Search for Dark Matter Around Neptune

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Introduction

On August 25, 1989, the Voyager 2 spacecraft will point its instruments to the presently most remote planet of the solar system. As the probe grazes the upper layers of Neptune's atmosphere, planetary science will take a step forward. This event is eagerly awaited by the scientific community, and as shown below, is a new example of how Earth-based and space observations complement each other.

Intense efforts in the last decade have been undertaken to better understand the structure, composition and environment of the giant planets. High quality observations and new theoretical works have shown that the giant planets store part of the memory of the solar system. This is true in particular for the rings encircling each of these bodies. In spite of the fact that the rings contain a very small fraction of the mass of the central planet, they exhibit an amazing variety of physical processes, which are precious clues to the dynamicist. A few examples should convince the reader:

– Space data have revealed in rings important mechanisms like spiral waves, strong confinement, sharp edges, particle size distribution, electromagnetic forces, dust production, and ring-like arcs in the vicinity of the four giant planets.

– The above mechanisms are not only important for better understanding the origin and evolution of planetary rings, but they are also common to many other astrophysical objects more difficult to observe. For instance, the galaxies often exhibit spiral structures akin to those observed in Saturn's rings. Accretion disks are thought to be submitted to the same kind of "shepherding mechanism" at work among Uranus' rings. In that sense, the circumplanetary disks are extremely important natural laboratories where new theories can be tested.

– Whether the rings are young or not, compared to the age of the solar system, they certainly experience today some processes at work during the early stage of solar system formation. The rings lie inside the Roche limit of the central planet, so that tidal stresses prevent the particles from accreting into a single small satellite. In other words, we are lucky enough to replicate today some of the conditions prevailing in the primordial collisional planetesimals swarm.

The Stellar Occultation Technique

Except for the case of Saturn's rings, the search and study of circumplanetary matter is extremely difficult from direct ground-based imagery. For instance, Neptune is only 2.3 arcseconds in diameter as seen from the Earth, with a visible magnitude brighter than 8, while its rings lie within less than one second of arc of the limb, with a magnitude fainter than 18! In such conditions, imaging the rings is a challenge . . . However, a powerful tool has been developed two decades ago, namely the stellar occultation technique.

While the planet moves in the sky, due to its orbital motion, it may block the light of a star and an "occultation" occurs (Fig. 1). This technique has been developed and used extensively by a group at Paris Observatory since the early 70's (M. Combes, J. Lecacheux, L. Vapillon), to observe among others occultations by Jupiter, asteroids and comets. In the early 80's, a systematic programme of observations of stellar occultations by Uranus and Neptune was set up by the authors in Paris, first to prepare for the Voyager encounters with the respective planets, but also to answer, at least in part, the many questions raised by the Voyager observations of Saturn's rings. Similar observational efforts were made at Cornell University (P.D. Nicholson, Ithaca), Massachusetts Institute of Technology (J.L. Elliot, Cambridge), California Institute of Technology (K. Matthews, Pasadena), University of Arizona (W.B. Hubbard, Tucson) and Lowell Observatory (L.H. Wasserman and R.L. Millis, Flagstaff).

The occultation of a bright star (e.g. one of the SAO catalogue) by a planet is actually quite a rare event, and several decades are necessary for such a coincidence to occur. However, the advent of fast infrared photometry in the late 70's increased the frequence of observ-

