 by Christopher Crockett

Specks Betwe

When thinking about cosmic wonders, we often sweep interstellar dust under the rug. But these humble particles play a huge role in the universe.

At the mere mention of dust in space, Karl Gordon's face lights up. "I love talking about interstellar dust," he says.

Interstellar dust, a cornucopia of microscopic flecks of solid debris, doesn't usually grab headlines. It's not as flashy as a supernova nor as exotic as an alien planet. It doesn't blaze like a star, nor does it bend the imagination like a supermassive black hole.

But for Gordon (Space Telescope Science Institute) and many other astrophysicists, interstellar dust is a fascinating puzzle, a playground of physics that ties together the cosmos.

"When I started, people were like, 'Ohh, you're going to have to find something else — I mean, you can't make a career out of this,'" Gordon recalls. "It turns out, you can!"

Gordon spends much of his time measuring the light from stars, both in our galaxy and others, not in order to understand the stars themselves but to learn more about the stuff between them. To him, "the stars are like a nuisance parameter," astronomer Julianne Dalcanton (University of Washington) said of Gordon during her lecture at the January 2019 meeting of the American Astronomical Society. "It's pretty adorable."

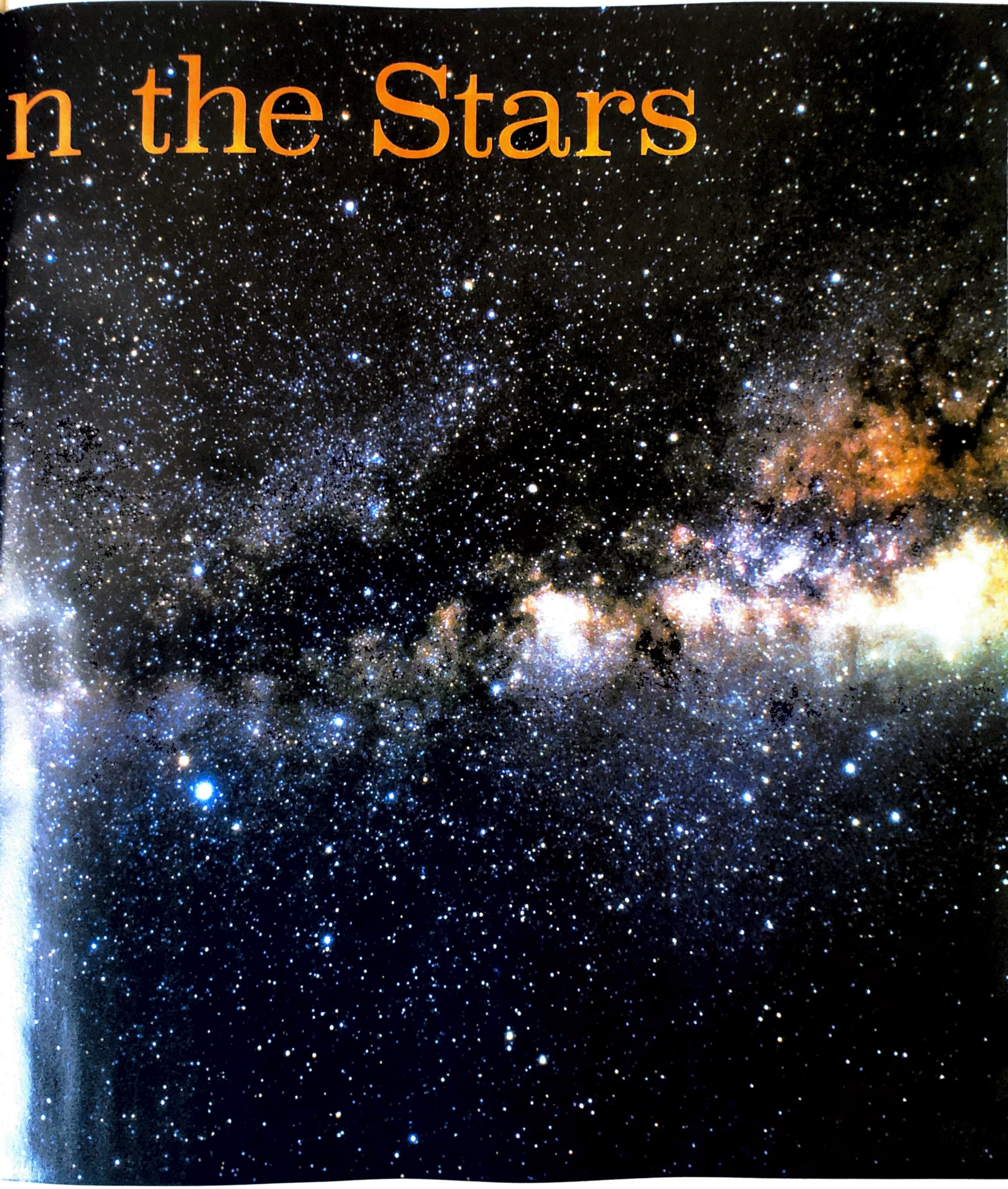
Although dust usually lurks in the background, it's essential for understanding the universe. Despite making up just a tiny fraction of all matter in the cosmos, dust helps build stellar nurseries, ferries newly forged elements from one generation of stars to the next, and lays the seeds for newborn planets. It's also a tool. Astronomers use dust to map the magnetic architecture of our galaxy, pinpoint the locations of nearby star-forming regions, and unlock secrets about the peak of cosmic star formation 10 billion years ago.

