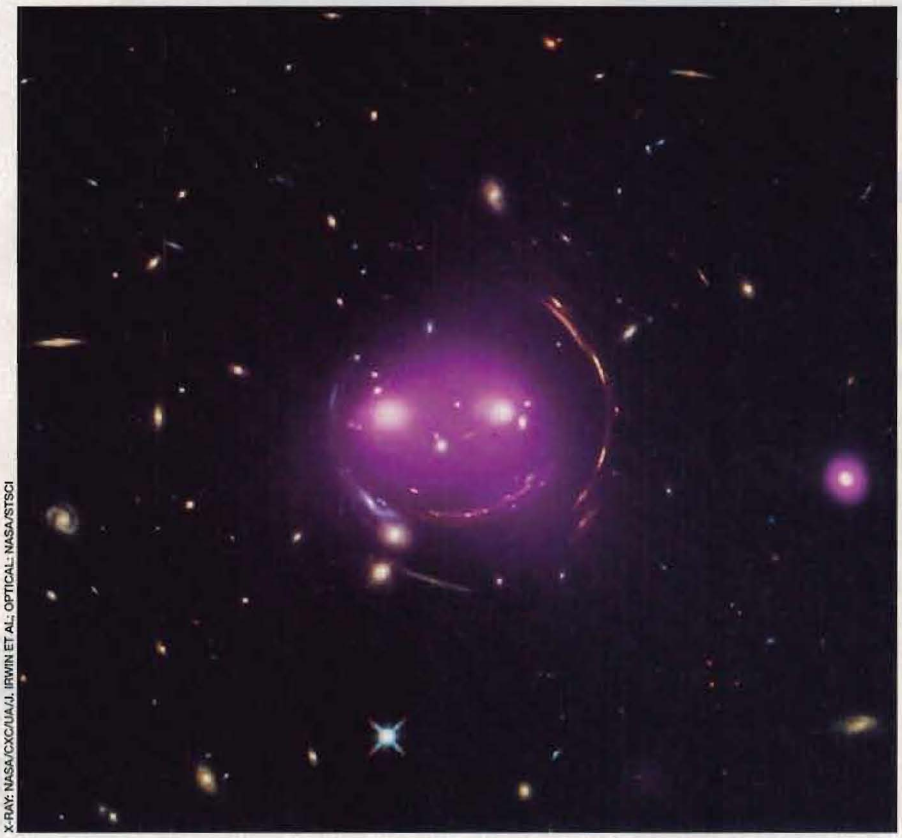
The Cheshire Cat

Light from far-flung galaxies can bend into a celestial grin.

There's always something delightful that catches my eye after the Sun has set: on one evening the artistic swoosh of a crescent moon, on another the striking pattern of stars that forms the Orion constellation, whose appearance in the northern hemisphere heralds the coming of winter. So, when looking up at the nighttime sky I often smile.

And the cosmos, I have learned, is smiling back...literally.

While searching through images collected by the Sloan Digital Sky Survey, astronomers from Great Britain, Russia, and Spain announced in 2009 that they had come across a familiar face in the direction of the constellation Ursa Major—that of the disappearing Cheshire Cat in Lewis Carroll's *Alice's Adventures in Wonderland.* The two "eyes" of the cat are giant elliptical galaxies, each the brightest member of a small group of galaxies. Both groups are situated some 4.6 billion light years away. NASA's Chandra X-ray Observatory more recently discovered that these two sparse clusters are, in fact, racing toward one another at around 300,000 miles per hour and will eventually merge about one billion years from now.



