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WEEKLY December 4 -10, 2021

WHAT IS NATURE?
Why we need to rethink our relationship with the wild

SPACE ODDITY
Is our solar system weird?

THE METHANE FIX
A way to buy time on global warming

HACK YOUR STRESS

How your mind and body can benefit from being under pressure

AND NOW FOR THE VERY BAD NEWS
Vacuum bubbles that could destroy the universe

PLUS OMICRON: WHAT YOU NEED TO KNOW / **AI READS CLOCKS** / **40,000-YEAR-OLD PENDANT** / RED LIGHT THERAPY BOOSTS SIGHT

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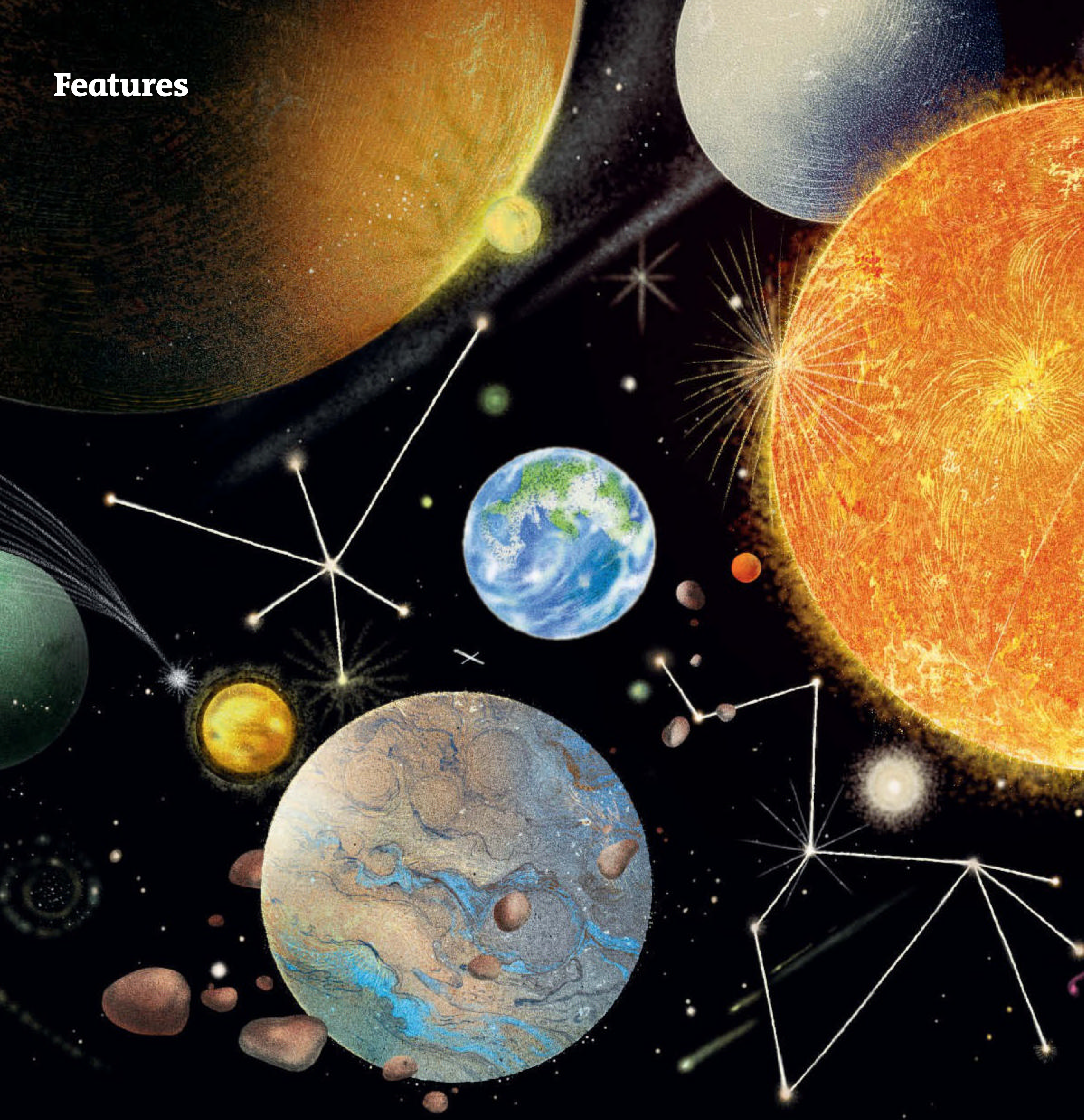
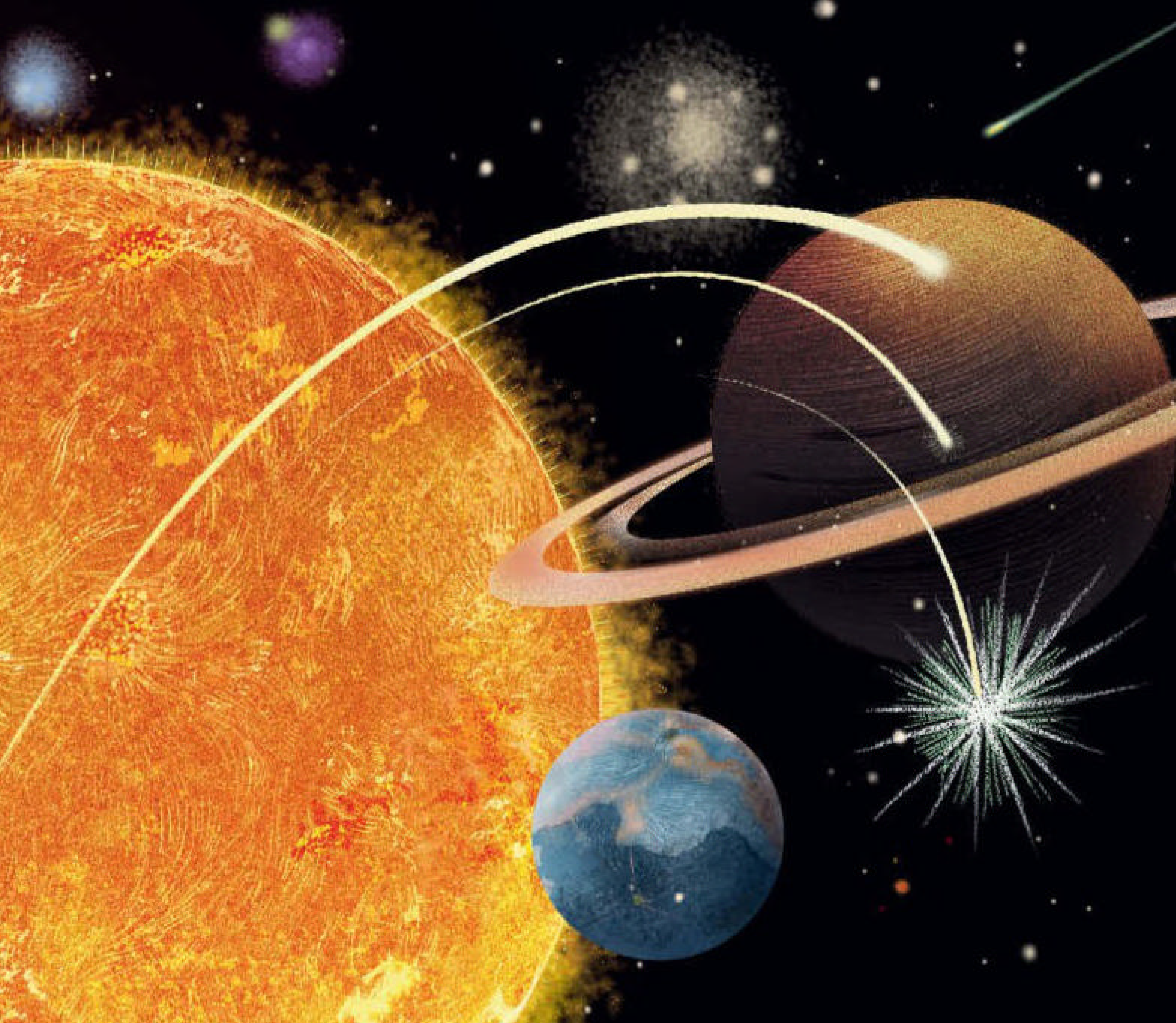