Even astronomers who aren't drawn to dust's vibrant life need to know something about its properties. Nearly every sightline to any celestial object, within or beyond our galaxy, runs through dust that interferes with observations. There

▶ **THE GREAT RIFT** Dusty clouds in the Milky Way block starlight from reaching Earth, creating the illusion of regions of empty space along our galaxy's disk.

AKIRA FUJII

n the Stars



are few cosmic investigations that interstellar dust doesn't impact in at least one way.

"If you want to understand everything from the space between stars, the envelopes of stars, [to] the circumstellar disks that form planets around stars, you need to know what the dust is doing," says astronomer Sarah Sadavoy (Queen's University, Canada). "You need to know what it is. You need to know how it's changing. And by doing that, you'll be able to better understand the universe and everything that you're using to probe it."

The Milky Way's disk, by mass (baryonic)

91%	9%	0.09%
Stars	Gas	Dust

Fine Galactic Soot

In early evenings, during late summer, the plane of the Milky Way arcs overhead, divided by a dark lane known as the Great Rift: a band made of clouds of solid particles in space that block distant starlight.

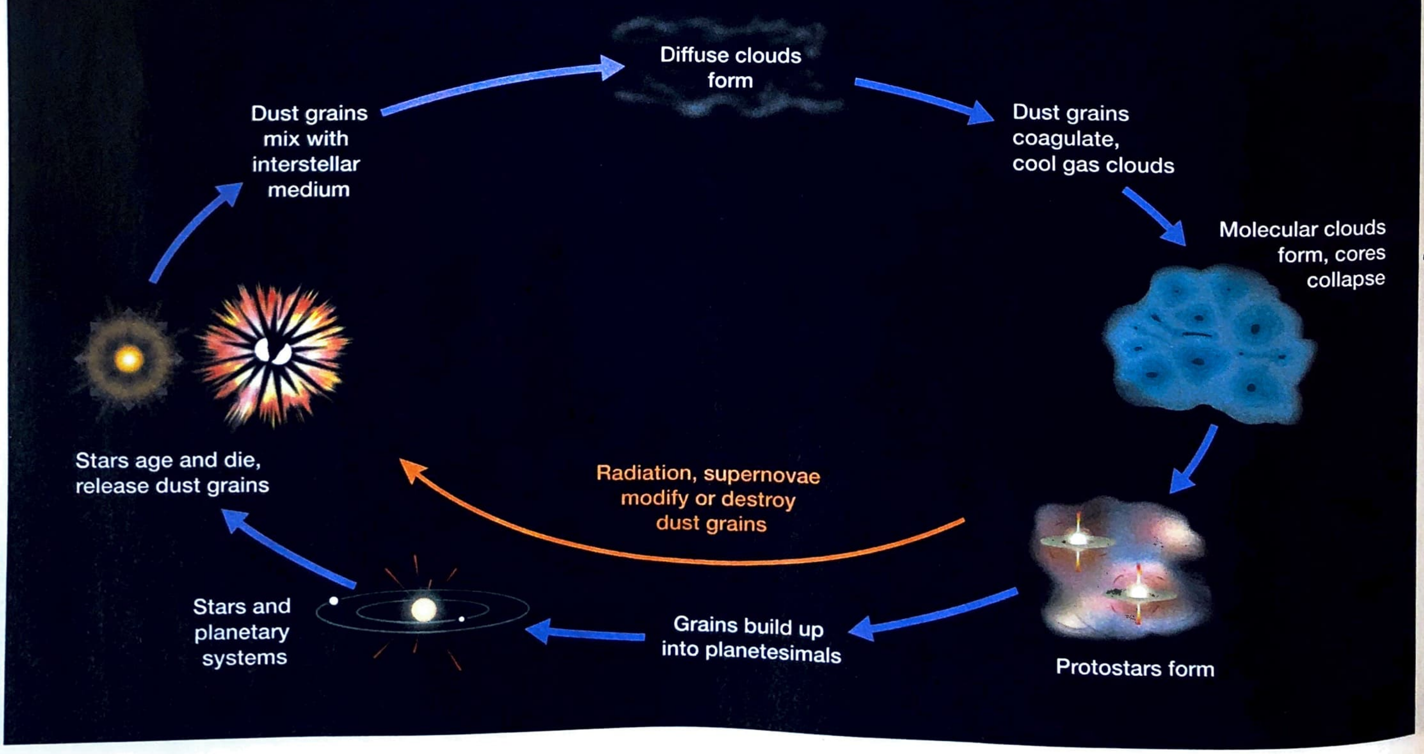
Long ago, people saw stories in those dark patches. To the Quechua people of Peru, these *dark cloud constellations* represented a menagerie of animals that recirculated Earth's water. The Milky Way was a great celestial river, and when it rose above the horizon, the animals ferried water into the sky and released it as rain.

