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WEEKLY July 23 - 29, 2022

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"Titan is like a firecracker waiting for someone to light a match"

Scott Bolton has spent two decades heading missions to Jupiter, Saturn and their exotic moons, such as Titan. He tells Joshua Howgego about the amazing insights and fresh puzzles that have been revealed

SOME 750 million kilometres from here, a huge ball banded in orange and white hangs in the blackness of space: Jupiter. Travel about the same distance again and you hit the ringed planet Saturn. Of all the planets, these two gas giants dominate our solar system – and over the past two decades, they have also worked their way into our collective imaginations as spacecraft sent to explore them and their moons have returned their findings. We have seen a hexagonal storm dancing around Jupiter's north pole, methane rain on one of Saturn's moons, Titan, and discovered liquid water spewing from geysers on the surface of another of Saturn's moons, Enceladus.

Many people have worked on these discoveries, but Scott Bolton at the Southwest Research Institute's Space Science & Engineering Division in San Antonio, Texas, has been a central figure. After overseeing the Galileo mission to Jupiter between 1989 and 2003, he was the lead scientist on the Cassini mission that studied Saturn for 13 years until 2017 and is now at the helm of the Juno mission, which has been orbiting Jupiter since 2016. *New Scientist* spoke to him about his two decades of exploring the gas giants and what we still have to learn.

NABIL NEZZAR

Joshua Howgego: You were a key scientist on the Cassini mission to Saturn and it turned out to be an iconic piece of space exploration. Take us back to the late 90s when it began.

Scott Bolton: Cassini was a follow on to Voyager [a mission preceding Galileo], which had gone by Jupiter and Saturn. There were two Voyager probes and they were both capable of going out to the far reaches of the solar system. But Titan, a moon of Saturn, was deemed so important to study that the path of one of the probes was tweaked, sacrificing the prospect of it going on to Uranus and Neptune just so it could get a close view of Titan. At that time, it was thought that Titan was like a prebiotic Earth. But when Voyager got close, we were only able to see Titan's atmospheric haze, which was so thick you could hardly see through it. Nevertheless, what Voyager found only increased interest. Cassini was designed to follow that up, to study Saturn and all its moons, including a major effort to study Titan both with a NASA-built orbiter and a probe that was provided by the European Space Agency (ESA).

What did the Cassini mission achieve?

It was a flagship mission [the most expensive and ambitious of NASA's mission classes], so it dealt with the full breadth of scientific targets that are associated with a giant planet. It had new radar instruments to see through the haze and map out the surface of Titan, which was a very high priority because of its possible habitability and features like lakes – liquid methane lakes, that is. I used to joke that Titan was a giant firecracker waiting for somebody to light a match.

Of course, there was also the study of Saturn and its rings. Initially, we kept Cassini away and didn't go through the rings because it was dangerous. But it had to go through the ring plane sometimes and that was a little iffy. Then there was the smorgasbord of satellites and moons around Saturn.

Were there any that were particularly interesting?

One of the most important was Enceladus. This little moon stunned Cassini scientists with the discovery of a global ocean under its icy shell, active geysers that spew 200 kilometres above the surface and signs of hydrothermal activity. We had another special instrument on Cassini, a mass spectrometer, and using that we could really look at the composition and try to understand what was going on in the geyser plumes. Cassini's mass spectrometry measurements at Enceladus were particularly exciting because they identified some of the › elements for habitability (or for life to develop): liquid water, carbon dioxide and organic materials alongside available energy.

What do you think about Cassini, looking back, and how did it compare with the Galileo mission to Jupiter, which came before?

It lasted a long time and it definitely represented a great accomplishment for both NASA and ESA. Galileo was also a great mission. Unfortunately, it had some elements that didn't work. It was disadvantaged by the fact that its main antenna didn't completely open and its old-fashioned tape recorder, which was used for storing scientific data, also had problems. Cassini didn't experience major failures – nearly everything worked. The amazing images that it could return, plus all of its discoveries regarding Saturn and its rings and moons, were inspirational. I loved working on Cassini.

What gave you the idea for the Juno mission to Jupiter?

The idea of a polar orbiter around Jupiter goes way back. But when we were going past Jupiter with Cassini on the way to Saturn, I was thinking about calibrating our instruments and what we could learn about Jupiter. Two colleagues of mine, Toby Owen and Daniel Gautier, came to me and asked if we could use the radar instrument to measure Jupiter's deep atmospheric temperature. They told me that if we could make this measurement it would help us understand how Jupiter formed. I thought that sounded pretty profound.

I went home and thought about it some more, and then said I don't think I can do it with Cassini. But if we get a spacecraft with this other kind of instrument – which didn't really exist at the time – and you put it into this kind of an orbit, I think we could. And they said: that's the basis of a whole mission.

