Neptune's misbehaving rings

Mark R. Showalter

Without confinement, the arcs of material orbiting Neptune would have spread out into rings long ago. But new observations show they are still there, challenging astronomers' best attempts at explaining them.

Consider this thought experiment. You are orbiting a planet and you open up a big bag of marbles. What happens? Well, at first the marbles stay together, because they and you are following roughly the same orbital path. But soon, jostling among the marbles will occur as they bounce off one another. Eventually they will spread apart, with each marble following a slightly different path. Some marbles will follow slightly lower orbits that circle the planet faster, whereas others will follow higher orbits that circle the planet more slowly. Eventually, the faster-moving marbles will lap the slower-moving ones, and you will find yourself within a continuous, uniform ring encircling the entire planet.

What could you do to prevent the marbles from spreading? Well, it wouldn't be easy. This is why the discovery in 1984 of an incomplete ring of material orbiting Neptune[1] represented such a dynamical puzzle — an arc shouldn't last for more than a few months. On pages 731 and 733 of this issue[2,3], two groups of astronomers report that the ring arcs of Neptune are alive and well, and still narrowly confined in space nearly 15 years after their discovery. Furthermore, they find that the arcs' current orbital position invalidates the most promising model of their confinement; for dynamicists, it is time to go back to the drawing-board.

Twenty-three years ago, Saturn was the only planet in our Solar System known to have rings. In the images of the day, Saturn's rings seemed to confirm dynamicists' crude expectation that all rings should be simple — broad, featureless, flat, equatorial, circular and symmetric — because collisions between ring particles would rapidly destroy any deviations from this set of properties. Since then, the pillars of this conventional wisdom have fallen one by one, with observers in the lead and dynamicists struggling to keep up.

Back in 1977, astronomers were observing Uranus as it passed in front of a particularly bright star. Such stellar 'occultations' make it possible to probe the atmospheres of distant planets with great sensitivity. On this particular occasion, Elliot *et al.*[4] noticed that the star blinked out briefly five times before the planetary occultation, and again five times afterwards. They had discovered the first five of Uranus' ten narrow rings. Unlike Saturn's broad rings, narrow rings require a confinement mechanism to prevent them from spreading radially. This led to the 'shepherding' model of ring confinement, in which gravitational perturbations from nearby moons are thought to define abrupt ring boundaries[5].

Hubbard *et al.*[1] were using the same occultation technique when they discovered the ring arcs of Neptune. This time the star blinked out on only one side of the planet, implying an incomplete ring. From this surprising result, two models for arc confinement emerged. Goldreich *et al.*[6] showed that, if the ring and a nearby moon had a particular type of orbital relationship called a co-rotation resonance, the moon could drive ring material into a set of uniformly spaced 'libration sites', with the material unable to cross between sites. The model seemed to predict a 'beaded ring' of regularly spaced clumps, and it placed very specific constraints on the relationship between the co-rotation resonance and the number of beads. In an alternative shepherding model, Lissauer[7] showed that perturbations by a moon embedded directly in the ring could stabilize arcs 60° (or one-sixth of the orbit) away, if another shepherding moon was also nearby.

It was in this context that Voyager 2 arrived at Neptune in 1989, finally showing the world what incomplete rings look like (Fig. 1). Images showed a faint ring containing a few brighter arcs all grouped together within a 40° sector. At first glance, it appeared incompatible with both models. Fortunately, the Voyager images also revealed a nearby moon, Galatea, orbiting just inside the ring. By carefully checking the orbital motions, Porco[8] showed that Galatea was indeed in, or at least very close to, a co-rotation resonance that should generate 86 stable libration sites in the ring, each 4.2° long. She argued that the Goldreich model could explain the data, providing only a subset of these sites happened to be filled with material. This model was almost universally accepted, because it would otherwise be too much of a coincidence for the arcs to fall so close to a co-rotation resonance.

Nonetheless, there were a few minor problems. First, the observed width of the ring was too great to fit neatly inside the (very narrow) co-rotation resonance. Second, the finest Voyager images clearly showed very small clumps of material within individual arcs, yet the model was unable to explain features less than 4.2° apart.