Quechuan storytellers weren't far from the truth: The particles in those clouds do circulate elements through the cosmos and are even a breeding ground for molecules of water. Today, astronomers know the clouds are loaded with solid grains, which appear not only in the Great Rift but in many cosmic environments, including the exhaust from dying stars, the majestic wakes of supernovae, and nascent planetary systems.

Interstellar dust grains are microscopic, ranging roughly in size from several to a few hundred nanometers, giving them the consistency of fine soot. Some grains are made of silicates, minerals composed of mostly silicon and oxygen. Carbonaceous, or carbon-laden, dust comes in an assortment of types, ranging from organic macromolecules to nuggets of graphite or diamond. Some dust grains are also coated with a veneer of frozen water and other types of ice.

Astronomers learned this largely by observing how clouds of dust filter starlight. The size, composition, and shape of dust particles affect how they absorb and scatter particular wavelengths of light. Dust also offers up some secrets via thermal emission of infrared light or, for the coldest dust just 30 or so degrees above absolute zero, emission at submillime-

THE LIFE CYCLE OF INTERSTELLAR DUST



DUST TEXTURE: SERGIO34 / SHUTTERSTOCK.COM ter and millimeter wavelengths, a part of the electromagnetic spectrum only detectable with equipment akin to radio dishes (*S&T:* Aug. 2020, p. 12).

"Our only way of understanding what interstellar dust is will be through making inferences from what we see and asking ourselves, what kind of physical stuff can make the world look the way it does," says dust researcher Bruce Draine (Princeton).