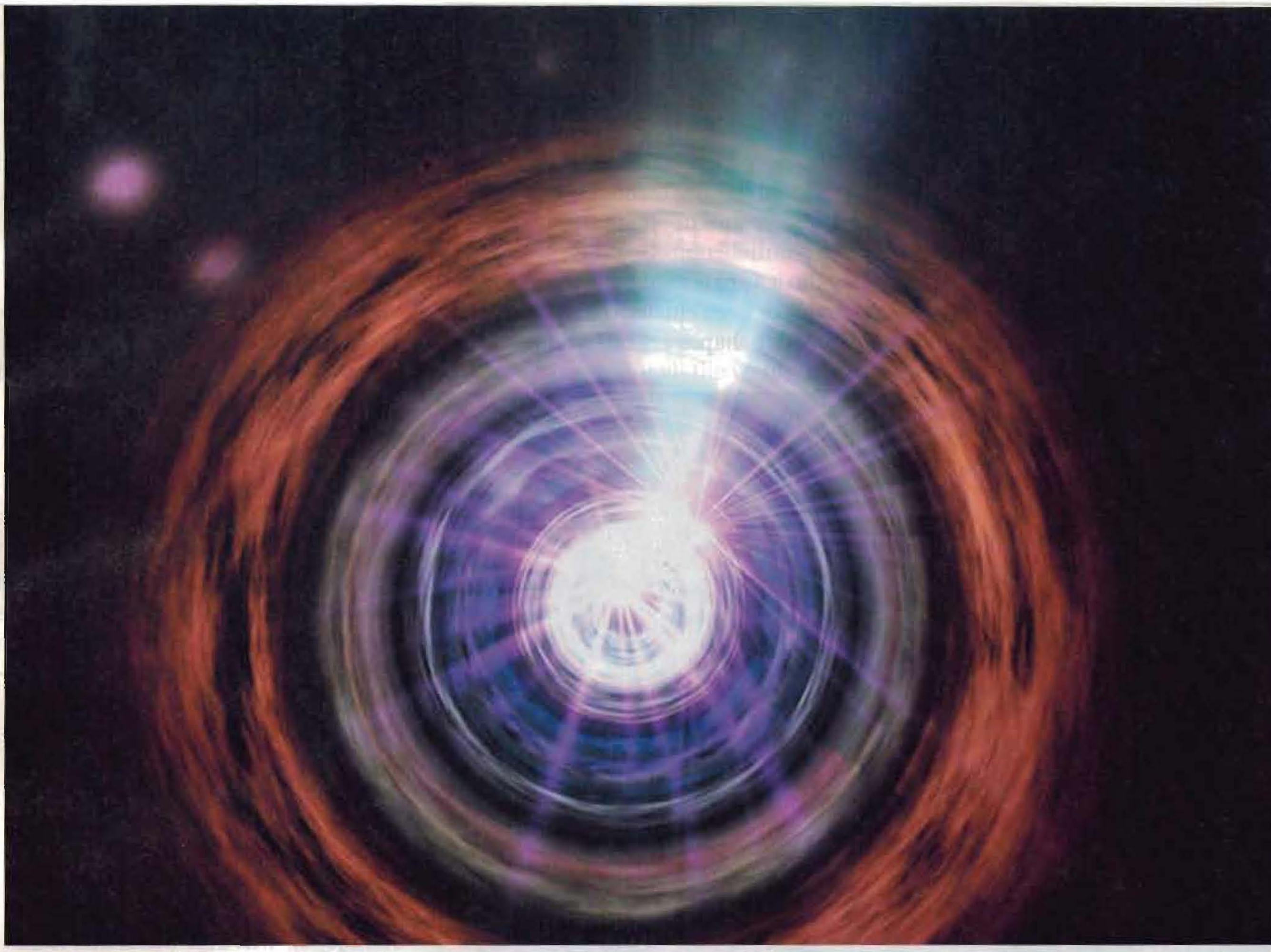
X-RAY: NASA/CXC/UA/J. IRWIN ET AL; OPTICAL: NASA/STSCI

This Cheshire cat image is a composite, blending an optical image with an X-ray image.

But what's most captivating about this celestial formation is its "grin," a lustrous smirk generated by the two elliptical galaxies and their surrounding matter. As the light waves from background galaxies farther out come upon the gravitational influence of all this matter in their journey through space, the distant light gets bent and stretched into long arcs. With a powerful enough telescope, you can see such smiles all over the celestial sky. The Cheshire Cat is only one of many examples of this funhouse effect that is fully explained by Einstein's general theory of relativity.

With his new gravitational theory, introduced in 1915, Einstein posited that space and time join up to form a palpable object, a sort of boundless rubber sheet (although in four dimensions). Masses, such as a star or planet, indent this flexible mat, curving space-time. With that image in mind, he predicted that a beam of starlight would noticeably shift as it passed by a massive celestial body, following the curved pathway. It was a prediction that thrust Einstein into the public eye: when astronomers, who were monitoring a 1919 solar eclipse, saw starlight graze the darkened Sun and get deflected by exactly the calculated amount, Einstein became world-famous overnight. "Lights All Askew in the Heavens...," blared the headline in *The New York Times*, "but Nobody Need Worry."

In this situation, the Sun had become the gravitational equivalent of an optical lens. Instead of glass deflecting the light rays, gravity was doing the job. It wasn't long before others wondered whether such "gravitational lensing" might be sighted farther out. In 1920 the British astronomer Arthur Eddington considered the possibility of seeing multiple images of a star, if that star were properly situated behind another stellar body. Although the physical principle is not the same, you might think of the star-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In the heart of an active galaxy (classified as a blazar), matter falling toward a supermassive black hole creates jets of particles traveling near the speed of light.

light as a stream of water that comes upon a rock and gets diverted into several streams on either side of the stone. Thus our eyes detect multiple images of the star, rather than just one. But in the end, Eddington figured that the effect would be so weak "as to make it impossible to detect it."

