Voyager 1 May Have Crossed Termination Shock

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NASA's intrepid Voyager 1, launched in 1977, may have recently become the first spacecraft to at least temporarily cross the termination shock of the solar system and enter into the heliosheath.

Or maybe not.

Different teams of scientists recently published conflicting papers about whether the spacecraft has entered this realm. Either way, the scientists agree that Voyager 1 is crossing through unexplored territory and likely will become the first human-made object to cross the termination shock and enter the heliosheath on its way toward the heliopause and interstellar space.

The termination shock is where the solar wind abruptly slows due to pressure from interstellar gas. Determining whether Voyager 1 has passed that point is not straightforward, however. The termination shock itself is located at about 95 astronomical units away from the Sun, plus or minus about 7 AU on average, according to Edward Stone. Stone is the Voyager project scientist at the California Institute of Technology in Pasadena.

The exact location fluctuates, depending on solar activity and the pressure from interstellar material. Also complicating the determination is that the instrument onboard Voyager 1 for measuring solar wind speed no longer functions.

Stamatios Krimigis, head of the Johns Hopkins University Applied Physics Laboratory's space department in Laurel, Maryland, is the lead author of a 6 November paper in *Nature* which argues that Voyager 1 briefly crossed the termination shock. The paper argues that Voyager 1 exited the supersonic solar wind on about 1 August 2002 at a distance of 85 AU from the Sun, and then re-entered the supersonic wind about 200 days later on 5 February 2003 at 87.4 AU.

Krimigis and his team base their conclusions on three pieces of evidence provided by Voyager 1's low-energy charged particle instrument. The instrument measured a 100-fold increase in low-energy protons, which passed along a magnetic field perpendicular to Voyager 1 at the period when the scientists indicate that the spacecraft passed the termination shock. The instrument also made an indirect measurement that the solar wind slowed from about 1,126,500 km per hour to less than 160,900 kph during that period. Also, the instrument found that particles in the region included signatures of interstellar material.

However, several other papers co-authored by Stone dispute that Voyager 1 has crossed the termination shock.

Frank McDonald, senior research scientist at the Institute for Physical Science and Technology at the University of Maryland in College Park, is lead author of a 6 November *Nature* paper which reports findings from the cosmic ray subsystem on Voyager 1. These findings, the paper notes, measured a significant increase in the numbers of energetic ions and electrons, and the persistence of this state for 7 months starting in mid-2002. The paper continues that "the low-intensity level and spectral energy distribution of the anomalous cosmic rays, however, indicates that Voyager 1 still has not reached the termination shock. Rather, the observed increase is an expected precursor event."

McDonald said his data indicates that Voyager 1 "is in the neighborhood" of the termination shock rather than having passed through it. However, he took note of another Voyager 1 milestone, crossing the 90 AU mark on 5 November. "The odometer rolls over at 100 AU," he mused. McDonald also noted that Voyager has continued to provide new data about cosmic rays and other aspects of its environment. "We haven't just been waiting to get to the termination shock," he said. "Half of the fun is getting there."

A 30 October paper in *Geophysical Research Letters* also argues against Voyager 1 having passed through the termination shock. Leonard Burlaga of NASA's Goddard Space Flight Center is the lead author of the paper, which states that "magnetic field observations do not provide evidence for exit from the solar wind, entry into a subsonic region such as the heliosheath, or transit of the termination shock near 85 AU."

Merav Opher, research scientist with the Jet Propulsion Laboratory in Pasadena, said passage through the termination shock "is as if we are piercing a hole in a carton that separates us from the rest of the galaxy." Continued data from Voyager 1 would provide an understanding about the influences of different regions of interstellar space on our solar system, she said.

Stone noted that whether or not Voyager 1 already has passed through the termination shock, there will be other opportunities for the spacecraft to observe this expanding and contracting location. "We will probably be surfing the termination shock over the next 3 to 4 years," he said.

Voyagers 1 and 2 are expected to continue operating until about the year 2020, when their electrical power and thruster fuel are anticipated to run out. Voyager 1, Stone said, possibly will go on to become humanity's first interstellar probe. "The only question is, will we get there while we still have electric power?"

Voyager 1 was launched on 5 September 1977, shortly after the 20 August launch of Voyager 2. Voyager 2 currently is about 17 AU closer to Earth than is Voyager 1. The spacecraft have taken different routes across the solar system during and after their primary missions of interplanetary exploration.

