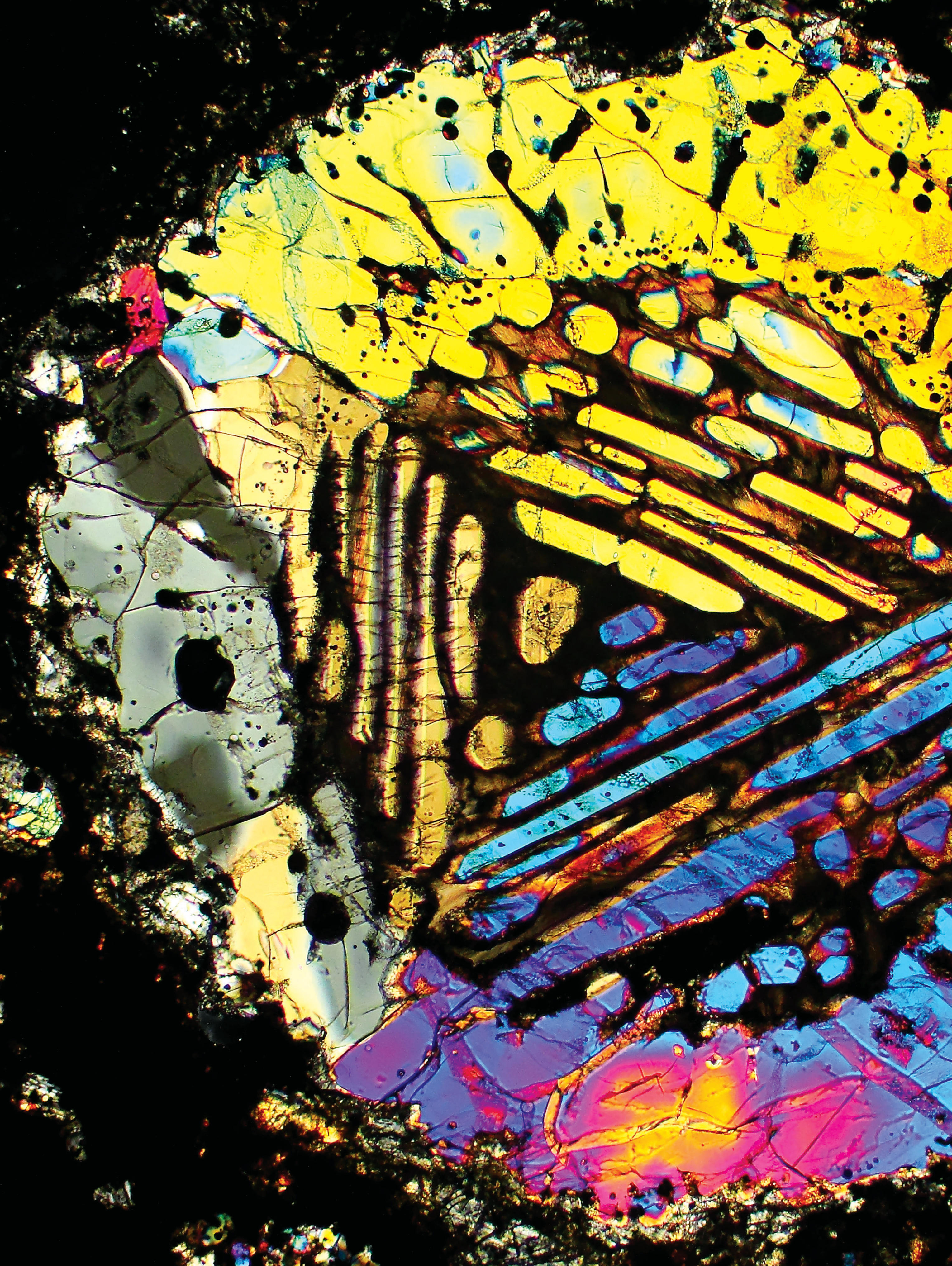

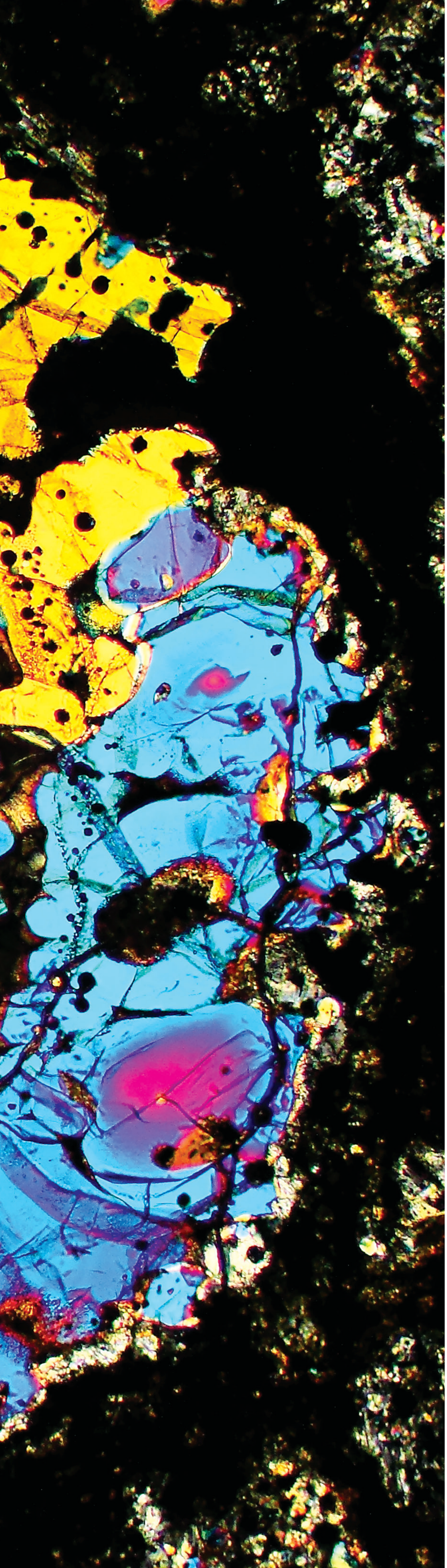

The Curious Science of Chondrules

PLANETARY SCIENCE

With material from the asteroid Ryugu, scientists may finally discover the origin of these enigmatic objects—and what they tell us about the birth of the solar system

By Jonathan O'Callaghan

THE TOASTER-SIZED CAPSULE HIT OUR ATMOSPHERE AT 12 KILOMETERS per second, enduring temperatures of 3,000 degrees Celsius during its fiery descent before deploying a parachute to slow its velocity. It continued to fall until it finally reached terra firma in the Australian outback. Within hours teams of scientists located the capsule's landing site with radar and rushed via helicopter to retrieve it. Onboard were pieces of an asteroid, the biggest such haul in history, captured millions of kilometers from Earth and returned safely to our planet.

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This event, the climax of the Japanese space agency JAXA's Hayabusa2 mission to the asteroid Ryugu, took place, in local time, on Sunday, December 6, 2020. It marked only the second time (the first being its predecessor, the Hayabusa mission, which launched in 2003) that a spacecraft has carried pieces of an asteroid back to Earth. With these samples, scientists hope to answer difficult questions about the history of our solar system and our own planet. How old are asteroids like Ryugu? How much water and organic material do they contain? And could they have first brought the raw ingredients for life to Earth billions of years ago?

