COSMOLOGY

THE EMPTIEST PLACE IN SPACE

Efforts to explain a strange cold spot in the cosmos have led to the discovery of something even odder: a vast area with very little matter

By István Szapudi
To glimpse the oldest light in the universe, simply tune an old television between channels: the tiny specs dancing on the screen result from the antenna being bombarded relentlessly by photons that were emitted shortly after the big bang, some 13.8 billion years ago. These photons fly uniformly through space from all directions, with an average temperature of 2.7 kelvins (−455 degrees Fahrenheit), composing a cloud of radiation called the cosmic microwave background (CMB). Because these photons are so old, the familiar two-dimensional map of the CMB is often called a “baby picture” of the universe, providing a window back into the primordial conditions that created the cosmos we see around us today.

Our baby picture, however, has a few imperfections. Physicists like myself call them anomalies because they cannot be fully explained by our standard cosmological theories. The largest of these anomalies, first found in NASA’s Wilkinson Microwave Anisotropy Probe (WMAP) map of the CMB in 2004, is the “cold spot,” an area of the sky covering about 20 times the width of the full moon, where the ancient photons are unusually chilly. The cold spot is not unlike a beauty mark on our baby picture: for some, it is an ugly mole that breaks the majestic symmetry of the CMB; for others, it enhances the features of the universe and adds to the excitement. I am in the latter camp: I have always been fascinated with this CMB anomaly and what might account for it.

That puzzle has stimulated much discussion among scientists. One explanation might be that it arose by sheer chance, with no specific cause. But the odds of chance being the cause are low: about one in 200. Other possibilities range from the mundane to the fantastic—from problems with the instruments analyzing the cosmos to the suggestion that the cold region is a portal to another universe or hidden dimensions.

In 2007, by extrapolating from some known features of the cosmos, I and other astrophysicists hit on the idea that just such a cold spot might be expected to form if the cosmos contained a supervoid—a vast expanse of space relatively devoid of matter and galaxies—in the same region of the sky. This void would be the emptiest place in space, a rare gigantic wasteland amid relatively dense surroundings. The theory had enormous implications. If such a void did indeed exist and cause the cold spot in the way we imagined, the huge empty region might, for complex reasons, also provide proof for dark energy, the theorized culprit behind the accelerating expansion of the universe. Today my colleagues and I at the University of Hawaii have confirmed the void, and we are finding tantalizing clues that it could indeed account for the cold spot.

**CROSSING THROUGH A VOID**

Scientists came to the idea that a supervoid might exist and give rise to the cold spot by contemplating the way we think light interacts with smaller voids. The postulated supervoid would be extreme, but regular midsize voids—areas containing...
SCANS OF THE SKY by the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) on Maui helped astronomers identify an immense expanse of relatively empty space—a "supervoid"—that may explain an enigmatic cold spot in the universe's oldest light.

relatively few galaxies—are common in the universe. So are their opposites, clusters, which are large conglomerations of up to thousands of galaxies. Cosmologists think that the seeds of voids and clusters arose in the very early universe, when random quantum-mechanical processes caused matter to be slightly less dense in some parts of space and slightly more dense in others. The greater mass in the overdense regions yielded a stronger gravitational pull that drew more matter to them over time, pulling it away from the underdense locations. The former eventually grew into clusters, and the latter became voids.

Because voids have little matter, they act like hills on anything passing through them [see box on page 35]. As a particle moves into the void, away from the stronger gravitational pull of surrounding higher-density areas, it slows down like a ball rolling up a hill; once it starts to move out of the void toward the dense areas, it accelerates as if rolling down the hill. CMB photons behave similarly, although they do not change speed (the speed of light is always constant). Instead they change in energy, which is directly proportional to their temperature. As a photon enters a void, it climbs the hill and loses energy—that is, it cools down. Rolling down the hill on the other side, the photon regains its energy. Hence, it would arrive on the other side with the same temperature it started out with—if the universe were not expanding at an accelerating rate.

