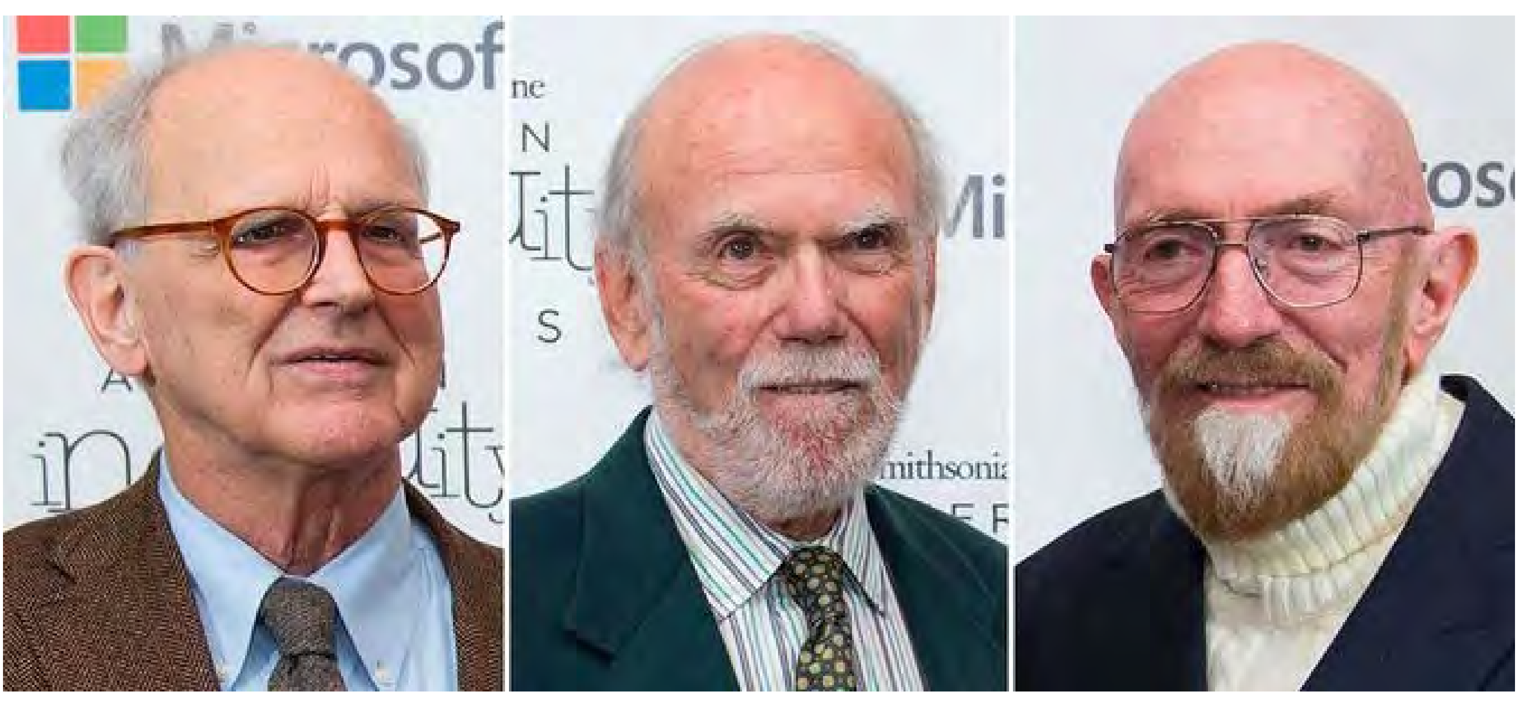
It was also the opening bell for a whole new brand of astronomy. Since then LIGO (recently in conjunction with a new European detector, Virgo) has detected at least four more black hole collisions, opening a window on a new, unsuspected class of black holes, and rumors persist of even more exciting events in the sky.

"Many of us really expect to learn about things we didn't know about," Dr. Weiss said this morning.

Who Are the Winners?