While most groups of Ryugu researchers grapple with these outsized questions, a more rarefied cadre will be preoccupied with another, deceptively smaller matter: whether or not Hayabusa2's samples contain an intriguing ingredient of nearly all known meteorites. So far no one has been able to explain this ingredient's origins, yet the ramifications of doing so are tremendous. It may reveal to us not just some nebulous history of the solar system but also never before seen details of the process by which our sun's retinue of planets formed. In our understanding of how Earth—any planet in the cosmos, in fact—came to be, there may be nothing as important as the mystery of the chondrule.

Chondrules are small, seedlike rocks measuring up to just a few millimeters across and are thought to have formed some 4.5 billion years ago, shortly after the birth of our solar system. From there they became embedded in larger rocks, called chondrites, which make up the majority of the roughly 60,000 meteorites that humans have discovered throughout recorded history.

"Chondrules are everywhere," says Fred Ciesla, a planetary scientist at the University of Chicago. Even so, scientists have been unable to agree on how they formed for almost two centuries. Some think they were by-products of planet formation; others posit they were the seeds of planet formation itself. Either way, the menu of chondrule creation scenarios is vast, ranging from lightning-fused dust to colliding chunks of protoplanets to giant, gas-heating shock waves rippling through the primordial cloud of material that surrounded our newborn sun.