Shaken and stirred

Discoveries in distant solar systems are disrupting ideas of why our own backyard looks like it does, says **Stuart Clark**



ONCE upon a time, there was a solar system. In it lived four small rocky planets called Mercury, Venus, Earth and Mars. Four big gassy planets lived there too: Jupiter, Saturn, Uranus and Neptune. The four small planets lived close to the sun because it was very hot there, and everything else had been blasted away, leaving only rocks to make planets. But further out it was colder and there was lots of ice around, so the planets there grew into great big gassy giants.

This story wasn't originally written as a fairy tale. Until relatively recently, it was our solidly sourced story of how our solar system formed – in fact, how any solar system would form. But in the past decade or so, it has started to look, well, just a little contrived.

As we find large numbers of solar systems elsewhere in our galaxy, none of them look like ours. There are gas giant planets close to their parent stars, rocky planets larger than Earth, compact systems with rocky worlds slotted in between gas giants – anything goes. At first, we could dismiss these exotic exoplanets as oddballs, but after thousands more discoveries, that is starting to look untenable.

Instead, a new picture is emerging of how solar systems form in a chaos of planet building with no certain outcome. That has made us revisit our own solar system's history, and as we do, a nagging question is becoming louder: instead of being the archetypal solar system, are we actually the freak?

Things started to look weird with our system in the 1990s, when the first exoplanets were discovered orbiting normal stars. These were so-called hot Jupiters: gas giants orbiting stars so closely that a year lasts just a few days.

They were clearly the wrong worlds in the wrong place. Planets form from a dusty disc of gas around a young star. To make a gas giant, you first need a solid core of material several times Earth's mass to accrete, as a centre of gravity around which gas can accumulate. The torrent of radiation that a young star emits makes this impossible close to the star. "It will vaporise everything because it's so hot in that region," says Hannah Wakeford at the University of Bristol, UK. "Nobody, and I mean nobody, would say that these ultra-hot Jupiters formed close to their stars," says Stephen Mojzsis at the Collaborative for Research in Origins based in Boulder, Colorado. That leaves only one option: hot Jupiters must have formed elsewhere and moved closer. But how do you relocate a planet within a solar system?

Theorists soon came up with an answer. As a planet accumulates mass, its gravity can create density differences across the gas disc in which it forms, in turn altering the planet's angular momentum, causing it to spiral inwards or outwards. This turns planet formation into a dynamic process rather than the sedate, ordered one we had envisaged, where everything forms in its place and stays there.

This dynamism helped explain other exoplanetary oddities. There were worlds like HD 37605 b, a gas giant close to its star almost three times the mass of Jupiter that follows a highly elliptical orbit more like a comet's than the near-circular orbits preferred by planets. There was the Kepler-20 system, in which two Earth-sized planets are shuffled between three Neptune-sized worlds. Or Kepler-90, whose eight planets, from Earth-size to Jupiter-size, circle a sun-like star. They come in the expected size order, but are squeezed into orbits that are all closer to their star than Earth is to ours.

It all pointed to the idea that the solar systems you see today aren't the ones you originally got. That is when some astronomers began to turn the telescope back on ourselves. Based on our old ideas, the further out from the sun a planet is, the more solid material there would have been to form it, and the larger it should be. Beyond a certain point, however, the density of material begins to decline and planets should get smaller again.

This is where, in our solar system, you find two big problems: Uranus and Neptune. While it is true these two ice giants are considerably smaller than Jupiter and Saturn, the solar system's two mega-planets, they are still way too large for our models to explain how they formed where they are now.

