A Dusty Road for Space Physics

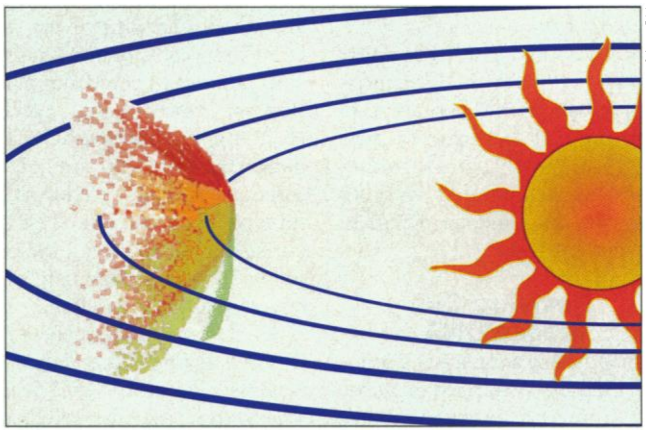
A growing minority of astrophysicists is convinced that forces affecting electrified dust particles could have been been key to shaping everything from rings to the planets themselves

The assumption that gravity dominates the dynamics of the heavens comes as naturally to most astronomers as setting down a coffee cup and expecting it not to move. Like a trusted ally, the laws of gravity have come through time and again for astronomers in their struggles to explain phenomena ranging from the structure of planetary rings to the formation of stars. However complicated in detail, the picture of the heavens as shaped primarily by gravity is so appealing that many researchers are looking on with decided ambivalence as some of the edges of this image begin to crumble into dust.

The dust at issue isn't the familiar, inert dust that coats furniture and boils up on dirt roads. It's a much livelier material: tiny particles immersed in the charged gases, or plasmas, that are common in the cosmos. Physicists have long known that dust particles in a plasma are likely to acquire a charge themselves, and that charged dust particles will respond to electromagnetic forces as well as gravity. But only recently have they realized just how important dusty plasmas—and the influence of electromagnetism, as opposed to gravity—might be. "You didn't even see [dusty plasmas] mentioned" in most astrophysical discussions until recently, says Asoka Mendis of the University of California, San Diego (UCSD), a dusty plasma theorist. Now, he says, "people are beginning to take these things seriously."

And there are good reasons why—among them the discovery of dust streaming from comets and from Jupiter in ways traditional mechanisms can't explain. The ability of dusty plasmas to explain these observations has led some researchers to speculate about other phenomena in which charged dusts might play a role. Electromagnetic forces acting on dusty plasmas might have shaped some features of Saturn's rings, and the interaction of these plasmas with magnetic fields could explain why most stars don't have nearly as strong a field as expected. Most provocative of all, a few theorists argue that electrostatic attractions between dust particles could have served as a kind of glue in the early stages of the formation of the planets.

One test of these ideas will begin in July, when the fragmented comet Shoemaker-Levy slams into Jupiter. If electromagnetic forces, rather than gravitational ones, govern the behavior of the swarm of micron-sized dust particles released when the comet broke up, theorist Mihály Horányi of the University of Colorado, Boulder, has predicted, the collision will leave Jupiter with a tenuous new ring. But many astrophysicists are skeptical of the prediction, and the skepticism mirrors wider uncertainty among gravitational theorists about the overall importance of dusty plasmas. "These plasma guys think they can explain everything in the universe with dusty plasmas," jokes Horányi's Boulder colleague Joshua Colwell.



SOURCE: HORANYI AND MENDIS ILLUSTRATION: E. CARROLL

Electromagnetic undertow. In one scenario, an interaction with the solar wind's magnetic field deflects charged comet dust; the effect is strongest for the finest grains (*green*).

In part, the disagreements reflect a cultural divide. Compared to gravitational phenomena most solar system physicists specialize in, says planetary ring specialist Joseph Burns of Cornell University, dusty plasma physics "is very different and nonintuitive." Dusty plasma theorists, on the other hand, tend to be trained in plasma physics and have an eye for electromagnetic interactions.

Even between these diverse groups, however, there's no argument about one thing: the abundance of fine dust in the solar system and its neighborhood. The dark bands of dust that block parts of the Orion, Lagoon, and other nebulas from view indicates that dust must have been abundant in the nebulas that coalesced to form the sun, planets, and other stars. Little of that primordial dust is left in the solar system, but new dust is constantly generated by colliding meteoroids, comets passing near the sun, and many other processes. And throughout the solar system and elsewhere, this dust is bathed in plasmas.

