VIOLENT BIRTH

LIGHTING UP THE UNIVERSE IS A ROUGH-AND-TUMBLE BUSINESS.

BY ADAM FRANK

OF THE STARS

The Orion nebula is one of the closest star-forming regions, 1,500 light-years away. Turbulent interactions inside such gas clouds may hold the key to our galaxy's destiny and play a role in explaining the origin of our solar system.

When most people gaze up on a clear, dark night, they are struck by how many stars there are. Astronomers have an opposite reaction: They marvel at the stars' amazing scarcity. Considering the total amount of raw material available in our galaxy for star formation, there should be up to 10 times the current count. Why, then, does the night sky not blaze with starlight?

It is not a bad thing that there are so few stars; quite the opposite. Stars burn gas, mostly hydrogen. All of the hydrogen gas in the universe was formed during the Big Bang, some 13.8 billion years ago. Each galaxy possesses a finite portion of this primordial fuel, and there is no way to make any more of it. If there were more stars, galaxies would burn through their fuel reserves more quickly and would shine more briefly before lapsing into eternal darkness.

Understanding how stars form and why they are so hard to make does much more than just foretell our far-off cosmic future. Star birth also explains where the atoms in our bodies come from and why the universe looks the way it does today. As astronomer John Bally of the University of Colorado puts it, "Star formation is the single most important process for determining the fate and evolution of normal matter in the universe." Yet until recently, the

details of how stars are born were literally shrouded in mystery: Stars form within dense clouds of dust and gas that block visible light.

Now astronomers are parting the veil with telescopes that detect infrared light, the kind of light central to terrestrial night-vision systems. "Seeing in infrared light is important because the diminution of visible light from inside a dusty cloud can be enormous," says Judy Pipher, a professor of observational and experimental astronomy at the University of Rochester in New York. "This is not a problem when you use an infrared camera because at those longer wavelengths the cloud will be a million times more transparent."

The picture of star formation given to us by infrared telescopes is one of unexpected violence, and it is this violence that is the key to understanding why there are so few stars. The birth of one disrupts the formation of others nearby, limiting the rate at which raw hydrogen can be assembled into shining stars.

Efforts to spy on the star-birth process got a huge boost with NASA's launch of the Spitzer Space Telescope in 2003. Pipher, considered by many to be the mother of infrared astronomy, worked for 20 years with collaborators William Forrest and Dan Watson to develop the detectors that form the heart of this 2,000-pound floating observatory.

Spitzer does not orbit Earth but trails behind us in space, following Earth's orbit around the sun at a distance of about 56 million miles. Spitzer was sent so far out because its delicate infrared-sensitive instruments must be kept at a frigid temperature just above absolute zero, and it is easier to maintain that temperature by operating far from the heat that radiates from the surface of our planet.

Spitzer's new views of stellar nurseries as places of chaos and turbulence contrast sharply with astronomers' old preconceptions. In the absence of the direct view provided by infrared telescopes, scientists spent the bulk of the last century building beautiful theories of individual gas clouds collapsing gracefully under their own gravity to form individual stars. The basic model of star formation was mapped out by British astrophysicist Sir James Jeans a little over 100 years ago. Jeans began with a large cloud of interstellar gas whose inward pull of gravity perfectly balanced the outward push of pressure from its own internal heat. Jeans found that this

