A New Recipe for Cooking Up A 'Mini Solar System'

SAN FRANCISCO, CALIFORNIA—A record 9300 earth, ocean, atmospheric, and planetary scientists gathered here last month for the union's fall meeting.

The four large Galilean satellites of Jupiter look like a doll's version of our solar system. But planetary scientists now doubt that the two systems could have formed in the same way.

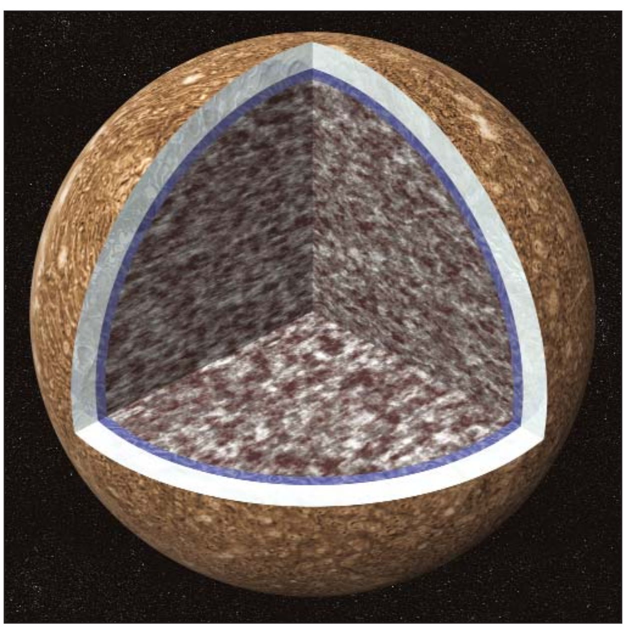
According to the conventional view, the jovian system got its start when Jupiter was still in the midst of forming. All the necessary ingredients were thrown into a seething ringlike disk orbiting the young planet, and the planetary bodies glommed together in a geologic instant. But although the solar system may have formed by that dump method, data from the Galileo spacecraft rule it out as an explanation for the jovian satellite system. Outermost Callisto, it turns out, is just too immature.

At the meeting, planetary dynamicists Robin Canup and William Ward of the Southwest Research Institute in Boulder, Colorado, offered a new recipe for the jovian satellites: Slowly dribble the makings into a thin gruel of a disk orbiting a nearly complete Jupiter. The resulting gradual accumulation of satellites would keep the mix from overheating and solve a number of problems, including Callisto's immaturity.

Galileo the spacecraft—named for the astronomer who lent his name to the large jovian satellites—flew close by each moon and measured the subtle variations in their gravitational pulls that reveal the nature of their interiors (*Science*, 13 June 1997, p. 1648). Innermost Io is all rock, Europa is mostly rock with a rind of ice and water, and Ganymede and Callisto are roughly half rock and half ice. Ganymede's rock separated from its accompanying ice to form a central core, but Callisto's rock never fully separated, remaining dispersed through its ice.

That's all wrong for the dump method of satellite formation. A dense disk of gas and solid debris circling a nascent Jupiter would likely have hit 1000°C—too hot for new satellites to retain much water. And the Galilean satellites would have formed in 1000 years or less, so fast that heat would have built up from the fiery impacts of rock and ice feeding satellite growth. Such high temperatures drive the separation of rock and ice. To make matters worse, any disk of orbiting gas and debris will drag a body growing within it inward toward the central body. The more massive the disk, the faster the migration; a conventionally massive disk would have dragged Galilean-size satellites into Jupiter in just 100 years.

A calmer, gentler satellite kitchen seemed in order after the Galileo mission's discoveries. Both planetary physicist David Stevenson of the California Institute of Technology in Pasadena and Canup and Ward concluded that the Galilean satellites were more likely to have formed slowly, late in the formation of Jupiter. After perhaps uncounted satellites had rapidly formed in a dense disk and been dragged to oblivion, Jupiter would have largely cleared away the gas and debris in its orbit that had been feeding the disk, although a trickle would have continued. Canup and Ward liken the process to water passing through a mineral-encrusted pipe. The water in the pipe at any one time couldn't have delivered the mass of minerals, but given time, the deposition of minerals from slowly flowing water could.