Dr. Weiss was born in Berlin in 1932 and came to New York by way of Czechoslovakia in 1939. As a high school student, he became an expert in building high-quality sound systems and entered M.I.T. intending to major in electrical engineering. He inadvertently dropped out when he went to Illinois to pursue a failing romance. After coming back, he went to work in a physics lab and wound up with a Ph.D. from M.I.T.

Dr. Thorne was born and raised in Logan, Utah, receiving a bachelor's degree from Caltech and then a Ph.D. from Princeton under the tutelage of John Archibald Wheeler, an evangelist for Einstein's theory who popularized the term black holes, and who initiated Dr. Thorne into their mysteries. "He blew my mind," Dr. Thorne later said. Dr. Thorne's enthusiasm for black holes is not confined to the scientific journals. Now an emeritus professor at Caltech, he was one of the creators and executive producers of the 2014 movie "Interstellar," about astronauts who go through a wormhole and encounter a giant black hole in a search for a new home for humanity.



From left: Rainer Weiss, Barry Barish and Kip Thorne, the architects and leaders of LIGO, the Laser Interferometer Gravitational-wave Observatory. Molly Riley/Agence France-Presse — Getty Images

Dr. Barish was born in Omaha, Neb., was raised in Los Angeles and studied physics at the University of California, Berkeley, getting a doctorate there before joining Caltech. One of the mandarins of Big Science, he had led a team that designed a $1 billion detector for the giant Superconducting Supercollider, which would have been the world's biggest particle machine had it not been canceled by Congress in 1993, before being asked to take over LIGO.

Subsequently, Dr. Barish led the international effort to design the International Linear Collider, which could be the next big particle accelerator in the world, if it ever gets built.

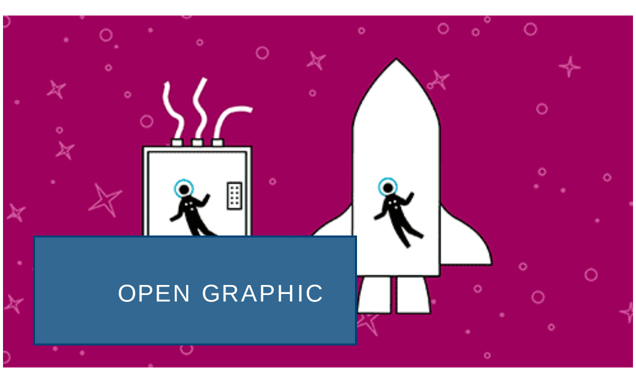
Reached by telephone by the Nobel committee, Dr. Weiss said that he considered the award as recognition for the work of about a thousand people over "I hate to say it — 40 years."

He added that when the first chirp came on Sept. 14, 2015, "many of us didn't believe it," thinking it might be a test signal that had been inserted into the data. It took them two months to convince themselves it was real.

GRAPHIC

What Is General Relativity?

Einstein presented his general theory of relativity 100 years ago this month.



In an interview from his home, Dr. Thorne said that as the resident theorist and evangelist on the project he felt a little embarrassed to get the prize. "It should go to all the people who built the detector and the members of the LIGO-Virgo Collaboration who pulled off the end game," he said.

"An enormous amount of rich science is coming out of this," he added. "For me, an amazing thing is that this has worked out just as I expected when we were starting out back in the 80s. It blows me away that it all come out as I expected."

Dr. Barish said he had awoken at 2:41 am in California and when the phone didn't ring he figured he hadn't won. Then it rang. "It's a combination of being thrilled and humbled at the same time, mixed emotions," he said. "This is a team sport, it gets kind of subjective when you have to pick out individuals." LIGO, he said, is very deserving. "We happen to be the individuals chosen by whatever mechanism."

For the National Science Foundation, the Nobel was a welcome victory lap for an investment of 40 years and about $1 billion. In a news release, France Córdova, the foundation's director, said: "Gravitational waves contain information about their explosive origins and the nature of gravity that cannot be obtained from other astronomical signals. These observations have created the new field of gravitational wave astronomy."

Sync your calendar with the solar system

Never miss an eclipse, a meteor shower, a rocket launch or any other astronomical and space event that's out of this world.