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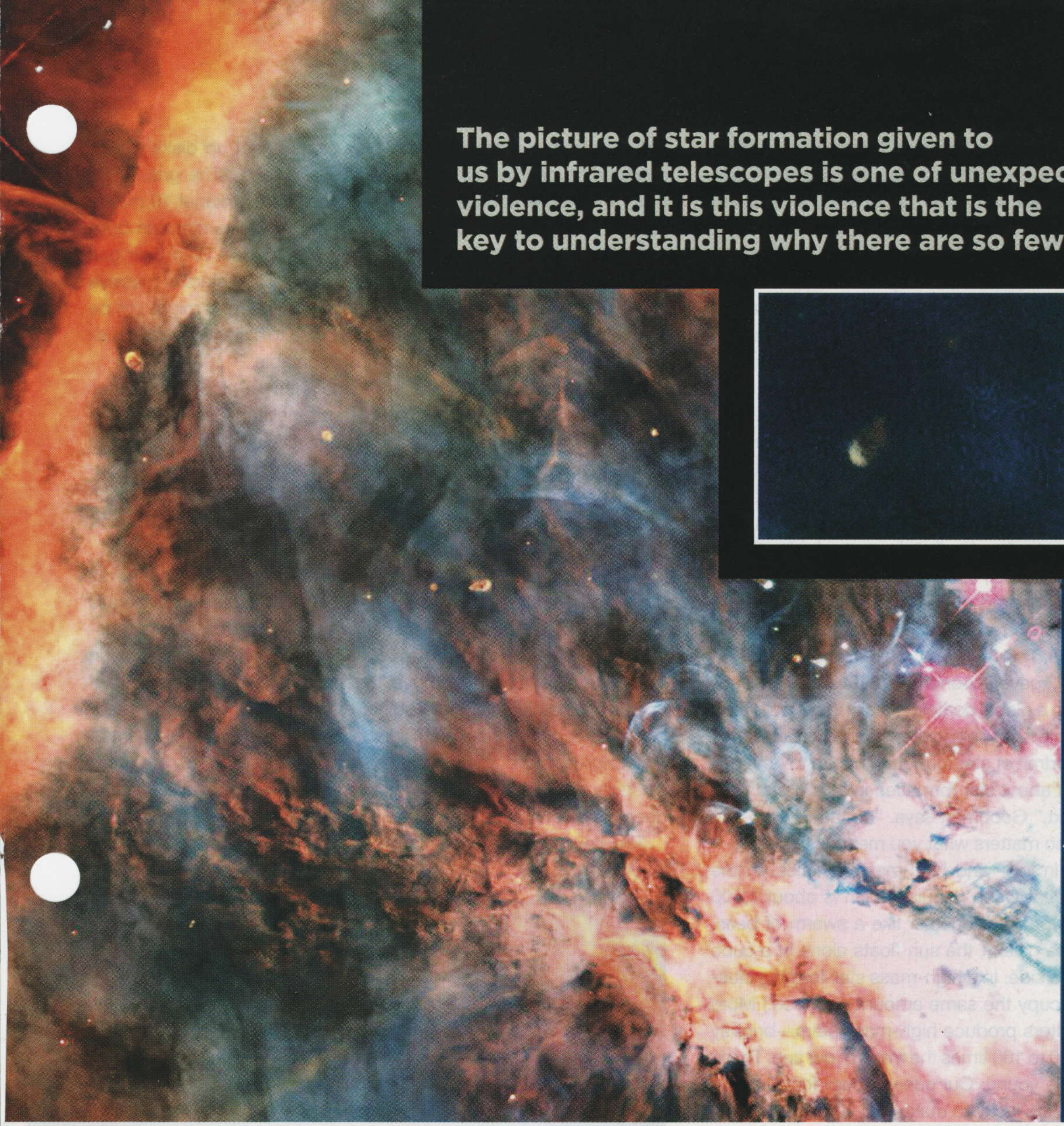


Far left: Young stars in the Orion nebula emerge from hiding in this superposition of infrared images from the Spitzer Space Telescope and visible-light images from the Hubble Space Telescope. Near left: In this Hubble close-up of the Orion nebula, nascent stars still surrounded by cocoons of gas (inset) can be seen.

balance was unstable. With just a nudge—from, say, the remnants of a supernova shock wave—gravity would win the tug-of-war and start the cloud's collapsing in on itself. At the center of the cloud, matter would pile up to densities and temperatures that (scientists later realized) were high enough to allow hydrogen atoms to fuse into helium. When fusion began, a star was born.