Understanding chondrule formation could, in other words, reveal our solar system's earliest moments. And now, with fresh or prospective results from missions such as Hayabusa2 as well as other avenues of research, chondrule-obsessed scientists are on the cusp of answering the long-standing question of where they—and perhaps we—came from. "They are stained-glass windows to the earliest time period of the solar system," says Harold Connolly, a cosmochemist and chondrule expert at Rowan University. "They are witnesses to processes that operated in the early solar system. The question is, What did they witness?"

DROPLETS OF FIRE

IN 1802 British chemist Edward Howard was one of the first scientists to recognize chondrules as "rounded globules" in meteorites. Their name, given later by German mineralogist Gustav Rose and Austrian mineralogist Gustav Tschermak, originates from the Greek *chóndros* ("grains") and the German *kleine kugeln* ("small balls"). In 1877 British scientist Henry Sorby would characterize them in greater detail, describing chondrules as "droplets of fiery rain," molten globules that condensed around the sun, although then, as now, no one knew exactly how they formed.

The broad outlines of our solar system's genesis are clearer. This creation story, which scientists have assembled through decades of observation and modeling, begins more than 4.5 billion years ago, when dust and gas from a giant molecular cloud gravitationally collapsed to create a protostar that would become our sun.

PRECEDING PAGES: JEFF HODGES

CHONDRULES make up most of the material in a slice of "Barratta," a 203-kilogram ordinary chondrite that fell in New South Wales, Australia.

MATTEO CHINELLATO *Alamy Stock Photo*

This protosun was surrounded by a spinning disk of gas and dust. Within this disk, a mix of gravity, aerodynamics and electrostatic force caused grains of dust to stick together, forming larger and larger agglomerations—such as planetesimals, the kilometer-scale building blocks of planets—and within a few million years the planetesimals coalesced into planets. These worlds gradually settled into the familiar forms and orbits we know today. But if the outlines of this story are clear, the details remain mysterious. Chondrules appear in the opening chapters, somewhere amid the leap from dust to planetesimals. How do you get from microscopic motes to entire worlds thousands of kilometers across?

Chondrules are essentially rocks within rocks. They appear as rounded flecks in chondritic meteorites. Some are visible to the naked eye, whereas others can be seen only under a microscope. It is difficult to overstate just how abundant chondrules are: Despite the fact that none are known to have survived the process of incorporation into planets, they are very common off-world, often constituting the bulk of material within chondrite meteorites. Some chondrites are so packed with chondrules they look almost like a conglomeration of beads.

