Images of Neptune's ring arcs obtained by a ground-based telescope

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Neptune has a collection of incomplete narrow rings, known as ring arcs, which should in isolation be destroyed by differential motion in a matter of months. Yet since first discovered[1] by stellar occultations in 1984, they appear to have persisted[2–6], perhaps through a gravitational resonance effect involving the satellite Galatea[6–8]. Here we report ground-based observations of the ring arcs, obtained using an adaptive optics system. Our data, and those obtained using the Hubble Space Telescope (reported in a companion paper[9]), indicate that the ring arcs are near, but not within the resonance with Galatea, in contrast to what is predicted by some models.

Our data set consists of nine 600-s exposures taken at the Canada–France–Hawaii telescope in Hawaii between 11:44 and 13:15 UT on 6 July 1998, using a 1.72-μm filter. After standard flat-fielding and background subtraction, each image was deconvolved with an estimated point-spread function, clearly revealing some of the small inner satellites, namely Proteus, Larissa and Galatea, and more marginally, Despina. Neptune's centre was determined to within half a pixel (~0.017 arcsec) using both the motion of the satellites and the planet cloud cover. To enhance the signal-to-noise ratio, each pixel in individual images was rotated into Neptune's equatorial plane according to the orbital motion at the corresponding point, so as to show the neptunian system at a prescribed time, namely 12:29:39 UT (Earth time). A median filter was then applied when co-adding the nine images, while bright pixels near the planet were masked out. On this final image, Proteus, Larissa, Galatea and the arcs are detected, while Despina is lost in the glare of the planet (Fig. 1).

Small differences were found between the observed orbital phases of the satellites and those predicted from Voyager observations[10,11]. Proteus, Larissa and Galatea are respectively 0.0 ± 0.3, 1.65 ± 1.0 and 4.75 ± 1.7 degrees ahead of their expected longitude. However, the accumulated nominal errors since the Voyager observations in August 1989 are respectively 2.9, 5.2 and 8.1 degrees for the three satellites. Thus, none of these discrepancies in longitude are significant.

The arcs appear in Fig. 1 as a region of enhanced intensity along—but slightly outside—Galatea's orbit, near its maximum western elongation (right side of Neptune). Such a structure is clearly absent on the east side (left of Neptune). The arcs are embedded in a tenous ring, Adams, which is about ten times fainter than the arcs[4], and is thus undetectable in our images. To eliminate the background illumination, the intensity distribution on the east side was locally fitted by polynomials and then symmetrically subtracted from the west side. The arc intensity was then integrated over a width of 6 pixels (~0.2 arcsec) and plotted as a function of longitude (solid line in Fig. 2). This intensity is expressed in terms of an 'equivalent width', E_{arc}; that is, the width of a perfect Lambert diffuser that would reflect sunlight at the distance of Neptune.

The dotted line in Fig. 2 shows the Voyager longitudinal arc profile, revealing the three main sub-arcs Liberté, Egalité and Fraternité[6]. Their position can be compared to the two possible solutions derived by Nicholson *et al.*[3] for the mean motion of the arcs n_{arc}, based on previous occultation detections and Voyager observations: $n_{arc} = 820.1194 \pm 0.0006\ \mathrm{deg\ d^{-1}}$ and $n_{arc} = 820.1118 \pm 0.0006\ \mathrm{deg\ d^{-1}}$, referred to as 'solution no. 1' and 'solution no. 2', respectively. These two solutions are easily distinguished in our data, since they yield a difference of 24.7 degrees in longitude on 6 July 1998. We find that the arcs are closer to the position predicted by solution 2. For instance, in Fig. 2, the Voyager