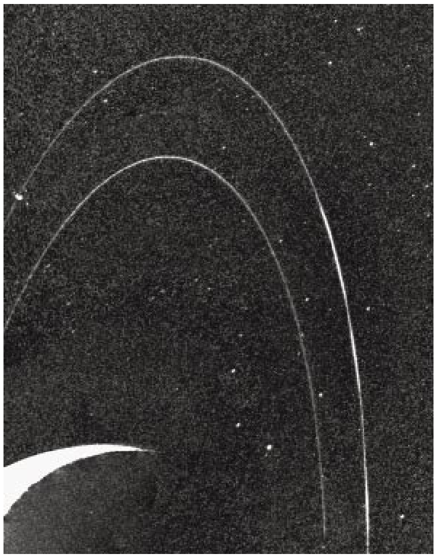

Figure 1 **This classic Voyager image shows two of Neptune's faint rings. The outer ring contains three bright clumps, which are the most prominent ring arcs, known as Liberté, Egalité and Fraternité. A fainter, fourth arc, Courage, falls outside this field of view. The inner LeVerrier ring is also visible. Nine years after this image was taken, new observations from Earth[2] and from space[3] conflict with the predictions of the most promising model for arc confinement, reopening the debate about the arcs' dynamics.**

In the ten years since the Voyager encounter, observing techniques have improved markedly. Now, for the first time, the arcs of Neptune have been imaged from the ground[2] and from a telescope in orbit around the Earth[3]. The advantage of these new observations is that they show global views of the arcs, rather than the single 'slice' of the system obtained by occultation studies. Unhappily, the new detections place the arcs about 20° away from the Goldreich model's prediction and definitely outside the co-rotation resonance[2,3]. This surprising result will force dynamicists to rethink once again the dynamics of arc confinement. The current consensus seems to support a variant on the Lissauer model[7], in which a small number of unseen moons confine arcs between them[9]. Unfortunately, such a model has enough free parameters as to be virtually impossible to test at this time. The moons needed to confine the arcs could be quite tiny, say 10–20 km in diameter, placing them far beyond the capabilities of Earth-based observations. We may have to wait until another spacecraft visits Neptune to settle this question.

Models of planetary ring systems have thrown up a recurring puzzle — although

100 YEARS AGO

The action of magnetism on the propagation of light in a transparent medium has been rightly regarded as one of the most beautiful of Faraday's great scientific discoveries. Like most important discoveries it was no result of accidental observation, but was the outcome of long and patient inquiry. Guided by a conviction that (to quote his own words) "the various forms under which forces of matter are made manifest have one common origin," he made many attempts to discover a relation between light and electricity, but for very long with negative results. Still, however, retaining a strong persuasion that his view was correct, and that some such relation must exist, he was undiscouraged, and only proceeded to search for it more strictly and carefully than ever. At last, as he himself says, he "succeeded in *magnetising and electrifying a ray of light, and in illuminating a magnetic line of force.*"

From *Nature* 17 August 1899.

50 YEARS AGO

Osborne Reynolds, in a short paper entitled "On the Action of Rain to Calm the Sea", discussed the action of rain in calming a rough sea. He expressed the opinion that each drop of rain produces a vortex ring which, on descending into the water, transfers momentum from the surface layers to the underneath layers, thus reducing the relative motion of the layers. It was suggested to us by Prof. A. H. Gibson that further experiments were desirable to confirm the above theory. It has now been found that whereas vortex rings are, in fact, produced when the height of dropping, and hence the velocity of the drop, is small, only 'splash and surface effects' are produced when the height is great. ... It may be concluded, therefore, that very few, if any, of the drops in a normal rain-storm actually produce vortex rings when they strike the surface of water. Rather is the kinetic energy of the drop dissipated in shock and splash at the surface, and thus the sphere of influence of the drop is not as great as suggested by Reynolds.

From *Nature* 20 August 1949.

rings now appear to be common features of the giant planets, their expected lifetimes are far shorter than the age of the Solar System. Rings should eventually collapse because of gravitational interactions with nearby moons, and the moons themselves should be destroyed by meteoroid impacts. The emerging view is that the ring–moon systems are not ancient structures existing since the Solar System began, but transient phenomena in which the death of a moon is also the birth of a new ring. If this is so, then the stable ring arcs of Neptune are of considerable interest as an intermediate structure between accreted moons and distributed rings. Perhaps we are seeing the cloud of debris from a disrupted moon, whose expansion was arrested by its chance proximity to a family of resonances capable of confining it.