Interstellar dust clouds didn't get a modern astronomical treatment until the early 1900s. Astronomer E. E. Barnard, along with his contemporary Max Wolf, spent the first decades of the 20th century photographing some of these dark regions and concluded that something in space was blocking the light from more distant stars.

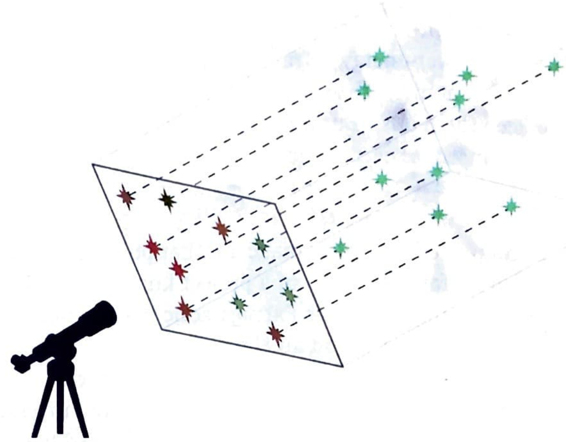
"I did not at first believe in these dark obscuring masses," he wrote in the January 1919 *Astrophysical Journal*. "[My] own photographs convinced me . . . that many of these markings were not simply due to an actual want of stars, but were really obscuring bodies nearer to us than the distant stars."

About a decade later, astronomer Robert Trumpler took a stab at dissecting these obscuring bodies. "Most likely the absorbing medium is made up of particles of various sizes, ranging from free electrons and atoms, small solid dust particles, up to larger meteoritic bodies," he wrote in the October 1930 *Publications of the Astronomical Society of the Pacific*.

Trumpler came to that conclusion after noting that stars in distant clusters were dimmer than expected for their distance and appeared redder than nearby stars of the same spectral type. He attributed this to fine particles permeating the galaxy that, much like Earth's atmosphere, preferentially scatter blue light and let red light pass. This reddening effect is a cornerstone of dust research to this day.

While astronomers quibble over the details, most agree that interstellar dust comes from dying stars, which spend their lives forging progressively heavier elements in their cores. At the end of their lives, stars release those elements into space via stellar winds (in the case of most stars) or powerful supernova explosions (for the stellar heavyweights). Regardless of how these atoms get into space, once there, and far enough from a star's radiation, they find each other and start to link up, forming ever larger conglomerates.

Dust contributes little to the overall mass of a galaxy. By



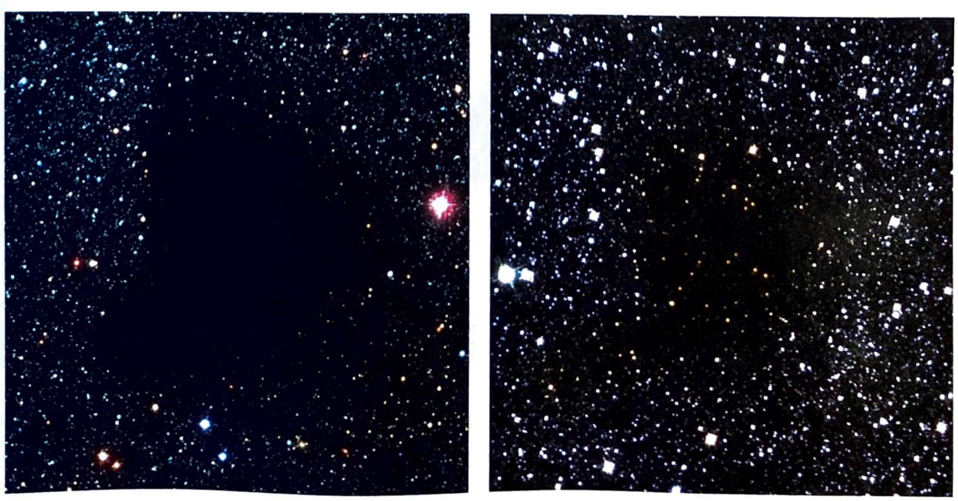
▲ **INTERSTELLAR REDDENING** Dust suffusing the galaxy preferentially scatters short wavelengths, making distant stars appear redder than they actually are. The farther or dustier the distance, the redder the star looks.

mass, the Milky Way is composed mostly of stars and dark matter, plus a relatively small amount of gas. The total mass of the dust is just one percent that of the gas. And yet it plays an outsized role in the formation of stars and planets.