Four years later, the Russian physicist Orest Chwolson noted that if the distant star were aligned just right—precisely behind a star that acts as a gravitational lens—its light would spread out to form a ring that completely surrounds the lens. Einstein was already aware of these possibilities. As early as the spring of 1912, three years before he published his general theory of relativity, he carried out some calculations of gravitational lensing in his notebook and jotted down the possibility that a lens might not only create a double image of a star, but might also magnify the intensity of the star's light. However, he then dropped the subject.

Einstein didn't return to the problem until 1936, and then only after he was prodded by a young Czech electrical engineer and amateur scientist, who asked him to once again consider cosmic lensing. "Some time ago, [Rudi] W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request," wrote Einstein in his paper for the journal *Science* entitled "Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field." He went on to say it was "a most curious effect" but also concluded (like Eddington) that there was "no hope of observing this phenomenon directly," since it defied "the resolving power of our instruments." Privately, Einstein wrote the editor of *Science* that his findings had "little value, but it makes the poor guy [Mandl] happy."

But California Institute of Technology astronomer Fritz Zwicky thought otherwise. The following year in *Physical Review* he pointed out that "extragalactic *nebulae* [galaxies] offer a much better chance than *stars* for the observation of gravitational lens effects." Acting like a giant magnifying glass, the galactic lens would enable astronomers to "see [other] nebulae at distances greater than those ordinarily reached by even the greatest telescopes," wrote Zwicky. It was a prescient vision, but one that was not confirmed for another forty-two years.

In 1979, British astronomer Dennis Walsh was closely examining a photographic plate to locate the visible counterpart of a newly discovered radio source, 0957+561, when he noticed that the radio object's position coincided with *two* star-like bodies, not just one. Additional telescopic observations from the Kitt Peak National Observatory in Arizona confirmed that the cozy pair were quasars. The spectra of these quasars were nearly identical, which hinted that they were not simply the chance

NASA, ESA, AND JOHAN RICHARD (CALTECH, USA)

Thousands of individual galaxies make up Abell 2218, a rich galaxy cluster, which belongs to the constellation Draco, located 2.1 billion light-years from Earth. Astronomers rely on Abell 2218 as a kind of lens to see farther and gauge vast distances: the arcs and rings of light that are emitted serve as a kind of gravity-boosted telescope.

alignment of two separate objects (which often happens). A celestial object's spectrum is as distinctive and exclusive as a fingerprint or personal sample of DNA. The spectral matchup strongly suggested that Walsh was seeing the *same* quasar—the brilliant core of a young galaxy some 9 billion light years distant—but in duplicate.

Walsh and his colleagues reported their suspicion that a gravitational lens was at work, and further observations by other astronomers at the Palomar observatory in California confirmed that conjecture. The lens turned out to be a giant elliptical galaxy, a member of a rich cluster of galaxies located halfway between the quasar and Earth.

It wasn't long before astronomers uncovered many other cases of gravitational lensing throughout the celestial sky—and not just multiple images of pointlike objects. When entire galaxies are lensed by intervening galaxies or even clusters of galaxies, their broader shapes are often smeared into long arcs and rings. That's how the Cheshire Cat got its grin.

Gravitational lensing, however, has turned out to be far more than an amusing or pretty optical effect. Today it is one of astronomy's most valuable tools. The amount a light beam is deflected depends on the total mass of the gravitational lens. So, by carefully measuring the deflections, astronomers can "weigh" entire clusters of galaxies. Their results have confirmed that around 90 percent of the mass in these clusters is indeed composed of an unknown dark matter. Moreover, both the position and intensity of the arcs formed around the cluster of galaxies allow astronomers to map how this matter is distributed through and around the cluster. Such information is offering clues as to the true nature of dark matter.

And just as Zwicky forecast eight decades ago, gravitational lenses are magnifying the images of galaxies residing in the most distant regions of the universe, galaxies that would have been too small or faint to be seen with a telescope alone. All of these applications are helping astronomers trace the growth of galaxies and clusters of galaxies through time, to examine how cosmic structures have evolved and changed over the eons. "The vistas we uncover with this new gravitational telescope," writes astronomer Evalyn Gates in her book *Einstein's Telescope*, "will take us further than ever..., providing answers that may unlock the door into a deeper understanding of the fundamental nature of space, time, matter, and energy."

With improved technology, astronomers have also come to see individual celestial objects act as gravitational lenses, the enterprise that both Eddington and Einstein had deemed hopeless. Background stars in our Milky Way and in the Magellanic Clouds are seen to briefly magnify—microlens—due to dark objects passing in front of them. This is one way that astronomers have revealed the presence of both brown dwarf stars and extrasolar planets, objects too dim to be seen directly. Such an amazing accomplishment brings a smile to astronomers' faces—or a broad, mischievous grin.

***Marcia Bartusiak** is a professor in the MIT Graduate Program in Science Writing. Her latest book is* Black Hole: How an Idea Abandoned by Newtonians, Hated by Einstein, and Gambled on by Hawking Became Loved *(Yale University Press, 2015).*