A trail of clues

The first hints that dust particles electrified by these plasmas might explain some heavenly features came in October of 1980, when Voyager 1 sped past Saturn and sent back pictures of mysterious dark "spokes" sweeping around the B ring, the planet's largest and brightest ring. UCSD's Mendis and the late Christoph Goertz, who was at the University of Iowa, independently proposed that the spokes might be charged dust, sculpted by electrostatic forces. Mendis argued that electrons hurled into the ring by aurora-like processes near Saturn might have electrified the dust, while Goertz attributed the electrification to bursts of plasma generated as micrometeoroids pelted the boulders in the ring. Both mechanisms would tend to produce spokelike regions of electrification, where electrostatic repulsion between dust particles and the boulders would raise trails of dust.

At the time, dusty plasmas were still an offbeat preoccupation, and neither theory was generally accepted, says Mendis. But in the mid-1980s, comet flybys showed that the tiniest dust particles in the comets' tails were distributed in ways that couldn't be explained by gravity or by the other force likely to act on uncharged grains of this size: the pressure of sunlight. Radiation pressure should push the grains directly outward from the sun, producing a tail symmetric above and below the comets' orbital plane. But the spacecraft that intercepted Comets Halley and Giacobini-Zinner found that the smaller grains were gathered on one side of that plane. Horányi says that according to classical theory, "the small dust particles...have no right to be" where they were observed.

He and other dusty plasma theorists had a ready explanation, assuming the particles had picked up an electric charge from the sun's "wind" of plasma. The theorists pointed out that charged particles moving through a magnetic field feel a force perpendicular to their direction of travel and to the field's direction. Since the pressure of sunlight was pushing the grains directly away from the sun, and the magnetic field of the solar wind

Raising Dust in the Laboratory

Gary Selwyn is no friend of dust. In his research on semiconductor manufacturing at IBM's Thomas J. Watson Research Center, Selwyn knew it was crucial to keep dust out, since microscopic defects are anathema to microchips. But, by accident, Selwyn wound up giving a lift to another kind of dust: the fine, electrically charged dust in the "dusty plasmas" some physicists think shape everything from the rings of Saturn to the birth of stars (see main text).


SELWYN/IBM

Cloud with a silver lining. The dust scattering this laser beam is bad news for circuit-making but good for dusty-plasma studies.

Selwyn's original goal was down-to-earth: He wanted to refine processes that use plasmas to etch features on computer microchips. In 1987, however, during a routine calibration, he noticed that laser light was being scattered from a plasma that should have been free of any contaminants. After months of what he calls "sanity checking," Selwyn proved that swarms of micron-size particles were forming in the plasma discharge after it was turned on, no matter how clean the vacuum chamber had been to start with.

His conclusion: Ions in the plasma were sticking together, and the clumps were growing into grains of dust. Because the particles were constantly bombarded by electrons in the plasma, they remained negatively charged and were suspended by electrostatic forces above the wafer by clouds of positive charges that gathered around them.

By now semiconductor manufacturers are beginning to use what Selwyn has learned about dust formation to clean up their act. But some researchers, such as the University of Iowa's John Goree, are doing just the opposite: exploiting the phenomenon Selwyn discovered to create dusty plasmas deliberately in the lab. These researchers prize Selwyn's levitated dust because it simulates the weightlessness of space, opening a window on interactions previously masked by Earth's gravity.

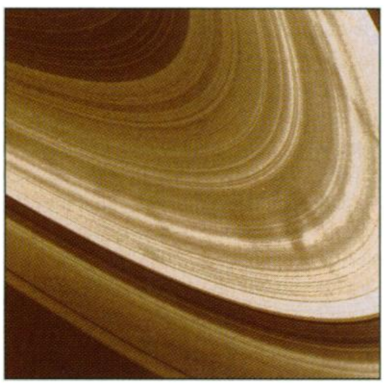
In his research, Goree sows an argon plasma with carbon atoms, which gradually grow into tiny, charged particles. By turning off the plasma, capturing the particles on a surface, and studying their shapes under an electron microscope, Goree has been able to study how dust grains might have grown under gas densities and temperatures typical of the nebula from which the solar system formed. The particles look like tiny cauliflowers pressed together in irregular strings—a growth pattern, he says, that offers clues to the rate at which dust particles in interstellar space turned into the clumps of matter large enough for gravity to assemble into planets.

Goree thinks that the importance of Selwyn's benchtop dusty plasmas for space physics will outlive their utility in semiconductor manufacturing. In industry, he says, "once you've made enough progress, interest in dusty plasmas will disappear. Space and Saturn's rings and the origin of the solar system are problems that will endure forever." Or at least until the dust settles.