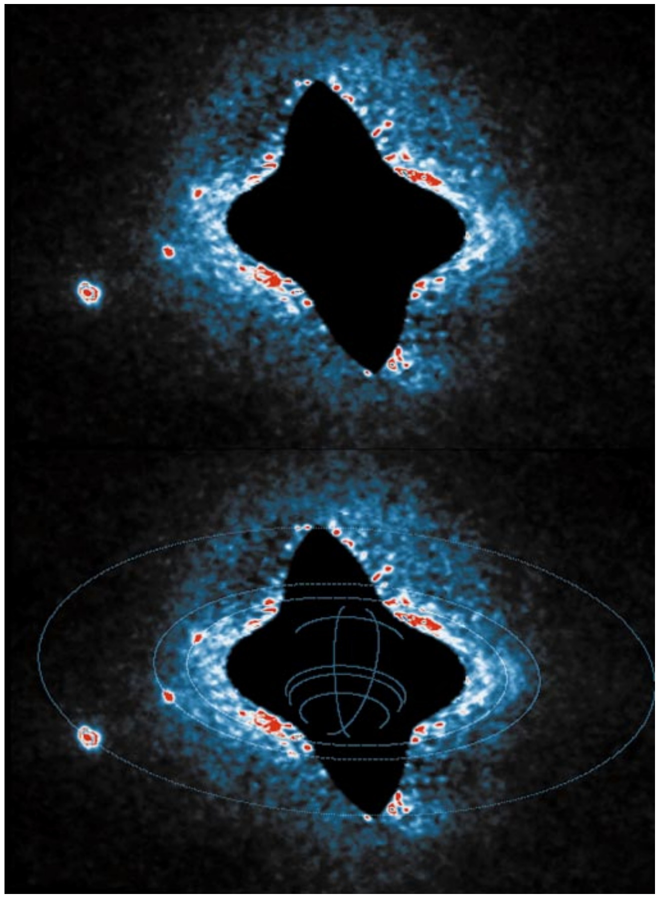

Figure 1 Images showing Neptune's ring arcs. Top, as observed; bottom, showing the orbits of the three moons (see below). The images were obtained by co-addition of nine 600-s exposures taken from the Canada–France–Hawaii 3.55-m f/36 telescope (CFHT), between 11:44 and 13:15 UT on 6 July 1998. Data were acquired through a narrow-band (120-nm) filter centred on a methane absorption band at 1.72 μm, thus minimizing the light scattered by Neptune. The image is 12 arcsec across, with a pixel size of 0.03425 arcsec. North is up and east is left, these directions being determined within 0.05 degrees by following the known motion of asteroid 554 Peraga with respect to stars during the same night. The CFHT was equipped with the 36-actuator adaptive optics (AO) camera Hokupa'a[15], specifically developed at the University of Hawaii for astronomical applications[16], and based on the concept of wave-front curvature sensing and compensation[17]. The AO technique compensates image degradation produced by the Earth's atmosphere. Optical aberrations are corrected at a kilohertz rate by means of a fast deformable mirror. Neptune itself (behind the black mask) was used as a guide source to sense the wave-front aberrations. Each image has first been rotated (see text) to show the system as it was at 12:29:39 UT, before being co-added to the others. On the bottom panel, ellipses have been drawn to show the computed orbits of Proteus, Larissa and Galatea, in order of decreasing distance to Neptune. The three satellites appear on the left side of Neptune as red spots, with a slight elongation due to their orbital motion during each of the 600-s exposures. The Adams ring arcs are seen at western elongation (right side of Neptune), just outside Galatea's orbit. The bright pixels between the planet and the arcs correspond the Le Verrier ring's orbit[18]. They are observed on only one side of the planet, and could be due to scattered light from the planet. New observations are needed to confirm this unexpected result.

dotted profile has been arbitrarily shifted by 4 degrees ahead of solution 2, in order to match the tallest peak (Fraternité) in our observed profile. We then note a mismatch of about 4 degrees in the positions of Liberté and Egalité, relative to Fraternité. Although it remains marginal in our data, this mismatch is confirmed by the recent Hubble Space Telescope (HST) observations[9]. Such change could be due to small libration motions of the arcs, as expected in the frame of the co-rotation model[6,12]. Overall, the entire arc system is 5.5 ± 3 degrees ahead of solution 2, which yields an average arc mean motion of $n_{\mathrm{arc}} = 820.1135 \pm 0.0009\,\mathrm{deg\,d^{-1}}$ between August 1989 and July 1998. Considering our error bars, the difference between our value of n_{arc} and solution 2 remains marginal.