That mission eventually became Juno. Where have we got to on its central mission, finding out how Jupiter formed?

There were a couple of measurements that were important for us. One was: what is the core of heavy elements – those heavier than helium – inside Jupiter like? Was there a kind of solid core, or no core at all? If Jupiter forms like the sun – a cloud of gas and dust that collapses in on itself – there might not be a core of heavy elements. If Jupiter formed more like a planet – you have rocky, icy things banging into each other and gluing together into a lump the size of Earth, say – then you expect to see that rocky core still inside Jupiter today.

> "We realised that neither of our original ideas of how Jupiter formed really work"

When Juno got there and made those measurements it was a humbling experience because neither of those scenarios turned out to be right. Instead, we saw a dilute, fuzzy core that was quite large. There may be a compact core inside, and now our mission has been extended, hopefully, we'll be able to determine that. But we have realised that neither of the original theories really work. To a scientist, this can be disappointing, but it is also exciting. We discovered something that we didn't expect, which is ultimately great. Theorists are now working to explain how to make a Jupiter with a core that's consistent with Juno's data. But there is no answer yet.

An illustration of NASA's Juno spacecraft passing above Jupiter's south pole

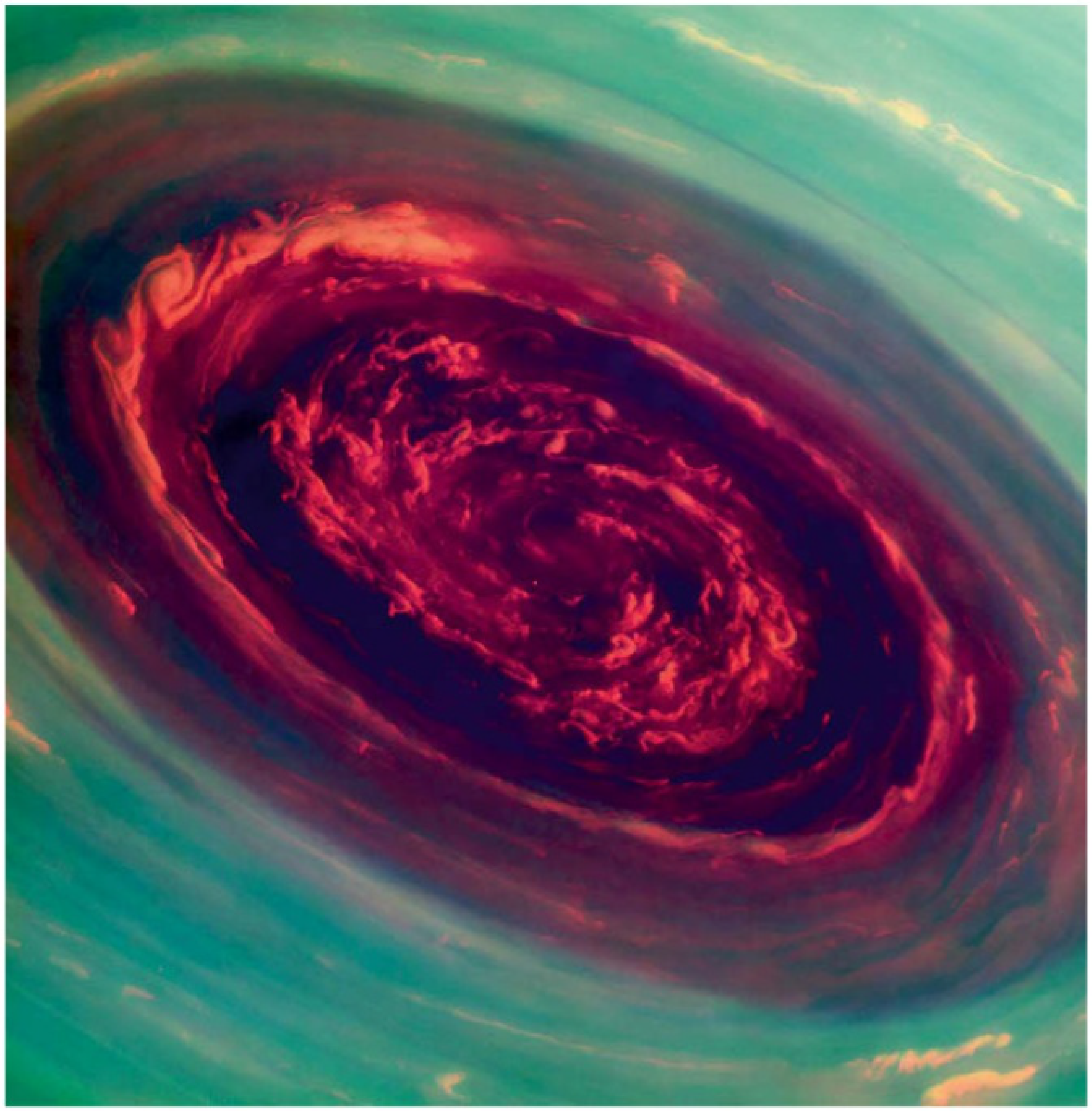
NASA/JPL-CALTECH

The other part of the mission was to find out what Jupiter is made of. Is that making any more sense?