October 22 The Orionids meteor shower will peak

November 1 Events we're watching starting in November

November 18 The Leonids meteor shower will peak

By Michael Roston. Produced by Gray Beltran, Sherman Hewitt and Britt Binler. Video by NASA, ESA, and M. Estacion (STScI).

The prize was greeted with praise around the world. "Well done Sweden," said Michael Turner, a cosmologist at the University of Chicago, addding about the result, "It took a village and 100 years to do this."

The awarding of a Nobel to Drs. Weiss and Thorne completes a kind of scientific Grand Slam. In the last two years, along with Dr. Drever, they have shared a cavalcade of prestigious and lucrative prizes including the Kavli Prize for Astrophysics, the Gruber Cosmology Prize, the Shaw Prize in Astronomy and a Special Breakthrough Prize in Fundamental Physics. Dr. Drever died last March, and the Nobel is not awarded posthumously nor can more than three people share the prize.

Who Else Has Won a Nobel This Year?

Jeffrey C. Hall, Michael Rosbash and Michael W. Young were awarded the Nobel Prize in Medicine on Monday for discoveries about the molecular mechanisms controlling the body's circadian rhythm.

Who Won the 2016 Physics Nobel?

David J. Thouless, F. Duncan M. Haldane and J. Michael Kosterlitz were recognized for research into the bizarre properties of matter in extreme states, including superconductors, superfluids and thin magnetic fields.

When Will the Other Nobels be Announced?

Four more will be awarded in the days to come:

The Nobel Prize in Chemistry will be announced on Wednesday in Sweden. Read about last year's winners, Jean-Pierre Sauvage, J. Fraser

Stoddart and Bernard L. Feringa.

¦ The Nobel Prize in Literature will be announced on Thursday in Sweden. Read about last year's winner, Bob Dylan.

¦ The Nobel Peace Prize will be announced on Friday in Norway. Read about last year's winner, President Juan Manuel Santos of Colombia.

¦ The Nobel Memorial Prize in Economic Science will be announced on Monday, Oct. 9, in Sweden. Read about last year's winners, Oliver Hart and Bengt Holmstrom.

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A version of this article appears in print on October 4, 2017, on Page A8 of the New York edition with the headline: Recording of Gravitational Waves Was 'Discovery That Shook the World'.

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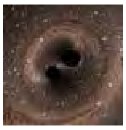

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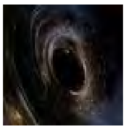


3 Who Studied Unusual States of Matter Win Nobel Prize in Physics OCT. 4, 2016

The Solar Eclipse: Highlights From Its Path Across the United States

By THE NEW YORK TIMES AUG. 21, 2017

Squeeze in among the crowds and witness the first total solar eclipse to cross the entire continental United States since 1918. An exclusive video by The New York Times in partnership with NOVA/PBS. By KAITLYN MULLIN, NATHAN GRIFFITHS and GUGLIELMO MATTIOLI on August 21, 2017. Photo by Jay Pasachoff for PBS/NOVA "Eclipse Over America". Technology by Samsung.. Watch in Times Video »

• A total solar eclipse made contact in Oregon just after 1:15 p.m. Eastern time on Monday, darkening skies as the moon obscured the sun and cast a long shadow across Earth.

• It concluded its path just before 3 p.m. in South Carolina, where clouds obscured the moment of totality.

• Weather may have been an obstacle to completing some solar research during the eclipse.

• In Washington, where the sun was about 80 percent obscured, President Trump and the first lady, Melania Trump, took in the partial eclipse at the White House.

• We've collected and shared your photos from the eclipse here. If these pictures give you "FOMO," your next shot at a Great American eclipse is 2,422 days away.

• Sign up for the weekly Science Times email newsletter and like our Science page on Facebook.

In Oregon, they savored the first moments.

At Depoe Bay, near where the line of totality first touched the United States, a flock of sea gulls hidden in fog called out loudly then went suddenly quiet. A chorus of gasps rang out among the scattered crowd of about a hundred still gathered at Government Point as the sun disappeared. Then a cheer went up as all dropped into darkness.

Tina Foster, here with her family, was nearly in tears.

