Solar analog. This region around another star resembles our heliosphere, which Voyager 1 may have left.

PLANETARY SCIENCE

It's Official—Voyager Has Left the Solar System

After 36 years of hurtling toward the edge of the solar system, the Voyager 1 spacecraft—its sensors failing, its energy running low—has crossed into the abyss of interstellar space. At least, that is now the consensus view of Voyager mission team leaders. This week, four team members are publishing new data from Voyager 1 in *Science* that the team deems conclusive: Its spacecraft has passed out of the heliosphere, the bubble inflated by the sun's wind of charged particles. Voyager, now six times farther from Earth than the orbit of Neptune, is where nothing from Earth has gone before.

The much-anticipated departure of the storied probe, which visited Jupiter and Saturn before heading out of the solar system, may sound like familiar news. Over the past year, there have been reports of its leaving, of its not quite leaving, of its being in a new, special place. There's a reason for the mixed signals. The space physicists' edge of the solar system "is not your usual planetary environment at all," says heliophysicist George Gloeckler, a Voyager team member since the 1960s. Even modern computer simulations could give the researchers no warning of the confusing weirdness Voyager 1 has encountered.

What's more, the instrument capable of detecting the clearest sign that Voyager had crossed the heliopause—the outer boundary of the heliosphere—failed long ago. So there has been plenty of room for interpretation and disagreement, with some members of the team and outside investigators offering interpretations at odds with the official word from the five Voyager instrument principal investigators, the Science Steering Group (SSG).

Online
sciencemag.org
Podcast interview with author Richard A. Kerr (http://scim.ag/pod_6151).

The arguments began in August 2012, when the counts of energetic charged particles, or cosmic rays, showering the spacecraft changed abruptly. On 25 August, a Voyager 1 instrument recorded a sharp drop in cosmic rays that are produced inside the heliosphere, a drop that soon continued to near zero. Another instrument recorded a simultaneous increase in cosmic rays produced outside the heliosphere far out in the galaxy.

"I thought we had crossed into interstellar space," says J. Randy Jokipii, a 50-year veteran of space physics theory at the University of Arizona in Tucson and a longtime Voyager guest investigator. Edward Stone of NASA's Jet Propulsion Laboratory in Pasadena, California, was more cautious. He is principal investigator of Voyager's Cosmic Ray Subsystem experiment, so he has a special affinity for last year's surprising data. But he has also been the mission's project scientist from the start—and the SSG's consensus-maker. "We knew we were in a new region close to the boundary" with interstellar space, he says. But had Voyager really left, he wondered? Or was this just an unexpected region of the outermost heliosphere?

The answer would be a downer. Astronomers had expected that the direction of the magnetic field that pervades all space would switch at the heliopause, where the fields carried by the charged particles of the solar wind give way to those of interstellar medium. But according to the lengthy calibration and analysis of the Voyager 1 magnetometer data completed in early December, "there was no change in direction" the previous August, Stone says, so "we were cautious to not claim a crossing. We all concluded we didn't have definitive evidence of crossing into interstellar space."

At December's American Geophysical Union (AGU) meeting in San Francisco, Stone played it cool. Instead of calling a full-blown press conference, he explained to reporters one at a time in a "media availability" that as of August, Voyager 1 was still inside the heliosphere. Things had clearly changed, he said; Voyager 1 had entered an unexpected heliospheric region dubbed the "magnetic highway." There, magnetic field lines somehow connected the heliosphere's interior with interstellar space, allowing energetic particles like cosmic rays to leak out and in. But Voyager hadn't left, because the magnetic field direction hadn't changed.

Voyager principal investigators followed Stone's lead in three papers submitted to *Science* early this year and published 12 July, which had Voyager 1 entering a "depletion region," jargon for the magnetic highway. But in Jokipii's view, "everybody punted. There was no consensus of what was going on."

Not everyone followed the official line, however. "Voyager 1 has left the solar system, sudden changes in cosmic rays indicate" was

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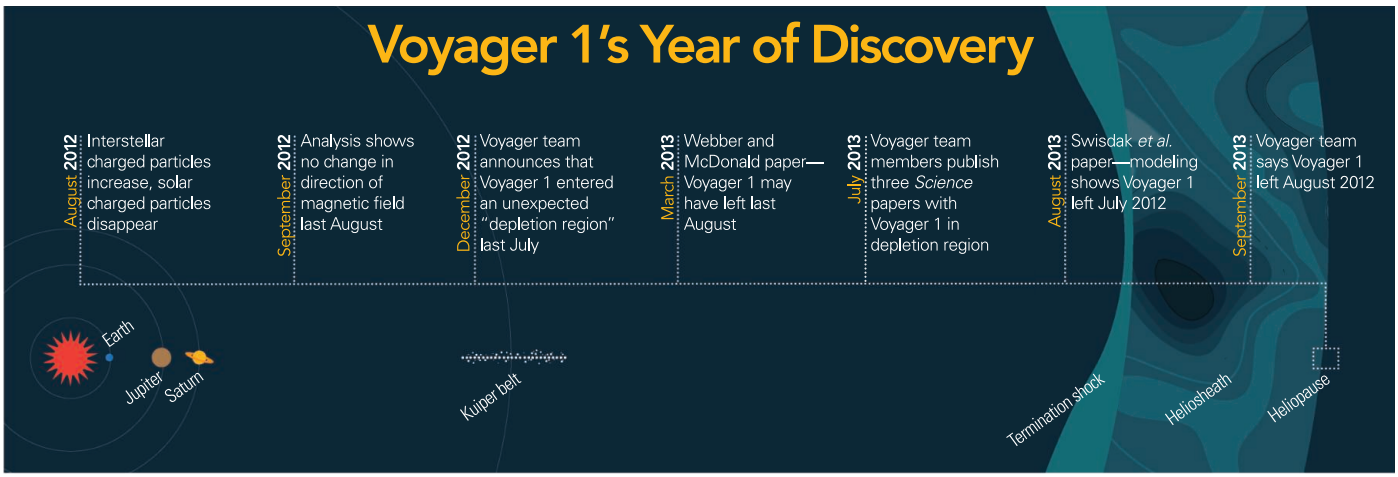