No chewy center. Jupiter's moon Callisto never separated its ice and rock to form a core, pointing to a gentler formation.

Canup and Ward have now done detailed calculations of the starved-disk conditions needed for the Galilean satellites to form. They find that the satellites could have grown as the last 1% or 2% of Jupiter's mass funneled through a disk orders of magnitude less massive than the earlier disk. Satellite formation could have taken 100,000 years or more rather than a millennium. Such a "slow-flow" process would have allowed time for a growing moon to lose heat and keep temperatures low enough to form the icy satellites. Lower temperatures would also have allowed Callisto's rock and ice to avoid complete separation. And a lightweight disk would have slowed inward migration of nascent moons enough to preserve them until the disk finally dispersed.

Canup and Ward's approach "leads to satellites that match all the present observational characteristics of the Galilean satellites," says planetary dynamicist Stanton Peale of the University of California, Santa Barbara. "I don't see any caveats to be raised." What the starved-disk model could use is more tests against observational constraints. That could come next year, when the Cassini spacecraft arrives at Saturn and Titan, its lone large satellite.

Volcanic Blasts Favor El Niño Warmings

What could a fiery erupting volcano have to do with El Niño's gentle ocean warmth? A good deal, according to a new statistical analysis presented at the meeting.

The new comparison of the timing of large tropical eruptions relative to ocean warmings during the past 300 years shows that an eruption doesn't trigger an El Niño every time, as some had argued. It does appear to double the chances of an El Niño in subsequent years. Aside from giving forecasters an occasional edge, the finding supports a controversial proposal that global warming will push the eastern tropical Pacific toward cooler, La Niña conditions, rather than making it more like El Niño.

The idea that volcanoes could trigger El Niños came to the fore after El Chichón's 1982 "eruption of the century" in Mexico ushered in the "El Niño of the century." Some speculated that the haze of volcanic debris thrown into the atmosphere triggered the tropical ocean warming by changing where and how much the sun heats the atmosphere or ocean. But the specific mechanisms offered were unconvincing, and there were too few possible eruption–El Niño pairs in the historical record to persuade anyone that it wasn't all just a coincidence.

Statistical climatologists Brad Adams and Michael Mann of the University of Virginia, Charlottesville, and Caspar Ammann of the National Center for Atmospheric Research in

Boulder, Colorado, took up the challenge, which included correlating 300-year records of El Niño and tropical volcanic eruptions developed by others since the 1980s. Independent records of volcanic activity included volcanic dust preserved in glacial ice and geologic evidence of the explosive power of specific eruptions. The researchers found up to two dozen large tropical eruptions, depending on the definition of "large." And Mexican tree-ring widths and global paleoclimate patterns served as more or less independent proxies for the climate state of the tropical Pacific: warm and El Niño–like or cooler and La Niña–like.

Using the statistical technique called "superposed epoch analysis" to gauge the likelihood that an eruption–El Niño pair was more than mere coincidence, Adams and his colleagues found that "the probability of finding an El Niño in the first year after [a large tropical eruption] is about twice as large as it is overall," says Mann. The odds go from a random 20% chance of an ocean warming in the next year—with all its associated climate effects around the globe—to a 40% chance following an eruption.

This volcano–El Niño link is statistically robust, say Adams and his colleagues, and they bolster their argument with a plausible mechanism. El Niño modelers Mark Cane of Columbia University's Lamont-Doherty Earth Observatory in Palisades, New York, and Amy Clement of the University of Miami have suggested that—contrary to most climate models—global warming would not push the tropical Pacific into a broadly warmer, more El Niño–like state, permanently skewing world climate in El Niño–type patterns.