Most of the 20th century was spent filling in the details of Jeans's story. "You begin with single stars because they are simple," says Héctor Arce, an astrophysicist at Yale University. "They are kind of a theorist's dream." These early models paid scant attention to the way infant stars might influence each other. "Before we could understand how neighbors affect individual star formation," explains Arce's former thesis advisor, Alyssa Goodman of the Harvard-Smithsonian Center for Astrophysics, "we had to understand the evolution of stars in isolation. That was pretty complicated in itself."

During the 1980s and 1990s, Spitzer's less sophisticated predecessors put astronomers on the trail of a more holistic model of star formation. From hard-won infrared images, a story much more complex than Jeans's emerged about the birth of stars and planets. Star formation, those first pictures hinted, is distinctly a family affair—with all the turbulence, chaos, and tumult that implies.

Astronomers realized that spinning disks of gas always form around the nucleus of a new star, feeding it matter and serving as an incubator for the development of planets. The disks form because of the natural rotation of the original gas clouds. Just as a spinning ice-skater who pulls her arms inward will increase the speed of her spin, gas in a collapsing cloud will rotate more quickly until it naturally forms a spinning disk. If interstellar magnetic fields thread the cloud, then they, too, will be carried downward with the collapsing, spinning gas. The twisting magnetic fields will act as drive belts, tapping the enormous energy of the spinning disk to launch powerful jets of gas along the axis of the disk and back out into space.

These jets are remarkably long lived, driving 10 light-years or more across the star-forming environment. The discovery of jets pushing away from dust-shrouded protostars at hundreds of miles per second was the first hint to astronomers that star formation was a far more chaotic process than they had envisioned.

Over the past couple of decades, intense effort in both theory and observation allowed astronomers to develop a coherent, consistent picture of how single stars were born that included gas disks and jets. But researchers knew their story was still woefully incomplete because it did not take into account how one star's formation might affect another's. "The problem," Goodman explains, "is that you need to see into the entire cloud where many stars are forming at once. But the clouds are dense, and they extend over large chunks of the sky. You need new instruments, and you have to be systematic if you really want to understand what is going on."

Spitzer was built, in part, to answer these needs.

With Spitzer's three-foot-wide infrared eye, astronomers can see deep into the youngest stellar nurseries where stars are just beginning to form. They can see protostellar disks taking shape and pushing their jets out into space, and they have worked to integrate the new data with results from optical and radio telescopes (radio waves, millimeter wavelengths in particular, can penetrate the dust and gas too). Combining radio and infrared observations, researchers like Goodman and Arce created high-resolution, multiwavelength images of entire star-forming clouds. This multiyear, multi-institution project, called the Complete Survey, gave astronomers the view they needed to study star formation in a global context. Finally they could map out the detailed nature of interactions between infant stars and their environment, and a true portrait of star formation began to emerge.

"You really have to think about star formation in a kind of urban, suburban, and rural context," Goodman says. "It matters who you are born close to, and it also matters what you mean by 'close.'"

Stellar nurseries come in low- and high-mass varieties. In the high-mass kind, like the great Orion nebula, which is about 1,500 light-years away, stars are packed together like a swarm of bees. (In our neighborhood of the galaxy, the sun floats alone in a cube about three light-years on a side. In a high-mass star-forming cluster, thousands of stars occupy the same amount of space.) More important, high-mass clusters produce high-mass stars—brightly burning nuclear furnaces 10 to 100 times the mass of our sun. These behemoths live fast and die young. Our sun will burn for 10 billion years, but high-mass stars are lucky to make it to 10 million. "Massive stars have a huge impact on star formation," Bally says. "They emit powerful winds and a lot of ultraviolet radiation." The winds and UV light tear apart the surrounding gas, carving vast, glowing "blisters" that disrupt the cloud. This turmoil can inhibit other stars from forming—or promote star birth in other regions.