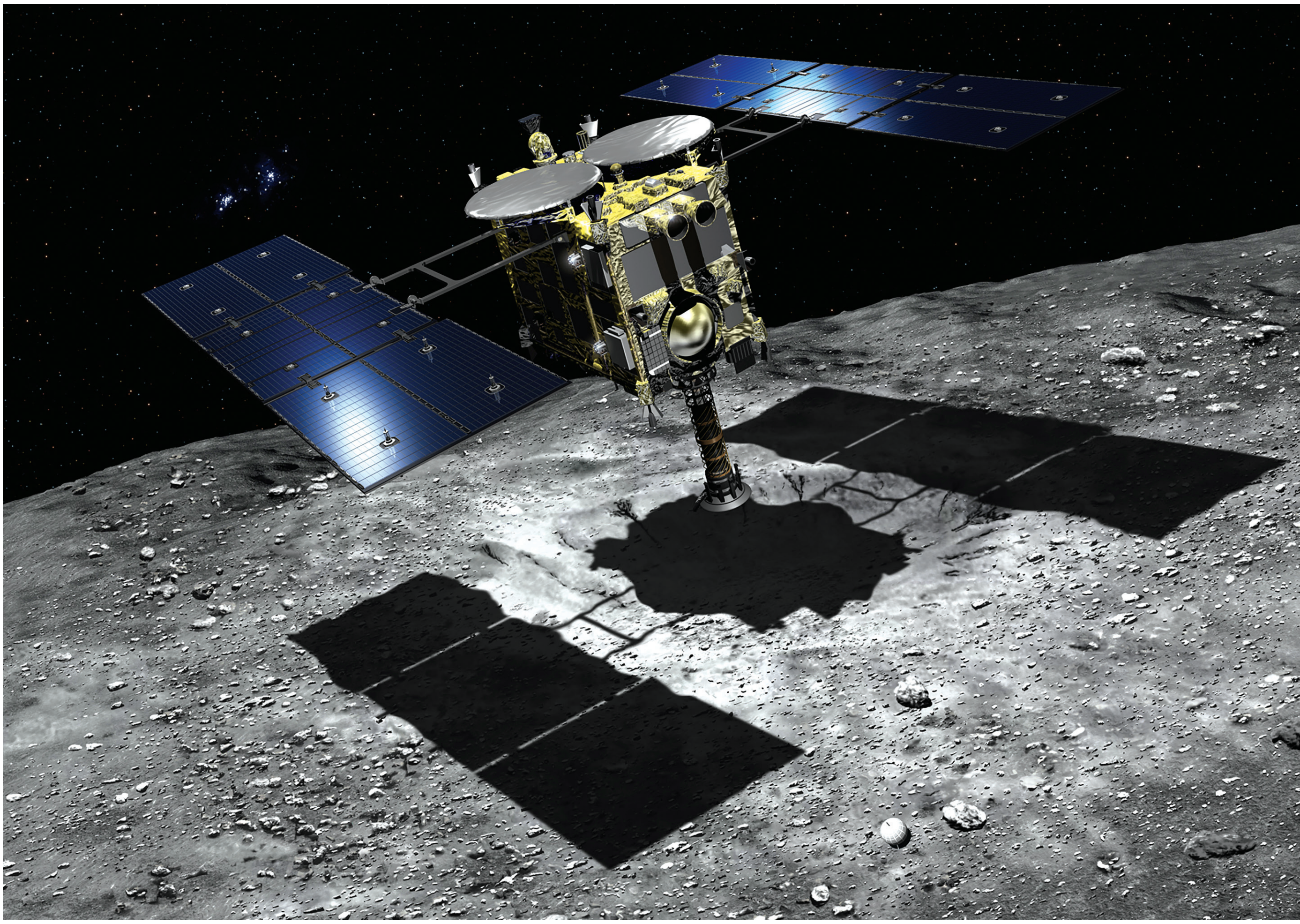
Made of minerals such as olivine and pyroxene and sometimes glass, chondrules themselves come in a variety of shapes, sizes and compositions. They often contain a glittering array of crystals. Scientists can date their formation to a window of a few million years, circa 4.567 billion years ago, by measuring the abundance of aluminum 26, a short-lived radioactive isotope they contain. That chronology makes chondrules the second-oldest recognizable objects in our solar system, after calcium-aluminum-rich inclusions (CAIs), specks of white in meteorites that are thought to have formed one million to three million years earlier by condensing out of the gas that surrounded our young sun.

There are many classes of chondrites. Ordinary chondrites, for example, are full of chondrules and account for more than nine out of every 10 chondrule-containing space rocks. Carbonaceous chondrites, which account for about 4 percent of all chondrites, typically have a high abundance of carbon; the most carbon-rich ones are thought to have formed in the outer solar system. A subgroup called CI chondrites possesses only microscopic chondrules because larger ones were weathered away by liquid water that once flowed through the parent body. And CB chondrites hold the distinction of being the only type of chondrite for which there is near-universal agreement on how they formed. "These are a group that we think formed during one giant impact," says Sara Russell, a planetary scientist at the Natural History Museum in London. That pinned-down provenance makes them "kind of magical."

As for the exact origins of all the other chondrite varieties? Those remain anyone's guess. "It's frustrating, but it's also kind of fun that we don't know," Russell says. "They're obviously telling us about some ubiquitous, super important process about how our solar system formed. We just have to work out what that is."

AN IMPOSSIBLE PROBLEM

IN 2000, at the Lunar and Planetary Science Conference in Houston, a stunned audience watched as John A.



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HAYABUSA2, seen here in an artist's rendition, recovered potentially chondrule-rich material from the asteroid Ryugu in July 2019 for later return to Earth.

