The Solar System's New Diversity

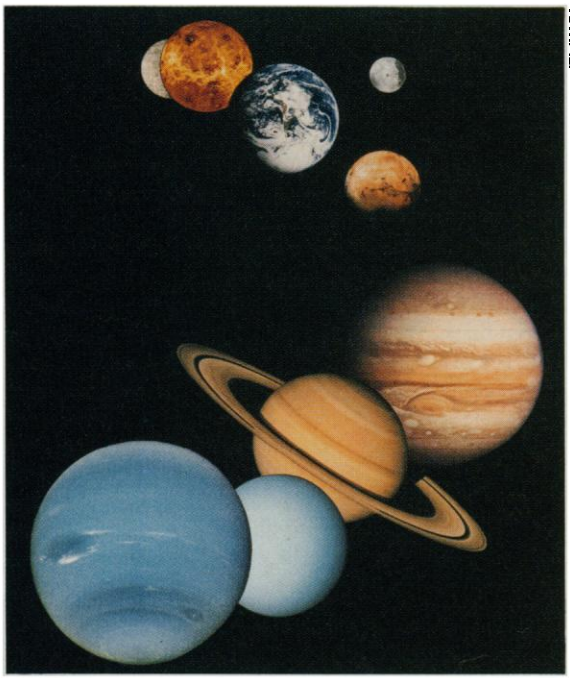
As planetary science enters a new era of long-term, intensive observations, researchers ponder the staggering variety of planets and moons that initial explorations have revealed

The solar system used to be a simple place. Before any spacecraft ventured forth from Earth, Venus seemed likely to be a warmer, wetter version of Earth. Smaller, more-distant Mars seemed chillier and drier, though conceivably habitable. Little Mercury might resemble Earth's moon, only hotter. And the four giant planets—all big balls of gas—presumably were much alike, except that those farther from the sun had less energetic weather.

But 30 years of planetary exploration have replaced that simple picture with a far more complex image. "The most striking outcome of planetary exploration is the diversity of the planets," says planetary physicist David Stevenson of the California Institute of Technology. Ross Taylor of the Australian National University agrees: "If you look at all the planets and the 60 or so satellites, it's very hard to find two that are the same."

Consider the erstwhile "sister planets," Earth and Venus. By now, the U.S. Pioneer and Magellan probes and the Soviet Veneras have shown that, far from resembling our own balmy water planet with its constantly shifting crust, Venus is a bone-dry, fiery hellhole whose surface is locked in an immobile shell. As Stevenson says: "Earth is Earth, Venus is Venus; vive la différence." The Pioneer and Voyager missions to the gas giants, meanwhile, have revealed a panoply of different magnetic fields, atmospheric circulation patterns, planetary heat flows, and internal structures.

Such discoveries are turning the field of comparative planetology on its head, as evidenced by a recent meeting* where the focus was on planetary differences. And along with that reversal have come some lowered expectations. One of the early hopes of planetary exploration was that learning why other planets differ from Earth would feed directly back into our understanding of our home planet. But with few exceptions (see box), such hopes aren't panning out. Planetary geologist Michael Carr of the U.S. Geological Survey in Menlo Park, California, speaks for many of his colleagues when he says, "I wish it were not so, but I'm somewhat skeptical that we're going to learn an awful lot about Earth by looking at other planetary bodies. The more that we look at the different planets, the more each one seems to be unique."



No peas in a pod. From Neptune *(front)* to Mercury, the eight explored planets defy simple classification.

As planetary scientists digest the detailed portrait of Venus returned by the Magellan spacecraft and prepare for similar floods of data from Galileo (when it arrives at Jupiter next year) and Cassini (due to reach Saturn in the next decade), the challenge will be to understand how, as Stevenson puts it, "you can start out with similar starting materials and end up with different planets." Stevenson and others are puzzling out how subtle differences in starting conditions such as distance from the sun, along with chance events like giant impacts early in solar system history, can send planets down vastly different evolutionary paths.

The Earth-centered view of planetary science was articulated most often by the U.S. National Aeronautics and Space Administration's (NASA's) public information machine; comparative planetology was, says Carr, "a buzzword, in part a selling point for the planetary program." Learning more about the chemistry of chlorine in Venus' atmosphere would help unravel chlorine's effect on stratospheric ozone on Earth; study of Venusian atmospheric circulation would yield clues to predicting monsoons over India. But planetary scientists themselves also looked for terrestrial parallels—and were often frustrated.

At the moon, says Don E. Wilhelms, a geologist involved with the Apollo moon missions, terrestrial thinking "misled us more than it helped." Wilhelms, author of last year's *To the Rocky Moon: A Geologist's History of Lunar Exploration*, tells of planning to send Apollo 16 to the Descartes highlands, an area that from Earth, and even from lunar orbit, looked as though it had been created by volcanic activity. But the samples the astronauts brought home told a different story: "They were all impact breccias," debris from meteorite impacts, not volcanoes. As it turned out, "there's almost nothing volcanic on the moon," notes Wilhelms.