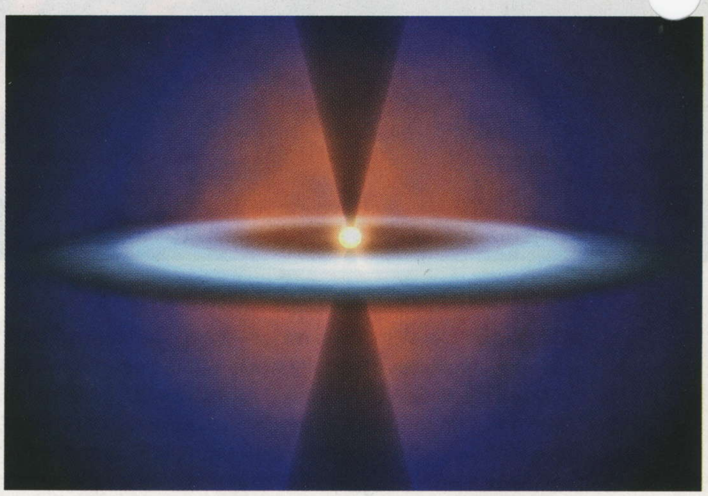
Only over the past decade have astronomers come to understand how common and significant the feedback between stars and their stellar nurseries can be. "There is a kind of self-regulation going on," Bally says. "The stars that form can change their own star-forming environment." The Pillars of Creation in the Eagle nebula (pictured in one of the most famous images captured by the Hubble Space Telescope) are one clear example of this feedback. Like the dense rock spires that form from erosion in a windblown desert, the gaseous pillars in the Eagle nebula have been shaped and compressed by the stellar winds and energetic ultraviolet light from the nebula's massive stars. Spitzer images of the Eagle nebula show that this compression is in turn triggering the formation of new stars within the pillars.

The complex environment in which a star forms affects the creation of planets, too. In fact, the effect of massive stars on the disks around infant stars—where planets arise—can be deadly. "The UV radiation from a massive star will ionize and heat up disks of gas surrounding nearby low-mass stars," Bally says. "The gas in the disks will then evaporate into space. It can take a planet 10 million years to form, but the UV radiation from a massive star can burn away the outer part of a disk in just 10,000 years." With their gas depleted, it may be impossible for the disks around stars in massive clusters to form giant planets like Jupiter or Saturn. It might still be possible for an Earth-like world to form close to a star where the disk is undisturbed, but that point remains debatable.