Planetary migration provided a nifty solution in the form of the Nice model, named after the French city in which it was formulated in 2005. This suggested that all four giant planets were originally in a more compact configuration, but interacted gravitationally – first with the debris left over from their own formation and then with each other – until they spread into their current orbits. Besides explaining the size of Uranus and Neptune, the gravitational instability caused by the stirring giants would have swept through the early solar system, which would cause asteroids to rain down towards the sun, explaining the cratered surface of the moon. It could also ›

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When solar systems collide

Might even bigger forces have been at work in the early solar system than those unleashed by planetary migrations? That is the conclusion reached by some astronomers studying the Kuiper belt, a ring of possibly more than 100,000 icy asteroids engirdling the solar system outside Neptune.

The Kuiper belt is itself thought to be the product of planetary migrations in the early solar system (see main story). But models of this process suggest that there should be a gradual decrease in Kuiper belt objects as we go outwards. Instead, astronomers see a precipitous drop off beyond about 50 times Earth's distance from the sun, a phenomenon known as the Kuiper cliff. Then there are Kuiper belt objects like Sedna that appear in highly elliptical, inclined orbits that defy conventional explanation.

Richard Parker at the University of Sheffield, UK, thinks he has an answer. He studies star clusters, jewel-box collections of stars that all form together from the same cloud of interstellar gas – a common origin that has consequences. "When stars are that tightly packed together, they know about each other," he says.

The basic idea is that gravitational interactions between stars mean they can throw each other's planets around, or disturb the disc of material from which those planets are forming. The very largest stars can even rain down a sleet of ultraviolet radiation on others, evaporating away the discs that the planets are feeding from, all of which would have profound effects on the orbits of the resulting planets.

According to Parker, our sun was born in a cluster and a close encounter with another star ripped away the more distant, smaller members of the Kuiper belt and disturbed the orbits of the larger ones. The interaction would also have resulted in the sun's ejection from its birth cluster – explaining why it now travels alone through space.

> **"There is now a clear puzzle: where are the other solar systems like our own?"**

account for how Jupiter acquired the Trojans, some 10,000 space rocks now trapped in two swarms in its orbit, and for the Kuiper belt, a ring of rocky material including Pluto beyond Neptune's orbit, which would have been scattered outwards during the migration.

The Nice model captured planetary scientists' imaginations, although one of its authors, Hal Levison at the Southwest Research Institute in Boulder, Colorado, sounds a note of caution. "If you'd have asked us whether we'd still be talking about it in 2021, we would have laughed because models come and go," he says. "It really did solve many problems, but it is just a model. That doesn't make it right."

Nevertheless, it has become a framework within which astronomers now picture a dynamic early phase of our solar system's history – one that may have even involved influences from beyond it (see "When solar systems collide", left). "It is generally accepted that giant planet migration happened in our solar system," says Mojzsis.

Migration could also explain our solar system's most puzzling omission. It has small, rocky planets like Earth and gas giants like Neptune and larger, but nothing in between – if you discount reports of a mid-sized "planet nine" orbiting way out. Such a middling planet could be a large rocky one (a super-Earth), or a small gas giant (a mini-Neptune). Together,

The moon's craters are evidence of violent changes in the early solar system

NASA

these mid-range worlds make up over half the planets we know. "The fact that they're pretty much everywhere we look suggests they're easy to make," says Wakeford.

The absence could be explained if Jupiter migrated inwards at some point, disrupting the space in which a super-Earth would have formed. That could also explain why Mars is strangely small, just one-tenth of Earth's mass: Jupiter's movements would have cannibalised the material, stunting its formation.

Left unchecked, Jupiter would have pushed the inner planets – including Earth – to a fiery end inside the sun, while becoming a hot Jupiter itself. It didn't, because our solar system has not one mega-giant, but two – and Saturn saved the day. "It's about 80 per cent the size of Jupiter and that meant that Jupiter had a leash on it," says Wakeford. In this model, Saturn was migrating inwards too, but faster than Jupiter. As they got closer, they became locked into gravitational interactions that slowed and then reversed their migration, a scenario known as the "grand tack".