–J.G.

spirals along the ecliptic plane like the grooves in a phonograph record, charged grains should get pushed either upward or downward with respect to the orbital plane of the comet, depending on their charge. Calculations of the interaction between the dust and the solar wind plasma showed that it would tend to give the grains a negative charge, and the resulting force would push them below the orbital plane—exactly where they were found.

Traditionalists demurred, arguing that inhomogeneities in the comet nuclei might be causing them to jet gas and dust preferentially downward. But the dust refused to settle. Unruly particles showed up again in early 1992, when the Ulysses space probe swung past Jupiter and recorded repeated bursts of grains streaming out from Jupiter at intervals of about 28 days. "We thought, 'What the devil is going on out there?'" says Herb Zook of the NASA Johnson Space Center. Adds Burns, "Jupiter has such great gravity that one would expect it to be sucking interplanetary objects in. And yet here it is spitting things out."


JPL

Dust-up at Saturn. Voyager 1 image of "spokes" in Saturn's B ring.

But the mystery came with a clue: the particles' uniform size, about .1 micron in diameter. In the scenario some theorists now favor, Jupiter's ethereal "gossamer" ring or eruptions of its moon Io act as the dust source. Drifting though Jupiter's magnetosphere, the envelope of plasma trapped by the planet's magnetic field, the dust particles would gain a positive charge as the energetic electrons of the plasma knocked away the particles' own electrons. The smallest of these charged particles—less than .1 micron in diameter—would be trapped around the magnetic field lines. Much larger particles would also be trapped near Jupiter, but in this case by the planet's terrific gravitational pull. Grains of intermediate size, however, would feel an electromagnetic force analogous to the one that kicks comet particles out of the comet's orbital plane. The force would be generated as Jupiter's magnetic lines of force—which rotate with the planet—whirled past the grains, creating a radial force powerful enough to hurl such grains from the Jovian system.

Such observations have raised the stock of dusty plasmas. An electrostatic explanation for the spokes in Saturn's B ring, for example, is now "the only game in town," says Burns. But that doesn't mean that he and his colleagues buy all astrophysical scenarios relying on dusty plasmas.

Dust storms?

Take Horányi's claim that electromagnetic forces will endow Jupiter with a new ring this July, when comet Shoemaker-Levy collides with the planet. Horányi calculates that the same forces that may be responsible for flinging dust out of Jupiter's magnetosphere could brake the comet's 1 to 2 micron dust particles by just enough to save them from plunging into Jupiter. If so, says Horányi in his paper, which will appear in *Geophysical Research Letters*, the dust should evolve into a ring spreading between 4.5 and 6 Jovian radii. The new feature wouldn't be visible from Earth, but the Galileo spacecraft, with a sensitive dust detector, will reach the Jovian system in late 1995 and should spot the nascent ring.

If Horányi is right. Which isn't likely, says Burns. "If the sorts of processes he's invoking [lead to rings], then they should be occurring in normal bombardment at all times—there is always infalling material into the Jovian system," he argues. Horányi remains confident, saying that it is much easier to create a ring from a single puff of dust particles, coming from a single direction, than from diffuse, random bombardment.

A more extensive test of dusty plasmas' ability to shape features of the solar system will come if funding holds out for Cassini, a space probe that would visit Saturn near the end of the century. The encounter would give planetary scientists a chance to test Mendis and Goertz's proposals about the origin of the spokes. It will also provide a test of other, more speculative proposals about dusty plasmas around Saturn: that electromagnetic forces could account for the thousands of ringlets and the positions of the sharp ring boundaries and gaps.

If some of these tests of dusty plasmas come up positive, researchers may be willing to entertain a much grander notion: that the plasmas had a role in the origin of the solar system itself. Decades ago, Nobel laureate Hannes Alfvén suggested that electromagnetic forces could have speeded the coagulation of material during the early stages of planet formation. Recent calculations by Mendis and Marlene Rosenberg, also at UCSD, have supported this idea by showing that the solar nebula could have been pervaded by positively and negatively charged dust particles, which would have attracted each other. Still, most astrophysicists have downplayed the importance of plasma processes in the solar nebula, because, says Stuart Weidenschilling of the Planetary Science Institute in Tucson, "most of the solar nebula had a very low degree of ionization." There simply weren't enough charges around to matter, he thinks.

But theoretical work by groups in Japan and the United States is now supporting an even grander role for dusty plasmas: in star formation. The magnetic fields of many newborn stars are curiously weak, given the amount of magnetism likely to be trapped in the clouds of dust and plasma from which they formed. The new calculations show that if the dust particles captured electrical charges from the plasma, forming a dusty plasma, they would increase the cloud's electrical resistance. And that, explains Rosenberg, might explain why the magnetic fields of the new stars are so weak: Magnetic fields can escape more easily from electrical insulators than from conductors.