"Without dust, it would be a very different galaxy and universe," Gordon says.

Stars form in dense pockets of gas, which gravitationally attract even more gas, building up to a critical mass, at which point the gas collapses and, eventually, ignites nuclear fusion. But to get under way, this birthing process needs a cloud of mostly hydrogen molecules, and it needs that cloud to be cold. If the gas is hot, the molecules whiz around too much for gravity to take hold.

Dust takes care of both requirements. It provides a surface upon which a hydrogen atom can alight, pair up with another hydrogen atom, and then pop off as a full-fledged molecule. (That surface is also critical for interstellar chemistry: The terrain provides a place where, for example, hydrogen atoms can meet up with hydroxide ions to form water molecules.) Dust is also an efficient cooling agent. It shields molecular



▶ **BARNARD 68** One of the dark nebulae that E. E. Barnard cataloged, B68 is a Bok globule: a dark, dusty cloud that blocks starlight at visible and near-infrared wavelengths *(left)*. But when seen in longer infrared wavelengths *(right)*, the cloud largely disappears and background stars shine through.

INTERSTELLAR REDDENING: GREGG DINDERMAN / S&T; DARK NEBULA: ESO (2) gas by absorbing high-energy ultraviolet light from stars and reradiating it as lower-energy infrared light.

For some astronomers, the inner life of dust is more than enough to keep them busy. But for others, dust is a means to an end — or sometimes even a decoy.

The Dirty Windshield of the Milky Way

In 2014, a group of cosmologists made a rather public blunder.

With much fanfare, the team of a project known as BICEP (Background Imaging of Cosmic Extragalactic Polarization) announced that they had found an elusive signal from the dawn of time. Imprinted on the cosmic microwave background, a remnant glow from a time when the entire universe was roughly 3000° Celsius (5000°F), this signal looked like one that theorists expected to have been made by the echoes of gravitational waves released during the epoch of inflation, a passing moment when the universe ballooned in size roughly a trillionth of a trillionth of a trillionth of a second after the Big Bang.

Early the following year, they issued a mea culpa: The signal was actually from interstellar dust in the Milky Way (*S&T:* May 2015, p. 12).

The BICEP flop was a cautionary tale on many fronts. But one takeaway is that if astronomers want to understand the cosmos, they need to understand the dust they're peering through to see it.

"One of the grad students I worked with in the past said, you have to look through the dirty windshield of the Milky Way to see anything," says Gordon.

Sadavoy echoes that sentiment. "Depending on what science you're interested in, you need to know the dust in order to disentangle it from your actual observations," she says.

But dust can also be a powerful tool for revealing things that might otherwise remain unseen. Take the BICEP saga: Dust grains filtered background light in a way that mimicked the sought-after signal because of how the grains aligned themselves to the magnetic field of the Milky Way. That means astronomers can use the grains to trace out our galaxy's magnetic structure.

In 1949, astronomers John Hall and Alfred Mikesell (U.S. Naval Observatory) discovered that some starlight was polarized: The lateral oscillation of the light waves had a preferred direction. What's more, they saw a connection between the degree of polarization and the amount of reddening. Raw starlight is not polarized, but dust was filtering it in such a way that preferentially allowed light waves of a particular orientation to pass.