Among the models for arc confinement are co-rotation resonances with a nearby satellite. The equilateral Lagrange points L_4 or L_5 of a co-orbital satellite are examples of such stable sites[13]. More general co-rotation sites can be generated by an inclined satellite, outside its own orbit[7]. The Voyager and occultation data did show that the arcs lie very close to a co-rotation inclined resonance (CIR) with Galatea[6]. Due to its inclination I_{G} with respect to the local Laplace plane, Galatea's perturbing potential contains terms revolving at the pattern speed $n_{\mathrm{cor}} = [(m_{\mathrm{cor}} - 1)n_{\mathrm{G}} + \dot{\Omega}_{\mathrm{G}}]/m_{\mathrm{cor}}$, where n_{G} and $\dot{\Omega}_{\mathrm{G}}$ are Galatea's mean motion and nodal precession rate, respectively, and where the integer m_{cor} is the co-rotation wavenumber. The co-rotation occurs when $n_{\mathrm{arc}} = n_{\mathrm{cor}}$, and it can be shown that $2m_{\mathrm{cor}}$ co-rotation sites are then created[7].

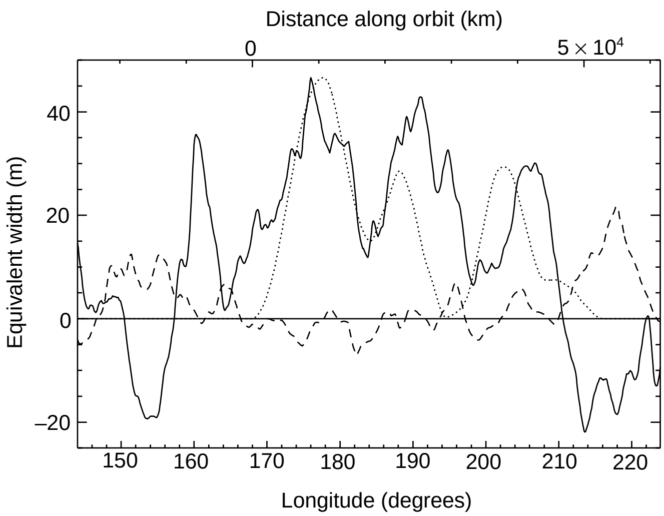

Figure 2 Analysis of the ring arcs. The thick solid line shows the equivalent width of the arcs derived from Fig. 1, as a function of longitude. The latter is counted from the ascending node of Neptune's equatorial plane on the 1950 Earth's Equator, for the epoch 8 August 1989, 12:00 Ephemeris Time at Neptune[4], using a Neptune's spin pole direction at epoch (6 July 1998) of right ascension $\alpha_{1950} = 298.2712°$, declination $\delta_{1950} = 43.4190°$ (ref. 19). The orbital motion of the arcs is from left to right (that is, towards increasing longitudes). The peak at 160 degrees and the drop at 155 degrees are caused by noise. The dashed line shows the noise level in a region just beyond the arc. Note the increase of noise on each side of the arcs due to the light scattered by Neptune. The dotted line shows the Voyager profile convolved by the orbital motion of the arcs during the 600-s exposures, taking the equivalent width derived from low-phase-angle Voyager images[4]. The three main arcs are Liberté (right), Egalité (middle) and Fraternité (left). A fainter arc, Courage, is visible as a bump just ahead of Liberté in the dotted profile. The Voyager profile has been arbitrarily shifted to match the position of the trailing arc Fraternité, as explained in the text. The integrated H (1.65-μm) magnitude of the entire arc system shown here is 21 ± 0.5. Note that the equivalent width that we obtain for the two brightest arcs Egalité and Fraternité (at a phase angle of 0.56 degrees) is comparable to the value derived from the clear filter images of Voyager (bandpass 0.31–0.56 μm) at low phase angle, ~8 degrees (ref. 4). Thus, within our error bars, we cannot detect any significant differences in the arc brightness between the visible and the near-infrared.

The wavenumber found for this CIR is $m_{\mathrm{cor}} = 43$, which creates 86 co-rotation sites spanning each $360/2m_{\mathrm{cor}} = 4.186$ degrees in longitude[6]. This resonance is referred to as the 42:43 CIR. From refs 6, 10 and 12, one can derive a maximum full width of each co-rotation site of $W_{\mathrm{cor}} = 0.5 \pm 0.2\,\mathrm{km}$. Consequently, if the co-rotation model is correct, the semi-major axis of the arcs should lie within $0.25 \pm 0.1\,\mathrm{km}$ from the co-rotation radius for the arcs to be stably trapped. The dynamical, and to a lesser extent, the collisional, stability of this model have been successfully tested by numerical integrations[8,12,14].