Despite these puzzles, rings remain useful as dynamical laboratories in which astronomers can observe the processes that work in much larger astrophysical systems, such as galaxies and protoplanetary disks. On one level, the new reports are noteworthy simply as illustrations of how far astronomical methods have improved in the past decade, enabling two teams to detect a tiny feature a fraction away (less than two arc seconds) from a planet that is 10^6 times brighter. The ability to image such features directly will reduce the need for astronomers to wait patiently for the occasional bright star to pass behind the rings (although stellar occultations will always remain useful because of the extraordinary geometric precision they provide). Even though the interactions between Neptune's moons and ring arcs just became a great deal murkier, the good news is that the dynamics of some of the Solar System's oddest structures are becoming much easier to study. □

Mark R. Showalter is in the Space Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California 94305, USA.
e-mail: showalter@ringside.arc.nasa.gov

1. Hubbard, W. B. *et al. Nature* **319,** 636–640 (1986).
2. Sicardy, B. *et al. Nature* **400,** 731–733 (1999).
3. Dumas, C., Terrile, R. J., Smith, B. A., Schneider, G. & Becklin, E. E. *Nature* **400,** 733–735 (1999).
4. Elliot, J. L., Dunham, E. W. & Mink, D. J. *Nature* **267,** 328–330 (1977).
5. Goldreich, P. & Tremaine, S. *Nature* **277,** 97–99 (1979).
6. Goldreich, P., Tremaine, S. & Borderies, N. *Astron. J.* **92,** 490–494 (1986).
7. Lissauer, J. J. *Nature* **318,** 544–545 (1985).
8. Porco, C. C. *Science* **253,** 995–1001 (1991).
9. Sicardy, B. & Lissauer, J. J. *Adv. Space Res.* **12,** 1181–1195 (1992).

Phytochromes

Tripping the light fantastic

Harry Smith

Photosynthesis fuels life as we know it, so we should all be grateful that evolution has provided plants with sensory mechanisms that allow them to adapt precisely to sunlight. These signal-transducing photoreceptors tell the plant about the intensity, spectral quality, direction and periodic timing of solar radiation, setting off metabolic and developmental changes that optimize the photosynthetic absorption of photons. The most intensively researched photoreceptors are the five members of the phytochrome family (known as phytochromes A to E in the tiny weed *Arabidopsis*). Phytochromes are photochromic pigments — that is, they are photochemically converted from the biologically inactive Pr form to the active Pfr form by absorbing red photons. Conversely, Pfr can be converted back to Pr by absorbing far-red photons.

For more than 40 years, the Holy Grail of phytochrome research has been the molecular mechanism of Pfr action. Ni *et al.*[1] now provide compelling data (on page 781 of this issue) about an interaction between phytochrome B and its putative reaction partner, phytochrome-interacting factor-3 (PIF3). The authors also speculate on a short-cut mechanism that links phytochrome photoconversion to gene regulation. This work is the latest stage in a sustained attack on the mechanism of phytochrome action from the laboratory of Peter Quail. And it is the first demonstration of photoreversible binding of a phytochrome to its putative signalling partner *in vitro*.

Quail's laboratory had already identified PIF3 by two separate approaches. In the first, Ni *et al.*[2] used a yeast two-hybrid screen to fish for factors that interact with non-photoactive carboxy-terminal fragments of phytochrome A and phytochrome B. (Phytochrome molecules are thought to act, at least in part, through a region in the carboxy terminus.) Ni and colleagues found[2] that PIF3 binds to native phytochrome A and phytochrome B. Overexpression of PIF3 in the sense orientation increased light sensitivity; overexpression in the antisense orientation strongly decreased it. Crucially, binding of PIF3 was reduced with a series of phytochrome A and phytochrome B molecules carrying missense mutations that caused loss of *in vivo* activity. In the second approach, Halliday *et al.*[3] isolated a new mutant of *Arabidopsis* with enhanced sensitivity to red light. The mutation turned out to be an insertion in the promoter of the *PIF3* gene, causing the gene to be overexpressed. This study provided further evidence that PIF3 is involved *in vivo*, and confirmed that it positively regulates phytochrome action.

Perhaps the most intriguing features of PIF3 are its nuclear localization and