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Jupiter's New "Red Oval"

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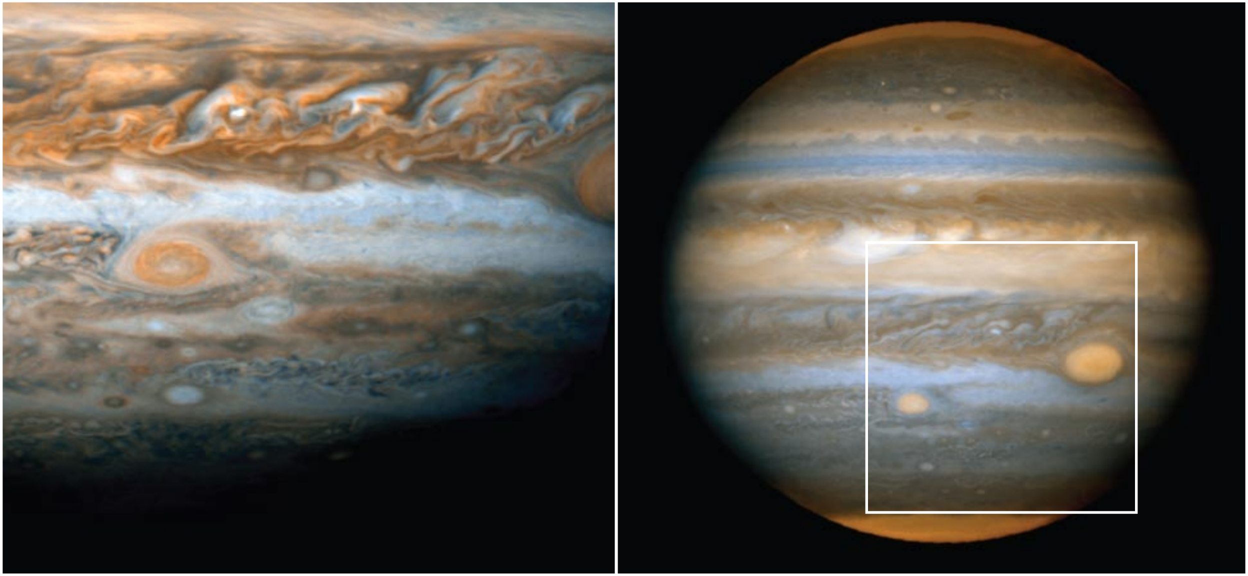
Jupiter has superlative visual appeal and scientific interest. Its size and intricate features—including multicolored bands and spots—have fascinated astronomers and the public for as long as telescopes have delivered Jupiter's disk to the eye. The telescopic view is of cloud tops over a fathomless atmosphere, with no palpable surface beneath. The bands are jet streams, which travel east and west at various rates. The spots are giant swirling storms, located in the turbulent boundaries between jet streams. These storms are unlike any on Earth; they are not driven by the heat of oceans, like hurricanes, nor by unstable weather fronts, like tornadoes. Instead, they are driven directly by Jupiter's jet streams. Because those jet streams persist indefinitely—unlike the transitory ocean temperatures or warm and cold fronts on Earth—the Jovian storms can persist for decades or centuries, and perhaps much longer. Astronomers study such storms on Jupiter to test their theories of weather, atmospheric circulation, and climate change. Sometimes Jupiter shows them an unexpected and potentially instructive event, as when a new red spot was discovered in 2006.

No feature on Jupiter has the strong identity and established longevity of the Great Red Spot. For centuries, astronomers have chronicled its changing position, shape, and size using the best technology of the day: sketchpads, photographs, and, most recently, digital images from *Hubble*, as well as from ground-based observatories, deep-space probes, and even the backyard telescopes of myriad amateur astronomers. Until recently, the Great Red Spot was the only one of its kind. Now, it has a likeness: a *second* red spot, gliding along just to its south. This new feature is so young that its name is still unsettled—"Redspot Jr.," "Oval BA," and "Red Oval" are current contenders.