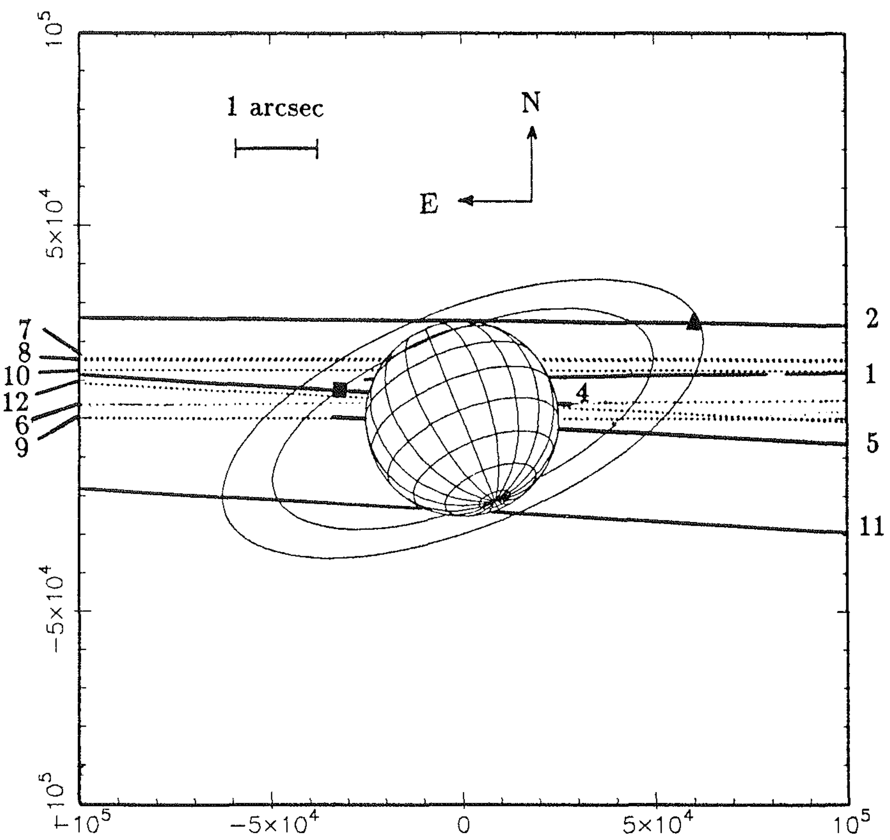

Figure 1: *Tracks of stars for different occultations observed by the Paris Observatory group between 1983 and 1987. Tracks 2, 5, 6, 8 and 11 were observed from ESO, the rest were observed from the Canada-France-Hawaii telescope, Brazil and Pic du Midi. Solid lines indicate observations with high signal-to-noise ratio. The triangle indicates the position of the arc observed on July 22, 1984 at ESO and Cerro Tololo, while the square gives the position of the arc observed on August 20, 1985 from CFHT (Mauna Kea, Hawaii). The distances on the axes are in kilometres, projected in the sky plane at the level of Neptune.*

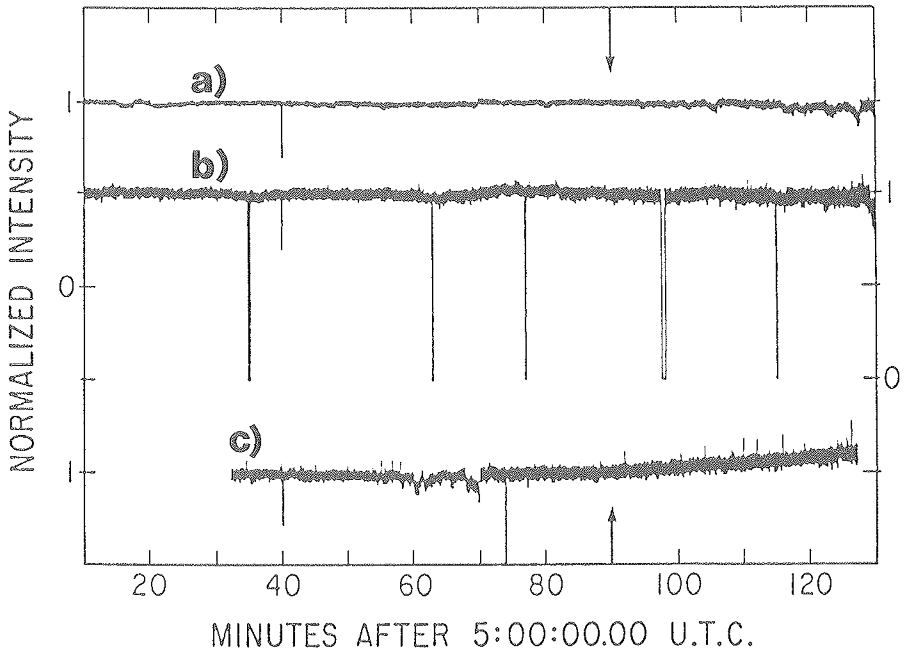

Figure 2: *Recordings made from ESO and Cerro Tololo on July 22, 1984. Curve a: 1 m ESO telescope (2.2 μm); curve b: 0.5 m ESO telescope (0.9 μm); curve c: 0.9 m Cerro Tololo telescope (0.9 μm). All three telescopes recorded a dip of signal around 5 h 40 mn U.T., while no corresponding event was observed when the star crossed the arc's orbit again (arrow).*