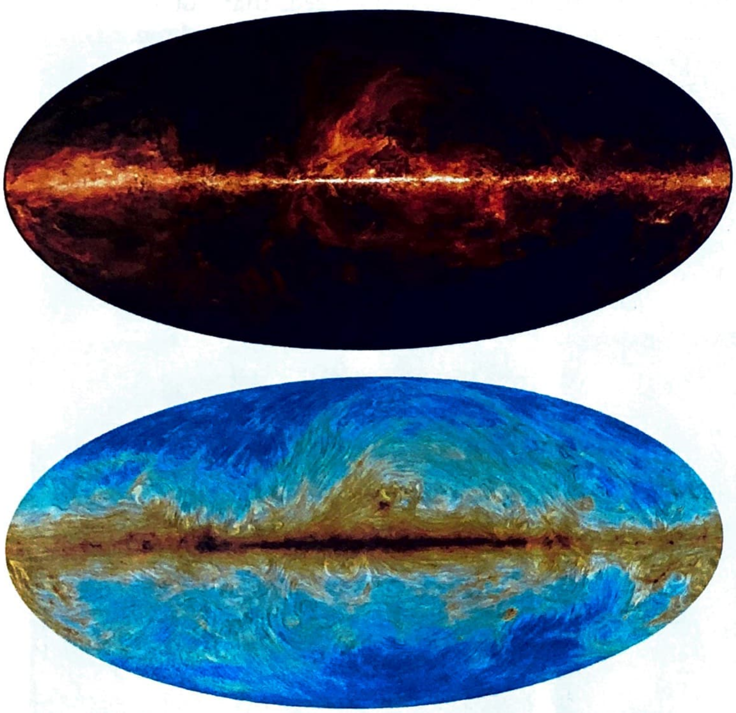
Since then, astronomers have recorded polarized light from all directions in the sky, which in turn provides sweeping vistas of our galaxy's magnetic field. Other galaxies have benefited from a similar treatment. In January, astronomer Enrique Lopez-Rodriguez (NASA Ames Research Center) and colleagues observed the polarized glow emitted by warm dust in the nearby galaxy NGC 1068 and found that the galaxy's magnetic field closely follows its spiral arms.

Astronomers are also using dust to discover large-scale structures in our galactic backyard. In January, João Alves (University of Vienna, Austria) and colleagues reported that many nearby star-forming regions are linked together in a coherent gaseous thread they dubbed the Radcliffe Wave, which bobs in and out of the plane of our galaxy (*S&T:* May 2020, p. 9).

Interstellar dust was the key to finding this structure. The team identified hundreds of stars in front of, within, and behind dust clouds that permeate these stellar nurseries. They then combined measurements of how much dust dims and reddens the starlight with new precision distances to those stars from the Gaia satellite to trace the 3D structure of the dust. Astronomers have started using the same idea to revise the distances to spiral arms in the Milky Way.

This 3D dust mapping is a relatively new tool, says Sadavoy. Historically, the distance to dust has been difficult to pinpoint, because background starlight reveals all the dust along a line of sight. "This 3D dust modeling tries to remove that challenge by taking into account the fact that you're not just measuring the extinction of stars, but you're measuring extinction of stars as a function of distance," she says. "That's the new element that we didn't really have before."

But using dust as a tool isn't just limited to the Milky Way and its neighbors. Dust is also revealing secrets about the peak of cosmic star formation, which occurred roughly 10 billion years ago.



▲ **MAGNETIC TRACER** Astronomers have used the emission from polarized dust grains *(top)* seen with the European Planck spacecraft to map the Milky Way's magnetic field *(bottom)*.

ESA / THE PLANCK COLLABORATION (2)

Dusty Star-Forming Factories

According to astronomer Caitlin Casey (University of Texas, Austin), the history of the universe as told through starlight is biased and inaccurate. The light from cold dust in distant galaxies, however, has revealed a major hidden character in this drama.

