Research News

Voyage to a Blue Planet

As in its previous encounters with Jupiter and Saturn, Voyager 2 provided an abundance of data at Uranus—and a generous helping of surprise, puzzlement, and wonder

WHEN the Voyager 2 mission scientists gathered at the Jet Propulsion Laboratory in Pasadena, California, for the spacecraft's late-January encounter with Uranus, they were presented in quick succession with one rakishly tilted magnetic field, one perversely circulating atmosphere, an ever-increasing number of charcoal-black rings, and five inexplicably dingy moons—three of which seemed highly improbable when examined up close, and two of which seemed flatly impossible.

Thus, when one reporter demanded to know why the researchers were still professing bewilderment "after all this time"—the time being 2 days after Voyager's closest approach to Uranus on 24 January—chief mission scientist Edward C. Stone of the California Institute of Technology could only laugh: "We're happily bewildered! If you understand something the first time you see it, then you probably knew it already. So in a sense, the more bewildered we are, the more successful the mission was."

By that measure, or any other, the Uranus encounter was very successful indeed.

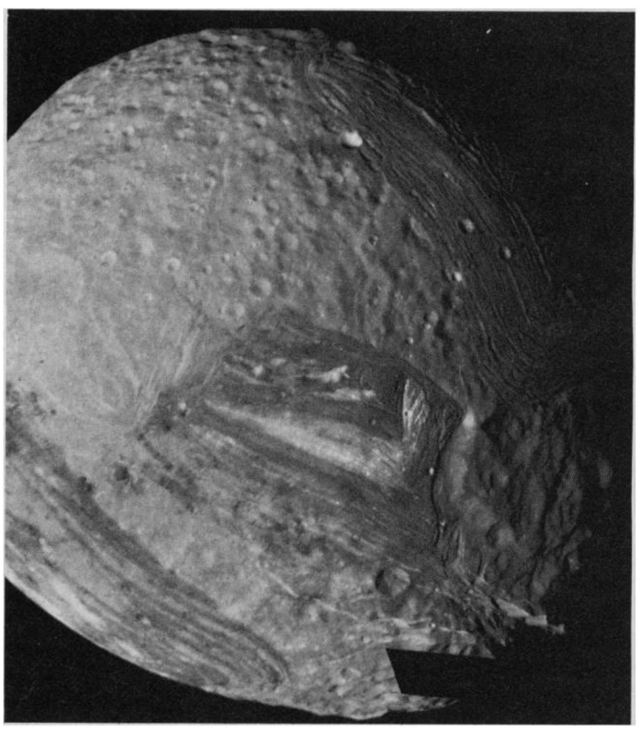
In retrospect, of course, some surprises were inevitable during this encounter simply because so little was known about Uranus beforehand. The planet was not even discovered until 13 March 1787, when Sir William Herschel found it by accident as he was surveying the sky for double stars. And even now, as assistant imaging team leader Larry Soderblom points out, observing Uranus from Earth across a distance of nearly 3 billion kilometers is like observing a pea across the length of five football fields. The planet is so far from the sun that Voyager's radio signals took 2 hours and 45 minutes to make the journey home, traveling at the speed of light. Sunlight is so faint at Uranus—roughly 1/400 its strength at Earth—that new engineering routines had to be worked out to stablize the spacecraft for long exposure imagery. The on-board computers had to be reprogrammed with sophisticated data compression techniques in order to cram more information into a fainter signal. And the receiving antennas here on Earth had to be linked together in arrays to reliably capture that signal.

On the other hand, the few facts that were known about Uranus prior to the encounter did point to a certain peculiarity. Consider the axis of rotation, for example: unlike all the other planets, whose axes are more or less perpendicular to the plane of their orbits (the plane of the ecliptic), Uranus is lying on its side with its axis *in* the plane. At the moment, in fact, its south pole is pointed almost straight at the sun, while its satellites and rings circle the equator as if tracing out a bull's-eye. The presumption is that something huge hit Uranus very early in its development and knocked it out of alignment. But nobody knows what that something was, or what other effects the collision might have had on the planet.

A more subtle peculiarity is Uranus' structure and composition. The first two planets visited by Voyager 2, Jupiter and Saturn, are in many ways a matched pair. They both have cores of silicate rock and other heavy compounds comprising roughly 25 Earth masses, and they both are swaddled in thick blankets of hydrogen and helium gas. Their total masses are respectively 318 and 95 times the mass of Earth; not surprisingly, they are known as gas giants.

Uranus, Voyager's third port of call on a Grand Tour of the outer planets that will take it on to Neptune in 1989, can also be classified as a gas giant. But it is a strikingly different subspecies of giant, in the sense that it has a much less massive hydrogen/helium atmosphere relative to its heavy core. In this respect Uranus is a near-twin of Neptune; their masses are respectively only 14.5 and 17 times the mass of Earth. One of the fundamental challenges of planetary science is to understand why these four gas giants—Jupiter, Saturn, Uranus, and Neptune—have cores that vary in mass by only a factor of 3 or 4, and gaseous envelopes that vary by a factor of 10 to 20.