able occultations to *several per year*. This is because all the giant planets exhibit strong methane bands in the near infrared, so that their albedo is reduced by several orders of magnitude in these bands (0.9 μm, 2.2 μm), while the star is essentially unaffected by these absorption bands. Consequently, the contrast of the occultation (fractional drop of signal when the star disappears behind the planet), is accordingly increased.

Many spectacular applications of stellar occultations have been made. The most obvious quality of this technique is its high spatial resolution. The latter is ultimately limited by diffraction of light on the edge of the occulting bodies and by the stellar diameter projected at the distance of this body. Both effects give typical resolutions of 4–20 kilometres at the distance of Neptune, i.e. an angular separation of 0.5 millisecond of arc! Consequently, the occultation technique is presently the most accurate method to derive the shape of the occulting bodies, and extract important parameters like the radius, oblateness, irregularities of the limb, etc. . . .

Also, the stellar flux observed from the Earth is extremely sensitive to small deviations due to a tenuous atmosphere. In particular, the temperature profile of the planet's upper stratosphere (1 to 10 μbar) may be inferred, together with the turbulent properties of this atmosphere. No other technique, including space observations, is presently able to compete with stellar occultations for studying such a dilute atmosphere. We shall also mention here the recent discovery of Pluto's atmosphere to illustrate the efficiency of the occultation technique (Hubbard et al., 1988, Elliot et al., 1989).

Finally, the occultation method is able to detect a very small amount of material orbiting the planet. Any drop of signal, observed before or after the occultation by the central body, may betray the presence of a small body, otherwise invisible in the glare of the planet. This method has been used with success for Neptune. An active collaboration among the different groups involved in this programme has allowed the elimination of spurious events, and to cross-check the real ones! This also tightened the links between colleagues observing at Cerro Tololo, Las Campanas, and the ESO La Silla observatories.

Dark Matter Around Neptune?

The history of the elusive Neptune rings is spotted with ups and downs, partly caused by the behaviour of these strange structures, and also by terrestrial difficulties (see the article by A. Brahic and W.B. Hubbard in the *Sky and Telescope* issue of June). The first recorded observation of a stellar occultation by Neptune occurred on April 7, 1968, when the bright star B.D. −17°4388 disappeared behind the planet. As several stations observed the event, an accurate radius and oblateness of the planet could be derived (Kovalesky and Link, 1969). More than ten years later, and after the discovery of the narrow rings of Uranus, an exhumation of the data led Guinan and Shaw to the conclusion that some dips observed in the 1968 lightcurve could have been caused by a ring orbiting close to the planet, at less than 10,000 kilometres from the planet's stratosphere (see the *Sky and Telescope* issue of August 1982).

However, an observation from Australia in August 1980, and a subsequent one from Chile (Cerro Tololo) in May 1981 did not reveal any rings (Elliot et