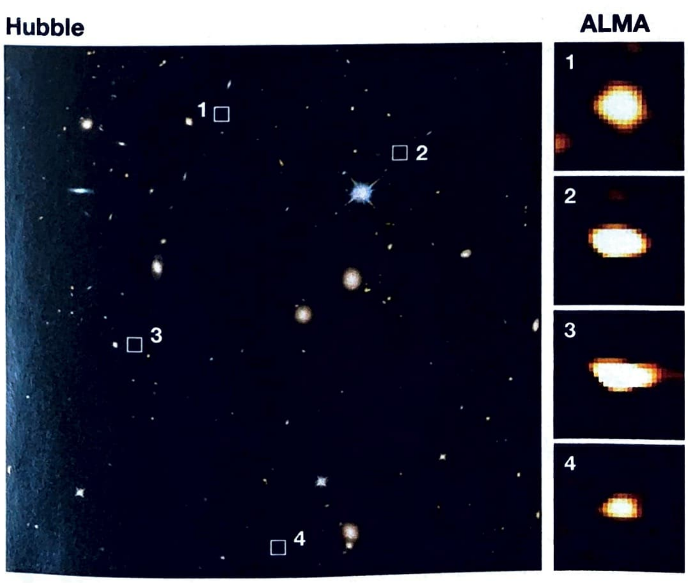
About 3 billion to 4 billion years after the Big Bang, the universe was populated with galaxies enshrouded in so much dust that no starlight escaped. Instead, the galaxies blazed with dustlight, the thermal glow of interstellar dust heated by massive crops of bright young stars.

The dust goes hand-in-hand with the star formation, says Casey. Lots of new stars leads to lots of dust production as the most massive stars quickly age and die off.

With no starlight to guide them, astronomers can only find and study these early galaxies with telescopes sensitive to millimeter-wavelength light, which is emitted from brutally cold gas and dust. At these wavelengths, the galaxies glow brightly, whereas in images taken with visible light, they are nowhere to be seen.

Dustlight has revealed that these obscured galaxies dominated star formation at a time when the universe, on average, produced stars at a rate 10 times greater than it does today. Whereas the Milky Way churns out a few new stars per annum, Casey says, these stellar factories produced roughly 5,000 stars every year. And they have few modern parallels. While there are a handful of comparable galaxies in the modern universe, "they were a thousand-fold more common 10 billion years ago," Casey says.

It's not yet clear why these galaxies were so prolific. One potential culprit is galaxy collisions, says Casey, but it's uncertain how widespread such mergers were 10 billion years ago. It's also possible that galaxies back in the day simply had more gas to fuel star formation than their modern counterparts. This mystery is driving Casey and colleagues to peer farther out into space — and hence further back in time — to pinpoint when these galaxies and their dust first came on the cosmic scene.



▲ **HIDDEN GALAXIES** Sections of sky that appear empty to the Hubble Space Telescope contain massive, star-forming galaxies when viewed in the submillimeter range with the Atacama Large Millimeter/submillimeter Array in Chile.

80%

Fraction of starlight in the Milky Way that is absorbed and reradiated by dust

"We don't know if these are still very common in the universe's first billion years," she says. She envisions that, eventually, "we'll start to see galaxies that have very high star formation rates but that are not yet polluted by dust." Such galaxies would have existed in a brief window of time after the first generation of stars switched on but before enough of them (or the second wave that followed) dirtied up those pristine infant galaxies.

Pinpointing the onset of cosmic dust could thus provide a window into the fleeting yet foundational epoch of the first stars. The first stars had to have formed without any help from dust. With no dust to cool the primordial gas, the first stars were likely bloated monstrosities hundreds of times more massive than the Sun.

But getting that galaxy census will require instruments that can survey large swaths of the sky at once, something that current millimeter-wavelength facilities aren't good at doing. A new camera under development for the Large Millimeter Telescope in Mexico, she says, will be a boon to this kind of work and enable astronomers to continue a century of investigations that have shown dust to be crucial in moving elements around the cosmos and helping stars form.

Only dust could have revealed this hidden chapter in the story of cosmic evolution. It's a lesson that astronomers continue to be reminded of, from the far reaches of the visible universe to familiar stellar nurseries sitting right next door: Interstellar dust is everywhere, and to ignore it is to risk missing a vital element of where we come from.

■ **CHRISTOPHER CROCKETT** is a freelance science journalist living in Arlington, Virginia. Formerly an astronomer, he found research to be too tedious and now writes about it instead.