Unlike the Great Red Spot, whose provenance is lost in astronomical prehistory, the origin and evolution of the Red Oval were well observed from the start. In the late 1930s, astronomers saw the white horizontal band just south of the Great Red Spot break up into three elongated features. In the 1940s, these features contracted into three giant, counterclockwise,

Pages 30–31: Data from two *Hubble* instruments (the Space Telescope Imaging Spectrograph and the Advanced Camera for Surveys) are combined in this spectacular image of the planet Saturn. The blue light encircling the pole is Saturn's equivalent of the Earth's aurora borealis.
Left: Jupiter's new red oval is seen toward left of center in this *Hubble* image. Its more famous cousin, the Great Red Spot, is partially seen farther to the right. The formation of the new oval, which is approximately the size of Earth, is described in this article.



Jupiter's Great Red Spot and new Red Oval as observed by *Hubble* on April 8, 2006 (left) and April 16, 2006 (right).

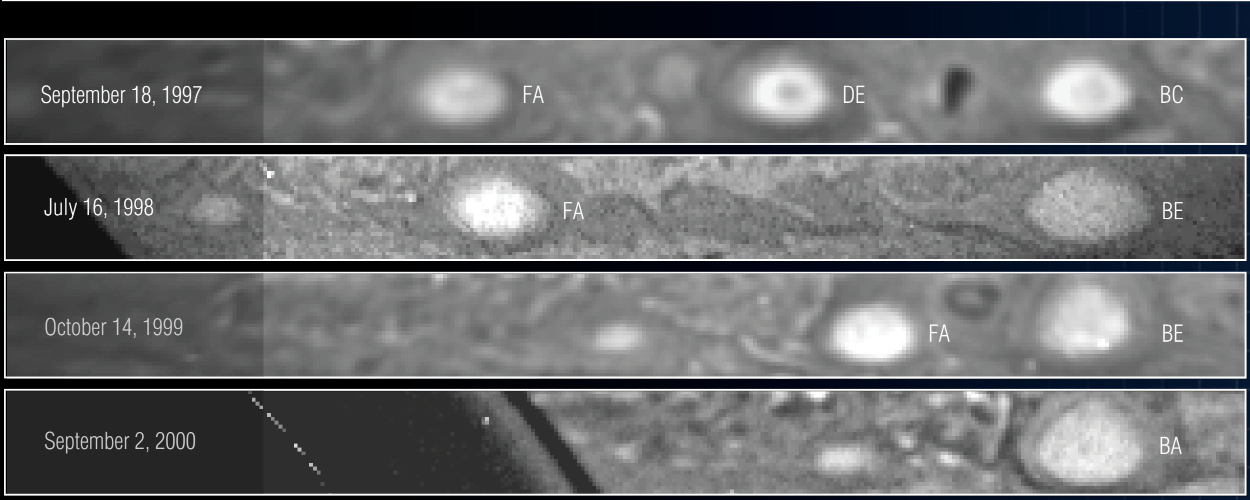
swirling storms, which were named "White Ovals." Filamentary clouds developed in each of the three gaps between the White Ovals. Later, it became apparent that each of the filamentary clouds was associated with a *clockwise* storm. (This association was difficult for scientists to make, because the Great Red Spot and the White Ovals had led them to expect that Jupiter's storm clouds would be bright, compact and oval, not extended and wispy.) These clockwise storms were arranged with respect to the White Ovals as the storm C is with respect to storms A1 and A2 in the second sidebar figure on page 39, that is, each White Oval became separated from its neighboring White Oval by one of these storms.

In the following decades, the three White Ovals shared the same latitude, but they were usually widely separated in longitude. Indeed, they seemed to repel each other when they came too close (but were, in fact, repelled by one of the intervening clockwise storms). Around 1996, a pair of White Ovals bunched up, trapping one of the clockwise storms between them. This trio paraded eastward for months, seemingly a bound unit. In 1998, the two White Ovals in the group merged into one storm, which in spring 2000, merged with the other remaining White Oval. Shortly after that, the solo White Oval became notably rounder than any of its progenitors or the Great Red Spot.