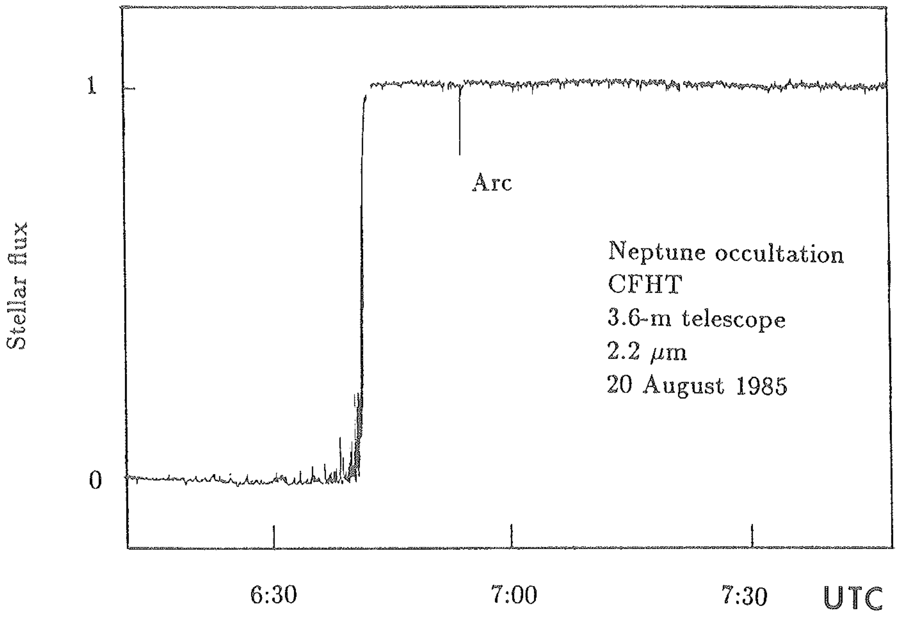

Figure 3: *A second arc was discovered on August 20, 1985 from the Canada-France-Hawaii telescope (Mauna Kea, Hawaii). Simultaneous observations made at ESO and Cerro Tololo show no event on the other side of the planet.*

al., 1981). In the meantime, an observation made from two telescopes in Arizona in May 1981, showed a coincident interruption of signal, while no such dip was observed in Flagstaff, only 600 kilometres away. The conclusion was then that the event had been caused by a new satellite of Neptune, 180 kilometres in diameter (Reitsema et al., 1982). Several other "isolated events" (i.e. observed with only one telescope, and thus not firmly established), were reported in subsequent observations, casting some confusion as to the existence or non-existence of Neptune's rings.

A very favourable observation made on June 15, 1983, from different stations scattered around the Pacific Ocean (Australia, Tasmania, Hawaii, China) showed no suspect events, besides the occultation by the planet, of course! The high signal-to-noise data obtained at the Canada-France-Hawaii Telescope put an upper limit of 300 metres for the width of any continuous opaque rings of Neptune, and an upper limit of 0.006 for the normal optical depth of diffuse rings of the planet (Sicardy et al., 1986).

As the observations of Neptune's surroundings were refined, and hope for detecting rings faded, it became more difficult to obtain telescope time for observing such events. However, the persistence of the Paris and Tucson group made possible simultaneous observations of an occultation of a bright star by Neptune on July 22, 1984, with two telescopes at ESO and one telescope at Cerro Tololo. The star actually missed the northern limb of the planet (see track 2 in Fig. 1), so that no occultation was observed, but all three telescopes recorded a dip in the signal, with virtually the same profile and same timing (Fig. 2). A careful analysis and comparison of the data by the Paris and the Tucson groups led to the conclusion that the event was due to an incomplete ring of Neptune (Hubbard et al., 1986). The basic reasons for such a conclusion are the following:

– The event was observed at the same time in the three curves, with identical shape. This ruled out spurious events due to bad seeing or electrostatic discharges.

– The width of the event corresponded to a 15 km wide body at the level of Neptune, while the distance between the two stations implied a 100 km long object. Unless a very improbable configuration took place, the dip could not have been caused by a spherical satellite of Neptune.

– The shape of the dip was compatible with the diffraction pattern of light caused by a body at the distance of Neptune, ruling out the possibility of an occultation by a closer object (like an asteroid in the main belt for instance).

– The slight time delay between the two stations put the segment of ring aligned with an equatorial ring of the planet, projected in the plane of the sky, thus confirming that the structure was probably associated with Neptune.

– The absence of dip when the star again crossed the orbit of the supposed arc ruled out the possibility of a continuous ring (Fig. 2). This was in any case known from previous high-quality data (see above).

From these arguments we could conclude that Neptune was orbited by a ring-like arc, at 67,000 km from the planet's centre (2.6 Neptunian radii), 15 kilometres in width, at least 100 kilometres in length, and 40% in optical depth.

This detection led to a renewal of interest in Neptune occultations. Search for infrared sources in the path of the planet were again supported, and led to new catalogues of events, in particular by Philip Nicholson, from Cornell University. In June 7, 1985, a double star was occulted by Neptune, and the event was recorded in South Africa. It turned out that one of the companions was occulted during its approach to the planet, but not the other! (Covault et al., 1986). If real, this event places a stringent limit of 5000 kilometres for the length of the corresponding arc.