"That was so amazing — to witness that in real life," she said. "That was kind of life-changing, especially for the kids."

Elsewhere in the state's zone of totality, electronic signs along the highways flashed warnings that stopping was not permitted. The rule was ignored. As the moon swallowed the sun, a rest stop along Interstate 5 overflowed with cars.

A crowd in Salem, Ore. observed the beginning of the eclipse. Don Ryan/Associated Press

In Salem, Ore., there were hugs, screams and tears, punctuated by cheers when the planet Venus became visible just before totality.

Jay Pasachoff, one of the world's leading eclipse astronomers, was grinning and walking through the crowd, hugging everybody after witnessing his 34th total eclipse.

"This was absolutely fabulous," he said. "As perfect as possible." — *Phoebe Flanigan, Thomas Fuller and Dennis Overbye*

The weather cooperated in some places, less in others.

Some viewers expected disappointment as clouds filled skies on their parcel of the path of totality.

At Homestead National Monument of America in Beatrice, Neb., the whole thing seemed in doubt.

"Go away, clouds," people chanted briefly as totality approached with the sun mostly obscured by a storm cloud. A few minutes later, when the sun became partially visible, the crowd cheered loudly.

When totality started, the sky turned dark, a few sparrows fluttered past and a star became visible. But it was several seconds until the sun poked through a gap in the clouds, prompting gasps and applause.

To the southeast, at Rosecrans Memorial Airport near St. Joseph, Mo., many visitors had traveled a long way to be disappointed by cloudy weather.

Watching the eclipse in Nashville. Joe Buglewicz for The New York Times

Daniel and Miriam Taylor from Auckland, New Zealand, reached the area around 5 a.m. Eastern time, Monday after a 36-hour trip, and sought to maintain an upbeat attitude.

"It's out of our control," Mr. Taylor said.

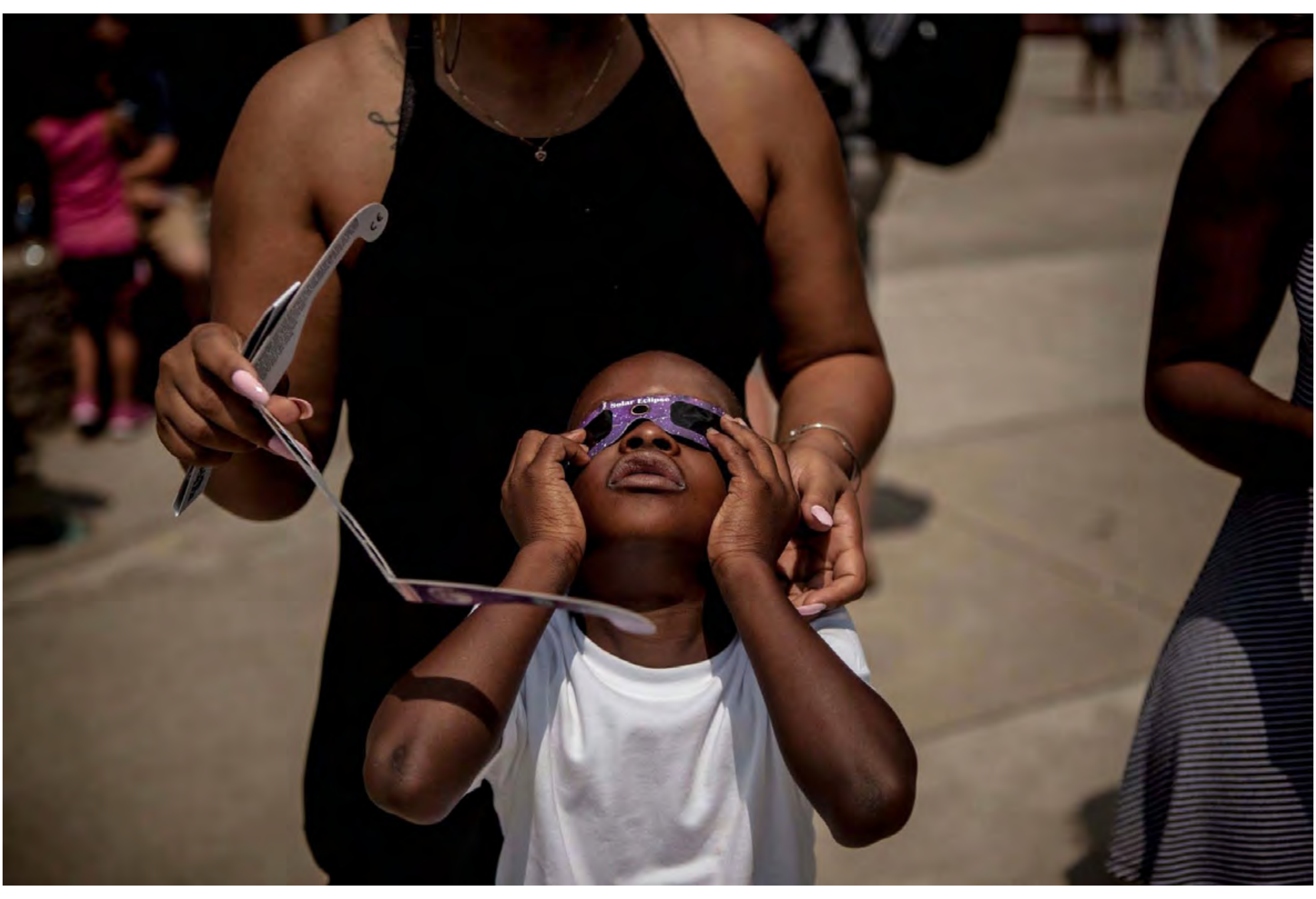
"Yeah, we're pretty chill about it," Ms. Taylor chimed in. "Obviously, it'd be amazing to see it. We were driving into this thunder lightning storm, and we're just like, 'This is part of it. Just being here is part of the atmosphere.'"