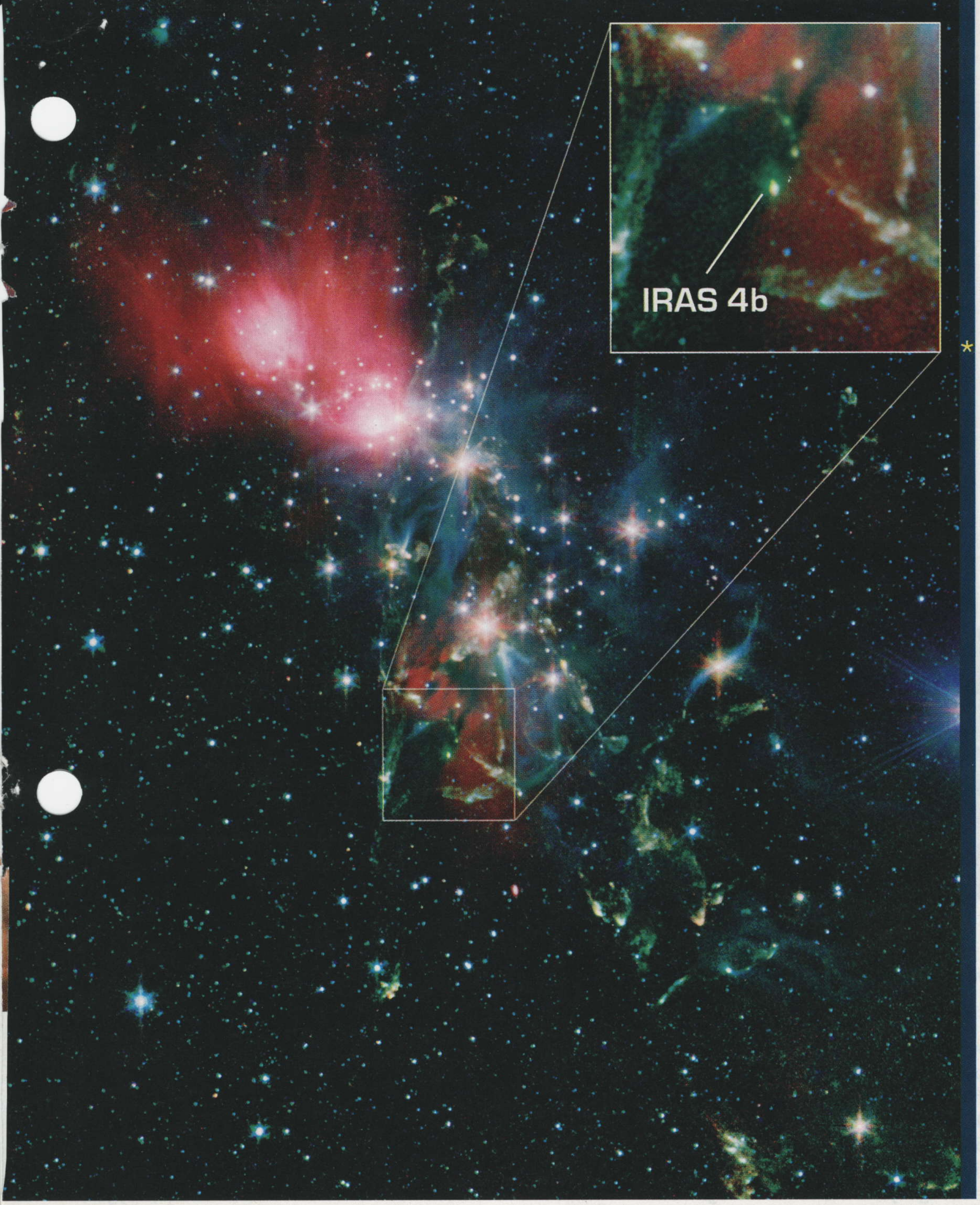
Massive stars can also cause havoc within a cloud when they die. At the end of its life, a massive star inevitably explodes as a supernova. This dumps apocalyptic quantities of energy into the surroundings: A supernova can briefly outshine an entire galaxy. Supernovas also create all the elements heavier than iron. With such short lifetimes, massive stars expire close to where they were born, often still within the star-forming region where they began.

Some astronomers have argued that the formation of our sun was triggered by a blast wave from a nearby stellar explosion. "There is strong evidence that our own solar system was born near a massive star that went supernova," Bally says. "Even if our formation wasn't triggered by a supernova, the presence of decay products of certain radioactive elements points to a supernova perhaps seeding the already formed young solar system with enriched elements." This implies that our star was born near the edge of a high-mass cluster—close enough to feel the effects of a supernova, but not so deep inside that our protoplanetary disk was shredded.

The havoc of star-formation feedback is not confined to high-



mass clusters. Low-mass clusters like NGC 1333 (a nebula and stellar nursery about 1,000 light-years away) contains only hundreds, rather than thousands, of stars. Even though no massive stars form in such clusters, the stars there all produce protostellar jets from their accompanying disks, and these, too, can play a dramatic role in shaping a cluster's fate. Spitzer images of NGC 1333 and other low-mass clusters show them threaded with graceful arcs of jet material that extend from one side of these stellar nurseries to the other. In low-mass clusters, feedback from the jets may play the same disruptive role as do winds and UV radiation from big stars in high-mass clusters. Unfortunately, we do not yet have enough infor-



Far left: When stars are born, leftover material forms a rotating disk that orbits the star. As surrounding gas and dust collapse into the disk, some material is ejected above and below, forming powerful jets that disrupt the formation of other stars. Near left: A Spitzer Space Telescope image of wisps in NGC 1333, a star-forming region about 1,000 light-years from Earth. Able to peer through dust and gas, Spitzer captured the infant star IRAS 4b and the protoplanetary disk that surrounds it.

mation to say whether most stars in the galaxy were formed in high-mass or low-mass clusters. If we knew the answer, we could move closer to estimating how many solar systems like our own exist.