New surprises were to come with the occultation of a very bright star (K = 6) by Neptune on August 25, 1985. The occultation took place as predicted, and two large telescopes at Mauna Kea mountain (3 m of the NASA Infrared Facility, IRTF, and 3.6 m of the Canada-France-Hawaii consortium, CFHT), recorded the emersion of the star from behind the planet. Ten minutes later, both instruments recorded a 15% drop of signal in the lightcurve (Fig. 3). The coincidence of the events ruled out again spurious effects, while an internal structure in the observed profile ruled out a satellite as the cause of the dip. The observed arc was however different from that observed in July 1984 since its distance to the planet was 52,000 kilometres (2.1 Neptunian radii), while its width and optical depth were comparable to the July 1984 event (13.5 km and 0.15 respectiveley, see Sicardy, 1988).

A simultaneous recording was made in Chile from the Cerro Tololo station and from ESO. Not surprisingly, no arcs were detected on either side of the planet from these two sites. However, a rare event took place since Chile passed in the middle of the Neptune's shadow, so that a "central flash" was observed. This flash was caused by the focusing of light by the planet's limb on the Earth. This was a unique opportunity to independently derive Neptune's oblateness and to put some constraints on the abundance of methane in the stratosphere of the planet (Lellouch et al., 1986).

The most recent positive detection of a possible body in the vicinity of Neptune was made on July 22, 1987 from the 3.6 m telescope of ESO. While the star and Neptune were moving away from each other after the occultation, it was noted that a near miss with the satellite Triton would occur. No occultation by this body was observed, but as the star crossed the satellite's orbit in the sky, a brief event was noted, corresponding to an object 10 kilometres in size (Sicardy, 1988). The excellent conditions of observation (near zenith, good seeing) argue for a real "event", however the ESO observation was not duplicated elsewhere on that night, so that no confirmation has been made of the "Triton torus".

We made special efforts in 1988 to observe Neptune occultations. Five occultations were recorded, three of them with a good signal-to-noise ratio (at ESO, CFHT and Pic du Midi), but without secondary events reminiscent of arc occultations. Although somewhat frustrating, the negative detections are as important as the positive ones, since they improve the statistics of the coverage. From all the occultations to date, the present status of Neptune arcs is the following:

– Unlike the other giant planets, Neptune does not possess significant continuous rings or ringlets. More precisely, the present upper limit for the normal optical depth of opaque continuous rings is 300 metres, and 0.006 for diffuse rings.

– Neptune is orbited by at least three structures. Two of them have been identified as parts of ring-like arcs, at 52,000 km and 67,000 km from the planet's centre, while the third one may be a 200 km moonlet of Neptune or a 80 km wide ring-like structure. The typical width of the two arcs is 10–20 km, and their maximum length is of the order of 3000 km. Thus the arcs occupy quite a small fraction of the orbital circumference, typically less than 3 degrees.

– Several other events are suspected to be due to arcs around Neptune. The number of "isolated events" is of the order of half a dozen, so that the probability to get a positive detection during an occultation is of the order of 10%. This shows that a small fraction of the azimuth inside the Roche limit of the planet is actually occupied by dense material.