A few minutes later, when totality hit, the eclipse was visible for a few fleeting seconds, and people all around cheered.

But Alex Shaller, 35, said he spent $800 to get to St. Joseph from Worcester, Mass., and that the weather was a bit of a letdown.

"It wasn't as good as it could have been," he said when asked about the experience. "I feel O.K. Not horrible, just O.K."

In Charleston, S.C., the last city on the eclipse route before it headed out over the Atlantic, heavy clouds obscured totality.



Cloudy weather nearly robbed eclipse-watchers like Lafiet McDade, 6, of Carbondale, of the experience. Andrea Morales for The New York Times

But the hundreds of students gathered at the College of Charleston were ready for a final party anyway, as classes start tomorrow. They hooted and hollered as the moon slowly worked its way across the sun — a sight that, with glasses, was visible through the clouds. And they screamed again after totality, when a crescent sun again made an appearance.

Then the moon's shadow headed out past Fort Sumter in Charleston Harbor, across the coastal wetlands and out into the Atlantic. — *John Eligon, Henry Fountain and Mitch Smith*

Clouds may have prevented some eclipse research.

Total solar eclipses offer marvelous opportunities to study Earth's intimate relationship with the sun. The eclipse's passage across the United States offered unprecedented opportunities for astronomers and other scientists to study the sun's mysterious corona and Earth's ionosphere.

But in Carbondale, Ill., where many scientists had gathered because of the duration of the eclipse there, weather almost deprived them of their chance for research.

The 2017 solar eclipse seen from up above and down below. By NATALIE RENEAU on August 21, 2017. Photo by Bill Ingalls/NASA, via Associated Press... Watch in Times Video »

In the football stadium at Southern Illinois University, gigantic, cotton-candy clouds seemingly appeared out of nowhere to block the sun just one hour before totality.

Sarah Kovac, a recent graduate of the university's physics department, was diligently taking observations with her telescope on the stadium's 40th yard line as a member of the Citizen Cate project.

"We're all excited to be here right now — as long as that doesn't happen," she said as she was interrupted by the first of many giant clouds to shroud the stadium.

Anxiety spread across the crowd of thousands in the stadium as clouds queued up to cover the sun.