—RANDY SHOWSTACK, Staff Writer

MEETINGS

Volcanic Gas Workshop Features State-of-the-Art Measurement Techniques

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Volcanic gas emissions can often be interpreted as signals from deep within the Earth. The study of volcanic gases increases our understanding of how magmatic systems behave, and in some cases it can be used as a predictive tool for eruptive activity and associated hazards. Not only are we concerned with the dangers of large eruptions, but if large volumes of gas are released, the gases themselves can pose a hazard to communities surrounding a volcano. The environmental impacts of volcanic gas emissions are observed on local scales, and the significant global contribution to the atmosphere is also an area of current interest, since it relates to global climate change. As we still have much to understand about volcanic eruptions and the environmental impacts of volcanic gas emissions, scientists benefit from working together to improve instrumentation and monitoring techniques.

Every 3 years, volcanologists from around the world gather at selected volcanoes to compare and improve volcanic gas monitoring methods, and to pool their knowledge as a scientific community. This year, the Eighth Field Workshop on Volcanic Gases, sponsored by the Commission on the Chemistry of Volcanic Gases (CCVG) and the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), was held in Central America. With the collaboration of the Instituto Nicaragüense de Estudios Territoriales (INETER) and the Observatorio Vulcanológico y Sismológico de Costa Rica (OVSICORI-UNA), the workshop attendees converged at Masaya, Cerro Negro, and Momotombo volcanoes in Nicaragua, and at Póas volcano in Costa Rica. The workshop attracted over 80 researchers from 20 countries, along with their various instruments and capabilities. The overall goals of the workshop not only included perfecting techniques and sharing ideas, but also working together to develop an integrated approach to volcanic gas monitoring.

Traditionally, volcanic gas geochemistry has focused on samples collected from high-temperature fumaroles. Recent technological developments and discoveries over the past decade have advanced the measurement and monitoring of volcanic gas emissions, with the result that this workshop was the largest and most varied to date. In addition to sampling fumaroles in the Central American volcanoes, research groups focused on carbon dioxide soil gas measurements, filter sampling of volcanic plumes, and new, ground-based remote sensing technologies.

Researchers interested in fumarole emissions compared different approaches to sample collection and their various analytical techniques, which have evolved over recent years. These samples give us our best look at trace elements transported in volcanic gases. In addition to the long list of inorganic species known to be emitted by volcanoes, organic compounds are now being identified that are stable in these hot, acidic gases. Although valuable information is gained from fumarole sampling, it can be dangerous, and requires the researcher to wear protective gear, including a full-face respirator. Due to such hazards, efforts have been made to develop complementary techniques of volcanic gas monitoring, such as remote sensing.

The most notable change in volcanic gas measurements has been the development of remote sensing techniques. For several decades, volcanologists have relied on the correlation spectrometer (COSPEC) for ground-based remote sensing of volcanic sulfur dioxide. However, miniature differential optical absorption spectrometers (e.g., mini-DOAS and FlySpec) have emerged as new tools that provide sulfur dioxide data similar to that of COSPEC. The low cost and small size are major advantages of these instruments, as arrays of several instruments can be deployed around volcanoes. Since a large number of spectrometers were present at the workshop, a number of interesting, multi-instrument experiments were attempted, such as estimation of wind speed for the volcanic gas plume. The spectrometers also have the potential to be developed into a multi-gas sensor to detect such species as ozone and BrO [*Bobrowski et al.*, 2003], thus providing new opportunities for better understanding the effects of volcanic emissions on the atmosphere's chemistry.

Quantification of diffuse gas emissions—for example, carbon dioxide—is important for determining the total volcanic gas budget, and for monitoring purposes. While other volcanic gases tend to be more reactive, carbon dioxide can degas diffusively and provide details of subsurface characteristics, such as locations of faults that are not visible on the surface. In some cases, a change in flux patterns could be an indication of subsurface magma movement. Six research groups at the workshop compared individual carbon dioxide flux measurements and methods to estimate total area emissions.

Fig. 1. Crater lake of Póas volcano, Costa Rica. The highly acidic crater lake (pH = 0.4) and surrounding fumaroles make up the persistent gas plume from this volcano. Fumarole gas sampling, soil gas studies, plume sampling, and volcanic gas remote sensing were all conducted in the crater of Póas volcano. Photo courtesy of T. Delfosse.