Wood, then at Harvard University and one of the most revered scientists in meteoritics, appeared to admit defeat in understanding the origin of chondrules. Like many before him, Wood became fascinated by chondrules at first sight. "[These] little balls of stone were so charming and interesting and mysterious that I just got seduced by them," he says. But he was frustrated at the lack of progress that had been made. "We still don't understand what the meteorites are telling us, and sometimes I wonder if we ever will," he wrote in a summary of his speech. A few years later, facing a lack of funding, he opted to retire, turning his attentions to oil painting and spending time with his wife. "I quit science cold turkey," Wood says.

The speech was a shock to many. "He basically said he'd wasted his entire life working on chondrules because it was an impossible problem to solve," says Conel Alexander, a cosmochemist at the Carnegie Institution for Science in Washington, D.C. "That got a lot of people pretty upset." Larry Nittler, also a cosmochemist at Carnegie, who was in the audience, says he "actually stood up" to defend chondrule research. "I said, 'I'm still excited about these incredible rocks from space,'" he recalls. "I don't think I've gotten as much attention or praise for anything I've done in my career. The whole room erupted in applause."

Wood's pessimism is understandable. After all, space scientists have managed to definitively solve a wealth of seemingly intractable mysteries. They have teased apart the first moments of the universe's existence, discovered worlds around other stars, observed gravitational waves and captured images of a black hole. Against such achievements, the stubborn enigma of the lowly chondrule seems to shrink even smaller than its already niche status. Today there are, the joke goes, as many theories about chondrule formation as there are chondrule scientists themselves—and tomorrow there will inevitably be more.

The problem of chondrules has from the start been intergenerational, inspiring one cohort after another to try tackling the issue, with varying success. The main problem is finding a model that can explain all the different, diverse properties of chondrules. "There are no models that tick all the boxes," Alexander says. For chondrules to form, dust must have been heated to temperatures of up to 2,000 degrees C by some process in the early solar system, before rapidly cooling over just days or even hours. This process, whatever it was, most likely occurred throughout the solar system; that seems to be the only way to account for the large abundance of chondrules found in chondrites on Earth. The telltale rings of accumulated dust found in the centers of chondrules suggest that they must also have drifted for a time through the dusty environs around our newly coalescing sun.

Most chondrule scientists fall into one of two camps. The first believes chondrules were among the earliest solid objects to appear in the solar system, forming directly from the solar nebula—the cloud of dust and gas that surrounded our young sun. This would make chondrules a key stepping-stone from minuscule dust to larger kilometer-sized planetesimals. The second camp believes that chondrules were not among the first solids to form but actually arose after planetesimals—perhaps even after the planets themselves. They were, in this view, by-products of the planet formation process rather than an active part of it.

Within the first camp, one idea is that gravitational instabilities in the disk of dust and gas around our sun resulted in "shock fronts" that fused some of the dust into chondrules. "If you look at a picture of a galaxy, you see spiral arms spiraling round, and the same thing would have happened in the protoplanetary disk," says Rhian Jones, a cosmochemist at the University of Manchester in England. "And you can produce shock fronts associated with those density differences between the clumpy arms and the gas."

The more radical nebula-lightning model, meanwhile, proposes that friction between dust and gas particles around the sun sparked immense discharges of electricity that fused this dust into chondrules—although it is not clear how such lightning would be produced. Some models propose chondrule creation factories emerging from sheets of electric current trapped by huge magnetic fields within the spinning protoplanetary disk. Such "hotspots" could have been tens or hundreds of thousands of kilometers across and would have melted dust grains to churn out the primordial globules.

In the other camp, whose members argue that chondrules formed after the planetesimals, one of the more prominent models is called impact jetting. Here planetesimals would collide at high velocities, creating the necessary heat to produce chondrules. "It essentially squirts out some molten material that could break up into droplets," says Brandon Johnson, a planetary scientist at Purdue University. A variant of this, called splashing, would have involved collisions between molten objects at lower velocities, releasing droplets into space that solidified into chondrules.

The nebula-shock model, meanwhile, posits that Mars-sized planetary embryos moving through the nebula could act like boats sailing through water, fusing dust into chondrules. "As it's moving through the gas at supersonic speeds, it drives a bow shock," says Steven Desch, an astrophysicist at Arizona State University. "The chondrule precursors, this dust, are heated by entering this compressed hot gas and are processed by it."