In the past two decades, though, scientists have discovered that the cosmos is not only expanding but that this expansion seems to be speeding up. Most cosmologists attribute the acceleration to dark energy, a putative kind of negative pressure throughout space that seems to be counteracting the inward pull of gravity. The acceleration of the universe adds a wrinkle to the hill scenario—from the perspective of our CMB photon, it means that while it crossed the void, the plain surrounding the hill effectively rose, so that the flat ground on the far side became higher than it was on the near side. As a result, the photon cannot regain all the energy it lost when it climbed the hill. The net effect is that CMB photons would lose energy when crossing a void. Consequently, we should see temperature dips on the microwave background near low-density regions. This phenomenon is called the integrated Sachs-Wolfe (ISW) effect. The effect also applies to superclusters, but in that case, photons would gain net energy when crossing vast areas with extra mass.

The ISW effect is expected to be tiny. Even for large voids, it would typically create temperature variations smaller than the average fluctuations in the CMB, which can vary by roughly one part in 10,000 because of slight differences in the density of the nascent universe when the light was released. But in the case of a truly huge void—a supervoid—the difference, we realized, might be enough to generate the cold spot. And if we could demonstrate that the supervoid existed and was the driving force behind the anomaly, we would do more than explain
the cold spot. We would also offer a smoking gun for dark energy because the ISW effect can occur only if dark energy is operating on the universe, accelerating its expansion.

**THE HUNT FOR A SUPERVOID**

Astronomers first began looking for a supervoid that overlapped with the cold spot in 2007. Detecting such a large structure is harder than it sounds. Most astronomical surveys produce 2-D pictures of the sky without telling us how far away the objects in the pictures lie. The galaxies we see could all be clumped together, or they could be widely spaced out along our line of sight. Astronomers must gather further information about each galaxy individually to try to estimate its distance—a laborious and often prohibitively expensive task.

In 2007 Lawrence Rudnick of the University of Minnesota and his collaborators were looking at the NRAO VLA Sky Survey (NVSS) catalog of galaxies in radio waves and found that a region of space approximately aligned with the cold spot has fewer galaxies than average. Although the NVSS did not contain any data on the specific distances to the galaxies in the survey, the astronomers knew that most NVSS galaxies are very far from us. Based on the data, they hypothesized that an extremely vast supervoid could produce the cold spot through the ISW effect might be present roughly 11 billion light-years away. One difficulty with this idea was that light reaching us now would have crossed through such a distant supervoid a long time ago—roughly eight billion years in the past. (It would not have been a full 11 billion years ago, because the universe has expanded to twice its size since the light was emitted.) At such an early cosmic epoch, dark energy would not have been as strong a force as it is today, and so the ISW effect might have been too slight to yield the cold spot.

Rudnick’s work, although it failed to turn up definitive evidence for a supervoid, nonetheless caught my attention. Along with Ben Granett and Mark Neyrinck, then a Ph.D. student and a postdoc, respectively, at the University of Hawaii, I conducted a statistical analysis to determine how often smaller features in the CMB—relatively warm or cool areas that were less extreme than the cold spot—appeared to overlap with smaller known clusters and voids in the universe, and we found that such overlaps were common. Even though none of these known structures could account for the cold spot, the results convinced us that the search for a supervoid that overlapped with the cold spot was not foolhardy and was worth continuing.

We then designed observations with the Canada-France-Hawaii telescope (CFHT) that targeted several small fields in the cold spot area and counted the number of galaxies in them. To our disappointment, when we made the observations in early 2010 we found no sign of a supervoid at the distance that Rudnick predicted. In fact, we could rule out the presence of a supervoid beyond distances of about three billion light-years. A similar search conducted by Malcolm Bremer of the University of Bristol in England and his collaborators yielded no results either.

At the same time, the statistical significance of the original paper by Rudnick was reevaluated by peers and turned out to be lower than thought. Thus, for a while it
2 HOW DOES THE SUPERVOID FIT IN?

In 2015 astronomers discovered a supervoid about three billion light-years from Earth that they think might explain the cold spot. To understand why the two might be connected, it helps to visualize the universe as a set of nested spheres. Space itself (inner sphere) is expanding outward, as is the point of origin of the CMB light (outer sphere), which was released about 13.8 billion years ago in the early universe. As this light traveled toward us, some of it crossed through the supervoid, where it might have lost energy and become colder because of the ISW effect. 3.