While Voyager will certainly not answer that question by itself, it did provide one important piece of information about the internal structure of Uranus when it detected a substantial magnetic field around the planet, comparable in strength to the fields around Saturn and Earth. Since astrophysical magnetic fields are thought to result from convective motions within a mass of electrically conducting fluid—molten iron in Earth's core, for example, or hydrogen plasma in the center of the sun—the implication is that Uranus contains a substantial body of such fluid in its core.



The patchwork moon

Uranus' tiny moon Miranda, photographed by Voyager 2 at a resolution of less than a kilometer, may have accreted from the pieces of a shattered predecessor.

By itself, of course, this finding was more gratifying than it was surprising, since theorists have long suspected that Uranus has a conducting core. Starting with the known cosmic abundance of the elements, their models of the early solar system suggest that a planet forming at Uranus' distance from the sun would have incorporated "rock"—that is, silicate compounds and other heavy elements—and water ice in roughly equal amounts. Their models of Uranus itself therefore call for three layers: a central core of heavy, rocky material; a mantle of water around the core forming an "ocean" thousands of kilometers deep; and finally, the previously mentioned atmosphere of gaseous hydrogen and helium extending outward for thousands of kilometers more.

This Uranian ocean, which likely contains substantial admixtures of methane and ammonia as well as water, is under enormous pressure from the weight of the overlying material and has a temperature of several thousand degrees kelvin. Under those conditions, explains Caltech's David Stevenson, the available data suggest that the water molecules will dissociate into hydronium and hydroxide ions, while the ammonia molecules produce ammonium ions and protons. (Methane may break down entirely.) Thus, the Uranian ocean is almost certainly electrically conducting—"The stuff is almost behaving like molten salt," Stevenson notes—and may even be metallic near the center.

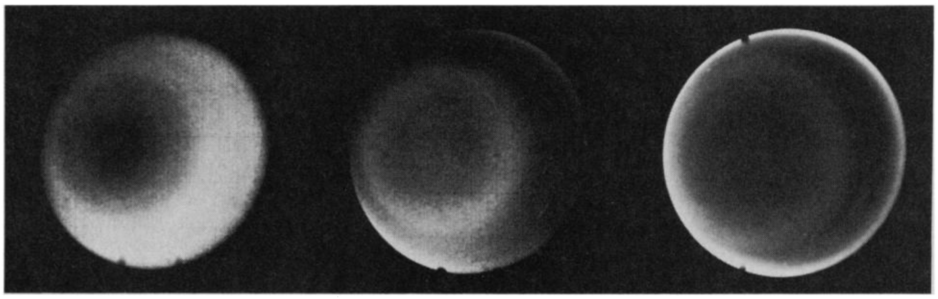
However, while the existence of the Uranian magnetic field was not particularly surprising, the *orientation* of that field was astonishing: Voyager found that it is offset from the planet's axis of rotation by 60 degrees, which makes it by far the largest such offset in the solar system. (Earth's field is tilted only 11 degrees.) In this respect, Uranus more closely resembles the so-called "oblique rotators" seen in other astrophysical contexts, such as neutron stars. Is the field going through the same kind of magnetic reversal that Earth seems to experience every half million years or so?

The tilted field does produce one effect that is both amusing and informative. Just as happens at the Earth and all the other planets, Uranus has its field swept back into a long "magnetotail" by the wind of charged particles streaming from the sun. However, because the field is so sharply tilted, the magnetotail gyrates like a corkscrew. The effect is that of a child twirling the end of a garden hose to make a spiraling stream of water. These gyrations have the invaluable property of precisely following the rotation of the planet's core, since that is where the field is generated. An analysis of the field data therefore yields the rotation period of the planet as a whole—a quantity that is otherwise very hard to come by on a planet with no solid surface. As discussed below, however, the figure derived from Voyager data, 17.3 hours, poses a considerable challenge for the scientists studying Uranus' atmosphere.

On the inbound leg, at least, the members of the Voyager imaging team found the atmosphere of Uranus to be a study in frustration. The psychedelic cloudscapes of Jupiter and the butterscotch banding of Saturn were nowhere to be seen; the aquamarine face of Uranus seemed less like an atmosphere than like the deep and slowly changing ocean of Earth. The planet is frigidly cold—temperatures at the top of the atmosphere hover around 60 K—and its deep gaseous envelope responds to variations in energy input only on a time scale of centuries. The color comes from methane, which is much more abundant on Uranus than on Jupiter or Saturn. The Jovian-style clouds, if they exist at all, lie so far down in the murk that they are screened from view as effectively as the mountains on the floor of the Pacific. In this context, the Voyager scientists were gratified to find latitudinal banding in the atmosphere. The features were faint, to be sure. But with image enhancements, Uranus turned out to have as rich a set of stripes as Saturn.