Their counterintuitive argument is that more warmth over the tropical Pacific would lead to a permanent tendency toward a La Niña state—warm in the west and cold in the east. In the east, wind-driven upwelling of cold water from the depths stabilizes the temperature and resists the warming, they said. That forces the tropical Pacific to do all its warming in the west and increases, rather than decreases, the east-west temperature difference. Similarly, Mann notes, the general cooling induced in the lower atmosphere by high-altitude volcanic haze blocking sunlight should cool the stable eastern tropical Pacific less than the west. That would decrease the Pacific's east-west temperature difference so that it resembles the broad warming of an El Niño.

The new analysis is a breath of fresh air for researchers pondering whether there's a link between the two phenomena. Climate researcher Alan Robock of Rutgers University, New Brunswick, says the new result "certainly seems plausible. They looked at a much longer time period, giving them a better chance to pick a weak signal out of the noise." The new mechanism also seems reasonable, he says. But he's not yet won over: "Does the real climate system work that way?" Robock and others say the next step is linking a volcano's fiery eruption to a model that depicts the behavior of the tropical Pacific.

Weathermaker. Tropical volcanoes such as El Chichón blast debris into the stratosphere that can encourage El Niño and its perturbations of the weather.

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Another Way to Take The Ocean's Pulse

Climate change may be slowing the heart of the ocean's globe-girdling circulation system, says a new study, with possible unpleasant effects for some nations bordering the North Atlantic.

Oceanographers have long had trouble gauging the ponderous flow of the ocean's "conveyor belt" that carries southern heat northward before sinking into the depths beyond Iceland. If computer simulations of global warming are correct in suggesting that it might already be slowing, the result could be an ice age chill in this century for northern Europe (*Science*, 27 September 2002, p. 2202). At the meeting, a group of oceanographers from the University of Bremen, Germany, proposed a sensitive means of gauging the conveyor's changing speed by simply measuring temperatures about a kilometer down in the tropical South Atlantic. A 50-year record of these temperatures hints that the conveyor belt may indeed be slowing.

Carsten Rühlemann and his Bremen colleagues looked to the south because that's where the conveyor's upper-ocean currents pick up heat as they head north and join the Gulf Stream. They eventually lose their heat and sink in the far North Atlantic before heading back south as deep, cold currents. Physical oceanographers have occasionally measured the southward flow of conveyor water through the deep passages to either side of Iceland with current meters or indirectly by measuring the distribution of density that drives deep currents. In fact, the strand of the conveyor to the east of Iceland does seem to have slowed in recent decades, but there are several strands, and year-to-year and decade-to-decade fluctuations in flow occur that may have nothing to do with changes driven by global warming. However, frequent, comprehensive surveys would be expensive.

As a supplement to North Atlantic observations, Rühlemann and colleagues suggest monitoring the buildup of heat in the south. A slowed conveyor would be able to carry away less heat into the North Atlantic, the way a slowed flow to your shower would draw less heat from your water heater. The upper South Atlantic could then warm, the way the water heater could get hotter without the extra drain on its heat. A model ocean behaved just that way when its conveyor was slowed, the group reported. And the real ocean did, too, during Earth's last deglaciation. Isotopic temperature records preserved in sediments bathed in northbound currents on either side of the tropical South Atlantic show "rapid and intense" warming at the same times that the conveyor slowed abruptly 16,000 and 12,000 years ago, they reported.

Looking at modern records, the Bremen group found an irregular warming of 0.1°C to 0.2°C during the past 50 years in the waters of the northbound conveyor. "That might be a first sign that the [conveyor] water is responding to climate change," says Stefan Mulitza of the Bremen group.

Physical oceanographer Robert Dickson of the Fisheries Laboratory in Lowestoft, U.K., and other physical oceanographers hope to find more than a temperature shift. They want to see a trend in the density of conveyor waters, which determines how much water sinks at the far North Atlantic turnaround. Density (a combination of salinity and temperature) has been measured only haphazardly over the years. Researchers are gearing up to measure oceanwide flow using clever spot checking on either side of the North Atlantic, but decades must pass for a clear trend to emerge. In the meantime, perhaps southern temperature can help.

–RICHARD A. KERR