3 HOW DOES THE ISW EFFECT WORK?

When light crosses a supervoid, it acts like a ball rolling over a hill. Because the supervoid lacks mass, its gravitational pull is less than that of surrounding dense areas and would cause an object entering it to slow like a ball rolling up a hill. As the object came out of the void, it would speed up like a ball rolling down the hill. Light does not slow down or speed up (because the speed of light is constant), but it loses and gains energy, which is directly proportional to its temperature.

In a stable universe the light would lose and then gain the same amount of energy, coming out just as it started, but the accelerated expansion of the universe changes the game. Because the void and all of space grow larger as the light passes through, it is as if the plain surrounding the hill rose while the ball was crossing it, so the ground on the other side is higher than the floor at the beginning. Thus, the photons cannot regain all of the energy they lost, and they come out cooler than they were going in.
Searching for a Supervoid

To look for a supervoid that could explain the cold spot, astronomers analyzed a catalog of galaxies created by the Wide-field Infrared Survey Explorer (WISE) satellite, the Two Micron All Sky Survey (2MASS) and Pan-STARRS. This catalog showed them the positions of many galaxies across the sky, but they needed to know how far away those galaxies were, to determine if there was an empty spot in space. To assign distances, the researchers looked at the optical colors of each galaxy, which gave a rough estimation of how much its light had been “redshifted,” or pushed toward the red end of the electromagnetic spectrum. This effect is caused by the expansion of the universe—when space stretches while light is traveling through it, the wavelength of the light photons stretches, too. The greater the redshift of a galaxy, the farther it lies from Earth. Combining the positions of the galaxies on the sky with their estimated distances, the scientists created a three-dimensional map of the density of galaxies throughout space in the direction of the cold spot.

STACK FOR 3-D VIEW
The researchers created three slices of the universe showing the density of galaxies in three ranges: within a redshift of 0.09 (up to 1.24 billion light-years away), between a redshift of 0.11 and 0.14 (1.5 billion and 1.9 billion light-years), and between a redshift of 0.17 and 0.22 (2.3 billion to three billion light-years). The closest slice does not reveal a void, and the farthest seems to show a small void a bit too off-center to correspond with the cold spot, but the middle range reveals a large empty area mostly centered on the cold spot. The researchers had found their supervoid.

A LUCKY BREAK
Fortunately for me, within a few years I would be able to obtain new data. About the time I was saying good-bye to Granett and Neyrinck, the Institute for Astronomy at the University of Hawaii, my home base, finished constructing a new telescope: PSI, the initial observatory for the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS). It was exactly what I needed. Equipped with the world’s largest camera, with 1.4 gigapixels, the telescope is located at 10,000 feet above sea level on the volcano Haleakala on Maui.

In May 2010, in a consortium with several other universities, my colleagues and I started to map three quarters of the sky with PSI. I remember trying to convince Nick Kaiser, then the principal investigator of Pan-STARRS, that we should map the cold spot area before anything else once the instrument was turned on. Although that did not happen, the region was within the area that was to be surveyed in the telescope’s first few years, and the measurements I needed would come in little by little.
While we were eagerly awaiting these new data, I started working with then graduate student András Kovács to use the publicly available CMB observations from the Planck and WMAP satellites, along with a newly released galaxy data set based on observations in infrared light by NASA’sWide-field Infrared Survey Explorer (WISE) satellite to study the ISW effect and, if possible, to search for a supervoid.

Kovács visited me in Hawaii several times for a few months at a time, and during the summers I visited Budapest, where he was studying at Eötvös Loránd University. Otherwise, we had weekly teleconferences, and because of the 12-hour time delay between Honolulu and Budapest, we often had conversations that ran deep into the night in European time. During one of these early sessions, I asked him to find the largest low-density regions, or voids, in the WISE catalog of galaxies. A few days later he sent me an e-mail with images and coordinates of the biggest voids in the catalog. Reading his message, I immediately realized that the voids he found coincided with the same region of the sky where the cold spot is. I had not yet told Kovács of my interest in a link between a supervoid and the cold spot, and so the finding was doubly exciting to me: with Kovács not knowing to look for the cold spot connection, the finding could not have been biased by hope for evidence of a relation. Because WISE finds galaxies that are closer than those in the NVSS data set, this was the second clue that perhaps we should look for the supervoid nearby.