Atmospheric banding is thought to be caused by temperature differentials, with regions of upwelling producing high, light clouds or hazes, and regions of downdraft producing low, relatively dark regions. The motions are then deflected into east-west zones by the planet's rotation. There had been some speculation before the encounter that sunlight shining directly on the pole of Uranus might disrupt this organization. However, the only obvious effect found by Voyager was a faint cap of brownish photochemical smog covering the sunlit pole. As imaging team member Garry E. Hunt of the Imperial College, London, pointed out, "The fact that Uranus has bands is a major discovery. It confirms that rotation, not sunlight, determines the motion."

On Jupiter and Saturn, the same forces that produce latitudinal banding also produce jet streams along the edges of the bands. Thus, the Voyager imaging team was eager to find individual clouds so that they could trace the winds of Uranus. Despite their most strenuous efforts at image enhancement, however, they could only find four clouds, lying between 25 and 50 degrees latitude. On the other hand, even with this small sample it was apparent that frigid Uranus possessed a subtle but undeniable vigor: the relative velocities of the clouds are on the order of 100 meters per second, whereas terrestrial jet streams typically reach velocities of only 40 meters per second. Moreover, the clouds themselves resembled terrestrial thunderheads: presumably they were billowing high over some kind of Uranian storm centers.



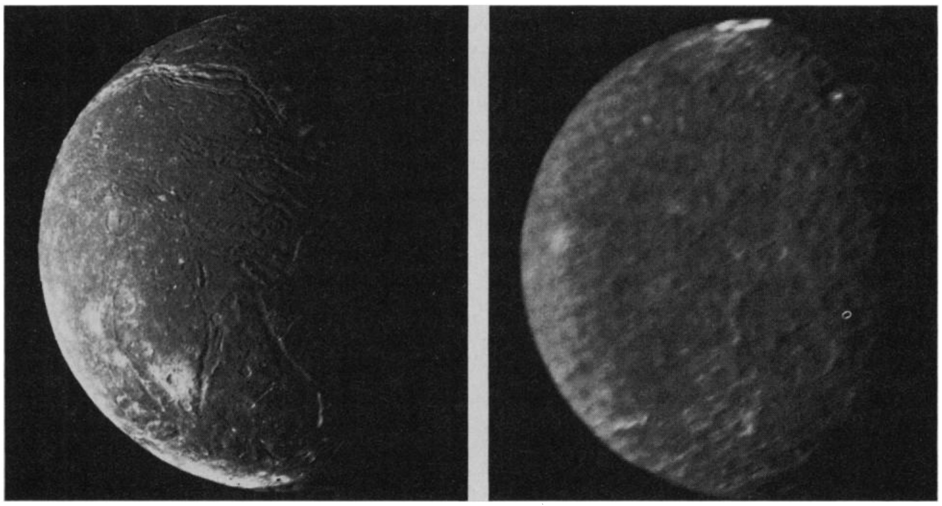
The sunlit pole of Uranus

From left to right, Uranus as seen through Voyager's violet, orange, and methane filters. All three images show faint zonal patterns ringing the pole. The second shows two clouds in the middle latitudes. And the third shows a high-altitude haze brightening the rim of the planet.

An even more striking feature of the winds was their direction. Pre-Voyager models of Uranus had predicted that the equatorial regions would be cooler than the poles by perhaps 5 K, simply because the planet's sidewise orientation allows the poles to receive a slightly greater input of solar radiation over the course of an 84-year Uranian orbit. Standard meteorological theory predicts that in such a situation, the winds at high altitudes should tend to blow in the retrograde direction, or opposite the planet's rotation.

Figuring out the direction of the winds was not quite as easy as it sounds, since the rate at which a cloud circles the planet means nothing until one knows how fast the planet itself is rotating underneath. However, once Voyager's magnetic field data had pegged Uranus' rotation period at 17.3 hours, it was apparent to the imaging team members that the winds of Uranus were resolutely blowing in the *prograde* direction, or in the same direction as the planet's rotation.

On the face of it, this finding suggests that Uranus is warmer at the equator, or just



Ariel and Umbriel: *The two moons are both the same size, about 1200 kilometers, and they occupy adjacent orbits. Yet Ariel (left) has clearly led a more active life. Why?*

the opposite of what the theory predicted—except that the temperature profiles from Voyager's infrared instrument indicated that neither conclusion is correct: the temperature is in fact virtually constant from equator to pole. (The most significant deviation was a band of slightly cooler temperatures between 20 degrees and 40 degrees latitude, possibly indicating a region of updraft.) Presumably, this means that something is going on deep in the atmosphere to redistribute the heat. But what? Clearly, this deceptively bland atmosphere is going to keep the theorists busy for quite awhile.