Fairy tales again? Perhaps. Mojzsis thinks that though the idea works dynamically, it is doomed geochemically. "Grand tack fails to explain the chemistry of the planets," he says. If you have Jupiter moving inwards, everything gets stirred up and mixed, but Earth and Mars have distinctly different compositions.

Whatever the details, however, we may now have hard evidence of some form of migration, if the analysis of a peculiar space rock that fell in India in 1870 is to be believed. Earlier this year, Fridolin Spitzer at the University of Münster in Germany and his colleagues showed that the Nedagolla meteorite contained a mix of ingredients from the inner and outer solar system, suggesting that something happened to blend these compositions.

But if planetary migration happens in our solar system as it does elsewhere, that leaves a puzzle: where are the other solar systems like our own? Back in the 1990s, astronomers were sure that after 15 years, we would find sister solar systems – above all, with Jupiter-sized planets where our Jupiter is. A quarter of a century on, nearly 5000 exoplanets are known. These are split between around 3600 planetary systems, with some 800 of those having multiple planets. Super-Earths, mini-Neptunes and hot Jupiters seem common, as are highly compact systems like Kepler-90. But precious

NASA/USGS

New ideas of how our own solar system formed could explain why Mars is titchy

few "Jupiter Jupiters" have been found.

This could still be to do with how we find exoplanets. The problem is detection bias, according to Hugh Jones at the University of Hertfordshire, UK. Every detection method has an inbuilt sensitivity towards detecting certain types of worlds. For example, radial velocity surveys detect changing colours in a star's light when it is pulled by an orbiting planet's gravity, and are most sensitive to large planets very close to their stars. "Transit" surveys such as the Kepler space telescope, meanwhile, spy orbiting planets by the dimming of a star's light as they pass across its face, and have found most of the highly compact planetary systems.

Such biases make it hard to make definitive statements yet about what "normal" is. Solar systems like ours could be relatively common, but we just haven't seen them yet. The 15-year figure for finding one like ours was based on Jupiter taking 12 years to orbit the sun, giving time for a similar planet elsewhere to reveal itself. But "astronomers tend to be optimistic folks", says Richard Parker at the University of Sheffield, UK. "So when they tell you 15 years, what they probably mean is 30 years."

Thanks to the Nice model, we are also realising just how sensitive planet formation is to the details of the process. While the model was designed to reproduce the solar system, tweak it slightly and you get a whole different solar system. "Any one tiny change results in something completely different," says Wakeford. For example, Neptune could be flung right out of the system rather than shunted into a distant orbit, or Earth could be forced onto an elliptical orbit that would make habitability difficult.

Wakeford says we haven't quite yet grasped how these nuances can result in wildly different outcomes. Parker agrees. "Why wouldn't we expect planetary systems to be different when the processes that an individual star goes through [in its formation] can be completely different?" he says.

Thankfully, new information is on the way. The European Space Agency (ESA)'s Gaia mission and the European Southern Observatory's Very Large Telescope Interferometer both look for exoplanets in a different way, watching for how stars change position in response to the gravity of planets. ESA's 2026 Plato mission, a souped-up successor to Kepler, has been optimised to search for Earth-sized planets in the habitable zones of sun-like stars. "All these are things which help to erode our biases in the different parts of the discovery space," says Jones.

Meanwhile, we can hope for progress in the story of our own solar system's evolution. NASA's Lucy mission is currently en route to the Trojans. During a 12-year mission, it will encounter seven different asteroids in the two swarms, characterising them close-up for the first time. If the Trojans really are the result of planetary migration, their compositions could hold vital clues to the dynamics of the early solar system. "I think we've evolved to the point where we have many ideas, and don't really have enough data to distinguish one model from another," says Levison, who has switched from being a theorist to become principal investigator of the Lucy mission.

It remains to be seen whether any of these advances will bring clarity to our ideas of how solar systems look, and where ours fits in, or just more messiness. What is undoubtedly true is that at least one solar system brought forth a rocky planet where life could flourish. Whatever the nature of the story that led us here, that's a happy ending of sorts. ▮

Stuart Clark is a consultant for *New Scientist* and author of *Beneath the Night: How the stars have shaped the history of humankind*