It wasn't until the second minute and 37th or 38th second that thinner clouds finally passed the eclipse, revealing a sensational diamond ring-like flash that drew deafening cries of excitement throughout the stadium.

Ms. Kovac was disappointed, but optimistic.

"We're backing up our data and hopefully we got at least a second or two because we can get an image out of that, we can still do science with it," she said.

Back in Salem, Ore., students from Williams College had greater fortune with the weather, and said they had succeeded in their goals for gathering data.

Celia Talbot Tobin for The New York Times

"It could not have been better," said Dr. Pasachoff, who led their team.

In the skies above the United States, scientists who oversaw pursuit of the eclipse's path of totality aboard specially-equipped NASA aircraft had positive results, too. They attained their goal of observing the total eclipse above the clouds for more than seven minutes.

"We got the data that we came for, and that's a successful observation," said Amir Caspi, an astrophysicist with the Southwest Research Institute who helped manage the mission from Houston. — *Nicholas St. Fleur and Dennis Overbye*

The eclipse got a thumbs-up in Washington.

In Washington, where the sun was about 80 percent obscured by the moon, President Trump, Melania Trump and their son, Barron Trump, took in the scene from the Truman Balcony just after 2:30 p.m. Eastern time.

By then, a busybody town had come to a quiet. Government workers clustered outside office buildings while tourists mingled next to the White House, unsure when, and where, to look.

Just before the first family appeared, Secret Service agents blew whistles to clear away pedestrians at the southern gates of the White House. Most scattered toward the Washington Monument.

Viewing the event from Folly Beach, S.C. Travis Dove for The New York Times

A vendor outside the White House grounds selling Trump merchandise said people had come all morning looking to buy glasses for the eclipse, which he did not have.

The president waved to the onlookers at the White House and gave a thumbs-up gesture when a reporter inquired about the view. He observed the eclipse at its apex wearing glasses with Mrs. Trump for about 90 seconds.

Cathy and Jerry Hickey were laying on their backs in the shadow of the monument, looking to the sky through eclipse glasses. Ms. Hickey had planned to be at the Washington Monument ever since she heard of the eclipse.

“It stands for our country,” she said. And “it points at the sun.”

To rescue families who had not yet found eclipse glasses, two National Park Service rangers sat at a folding table by the monument, handing out the last of what had been hundreds of pairs. The rangers also gave away eclipse-themed “junior ranger” booklets to children. — *Noah Weiland*

The spectacle seemed to put New York in a good mood.

Farther north in New York, where the partially eclipsed sun appeared fitfully behind clouds, a positive mood swept over viewers at the American Museum of Natural History.

Gathering to watch the partial solas eclipse at the American Museum of Natural History in Manhattan. Todd Heisler/The New York Times

Nicole Yong, 30, said the event felt like an extension of the weekend and noted that the eclipse seemed to be bringing people together, with “everyone sharing their glasses, making room for others to sit down, taking only what they need so there’s enough for everyone else.”

At the New York Hall of Science in Queens, children and their parents were in the majority among the hundreds gathered to take in the celestial phenomenon.

Patrick Rooney, 45, a New York firefighter from Bayside, arrived at the hall with his welding mask — protective gear equipped with auto-dimming goggles strong enough to filter out damaging sunlight.

He occasionally handed the mask to his son, Patrick, 3, and daughter, Catherine, 4, who all but disappeared from the shoulders up under the adult-sized headgear.

“I’m not sure they know exactly what they’re looking at,” Mr. Rooney said. “But they’re enjoying themselves and that’s all that matters.” — *Emily Palmer and Sean Piccoli*

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Phoebe Flanigan contributed reporting from Depoe Bay, Ore.; Thomas Fuller from Eugene, Ore.; Dennis Overbye from Salem, Ore.; Dave Phillips from Jackson, Wyo.; Julie Turkewitz from Glendo, Wyo.; Mitch Smith from Beatrice, Neb.; Tim O’Neil from St. Louis; Nicholas St. Fleur from Carbondale, Il.; Hollie Deese from Gallatin, Tenn.; Kenneth Chang from Loudon, Tenn.; Henry Fountain from Charleston, S.C.

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