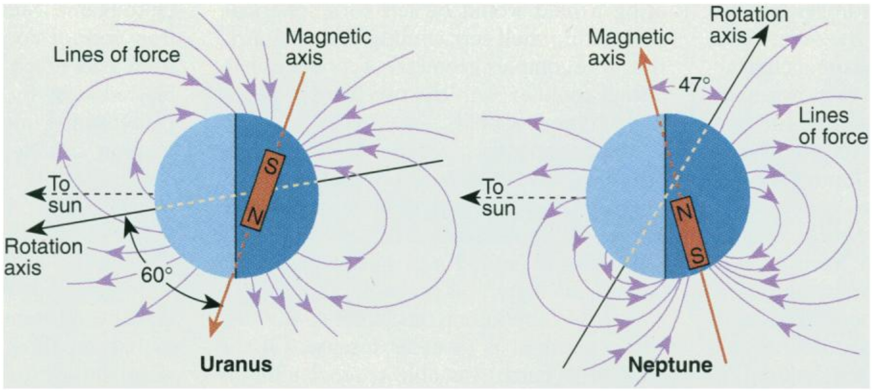
Magnetic anomalies

Similar surprises awaited magnetosphere specialists at the gas giant planets, recalls Alexander Dessler of the University of Arizona. As the Pioneer and Voyager spacecraft visited the giant planets, from Jupiter to Neptune, in the late 1970s and the 1980s, researchers predicted what each planet's magnetic field and the charged particles trapped within it would be like, based on theory developed for Earth's magnetosphere. Unfortunately, they never got it quite right.

Jupiter's field had roughly the same orientation as Earth's—slightly tilted with respect to its spin axis, an offset required by the theory of how a churning liquid core generates a magnetic field. But the parallels ended there. In part because of ionized debris spewed into the magnetosphere from the volcanoes of its satellite Io, the Jovian magnetosphere is far more energetic than Earth's. By linking the magnetosphere and Jupiter's conductive upper atmosphere, the debris captures 100 trillion watts of power from the planet's spin and feeds it into the magnetosphere, supplementing the power derived from the wind of charged particles blowing outward from the sun. The extra power helps drive intense radio emissions and aurora and accelerates streams of high-

*First International Conference on Comparative Planetology, 6–8 June 1994, Pasadena, California. Co-chairs: M. T. Chahine, JPL, and M. F. A'Hearn, University of Maryland.

SOURCE: NORMAN NESS *ET AL.*



Topsy-turvy fields. The off-center, tilted magnetic fields of Uranus and Neptune, as well as Uranus' steeply tilted rotation axis, are probably the result of giant impacts.

energy electrons.

In the case of Saturn the surprise wasn't in the field's behavior, which more closely resembles that of Earth. It was the field's orientation: nearly perfectly aligned with the planet's rotation axis. In spite of those disappointments, when it came to Uranus space physicists still clung to terrestrial theory. In a 1987 special issue of *Geophysical Research Letters* devoted to predictions about Uranus, "every single one of the magnetospheric papers assumed that [Uranus' field] would be parallel or tilted at a small angle relative to the spin axis," says Dessler, who oversaw the issue. "It turned out it was closer to perpendicular"—tilted by 60° from the planet's spin axis (which itself has an unusual orientation, lying nearly flat in Uranus' orbital plane).

The same drama was played out again at Neptune. "Everybody was convinced [the field] would be normal," says Dessler. Wrong again: It was tilted 47° from the planet's spin axis, so that the magnetosphere thrashes about in the solar wind as the planet turns, greatly complicating its interaction with the solar wind. "I'm surprised at the versatility of nature," says Dessler. "You put together the same basic materials and get startlingly different results. No two are alike; it's like a zoo."

The realization of just how many different creatures there can be in the zoo was even slower in coming in the case of the rocky planets of the inner solar system. At first glance, after all, they are far more like Earth. It took Magellan's intense geological and geophysical survey of Venus, which is only now being completed, to dash the last hopes of drawing parallels between Venusian geologic processes and those on Earth, which Venus resembles so closely in size and composition.

Until recently, some geophysicists thought that Venus might have counterparts to the rifts and collision zones created by plate tectonics on Earth. But the full Magellan survey has now convinced most researchers that the Venusian surface is a single shell devoid of global plate tectonics. And that undercuts other efforts to draw parallels between Earth and Venus, says Stevenson. "Plate tectonics plays such a dominant role in how Earth works that I'm uneasy about any attempt to use our experience on Earth directly in the modeling of processes on Venus."