Masaya

The workshop field measurements began at Masaya volcano in Nicaragua, which is of particular interest, due to its basaltic composition—unusual for a subduction zone setting, such as that in Central America. Masaya has been frequently active since the arrival of the Spanish conquistadors and exhibits cycles of major, non-eruptive degassing crises [*Stoiber et al.*, 1986]. The summit is easily accessible by road, so that even large instruments can be positioned at the edge of Santiago crater, a 250-m-diameter active crater that has been degassing continuously since 1993. Looking into the 600-m-deep crater, gases can be seen emanating from the vent formed by the April 2001 eruption, which threw boulders onto cars parked in the observation area. During the dry season between November and May, the wind predominantly blows from the east, and areas of damaged vegetation can be seen downwind of the volcano. The plume passes over several roads, allowing ground-based remote sensors to make traverses normal to the plume at multiple downwind locations. In addition, large quantities of CO_2 are discharged diffusely from a fracture zone located on the northeastern flank of Masaya. Research groups thus had the opportunity to make comparative carbon dioxide flux measurements along this fracture zone.

Masaya did not offer an opportunity to sample high-temperature fumaroles, but its neighbors, Momotombo and Cerro Negro volcanoes, are noted for their fumarolic activity. A group of "fumarolists" left the hotel at 3 a.m., made the 5-hour ascent to the summit of Momotombo, and were rewarded with fumarolic temperatures of near 800°C. Temperatures of this magnitude are rarely found, but are important, since the high temperature suggests that the gases are coming directly from the magma, and have not undergone extensive interaction with hydrothermal or meteoric fluids. The insight provided by these magmatic gases is important for long-term monitoring of Momotombo, as eruptions from this volcano are explosive in nature, and have occurred at intervals of 3–85 years [*Menyailov et al.*, 1986].

Cerro Negro

Many of the workshop attendees also spent a day conducting measurements and collecting samples on Cerro Negro volcano in Nicaragua, the youngest volcano in Central America. Not only is Cerro Negro one of the most active volcanoes in Nicaragua, it is one of only several cinder cones in the world that is known to have erupted more than once, which makes it difficult to classify as a basaltic cone or composite volcano. In addition, the variability in its eruption style adds to the unusual nature of this volcano. The violent 1992 eruption propelled ash and gases as high as 7.5 km, and caused the evacuation of 28,000 people. The 1995 eruption was less explosive, and was characterized by a lava flow [*Roggensack et al.*, 1997]. Work by *Roggensack et al.* [1997] showed that the difference in behavior is related to the amounts of H_2O and CO_2 that were released prior to eruption. Therefore, long-term monitoring of CO_2 emissions at Cerro Negro may help characterize the amount of degassing prior to eruptions and could serve as a predictive tool. This is also a situation in which diffuse soil degassing could be an important tool, as previous work found an anomalously high output of diffuse CO_2 [*Salazar et al.*, 2001].

Póas

The second part of the workshop was held in San Jose, Costa Rica, to focus on Póas volcano. Póas provided a strong contrast to the Nicaraguan volcanoes. It is andesitic, and therefore more characteristic of the subduction zone setting of the Central American chain of volcanoes. The main gas plume of Póas emanates from the acidic crater lake and surrounding fumaroles. The crater lake at Póas is known for its low pH, which was approximately 0.4 during the workshop (M. Martinez, pers. commun., 2003). Póas offered the unique opportunity for the different research groups to sample or remotely monitor its persistent plume, directly sample its fumaroles, and measure diffuse carbon dioxide emissions from an intra-crater terrace.

During the final day of the workshop, the participants met as three informal research groups to summarize and compile the knowledge gained during the workshop for high-temperature fumarole sampling, diffuse degassing, and ground-based remote sensing. In addition, a fourth group met to consider current and future gas sampling approaches and initiatives for Central America and northern South America. This was an effort to build cooperation among volcanic gas scientists from the different countries in the region. Researchers are currently analyzing collected samples and data, and plan to make the results accessible to all workshop participants in a Web-based format to integrate the different areas of volcanic gas monitoring, as well as provide direct sampling data to validate remote sensing results.

The Eighth Field Workshop on Volcanic Gases was held 25 March 2003–2 April 2003 in Managua, Nicaragua and San Jose, Costa Rica, Central America.