Other ideas include radiative heating, a relatively new inclusion in some models that suggests planetesimals flying low over molten bodies could have been roasted and then cooled to produce chondrules. Rocks that underwent this natural "heat treatment" would be sturdier and more likely to survive the passage through Earth's atmosphere, which would explain why most of the meteorites we find are chondrites. "The meteorites got hardened, and Earth's atmosphere is a filter that is weighted toward really dense and hard stuff," says astronomer William Herbst of Wesleyan University, one of the researchers behind the idea.

Today there are as many theories about chondrule formation as there are chondrule scientists—and tomorrow there will inevitably be more.

Against this rising theoretical tide, some wilder notions have already been ruled out. Events from outside the solar system such as gamma-ray bursts—enormously energetic explosions from sources such as merging neutron stars or black holes—were once considered a possibility but now seem implausible because of the great distances involved. Even so, many models still remain, complicated by the fact that chondrules are not really predicted by planet formation at all. "We can build a story about how planets form without ever invoking chondrule formation," Ciesla says. "It's obvious that there's a piece of the story that we're missing."

Narrowing down which of the remaining theories is correct is hard, and arguments can get heated. "The best way to make friends and enemies in meteoritics is to publish another chondrule-forming model," Connolly says. At stake is what role chondrules played in our solar system. If they were among the first solids to form, then some inescapable process took place around our young sun that could explain how planet formation begins around most any star. But if not, are they less vital to the process than once thought?

"I'm putting my money on collisions right now," says planetary scientist Eugene Chiang of the University of California, Berkeley. "And to be totally up front about it, that makes [them] a little less interesting. Because if you're interested in planet formation, it means the chondrules are not the most primitive objects. They're secondary products."

COOKING UP CHONDRULES

MOST OF OUR IDEAS on chondrule formation come from modeling the early solar system and performing experiments on Earth to replicate different formation methods. Meteorite scientist Aimee Smith of the University of Manchester and her colleagues are one of several teams around the world that perform such experiments, mixing chemicals into a powder to resemble different types of known chondrule compositions. Then they place the powder in a furnace and heat it to extremely high temperatures for anywhere from hours to days, before cooling it to mimic different formation models. "If we get ones that look similar to the natural chondrules that we've studied, then we have a better idea of how they formed," Smith says.

Experiments such as these are designed to work in concert with solar system modeling. "The experiments are just defining the conditions for chondrules," says Jones, Smith's collaborator. "But models are trying to come up with scenarios in which those conditions are satisfied." And in our solar system, such modeling is starting to paint a new picture of its earliest moments.

Recent work on measurements of isotope ratios in meteorites indicates that two different reservoirs of chondrites formed early on—one in the inner solar system and one in the outer solar system, where chondrules may have been produced separately. These separate populations would have mixed together after Jupiter, having initially formed more than twice as close to the sun, migrated out to its present position, an idea called the grand tack hypothesis. If true, this would suggest that the story of our solar system's turbulent history is stored within chondrules themselves, offering yet another reason to lavish them with careful attention.

Elsewhere, observations of other solar systems—in particular, protoplanetary disks of dust and gas around young stars—are yielding information about possible scenarios for chondrule creation. In 2014 astrophysicist Huan Meng, then a graduate student at the University of Arizona, and his colleagues reported a flash of infrared light around a star called NGC-2547 ID8 over 1,000 light-years from Earth—evidence for a potential protoplanetary smash-up. Though not definitively linked to the formation of chondrules, the observation at least showed that suitably energetic collisions to make them do seem to occur in young systems. "Before [our] paper, we didn't have any direct hard evidence of any extrasolar planetary impacts," Meng says.

In the future, astronomers should also be able to probe the distribution of dust around young stars with higher-resolution images, which could make it possible to refine some models of chondrule formation. "With improvements in techniques and telescopes, now we can start to see the dust production around young stars," says Yves Marrocchi, a planetary scientist at the French National Center for Scientific Research. "Maybe in the near future we can see the formation [process] of chondrules." Such telescopes may include NASA's much delayed James Webb Space Telescope, scheduled to launch this October.