Formative influences

Understanding why conditions are so different on apparently similar planets is what comparative planetology should be all about, say researchers. To distinguish it from the Earth-centered version, cosmochemist Jonathan Lunine of the University of Arizona suggests the term "contrasting planetology.... You have to look at processes [occurring] early on that sent similar objects on very different evolutionary paths," he says.

Doing so may mean searching for influences in the planets' earliest childhoods. Stevenson thinks the differing orientations of the magnetic fields surrounding Jupiter and Saturn, for example, might date from 4.5 billion years ago. That was when moon-sized building blocks known as planetesimals, made up of rock and ice, were agglomerating to form the cores of the outer planets. Once these cores grew massive enough, they could

When Comparative Planetology Hit Its Target

Would studying the fiery greenhouse of Venus clarify the looming threat of global warming on Earth? Would understanding Jupiter's Great Red Spot greatly advance terrestrial weather forecasting? Once, such questions spurred planetary studies. But the more researchers learn about other solar system bodies, the more they doubt that many insights into the Earth are waiting out in space (see main text). Still, the Earth-centered approach to comparative planetology hasn't been completely devoid of benefits, researchers are quick to point out.

Chief among them has been the insight that impacts shaped the formation and history of Earth. "We never would have appreciated the role of impacts in the history of Earth if we didn't see and study the much more obvious impact processes on the moon, Mars, and elsewhere," says David Morrison of the Ames Research Center in Mountain View, California. On Earth, after all, most impact craters have been eroded away, buried by sediments, or deformed beyond recognition. And studying the craters on the moon wasn't necessarily all that helpful, because a vocal contingent argued that they might be volcanic calderas.

But the space missions that began in the 1960s left no doubt: The lunar features were impact craters, and the other solid bodies of the solar system showed signs of similar battering. Earth could not have been exempted, researchers realized, and that insight helped them identify previously mysterious features on Earth as impact craters. What's more, the cratering record preserved on the faces of Mercury, Mars, and the satellites of the outer planets showed that the impacts were most frequent in the early days of the solar system.

This evidence of early bombardment, together with chemical clues in the Apollo moon rocks, eventually suggested an answer to the mystery of how Earth's moon was formed. In the mid-1980s researchers began to embrace a decade-old idea, proposed by William Hartmann and Donald Davis of the Planetary Science Institute in Tucson, Arizona, that a Mars-sized planetesimal smashed into the still-forming Earth, a bit off-center. The impact would have sped up the planet's rotation from the once-a-week pace expected for a planet forming at that point in the solar system. And it would have splashed enough debris into Earth's orbit to form the moon and guarantee moonlit nights for eons.

The moon, in turn, may help explain the relatively stable climate that is one factor making Earth hospitable to life. Mars, for example, is subject to chaotic wobbling that, over geologic time, changes the tilt of its axis of rotation, altering the distribution of sunlight between the equator and poles and thus the climate. But Earth's massive moon holds it—and its climate—steadier. In this case, at least, clues to Earth's story were found by looking to the heavens.

–R.A.K.

start gathering a shroud of hydrogen and helium, the gases that make up the outer layers of the giant planets. Saturn's core, being farther from the sun, would have grown more slowly and drawn in less gas. By the time the gas dissipated, Saturn would have ended up with one third of the mass of Jupiter and one tenth of the internal pressures.

Saturn's lower internal pressures, Stevenson suggests, would in turn have allowed more of its helium to separate from hydrogen—a pressure-sensitive process. The result would have been a separate, helium-rich shell rotating around the planet's core. Because the shell would be electrically conductive at the pressures of Saturn's deep interior, it would be able to put its own stamp on the magnetic field generated in the core. The core's magnetic dynamo could be generating a tilted field, as conventional theory would call for, but the conductive shell might nullify any part of the field not symmetric about the rotation axis.

The wild tilts of the magnetic fields generated by Uranus and Neptune may be more a matter of chance events in the planets' infancies. Uranus seems to have taken a heavy, off-center hit by one of the larger planetesimals falling into it; that would explain why it is spinning on its side. A giant impact might also have mixed the growing planet's rocky core just enough to eliminate the density differences that drive convective flows. Because convection is what powers the dynamos that generate magnetic fields, Stevenson speculates that the task of generating a field would be left to a spherical, convecting shell surrounding the core. And the more complex geometry of convection in a shell could explain the two planets' tilted, highly complex fields.

In the inner solar system, says Stevenson, "the profound question, of course, is why doesn't Venus have plate tectonics [unlike Earth]?" The crucial factor, says planetary climatologist James Kasting of Pennsylvania State University, was probably Venus' position 40 million kilometers closer to the sun, where sunlight is twice as intense. Of the pair, only Earth was able to cool after its formation, with two consequences that could have been crucial to initiating plate tectonics. The cooling boosted the density of Earth's crust and made it more prone to sink into the interior, driving plate motions at the surface. And water vapor in the atmosphere condensed into permanent oceans, where the water could be carried into Earth's interior by sinking plates, providing a lubricant for plate motion. On Venus, in contrast, the surface remained hot and buoyant, and the water vapor in its atmosphere gradually broke down and was lost to space, closing off the possibility of plate tectonics.