As almost nine years elapsed since the Voyager observations, we derive a significantly improved value of $n_{\mathrm{G}} = 839.66126 \pm 0.00052\,\mathrm{deg\,d^{-1}}$, which agrees with the Voyager value[10], 839.6598 ± 0.0025, within the error bars. The parameter $\dot{\Omega}_{\mathrm{G}}$ can be accurately calculated from the dynamical parameters of Neptune[10], yielding $\dot{\Omega}_{\mathrm{G}} = -0.714 \pm 0.002\,\mathrm{deg\,d^{-1}}$. We finally obtain $n_{\mathrm{cor}} = 820.11765 \pm 0.00052\,\mathrm{deg\,d^{-1}}$, where most of the uncertainty comes from the uncertainty on Galatea's mean motion.

We detect a small but significant drift between the mean motion of the arcs and the pattern speed of the CIR, $n_{\mathrm{arc}} - n_{\mathrm{cor}} = -(4.2 \pm 1.0) \times 10^{-3}\,\mathrm{deg\,d^{-1}}$. Between August 1989 and July 1998, this drift results in an observed lag in longitude of 14 ± 3 degrees for the arcs, with respect to the CIR potential. This lag represents more than three times the azimuthal extension of one given site (4.186 degrees), thus calling into question the validity of the model of azimuthal confinement by the 42:43 CIR. This is confirmed by the fact that the value of $n_{\mathrm{arc}} - n_{\mathrm{cor}}$ represents a difference between the geometrical semi-major axis of the arcs and the radius of the 42:43 CIR of $a_{\mathrm{arc}} - a_{\mathrm{cor}} = 0.210 \pm 0.05\,\mathrm{km}$, thus putting the arcs very near the separatrix between stable libration and unstable circulation. None of the direct numerical integrations performed so far[8,12] have shown evidence for a drift $n_{\mathrm{arc}} - n_{\mathrm{cor}}$ once a particle is stably trapped into a co-rotation site. One way of accounting for a non-zero value of $n_{\mathrm{arc}} - n_{\mathrm{cor}}$ would be to change the value of $\dot{\Omega}_{\mathrm{G}}$ ($= -0.714\,\mathrm{deg\,d^{-1}}$) by $0.2\,\mathrm{deg\,d^{-1}}$; such a large correction would require an unrealistically large nearby satellite perturbing Galatea.

We note that the arcs should also be perturbed by a nearby Galatea outer Lindblad resonance[6,7]. With our new orbital solutions, the 42:43 outer Lindblad resonance is now situated 1.86 km inside the arc geometrical radius, instead of 1.65 km as previously calculated[6]. With this new value, the radial structure of the arcs, and of the entire Adams ring, may still be dominated by Galatea, as predicted by Porco[6], even though the azimuthal confinement of the arcs by the CIR now appears problematical.

An alternative solution is that the arcs are in fact trapped near a Lagrangian point L_4 or L_5 of a hypothetical neptunian satellite, as originally proposed by Lissauer[13]. For instance, a 6-km icy satellite (the detection limit of Voyager[5]) would create co-rotation sites with a maximum radial width of ~0.6 km, similar to the co-rotation sites generated by Galatea, but with a longitudinal extension which could easily encompass the full azimuthal range of the arc system (~40 degrees). In this case, the mean motion of the arcs would simply reflect the mean motion of this unknown satellite, while being still perturbed by the 42:43 CIR with Galatea. But this would require an apparently fortuitous proximity of this undetected satellite to the 42:43 CIR with Galatea, and appears for the moment as a rather *ad hoc* explanation. □

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Stability of Neptune's ring arcs in question

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Although all four of the gas-giant planets in the Solar System have ring systems, only Neptune exhibits 'ring arcs'—stable clumps of dust that are discontinuous from each other[1]. Two basic mechanisms for confining the dust to these arcs have been proposed. The first[2] relies on orbital resonances with two shepherding satellites, while the second[3] invokes a single satellite (later suggested to be Galatea[4]) to produce the observed ring arc structures. Here we report observations of the ring arcs and Galatea, which show that there is a mismatch between the locations of the arcs and the site of Galatea's co-rotation inclined resonance. This result calls into question Galatea's sole role in confining the arcs.