If chondrules are among the first solids to form around stars, they may be crucial catalysts for subsequent planet formation, in particular the jump from dust-sized to kilometer-sized objects. "There's a gap when you need multimeter- to kilometer-size objects to actually form the rocky parent bodies of planets," Connolly says. "What happens in that gap becomes really important." And perhaps chondrules are even more essential; one model of planet formation, pebble accretion, posits that larger bodies swept up pebblelike dust to grow into planets. Could those pebbles in fact be chondrules? "We don't know if they're the same," says André Izidoro, a planetary scientist at Rice University. Finding out would likely require "a big sample of an asteroid," he says. And as it happens, we just got one.

"NO SINGLE-SENTENCE ANSWER"

EARLY ASSESSMENTS revealed that Hayabusa2 managed to bring back more than five grams of material from asteroid Ryugu. According to Shogo Tachibana, who leads JAXA's sample-analysis team, that should be more than enough to see if chondrules are present. He and his team began studying the samples early this year, after they were transported from Australia back to Japan. Most of their results are still forthcoming. "We don't know if chondrules in Ryugu are different from other types of chondrules in other chondrites," Tachibana says. Ryugu appears to be similar to Earth's carbonaceous chondrites, so most experts expect chondrules to be present in the samples, but as of this writing, no one yet knows whether they will resemble those already in collections or will be like nothing ever seen before.

It is possible that Hayabusa2's samples do not contain chondrules at all. "I think that would be shocking to the chondrule community," Herbst says. "If there were no chondrules, and it looked like there had never been chondrules in them, then maybe chondrule formation is not such a ubiquitous process," Russell says.

Early results from a lander called MASCOT, deployed by Hayabusa2 onto Ryugu in October 2018, have already tantalized scientists. Images from the lander showed many white markings on the surface, which may have been CAIs but also could have been chondrules. "We were surprised that we really could see [the markings] and that there were so many of them," says Ralf Jaumann, head of MASCOT's science team at the German Aerospace Center, or DLR, Germany's space agency. Only chemical studies of the samples conducted back on Earth will reveal the nature of those markings.

If there are chondrules in the Hayabyusa2 samples and if they are similar to chondrules scientists have already studied, it will be possible to pinpoint the location, time and perhaps even conditions in which they formed. If the samples contain new types of chondrules, however, that could provide a fresh perspective on the larger problem of the origin of the solar system. Scientists such as Connolly would welcome such a scenario. "I certainly hope there are a few surprises and we find

objects we didn't expect," he says. And even if chondrules are not present, that could simply suggest that water made liquid from the heat released by radioactive decay, impacts and other sources had long ago erased evidence of its chondrules, similar to the origins of CI chondrites found on Earth.

Hayabusa2 is not the only sample-return mission with extraterrestrial gifts in store for chondrule scientists. NASA's OSIRIS-REx spacecraft is scheduled to return to Earth in September 2023 with recently acquired samples of another asteroid, called Bennu, that are expected to be chondrule-rich. "It would be really disappointing if we didn't find chondrules in the material," says Connolly, who is also part of the OSIRIS-REx team. "I'm looking forward to finding chondrules that I know and chondrules that I don't know."

If researchers ever manage to definitively determine how chondrules formed, that could go a long way toward revealing whether or not they were crucial to the subsequent creation of Earth and our sun's other small worlds. Presuming, of course, that the creation story ultimately revealed is relatively straightforward. Some experts, however, suspect no simple solutions will be found, in part because more than one theory is correct. "I do not think it is a single-sentence answer," says planetary scientist Sarah Stewart of the University of California, Davis. "There were probably many droplets being made in different ways." Russell agrees: "My favorite theory is that everyone's right. All these processes happened somewhere in the solar system. There were shock waves, there were impacts, there were bow waves, there was lightning. I think these things all happened, and they all formed chondrulelike objects."

Which may mean Wood was on the right track all along when he made his infamous, career-capping declaration of futility: If nearly every idea for chondrule creation reflects a process that actually occurred in the solar system's ancient history, there may be no deeply meaningful distinctions among them. But that possibility won't keep new generations from trying, just as their predecessors did. "If I had to do it all over again, I would have made the same attempt," Wood says. And to anyone following in his footsteps? "I would wish them good luck." SA

TEAM MEMBER of the Hayabusa2 mission carries the spacecraft's sample-return capsule after its reentry and recovery near Woomera, Australia, in December 2020.

JAXA VIA AP PHOTO

FROM OUR ARCHIVES

Chondrites and Chondrules. John A. Wood; October 1963.

scientificamerican.com/magazine/sa