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FORUM

Disasters at the Interface of Nature and Society Provoke Thought

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A casual remark, a chance encounter in the corridors of power, decisions made at the administrative level; those are the things disasters are made of. We didn't know this until September 11, 2001.

What is a disaster? Natural and social causes, like separate strands, are closely intertwined. In the 5th century, attributing earthquakes to natural causes was a crime: there is a heresy that claims that earthquakes are supposedly caused by the elements of nature rather than by the righteous judgment and wrath of God, quoth Saint Philastrius. It took 14 centuries to replace this paradigm with another: one should not view God as an irrational being, capable of destroying His own temples, in the words of Camilo Henriquez, S.J., after the 1822 Valparaiso earthquake. This was a giant step forward, but it was not enough. We now realize that all disasters are social, as well as natural.

Bunde et al. [2002] have mounted a resolute attack on the paradigm of natural hazards. They showed that disasters—including earthquakes, terrorist attacks, stock market crashes, epidemics, climate change, oil depletion, and a variety of other calamities—are critical phenomena in non-linear complex systems. They criticize the approach of disciplinary communities accumulating utterly specific knowledge about the specific phenomenon in question, but ignoring the structural generalities this phenomenon may share with critical dynamics observed in many other fields. Is this a fair critique?

Earthquake Hazard

The Federal Emergency Management Agency (FEMA) recognized the likelihood of a large earthquake in Memphis to be substantially lower than it is in San Francisco, yet the IBC 2000 Building Code assigns similar earthquake safety requirements to Memphis and California. *Stein et al*. [2003], *Frankel* [2003], and *Hough* [2003] have plausibly argued for and against this apparent inconsistency. In the meantime, FEMA has been swallowed whole by the Department of Homeland Security as a result of the September 11 attacks. It seems that disasters are affecting us on a rather short time scale.

Geophysical disasters occur in Mexico City today at a rate of a dozen a year and rising. But the American continent was uninhabited 14,000 years ago, and a seismologist working at that time would hardly have been able to foresee the existence of Mexico City. Does it make sense for geophysicists to try to predict events over periods substantially exceeding the human lifespan?

An Earthquake Disaster

The 1985 Mexico City earthquake disaster was caused by an unforeseen, monochromatic coda wave of very long duration. It was identified immediately after the earthquake [e.g., *Lomnitz and Castaños*, 1985], but there is no agreement about its nature and origin. The wave is only found on a local layer of soft mud. Efforts to reproduce the observed signal by linear modeling have not been very successful [*Chávez-García and Salazar*, 2002].

One explanation has to do with the possibility that sedimentary basins may act like non-linear complex systems. A Rayleigh mode might transfer energy by coupling to a resonant mode of the same frequency or phase velocity [*Butler and Lomnitz*, 2002]. Although "scientists working on fluid dynamics and plasma and solid-state theory have developed a multitude of new methods to deal with nonlinear waves" [*Infeld and Rowlands*, 2000], such a scenario is not easy to confirm. We are schooled to look for non-linear explanations only as a last resort, after the possibilities of a linear paradigm have been exhausted.

Why? Isn't non-linearity the rule and linearity the exception? Once a cause is positively identified, damage from future earthquakes can be forestalled. The rewards of recognizing the cause of earthquake disasters may be great. If resonance on soft ground is the cause of collapse in Mexico City, fluid-viscous dampers can be installed in future or existing high-rise buildings to filter out the noxious ground frequency. In principle, Mexico City could be made as safe against earthquakes as, say, London or New York. The same goes for Memphis or San Francisco.

Could a similar approach work in all types of disasters? Or do terrorists have better minds than their potential victims?

The World Trade Center Disaster

Perhaps we are not asking the right questions. Complexity is the ability of a system to display long-range coherence in space and time and to undergo transitions between different states [*Davies*, 1989]. In this sense, the Twin Towers behaved as a complex system. They remained standing for an hour after impact. Why not 10 hours, or 10 days, or 10 months? This question has not been exhaustively considered. Let us attempt a brief analysis.

- Disasters should always be defined "on specific space-time scales" [*Bunde et al*., 2002]. This means that disasters have a history. The original World Trade Center (WTC) architectural competition called for an 80-story structure, but the architects were asked to change the design to 110 stories. This called for a different structural approach.
- The purpose of the decision to increase the height of the WTC was to make it the tallest building on Earth. But the WTC was founded on artificial fill borrowed from the