A new determination of the mean motion of the arcs was made possible by the Hubble Space Telescope (HST), using the Near Infrared Camera Multi-Object Spectrometer[5] (NICMOS), which observed the system of Neptune's faint arcs on two occasions in 1998. To aid in the rejection of background light at the radial angular distance of the ring arcs (~3 arcsec) from the planet centre, a filter with a bandpass centred at 1.87 μm wavelength was used. This wavelength corresponds to a strong absorption in the reflective spectrum of methane, one of the main constituents of Neptune's atmosphere. The projected azimuthal resolution was 3.2 degrees per resolution element (1.6 degrees per pixel) at the distance of the Adams ring, which corresponds to a resolution of 3,500 km along the ring. The first images of the arcs since the Voyager fly-by[6] were obtained by NICMOS on 3 June 1998. The arcs were clearly detected at the maximum of eastern elongation (Fig. 1) during a single 832-s exposure. The orbital motion of the arcs smeared the image by 8 degrees along the azimuthal direction; this is about the full length of the longest arc, Fraternité. Nevertheless, the mean motion was unambiguously determined to be very close to the proposed value (or 'solution') of 820.1118 deg. d^{-1} (ref. 7). Before these observations, another solution (820.1194 deg d^{-1}) was preferred because it supported better the action of the 42:43 co-rotation inclined resonance (CIR) with Galatea[4].

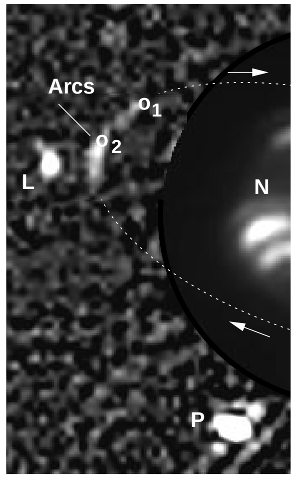

Figure 1 Initial image of Neptune's ring arcs obtained by the HST and its near-infrared camera NICMOS on 3 June 1998 at 19:40 UT. We used camera 2 (~0.076 arcsec per pixel) to image the vicinity of Neptune at 1.87 μm while the planet's phase and aspect angles were respectively 1.9 and 63 degrees. Neptune's disk was positioned partly outside the field of view of the camera to reduce the scattered light coming from the planet. In this image, Neptune's contribution to the background has been modelled and removed. An image of Neptune's clouds has been superimposed for better clarity of the system geometry. The two circles (labelled 1 and 2) correspond to the positions of the middle-point of the trailing Egalité arc derived from the two possible solutions[7] for the arcs' mean motion: $n_1 = 820.1194$ deg d^{-1} and $n_2 = 820.1118$ deg. d^{-1}. The letters L, P and N mark respectively the positions of Larissa, Proteus and Neptune, and the arrow shows the direction of motion of the ring arcs along their orbit. The measured location of the trailing Egalité arc fits better the position obtained with the mean-motion solution n_2 than n_1.

We then modified our observational strategy to improve the image quality and spatial resolution for the two remaining HST orbits. Additional NICMOS observations were obtained on 20 and 22 October 1998. An image of the system of ring arcs is given in Fig. 2, as seen by an observer viewing from the ring-plane normal. The arcs extend over 40.7 ± 3.3 degrees and the brightest trailing arcs, Egalité and Fraternité, are clearly seen. The faintest leading arcs, Courage and Liberté, are just above the noise-level (3.5σ above background for Courage, the faintest arc). The centre of Egalité was used as a fiducial point to measure the locations of the ring arcs. The arcs were found to be 0.8 ± 1.5 degrees ahead of the ephemerides prediction employing a mean motion of 820.1118 deg d^{-1}. This measurement confirmed without ambiguity the results obtained during the June 1998 observations[8]. The new value for the arcs' mean motion is 820.1120 ± 0.0004 deg d^{-1}. Similarly, we determined a revised mean motion for Galatea of 839.6617 ± 0.0004 deg d^{-1}.

The brightness profile in backscattered light (Fig. 3) was obtained by integrating the flux, radially, over the photometric width of the arcs. Following the practice employed in earlier studies of Neptune's rings[6,9], we measured the equivalent width E_i seen by NICMOS in the optically thin case. Assuming that the optical depth of Egalité has not changed since 1989, its equivalent width, E_i, and geometric albedo, $p_{1.87\,\mu m}$, are 45 ± 5 m and 0.048 ± 0.005, respectively. The letter is very close to that measured by Voyager at visible wavelength ($p_{0.5\,\mu m} = 0.055 \pm 0.004$), demonstrating that the colour of the material making up the ring arcs is similar to that in the rings of