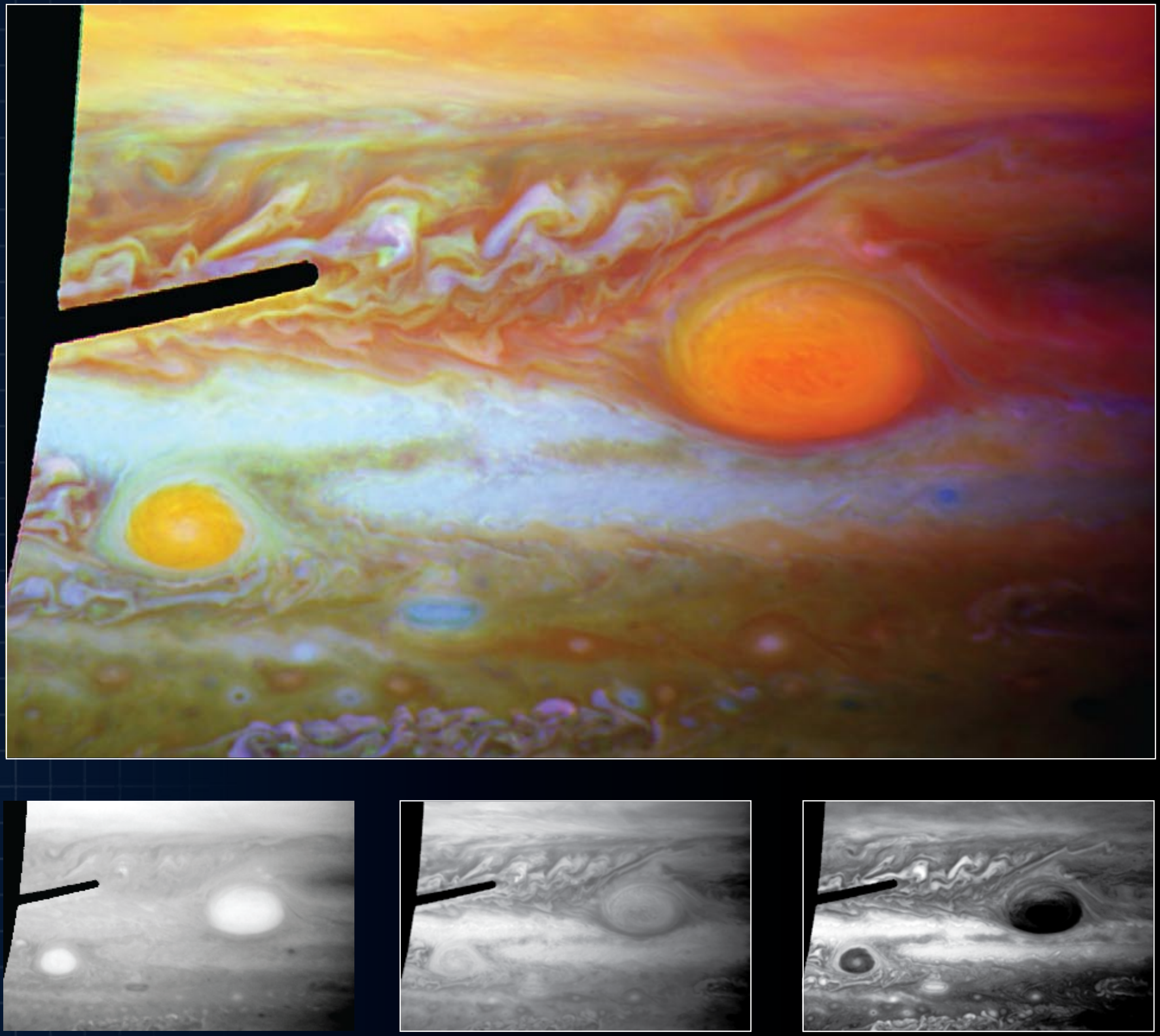
On February 24, 2006, Filipino amateur astronomer Christopher Go alerted the Association of Lunar and Planetary Observers that the solo White Oval had changed color to red. The news swept through the community of amateur and professional Jupiter watchers, who quickly confirmed the finding. Shortly thereafter, the Director of the Space Telescope Science Institute approved two requests for observations by *Hubble*'s Advanced Camera for Surveys to obtain a sequence of images at several wavelengths of the Great Red Spot and the new Red Oval.

Astronomers generally agree that the whiteness of Jupiter's white features is due to ammonia ice. Surprisingly, no one knows for certain what causes the redness of the Great Red Spot and the Red Oval. The most likely cause is a coloring agent or "chromophore" contaminating the ice particles in the clouds.