Gone or not? In the past year, Voyager 1 sent back data that led to conflicting interpretations. Had it left the heliosphere in August 2012? The latest data suggest that it did.

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the headline of a press release accompanying a paper on the August cosmic ray measurements, accepted on 20 March at AGU's *Geophysical Research Letters*. Within hours, AGU changed the headline to "Voyager 1 has entered a new region of space." The paper's first author and Voyager team member William Webber privately agreed with the initial headline. "We thought it was at the crossing, but in deference to the team, we didn't push that aspect of it" in the paper, says the professor emeritus at New Mexico State University in Las Cruces.

Six months later, a group of Voyager outsiders again placed the spacecraft in interstellar space. "We think we are outside the heliopause," says space physicist Marc Swisdak of the University of Maryland, College Park.

As they reported in the 1 September *Astrophysical Journal Letters*, Swisdak and his colleagues used the most detailed model yet to simulate how particles and fields behave at the heliopause. "The boundary is very different than we thought," he says. "The very nature of the heliopause may come into question." Their picture of the heliopause accounts for both the changing cosmic ray counts and the unchanged magnetic field direction, he says. In their model, the two magnetic fields, inside and outside the solar system, line up and connect to each other.

Now comes the latest official word from the Voyager team, and the verdict is that the 25 August 2012 changes did signal an exit from the heliosphere. "That is the collective point of view" of the Voyager team, Stone says. What prompted the change of heart was observations by Voyager 1's plasma wave instrument, which measures oscillations in the plasma, the soup of low-energy charged and neutral particles pervading space.

A jump in the density of plasma "is the way the heliopause has been defined for years," says Donald Gurnett of the University of Iowa in Iowa City, who is the principal investigator of the plasma wave instrument. An instrument that could directly measure the plasma density broke shortly after the spacecraft passed Saturn. In the debate over the heliopause, "the key thing missing was plasma," Gurnett says. But Gurnett's instrument can be used to infer plasma density indirectly, at least when the sun sends a blast out Voyager's way, triggering distinctive oscillations in the plasma.

This past 9 April, Voyager 1 recorded the sudden onset of plasma oscillations at a frequency of 3.1 kilohertz following a solar outburst. "When we saw that, it took us 10 seconds to say we had gone through the heliopause," Gurnett says. That frequency implied a plasma density 80 times larger than ever seen inside the heliosphere and close to the density that astronomers were expecting in interstellar space. As Gurnett and three other Voyager team members report online in *Science* this week (http://scim.ag/DGurnett), they could infer a departure date of 25 August 2012 by extrapolating back through a weaker, recently recognized oscillation episode of lower frequency last October. "Plasma trumped magnetic field in this case," Gurnett says.

Gurnett's "conclusions are remarkable and probably correct," Jokipii says. "Now we have three detectors all consistent in suggesting strongly we're in the interstellar medium." And for most researchers in and out of the Voyager team, that is enough; Voyager 1 has left.

That conclusion is far from unanimous, however. "I don't think it's a certainty Voyager is outside now," says space physicist David McComas of the Southwest Research Institute in San Antonio, Texas. "It may well have crossed," he says, but without a magnetic field direction change, "I don't know what to make of it."

Heliophysicist Gloeckler and heliosphere theorist Lennard Fisk, both research professors at the University of Michigan, Ann Arbor, simply reject the Voyager team's interpretation. "We have not crossed the heliopause," Gloeckler says. "We're way out there, by far a minority, but we can explain every Voyager result in a pretty natural way." The jump in plasma density is merely the solar wind piling up just inside the heliopause, he says.

Time should tell. The radioisotope thermoelectric generators powering Voyager 1 and Voyager 2—which is cruising a few years behind its twin—have been running down since before launch. Starting in 2020, Voyager 1's instruments must share power by rotating on and off. By 2025, its last instrument will be shut down for good. But that could still be time enough for a direction change in the magnetic field to turn up, or not. Or Voyager 2's still-intact plasma instrument could prove Gloeckler and Fisk right. At only $5 million a year in operating costs for both spacecraft, NASA isn't likely to bring this interstellar mission to a premature end.

And Voyager team leaders are preparing for an even longer run. "I never knew I was signing up for a lifetime," says Voyager principal investigator Stamatios Krimigis of the Applied Physics Laboratory in Laurel, Maryland. "It's a marvelous mission, but I'm doing succession planning."

–RICHARD A. KERR

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