Thanks to dusty plasmas, says Frank Shu, a leading authority on star formation at the University of California, Berkeley, "a new direction is becoming clear" in understanding star formation. If the same turns out to be true for some mysteries closer to home, among the planets, some dusty byways may soon become as familiar to astronomers as the well-worn paths ruled by gravity.

–James Glanz

James Glanz is a science writer in Chicago.

TOXICOLOGY

Study Implicates Second-Hand Smoke

DALLAS—The only chickens that engage in such human follies as smoking cigarettes are the ones drawn by cartoonist Gary Larson in *The Far Side*. But don't be too quick to cluck at cockerel caricatures of people: Researchers at New York University (NYU) have found that cockerels exposed to environmental tobacco smoke (ETS) develop plaques in their arteries that resemble the damage seen in human victims of arteriosclerosis, a chronic disease in which artery walls gradually thicken and harden.

This finding is the strongest direct evidence yet obtained that ETS causes physiological changes and it appears to solidify the position adopted 2 years ago by the Environmental Protection Agency (EPA) that "widespread exposure to ETS in the United States presents a serious and substantial public health impact." At that time, EPA labeled ETS a known human carcinogen on the strength of an analysis of 31 epidemiological studies (*Science*, 31 July 1992, p. 607), and the agency estimated that second-hand smoke causes about 3000 lung cancer deaths a year. Recent epidemiological studies have suggested ETS may cause 10 times that number of deaths from heart disease.

The tobacco industry has disputed the heart-disease findings by noting an anomaly: ETS appears to be nearly as potent as direct tobacco smoke in causing heart disease, even though direct smoke delivers a far higher dose of chemicals. Although the new finding, presented here last month at the annual meeting of the Society of Toxicology, doesn't solve that puzzle, it is "real important" because it "bolsters human epidemiological studies that point to a correlation between ETS and cardiovascular disease," says long-time tobacco researcher Stanton Glantz, a cardiologist at the University of California, San Francisco.

The team that carried out the study, led by Arthur Penn of the Nelson Institute of Environmental Medicine at the New York University Medical Center, used cockerels because those exposed to chemicals implicated in human plaque growth develop plaques similar to those found in people. Moreover, the researchers had already found that benzo-a-pyrene, a carcinogenic chemical in cigarette smoke, accelerated the growth of plaques in cockerels. Based on these findings, Penn and an NYU colleague, inhalation toxicologist Carroll Snyder, exposed young cockerels to second-hand smoke from burning cigarettes, mixed with air, for 6 hours a day for 16 weeks. In a study reported last October in *Circulation* (vol. 88, p. 1820), the scientists found that plaques in the abdominal aorta of ETS-exposed cockerels grew much faster than those in control cockerels.


A.D. SULLIVAN/POULTRY TRIBUNE

Have a heart. Environmental tobacco smoke spurred plaque growth in white leghorn chickens.

Soon after the study appeared, however, the tobacco industry wrote a scathing letter to *Circulation* asserting that the cockerels in Penn's study were exposed to 300 times the level of particulate matter (a suspension of compounds released by a burning cigarette) measured in a private contractor's study of smokers' homes. In Penn's study, cockerels were exposed to between 7.5 and 8.5 milligrams per cubic meter (mg/m^3); the levels in smokers' homes were about 0.05 mg/m^3. "He was effectively pumping mainstream smoke into these big fat cockerels," says Chris Coggins, an inhalation toxicologist at R.J. Reynolds Tobacco Co.

In response, Penn argues that particulate levels vary greatly depending on an exposed subject's proximity to a smoker. Nevertheless, he conducted a follow-up study in which the concentration of particulate matter was reduced to about 2.4 mg/m^3. Penn also used a marker for exposure to ETS—carbon monoxide levels—and compared those in the experiment with levels at four bars in upstate New York. "We found that carbon monoxide levels in the presence of smokers were equal to or higher than levels the cockerels were exposed to," Penn says. These ETS-exposed cockerels, like their brethren, developed plaques faster than controls.

Coggins remains skeptical of Penn's findings, suggesting the cockerels developed the plaques in response to the stress of being placed in a smoky environment. Penn scoffs at the explanation. "After we put them in the cages, these cockerels become really docile—it's almost like having pet rocks around," he says. These pet rocks, however, have the potential to inflict pain on a multibillion-dollar industry.

–Richard Stone