In the 1970s, atmospheric chemists proposed that Jupiter's red chromophore originates with phosphine gas, PH_3, a colorless, flammable, poisonous gas. Astronomers had detected PH_3 on Jupiter, and the *Cassini* spacecraft, which flew by Jupiter



Merger sequence of the three original White Ovals. In the late 1930s, these latitudes became white—completely around the planet—perhaps because they became clouded over. Shortly after, the white strip was pinched at six points, which were labeled A to F. These pinches broadened until they created separate sections, which were labeled by their end points: FA, BC, and DE. During the 1940s, these sections shrank in longitude until they formed ovals. In 1998, BC and DE merged, forming BE. In 2000, BE merged with FA, forming White Oval BA, which changed color in late 2005 or early 2006, and now merits the name Red Oval.



892 nm - Methane

550 nm - Visible Light

330 nm - Ultraviolet

Family portrait of the Great Red Spot and the Red Oval obtained by *Hubble*'s Advanced Camera for Surveys on April 24, 2006. The red-green-blue composite image was constructed from individual exposures through filters at nominal wavelengths 892 nm (“red,” methane absorption), 550 nm (“green,” visible light), and 330 nm (“blue,” ultraviolet light). The brightness of the two storms in the absorption band of methane indicates less light is lost going in through the atmosphere to the cloud top and back out than going to the clouds surrounding the storm and back out. In other words, the tops of the clouds in the storms are significantly higher than those of the surrounding clouds. (The black protrusion is an instrumental artifact.)

in late 2000, found it to be more abundant above the Great Red Spot than at other locations. In this theory, ultraviolet light from the Sun helps convert PH_3 to the chromophore, which is the red form of the phosphorous molecule P_4. Other scientists have challenged this theory, saying that phosphine is more likely to react with the methane and ammonia in Jupiter's atmosphere to form other compounds.

More recent studies suggest that the chromophore is pure sulfur in the form of various chain- or ring-molecules, which vary in color from red to yellow. In this theory, the source of sulfur is particles of ammonium hydrosulfide, NH_4SH. Vertical winds in the Great Red Spot and Red Oval would loft the NH_4SH particles high enough for ultraviolet light to break them up, and subsequent chemical reactions would produce the long molecules of liberated sulfur atoms.

Assuming that a chromophore is implicated in the color change from White Oval to Red Oval, there are at least three possibilities for *why* the change occurred—including some combinations of the three. First, the cloud top of the White Oval could have initially been below the level of a chromophore in a higher atmospheric layer, but then the cloud top rose, permitting mixing, interaction, contamination, and color change. Second, the storm could have become more efficient in dredging up the coloring agent (or its antecedents) from a deep layer, increasing its abundance in the cloud tops. Third, a temperature change at the latitude of the Ovals could have increased the abundance of the chromophore, because the chemical reactions producing it are expected to depend strongly on the ambient temperature.

All three possibilities are consistent with a conjecture by one of the authors (PM) that Jupiter is entering a period of climate change precipitated by the merging of the three White Ovals. "Climate" means the global distribution of temperature. Before the mergers, astronomers had observed that Jupiter's cloud-top temperatures were nearly the same at all latitudes, even though the Sun deposits much more heat at the equator than at the poles. This observation implies an efficient mechanism to transport heat away from the equator, which, if blocked, could cause the temperature at the poles to fall by 10° C or more.

Simulations of Merging Storms

Using computers, scientists can simulate the fluid dynamics of Jupiter's atmosphere, including the effects of rotation, gravity, and gas physics. One goal is to provide a qualitative understanding of merging storms.

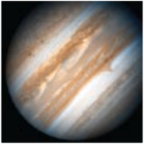
The simplest simulation involves giant, counterclockwise, swirling storms in a row, at the same latitude, between two opposite jet streams. In general, such storms will move with the local jet velocity, which here, midway between the jets and at the initial latitude of the storms, is zero. If left undisturbed, this initial situation would not change: the storms would maintain their separations and not merge. This situation is fundamentally unstable, however, because the smallest perturbation will lead to a merger. In the first panel, if the storm A2 moves slightly upward in latitude, it is carried to the left in longitude by the jet stream above it, following the dashed path. The opposite displacement of A1 produces the opposite effect. The separation between A1 and A2 becomes less than a storm's diameter within weeks. After that, the A1 and A2 quickly merge into a single storm—"A12," using the nomenclature of the White Ovals. This result is *contrary* to the observations that giant, counterclockwise, swirling storms on Jupiter can persist for many decades.