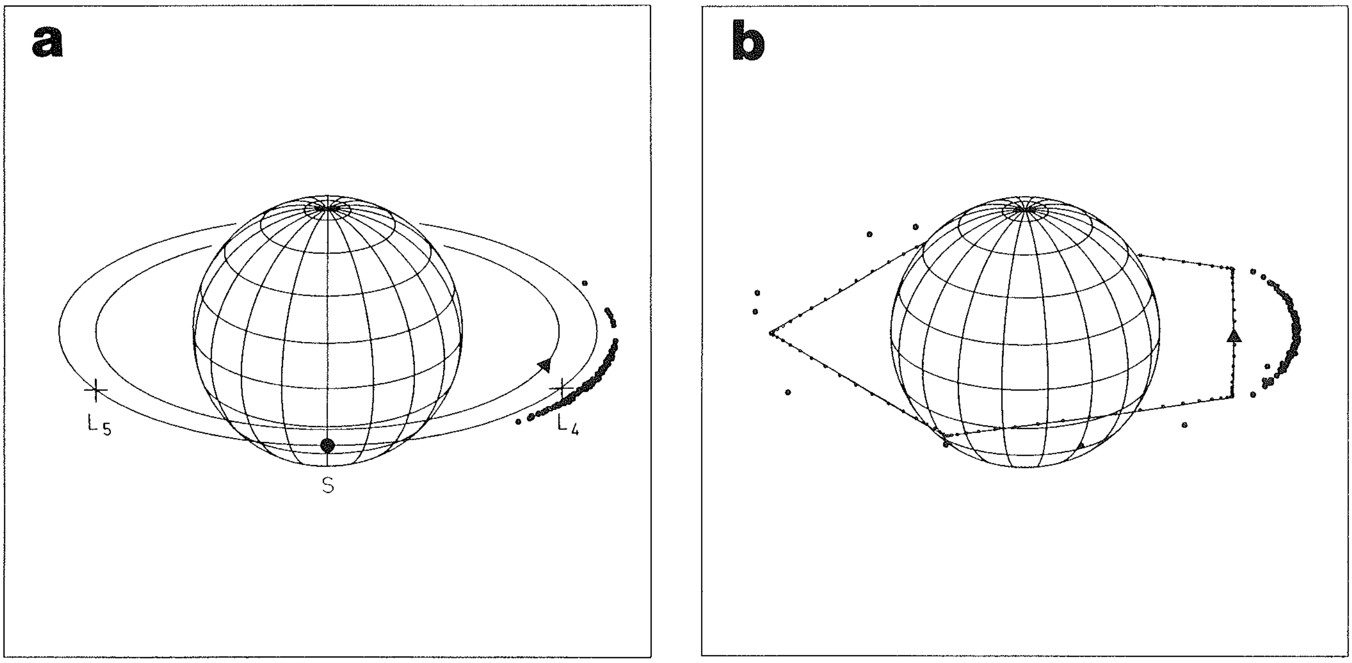

Figure 4: *Two cases of stabilization of ring arcs by small satellites of Neptune. The two diagrams show the results of a numerical simulation implemented on a CRAY computer. The particles are identical spheres, colliding inelastically, while being perturbed by nearby satellites. The typical masses of the satellites used in this simulation are* 10^{-4} *to* 10^{-5} *the mass of the central planet.*
Case a: The arc lies near an L_4 *Lagrange point of a satellite S, and receives energy from a second satellite in resonance with the arc (inner orbit with the arrow). After more then 200 collisions per particle, the arc is still well confined. If the satellites were not there, everything equal besides, the same kind of simulation would show that the spreading of the arc is very rapid (a few collisions per particle).*
Case b: The arc is at a corotation resonance of an eccentric satellite. The satellite's orbit, as observed in the frame corotating with the arc, has been drawn as a solid line. The satellite is then able to confine the arc in azimuth, and also to provide the energy lost by collisons, through a resonance with the arc. The system is shown after about 120 collisions per particle.

Interpretation

From such a small sample, it may seem hazardous to propose a theory accounting for the observations. After all, nobody knows at present whether the arcs are really well-defined clumps of material, or rather the densest parts of a more complex continuous ring. In any case, these structures may be an important clue to a much more general problem, namely the origin of the planets. The image of rings a decade ago was smooth collisional disks, where any structure would be rapidly erased by diffusion. The current image is the opposite, with many highly detailed structures, and a great variety of different physical processes. In particular, the efficiency of resonances to confine material in narrow regions of space has been widely demonstrated. Such "shepherding" mechanisms may have played an important role at the beginning of the solar system, where a multitude of small bodies were to accrete and form a small number of big planets.

Neptune's arcs may be an extreme example of confinement since not only they are confined in radius, but also in azimuth. The stability of such structures is problematic. Any free arc would spread around the planet in a few years, because of the differential Keplerian motion between the inner and the outer edges. Lissauer (1985) proposes a model where the arc is confined near the stable Lagrangian points of a small moon of Neptune. Such an equilibrium, although dynamically stable, is however secularly unstable because collisions will inevitably dissipate energy, and drive the particles away from the Lagrange points (which are local *maxima* of potential). For reasonable assumptions on the particle size in Neptune's arcs, it would take less than 10,000 years to spread these structures in horseshoe orbits. Lissauer proposes that a second moonlet may confine the arc, which would receive, through a series of resonances, the energy lost by collisions.