From this point, we worked for years to turn our initial clues into a discovery. We used a combined data set of galaxies from WISE, Pan-STARRS and the Two Micron All Sky Survey (2MASS), but we needed to assign distances to these galaxies. One way of measuring distance is to observe an object’s “redshift”—the amount that its light has been shifted toward the red side of the electromagnetic spectrum. The farther away a galaxy is, the faster it recedes from us, and the greater its redshift is. Although we did not have access to precise redshift measurements for our galaxies, we could estimate their approximate redshifts by analyzing their colors, comparing our guesses of a galaxy’s un-redshifted brightness in various color bands with what we observed.

Finally, we could assign a distance to each galaxy in the direction of the cold spot, and we created a series of tomographic slices—flat pictures of the universe corresponding to different distances from Earth. The first set of images looked like vertical slices of an apple, revealing a supervoid that is approximately spherical and growing toward its center. It turns out this giant void has been hiding very near us, about three billion light-years away, which is why it was so hard to discover.

In the next few months we looked over the statistics of our data and found that the evidence for the supervoid is overwhelmingly significant—in other words, we are extremely assured of the existence of a low-density region aligned with the cold spot. And this supervoid, in fact, is huge: 1.8 billion light-years across, making it possibly the largest structure ever identified by humanity. It is probably a very rare object—cosmological theories suggest there should be only a few more of these within our observable universe.

### UNDERSTANDING THE COLD SPOT

We had finally found our supervoid. We knew from our earlier study that voids and clusters have a measurable effect on the CMB, producing small cold and hot spots. And the supervoid we found was indeed aligned with the most significant of anomalies in the CMB. Puzzle solved, right?

Not quite. The mere presence of the supervoid and even its alignment with the region of the cold spot are not enough to definitively conclude that one causes the other. They could be lined up by chance. Our analysis, though, conservatively estimates that the possibility that the supervoid created the cold spot is 20,000 times more likely than the chance that it was just a coincidence.

We have a bigger problem, however. Although the supervoid is in the right place to explain the cold spot, it is not quite the right size. To explain why the cold spot is so much cooler than the average CMB temperature, the supervoid would need to be even larger than it seems to be, perhaps by a factor of two to four. This discrepancy is so hard to stomach that some scientists think the fact that the supervoid overlaps with the area of the cold spot is merely a fluke. They suggest we look for other explanations, such as the possibility that galaxies are releasing less radiation into space than we expect—a phenomenon that could mimic the ISW effect to some extent. Also, although our observations clearly prove the existence of the supervoid, we cannot be sure enough of its size, shape and position to make precise calculations about the effect it should have. In particular, if the shape of the supervoid is elongated toward us, or if several spherical voids are stacked next to one another in the direction of the cold spot (like a snowman), then the void could more easily explain its presence. Thus, we do not yet know how much of a difficulty the size of the supervoid poses for our theory.

We need more data. Already we are planning to repeat our study for the full area of the sky that has been mapped with PSI, rather than the initial partial section, using observations that scientists have additionally refined to reduce uncertainties. With this data set we can quantify the divergence between our measurements and theory to determine whether it necessitates modifying our thinking about the ISW effect and voids. It may be that this discrepancy is telling us something interesting. For instance, a class of alternative theories of gravity that diverge from general relativity has a unique signature that would appear only in voids, and if one of these turns out to be correct, the ISW mechanism may operate differently as well. And if our supervoid has offered up a hint of these theories, we may have an exciting opportunity to understand the universe on a deeper level than we currently know.

No matter what, the discovery of the supervoid stands to tell us something significant about physics—perhaps it is proof of the existence of dark energy, or maybe it reveals an even more surprising truth about how gravity operates. In coming years we should know more about the supervoid and thus the nature of the universe we live in.

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**From Our Archives**

Is the Universe Out of Tune? Glenn D. Starkman and Dominik J. Schwarz; August 2005.