If two plausible features are added to the simulations, the merger of A1 and A2 can be prevented. The first is a giant, *clockwise*, swirling storm C above A1 and A2, like was observed above BE and FA in the period 1996–1998. The second new feature is a bend in the jet stream below A1 and A2, like the waves often observed in the Earth's jet stream. Such bends have been observed corralling storms. Simulations show that this configuration of storms and jet streams is stable for long periods of time, with the positions of the storms oscillating around a neutral point. For example, if storm A2 is perturbed upward, the jet stream above it moves it left, as before, but then it is carried downward by the clockwise flow around C, until the bottom jet stream moves it right again, and the upward swing of the bend brings it back to its original position.

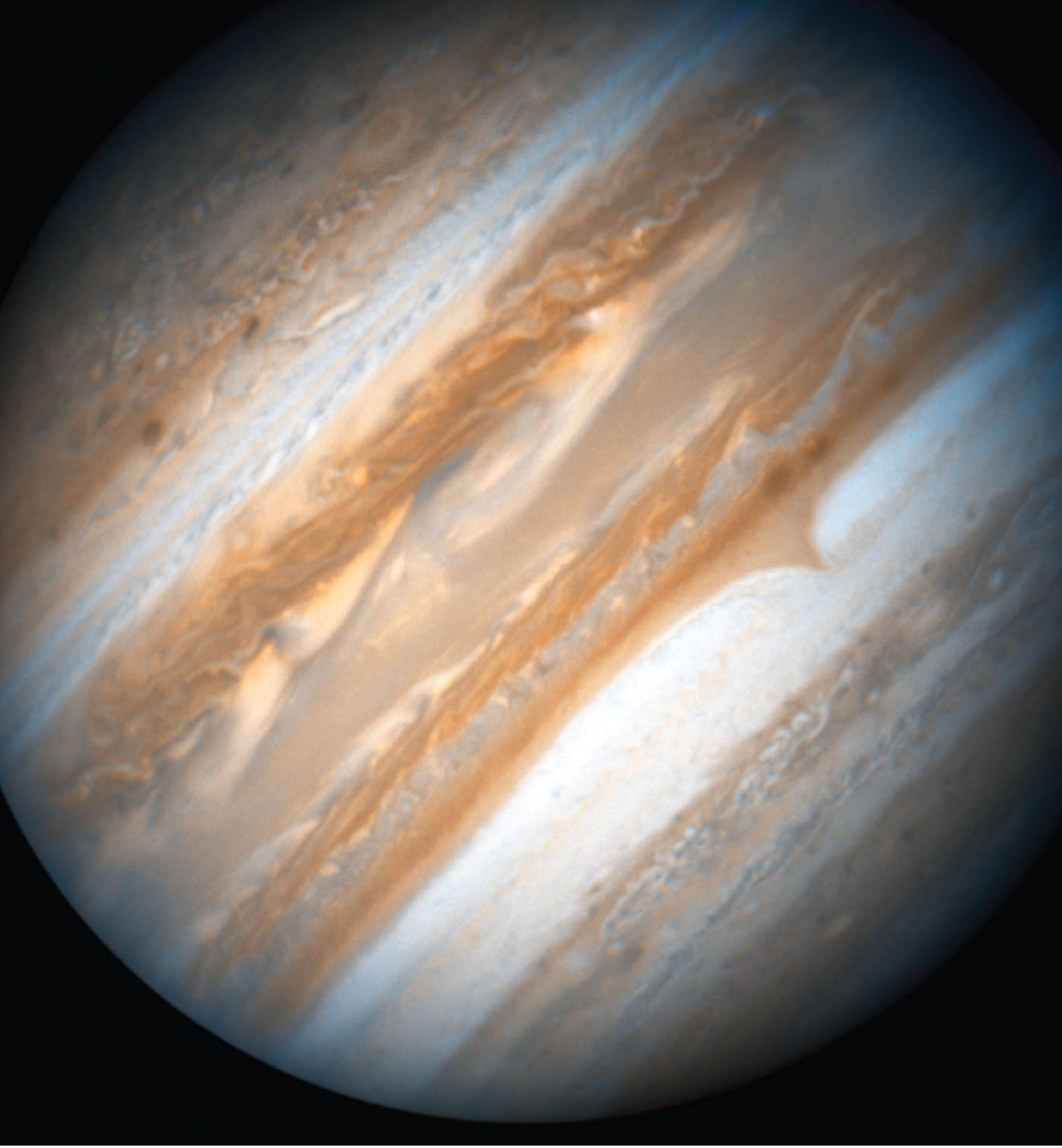
The position of storm C is constrained less strongly than A1 and A2. A minor perturbation, such as a collision with a rogue storm, can dislodge it from its position. In that case, simulations show that A1 and A2 quickly come into contact and merge.