An alternative model has been developed by Goldreich, Tremaine and Borderies (1986). Instead of two satellites, only one is required, but its orbit must be inclined with respect to the equatorial plane of the planet. Although equivalent to Lissauer's model from the dynamical point of view, this new theory is more "economical" since it requires fewer satellites around the planet. In any event, both models agree that the putative satellite(s) responsible for the arc stability should be at least 200 kilometres in diameter, i.e. visible from the Voyager 2 spacecraft quite early (June 1989) in the encounter. If actually made, this detection could usefully constrain the possible sites for the arcs, and thus allow a more efficient coverage of these objects during the closest approach (August 1989).

Some illustrations of these theoretical models are given in Figure 4. They are derived from a numerical simulation of colliding particles near corotation resonances, and were intended to check the validity of the previously described analytical approaches (Sicardy, 1988). It can be seen that the combined effect of the satellite perturbations can efficiently confine a swarm of particles. It must be emphasized however that all these models do not take into account non-gravitational forces like Poynting-Robertson or plasma drag. Such forces could in particular spread away the dust produced in the arcs by meteoritic impacts or inelastic collisions. Although the arcs themselves do not present a hazard for the Voyager probe, because of their vanishingly small cross section, an extended sheet of diffuse dust may well endanger the spacecraft as it crosses the equatorial plane of the planet, at about three Neptunian radii.

Conclusion

Neptune's arcs represent a challenge from the triple point of view of the observer, the theoretician and the space engineer. It is remarkable, and fortunate, that a successful effort was made at the very moment when a spaceship was about to observe for the first time the remote planet. The harvest of data sent by Voyager is eagerly awaited, but no doubt several more earth-based observations will be necessary for fully understanding these mysterious formations. In the meantime, a very favourable occultation will be observed from ESO, Brazil, Tenerife and Pic du Midi on July 8, 1989, giving a last terrestrial glance before the rendez-vous . . .

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International Halley Watch Meets at ESO

On April 22, 1989, members of the Steering Group and Discipline Specialists of the International Halley Watch (IHW) met at ESO Headquarters to discuss recent progress with the Halley Archive.

This group of cometary scientists was established in 1982 through an initiative by NASA; the same year it was recognized by the International Astronomical Union as the body responsible for coordination of the various programmes in connection with the Halley passage in 1985–86.

At this supposedly final IHW meeting with about 40 participating scientists, mostly from North America and Europe, it became clear that the main goal is now within reach. All of the "Networks" reported good progress in collecting the available data from all over the world. It is expected that the "final" deadline will be June 30, 1989 and by that time, about 22 Gbytes of data will have been gathered. In addition to the ground-based data, many will come from the highly successful space experiments in March 1986.

The archive will be made available on 22 computer readable Compact disks, of which 20 will include about 1000 selected, large scale images of the comet, the others carry spectra and photometry in the visible and infrared regions, astrometric positions, radio observations, meteor data, close-up images of the near-nucleus region and the best amateur observations. A magnetic tape version will also be produced. It has not yet been decided whether a subset of this enormous quantity of data will be published in printed form, although a book with the best pictures will appear in early 1990.

By early May 1989, Comet Halley was more than 1600 million kilometres from the Sun and still going strong. The false-colour picture shown here was made when it was at heliocentric distance 10.14 A.U., or 1517 million kilometres, i.e. beyond the orbit of Saturn. It is a composite of 29 CCD exposures obtained with the Danish 1.5 m telescope at the ESO La Silla observatory during five nights in early January 1989. The total integration time is 860 minutes.

The nucleus is seen as a point of light near the centre of an asymmetric dust cloud (coma) which measures ~ 80 arcsec across, or 550,000 km. The mean magnitude of the nucleus is V = 23.5, and its brightness is seen to vary by ~ 1 mag from night to night. The total magnitude of the comet is V = 18.4.

A comparison with the coma observed with the same equipment in April–May 1988 shows that the overall