There has been a long assumption that if we could drop below Jupiter's cloud base, below the weather, then all the gas would be well mixed and we would be able to get an accurate sense of the overall composition of Jupiter. That was the goal for the Galileo probe: measuring the global abundances of heavy elements in Jupiter. A key question was the oxygen or water abundance. If we knew that, we could plug it into models with the other heavy elements to understand how we could have got a Jupiter with the measured composition.

Unfortunately, the Galileo probe measurements were puzzling and scientists believed they were not representative of a global Jupiter; that we were unlucky in sampling a spot that was unusually warm and dry – sort of the Sahara desert of Jupiter.

So Juno was created to evaluate the atmosphere at many locations using its Microwave Radiometer instrument that can look far into the atmosphere, much deeper than a probe could reach. With Juno, way below the clouds, we saw that the ammonia and water abundances are still varying. This was a complete surprise as scientists believed that below the weather layer, where water and



NASA/JPL-CALTECH/SSI

False-colour image of the storm at Saturn's north pole, captured by NASA's Cassini spacecraft

ammonia condense, the atmosphere would be well mixed. But this isn't true, and nobody knows why or how that could be. It is very hard to get a global average – and even if you do, you have to wonder whether it represents a global average that goes all the way down to the middle of Jupiter.

What is the best explanation for this so far?
There was a paper published in 2021 by Tristan Guillot at the Côte d'Azur Observatory in Nice, France, and his colleagues. They hypothesised that maybe there is something like mushy hail – they called it "mushballs" – that were formed in the storms of Jupiter high up in its atmosphere. And so these mushballs, which are about the size of a baseball, would trap either water, ice or ammonia that could be carried down as a liquid below the condensation level before it evaporated, leaving it unevenly distributed.

One of Juno's latest undertakings was flying past Ganymede, Jupiter's largest moon. Tell us about that.
In June 2021, Juno finished its primary mission, but since it has now been extended, we didn't have to dispose of the spacecraft. Instead, we were able to modify the orbit to move closer to Jupiter's largest moons [Io, Callisto, Europa and Ganymede]. The first was Ganymede. We flew by at a distance of about 1000 kilometres and did a full sweep of satellite science.

For instance, we have this microwave instrument that observes in six different frequencies. Each frequency sees into the ice that covers the moon at a different depth. What we are trying to do is understand how that ice varies – how thick it is and what it's like. Ganymede is covered with different terrain types that we already knew about: dark, bright and middling stuff, and even linear-looking features that suggest tectonic activity. I think what's equally exciting is that we are going to get the same kind of map of Europa in a few months and its ice is very different to Ganymede's. I'm not sure we'll fully understand the Ganymede data until we see the same data on another body. Comparative studies like this are probably the most important tool of science and we're going to get that – it is really exciting.

Will all these observations lay a clearer path for JUICE and Europa Clipper, the other missions set to explore the Jupiter system?
Yes, both of those missions are being informed by Juno. Up until now, we had never been to the places that JUICE and Europa Clipper are going to go through, but as we go by the moons, we're taking measurements of the land on their surfaces, and we'll update our models of the radiation in the area, which is something that we all fear because it can fry spacecraft. On top of that, we're getting the first close up views of the satellites for many, many years, which helps inform future missions too.

Your work has been focused on Jupiter and Saturn. But there are other less well-explored planets in the solar system too. Where do you think we should go next?
Well, before two Venus missions were announced recently, I was one of those who felt quite strongly that Venus had been left out. Maybe we should have more Venus missions, some would argue, and I'm not against it – Venus is a very important target.

I think the ice giants of Neptune and Uranus represent a good next step as well. The big question is, how fast can you get there, because it takes a long time to develop the mission and get it approved, and then it takes a long time to travel out there. In the latest decadal survey [where once each decade NASA and its partners ask the National Research Council to prioritise future research areas, observations and notional missions], the Uranus mission was the number one flagship recommendation, but it also recognised that, given NASA's budget, it might not be possible to start that mission in the next decade.

I think one of the nice things Juno has shown is that something that you thought you needed a flagship mission for might be possible in a New Frontiers Program, which is intrinsically faster and less expensive. Juno's extended mission is demonstrating that we can not only study Uranus or Neptune with a Juno-like spacecraft, but you could actually do a good job on the satellites as well. I think that gives us hope that maybe another ice giant mission doesn't have to wait 20 years. ■

Joshua Howgego is a feature editor at *New Scientist*