Numerical calculations show that the stirring action of the three large, counterclockwise, vigorously spinning storms could easily account for the needed heat transport—but that a solitary White (or Red) Oval could not. The earliest effects of blocking the heat transport system in 1998–2000 were predicted in 2001 to start becoming visible in 2006, taking into account a time lag for the atmospheric temperature to respond to the change in heating. Some of the more striking predictions were large waves on the jet streams and the formation of new storms, which would be eminently detectable by *Hubble*. These new features have not yet been observed, so it is an open question whether the color change of the new Red Oval was a random local event with no wider ramifications, or whether it was a consequence of blocked heat transport and therefore, a harbinger of more changes to come. *Hubble*'s watchful eye on Jupiter should help settle this question.

The *Hubble Space Telescope* is the premier observatory for observing unexpected phenomena on Jupiter—like the crash with Comet Shoemaker-Levy 9 in 1994 and the color change of the White Oval observed in 2006. No other telescope offers the same combination of synoptic perspective with the ability to capture exquisite detail over a wide range of wavelengths. These unsurpassed qualities have allowed astronomers to witness rare events and obtain unique data records of the highest quality, which will advance understanding of the ever changing and always intriguing Jupiter.

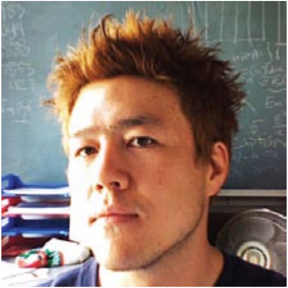


Page 40: The ever changing cloud patterns of the giant planet Jupiter are the subject of this article. This *Hubble* image shows the planet's trademark belts and zones of high- and low-pressure regions in crisp detail. Careful study of these features results in a better understanding of planetary atmospheres—including our own.



Imke de Pater is a Professor in the Department of Astronomy and Department of Earth and Planetary Science at the University of California at Berkeley. She started her career observing and modeling Jupiter's synchrotron radiation, and later, she studied the planet's thermal radio emission. In 1994, she led a worldwide observing campaign on the impact of comet D/Shoemaker-Levy 9 with Jupiter. Currently, she uses adaptive optics in the infrared range to obtain high angular resolution data on a variety of planetary phenomena, including volcanoes on Io, weather on Titan, planetary rings, and Jupiter's new Red Oval. She and Jack Lissauer wrote the graduate-level book, *Planetary Sciences*. Professor de Pater was a Carolyn Herschel Distinguished Visitor at the Space Telescope Science Institute in 2006.

Philip Marcus is a Professor of Fluid Dynamics in the Department of Mechanical Engineering at the University of California at Berkeley. He has a long-standing interest in the theory, modeling, and numerical simulation of the dynamics of Jupiter's atmosphere, including its Great Red Spot and long-term climatic change. His other astrophysical interests include the dynamics of fluids and dust in the formation of stars and planets. His overarching goal is to understand how the fundamental physics of turbulence, chaos, and nonlinear dynamics, which are inherent to fluid dynamics, operate in astrophysical phenomena. To complement his theoretical and computational analyses, he works closely with laboratory experimentalists, often co-designing laboratory experiments that test or elucidate basic astrophysical processes involving fluid flows.



Mike Wong is a Research Scientist in the Department of Astronomy at the University of California at Berkeley. His interest in cloud-forming gases in Jupiter's atmosphere began with analyzing data from the mass spectrometer on the *Galileo* probe. Later, he participated with the investigator team for the Composite Infrared Spectrometer on *Cassini* in the discovery of the signature of ammonia ice in Jupiter's thermal spectrum. With Franck Marchis, he discovered the first moonlet binary among the Trojan asteroids, a large group of objects that share the orbit of Jupiter around the Sun.