The combined effects of jets, winds, radiation, and supernova explosions show that nature may enforce a kind of celestial family planning. Stars can beget other stars, but they can also shut down the birthing process. "We can see the jets from different stars interacting with each other," Arce says. "Those outflows can either trigger the formation of new stars or disperse gas that would have been part of the star-formation process."

The impact of this stellar birth control is still hotly debated, however. Some astronomers believe that such internal processes are not the key players in inhibiting star formation. They say factors external to the cluster, such as shearing forces produced by the galaxy's rotation, disrupt the cluster more intensely and prevent stars from forming. But images from Spitzer have provided stunningly beautiful evidence to support the case for internal processes. Recent computer simulations have shown how hundreds of jets can act as hypersonic swizzle sticks stirring a cluster's gas into turbulent motion that inhibits new stars from forming. And new studies give added weight to the idea of stellar feedback. "With

Near right: The Eagle nebula, about 7,000 light-years away, is home to one of the most famous star-forming regions, known as the Pillars of Creation. Far right: A closer view of one of the pillars reveals that these formations are being sculpted and eroded by harsh radiation from recently formed stars.

If galaxies raced through their fuel reserves, creating lots of first-generation stars early on, few stars with rocky planets would be born later. The odds for life would be much worse. Earth might very well not even exist.

the Complete Survey we nearly tripled the number of outflows we could see impinging on the cloud," Goodman says.

As astronomers have investigated the feedback mechanisms that operate in high- and low-mass clusters, there remains a mystery related to the biggest potential star-forming regions of all. Both low- and high-mass clusters form within larger complexes of gas and dust called giant molecular clouds. Some of these clouds are dominated by high-mass clusters, others by low-mass clusters, and some have both. A typical cluster will extend across a few light-years. Its parent cloud can stretch across 300 light-years and contain enough matter to make a million stars. But a million stars do not form. Instead, star formation across a giant molecular cloud is a rather anemic process, and relatively few stellar nurseries arise. Only 10 percent of the mass of the cloud, on average, is converted through gravitational collapse into stars. The rest of it never collapses and eventually disperses into the tenuous interstellar medium throughout the galaxy. What is preventing the vast clouds from collapsing under their own weight?

Some astronomers believe the answer rests with the powerful magnetic fields that are known to thread the clouds. Others think galactic shock waves that ripple through them keep the bulk of their gas from collapsing. Still others say the stellar feedback that astronomers see operating in high- and low-mass clusters is sufficiently powerful to disrupt even the much larger molecular clouds.

"You have to ask why only 10 percent of the cloud turns into stars," Bally says. "But we know that star formation adds energy to the system through winds, radiation, and jets. The supernova blast waves, of course, just add insult to injury."

"If all these stars create turbulence," Goodman says, "then that turbulence acts like a kind of heat that keeps the cloud inflated."

The mechanism that prevents giant molecular clouds from collapsing—whatever it may be—has a lot to do with why we exist in the first place. Stars are factories that convert lightweight elements into heavier atoms. These atoms include carbon, oxygen, nitrogen, and all the other elements that are essential for life as we know it. When a star dies, this material is cast into space. When later generations of stars form, some of that material congeals into rocky planets like Earth. If galaxies raced through their fuel reserves, creating lots of first-generation stars early on, few stars with rocky planets would be born later. The odds for life would be much worse. Earth might very well not even exist.

By looking out to star-forming nurseries across the galaxy, astronomers have shown us something innate and strangely familiar about the birth of our own star and planet. Psychologists know that in human families the role of siblings can be just as important as that of parents. Thanks to the Spitzer telescope, the same might now be said of the heavens. ■