These examples of "psychoanalyzing" the planets—explaining their adult characteristics through their childhood experiences—are only a few of the cases that could be tackled by comparative planetology. Why does Mercury have an iron core twice as massive, relative to its size, as any other rocky planet? Again, a chance impact early on may be to blame. Mercury could have formed an iron core of conventional proportions and then had much of its outer rocky mantle blasted away by one of the last and largest planetesimal impacts.

How can Neptune sustain 1400-kilometer-per-hour winds—faster than Jupiter's—when it is so far from the sun, whose heat powers atmospheric circulation? One hypothesis holds that less solar energy means less small-scale turbulence, which can slow global wind systems. How could Mars—now more than 50°C below freezing—have been warm enough in its early days to have water flowing on its surface? Perhaps geothermal heat played a role.

To Moustafa Chahine, chief scientist at the Jet Propulsion Laboratory and a co-chair of the comparative planetology meeting, such questions are a sign that it's time to adopt a mindset diametrically opposed to the one that was prominent in the past. Instead of looking to the other planets for answers about Earth, he says, it's time to draw on the understanding of the most intensively studied processes on Earth to help sort out the stunning differences among the planets. Chahine and his colleagues are now developing a joint NASA–National Science Foundation program embodying this "contrasting" version of comparative planetology. With only nine planets to study, it would never do to leave Earth out of the picture. As Stevenson puts it, half jokingly: "To make more progress, we need more planets."

–Richard A. Kerr

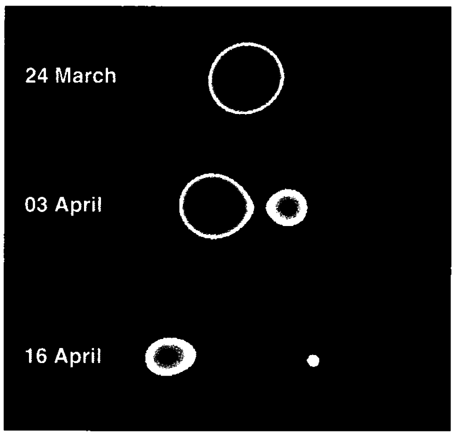
ASTRONOMY

Micro-Quasars Found in Our Galaxy

THE HAGUE—You wouldn't want to get too close to a quasar, but astronomers would love to get a better view of these enigmatic beasts. Seen only in the farthest reaches of the universe, quasars shine thousands of times more brilliantly than entire galaxies and spew radio-emitting jets of material out to distances of hundreds of thousands of light-years. Only the gravitational pull of black holes weighing as much as millions of suns, most astronomers believe, could supply enough power to explain these displays. But, forced to observe quasars at a safe distance, astronomers have remained largely in the dark about their inner workings.

Now a discovery announced at the International Astronomical Union (IAU) meeting here and a subsequent finding reported in an IAU circular suggest that small-scale counterparts of quasars lie within our own galaxy, conveniently close for study. The clue was a phenomenon characteristic of some quasars: They seem to fling out clumps of material at greater than the speed of light. The effect is thought to be an optical illusion, produced when the quasar's jet is pointed in the general direction of Earth. The cosmic speed limit isn't violated, but the effect requires that the material actually be moving at very close to light speed.

Last week, radio astronomers reported such "superluminal" jets emerging from two x-ray–emitting objects in our own galaxy, implying that the inner workings of these x-ray sources may resemble those of quasars. "These findings are extremely important because they provide a clear link between x-ray [sources] in our galaxy and distant quasars," says Rashid Sunyaev of the Space Research Institute in Moscow. And that, says Gerald Fishman of the Marshall Space Flight Center in Huntsville, Alabama, qualifies these near-by sources as "two of the most exciting objects discovered in recent years."



MIRABEL AND RODRIGUEZ/NATURE

Pushing the limit. Blobs of radio-emitting gas race outward from GRS 1915+105 at an apparent speed greater than that of light.

Astronomers had already suspected a distant kinship between quasars and some galactic x-ray sources, because both classes of objects are thought to be powered in roughly the same way. The x-ray sources are believed to be binary star systems in which one star has collapsed into a small black hole or a compact neutron star. This stellar cinder greedily bolts chunks of its companion, just as the massive central black hole of a quasar drags in matter from its surroundings. Most of this matter spirals inward, gets fiercely heated by friction, and gives off x-rays.

But now it seems that, as in quasars, some