Because Uranus is tipped on its side, and because its axis currently points toward the sun, Voyager flew through the plane of the rings and satellites as if it were an arrow piercing a target; all the major observations at Uranus thus had to be crowded into one 6-hour interval around the moment of closest approach. By the same token, Voyager had to pass the planet at just the right point, so that Uranus' gravity would swing it around toward Neptune. So the mission planners had very little choice about exactly *where* Voyager pierced the target. They could get closeup, high-resolution imagery of at most one satellite. And as luck would have it, that satellite was Miranda.

Discovered in 1948, 500-kilometer–wide Miranda is the innermost and smallest of the five moons known before Voyager. Like all the other Uranian moons it is largely made of ice, perhaps intermixed with rock and methane frost, and it might easily have turned out to be a boring little sphere pocked with craters. In fact, Miranda is the most disconcerting single object yet seen by Voyager. It is a Rube Goldberg moon, a helter-skelter patchwork of sinuous valleys reminiscent of Mars, grooved terrain that might have come from Jupiter's moon Ganymede, cratered highlands not unlike the highlands of our own moon, shear scarps higher than the walls of the Grand Canyon, and more. "A bizarre hybrid of every kind of exotic terrain in the solar system," Soderblom called it.

Indeed, the word *patchwork* may describe Miranda quite literally. According to the imaging team's first tentative hypothesis, Miranda started out as an iceball much like the other moons. After it had formed, however, and after any rocky material had had time to settle toward the center, this proto-Miranda was disrupted by an impact of some kind. Then, as more time passed, the angular chunks of the original moon came together again. Some chunks were ice-side out; they gave rise to the ordinary-looking terrain. Other chunks were core-side out; these surfaces exposed dark, rocky material and presumably gave rise to the squarish chevron feature in the center of the Voyager images, as well as the much bigger "Circus Maxima" images seen on either limb of Miranda. Needless to say, this scenario needs a lot of work before it can be accepted as anything more than plausible hand waving. But no one has yet come up with a better idea.

The other four large satellites, although not as dramatic as Miranda, are challenging in their own right. Considering that they are made of ice, for example, they are all surprisingly dingy, with reflectivities on the order of 20 percent. On the other hand, the ice may have incorporated a significant amount of methane as the satellites were forming—the surfaces are at roughly 80 K—in which case radiation damage over the 4.6-billion-year history of the solar system could have caused the methane to form darker organic material. (Voyager showed that Uranus' radiation belts do impinge upon the satellites.)

More striking is the fact that, as one moves closer to Uranus, the satellites show signs of increasingly ferocious activity. The outermost moon, Oberon, is heavily cratered and shows almost no evidence of internal activity—except that several of the craters appear to have been flooded with some kind of dark "lava." Is it pure, radiation-darkened methane ice, perhaps?

Titania, the next moon inward, has a similar array of craters. But the Voyager images also showed trenches, scarps, and other subsidence features. Titania and Oberon are both about the same diameter, 1600 kilometers.

Skipping over the next satellite, Umbriel, one comes to the fourth satellite, Ariel. At 1200 kilometers Ariel is slightly smaller than the outer two moons, but it is dramatically more active. The surface is crisscrossed with valleys and fault scarps; moreover, where many of the larger valleys cross their floors are smooth and continuous, indicating that they have been flooded with more of this mysterious, icy "lava." Some observers see signs that the ice has actually undergone glacierlike motion down these valleys.

The innermost of the large satellites is, of course, Miranda.

The question is, Where did a set of iceballs at 80 K get all this energy? Some theorists have argued that sufficient heat could have been generated by tidal interactions among the moons in the distant past, much as tidal interactions are currently heating Jupiter's volcanic moon Io. Caltech's Stevenson also points out that by being as cold as they are, the Uranian moons may actually be *more* active than warmer bodies: at 80 K they can incorporate methane and ammonia ices, which have low melting points and which can therefore produce tectonic activity with very little input of energy.

However, any neat theory of the Uranian moons has to reckon with Umbriel. Orbiting between the two active satellites Titania and Ariel, Umbriel is old, dark, and inert. Its surface appears uniformly saturated with large craters, roughly 100 to 200 kilometers across, and it shows very little variation in color or brightness. Given the energetic goings-on all around, Umbriel is remarkable for its very blandness. Its only idiosyncracy seems to be a white ring, about 150 kilometers across, sitting on its upper edge like a little party hat. Aside from some conjectures about a frost-lined crater, no one has any idea what it is. ■

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ADDITIONAL READING

R. A. Kerr, "Voyager finds Uranian shepherds and a well-behaved flock of rings," *Science* 231, 793 (1986).