8

Present knowledge of the Neptune ring system

8.1 INTRODUCTION

In Chapter 5, we discussed the discovery and early observations (including some of the Voyager observations) of the Neptune ring system, last of the ring systems to be discovered around a giant planet in the solar system. All of the four giant planets of the solar system have rings, and none of the terrestrial planets possess such rings. That difference must have had its origin in the processes and subsequent evolution that shaped the giant planets.

Voyager 2 is the only spacecraft that has visited Neptune. The spacecraft's closest approach to Neptune occurred at 4 a.m. Greenwich Mean Time on August 25, 1989. The only close-range data collected on Neptune's ring system were collected over a 2-week period surrounding that date of closest approach; Voyager 2 data are also the sole available data for phase angles larger than a few degrees. Only recently has Earth-based telescopic equipment achieved the sensitivity and resolution to begin additional low-phase-angle observations of Neptune's tenuous rings. Hence, the most comprehensive treatise to date on the Neptune ring system is a compilation of pre-Voyager and Voyager observations and their interpretation included as a chapter by Porco *et al*. [1] in the University of Arizona Press text *Neptune and Triton*, edited by D. P. Cruikshank. A somewhat less formal and much shorter summary is given in chapters 3 and 11 of the book *Neptune: The Planet, Rings and Satellites*, written by two of the authors of this book [2].

Nearly 800 images of the Neptune ring system were returned by Voyager 2. A handful of observations were also carried out by other investigations aboard Voyager 2. These included a stellar occultation measured by the photopolarimeter and the ultraviolet spectrometer, in which the light received from the star sigma Sagittarii was carefully monitored by Voyager 2 as the spacecraft motion caused Neptune's rings to pass across the star, partially blocking the starlight. Voyager's very precise X-band and S-band radio signals were also monitored on Earth as the spacecraft passed behind the rings in what is known as a radio occultation experiment. Dust and plasma near the spacecraft were also measured by the Voyager plasma wave, planetary radio astronomy, cosmic ray, and low-energy charged particle instruments. All of these data assisted ring scientists to better understand the nature of the Neptune rings. However, it is clear that there remain many questions that may not be answered without additional data from a future Neptune-orbiting spacecraft similar to the Cassini Orbiter at Saturn or by far more sophisticated Earth-based observations than are possible today.

8.2 RING RADIAL CHARACTERISTICS

Neptune is thirty times as far from the Sun as the Earth is. That translates to sunlight that is a scant 1/900th as bright as sunlight at Earth, or something akin to late twilight on Earth. Combine with that the fact that Neptune's rings are inherently dark (as well as being optically thin) and the problem of imaging Neptune's rings becomes something like trying to image pieces of coal when the sole illumination is a full Moon. Because of the dust content of the rings, they become somewhat easier to see when back-lighted, so some of the best images of Neptune's rings come from phase angles (the angle between the Sun and the observer as seen from the target) of about 135°. Most of the images of the Neptune rings were shuttered either during approach to the planet, where the phase angle was about 15°, or during departure, where the phase angle was about 135°. Only a few images obtained about 6.5 hr before closest approach (phase angle $\sim$8°) and 37 to 77 min after closest approach (phase angle $\sim$155°) were appreciably different from the approach and departure phase angles.

A table of the radial structure of the rings of Neptune was given earlier in Chapter 5 (Table 5.3). There are three continuous narrow rings (Adams, Le Verrier, and Arago), one faint and possibly intermittent narrow ring (which shares it orbit with the satellite Galatea), and two broad rings (Lassell and Galle). A radial scan of the measured brightness of the rings at 134° phase angle is shown in Figure 8.1 [3].

The radio science occultation experiment, which had yielded such a rich store of data for the Saturn and Uranus ring systems (no radio occultation of the Jupiter ring was attempted), yielded very little for the Neptune ring system. Tyler *et al.* [4] reported detecting no Neptune ring material down to the noise level of the radio signal, which corresponded to about 1% of the received signal strength for a radial resolution of 2 km. The team had three caveats on their non-detection: (a) only the Adams ring was probed on both the immerging and the emerging sides of Neptune and the Galle ring was not probed at all, (b) neither side probed the longitudes in the Adams ring that contained the denser ring arcs (see Section 8.3), (c) the radio data were affected by passage through Neptune's ionosphere, thus perhaps masking a weak ring signature.

The stellar occultation measurements of sigma Sagittarii occurred as Voyager 2 was inbound toward the planet, about 5 hr from closest approach. The occultation covered a range of radial distances from Neptune of 42,414 to 76,056 km. The lower end of this range is unfortunately at the outer edge of the Galle ring, but the upper end of the range is well outside the Adams ring. The Adams ring was detected by both the

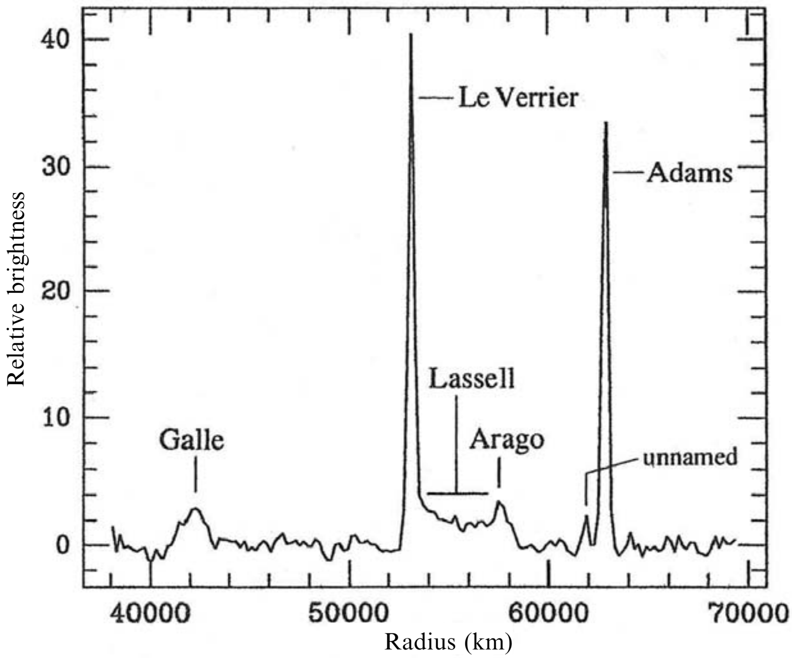

Figure 8.1. This plot of relative brightness versus radial distance was produced by Mark Showalter by radially scanning a wide-angle image (FDS 11412.51) of the rings taken at a phase angle of 135°. The data are azimuthally averaged to reduce image noise. The six rings of Neptune are clearly seen in the plot, which appears as fig. 3 of Porco *et al.* [1].

photopolarimeter (with an effective wavelength of 0.26 micrometers) [5] and the ultraviolet spectrometer (with an effective wavelength of 0.11 micrometers) [6]. Both wavelengths are well below the range of visible light wavelengths in the far ultraviolet. The value of the radial distance depends somewhat on the inclination of the Adams ring, which is not well determined, but is close to 62,900 km, in reasonable agreement with the value of 62,932 given in Table 5.3.

At this point, let us pause for a moment to remind our reader of the concept of *equivalent depth* introduced in Chapter 7 in the discussion of the variable-width Uranus rings. Equivalent depth is basically the optical depth (mathematically corrected to vertical viewing) times the physical width (in kilometers) and is a measure of the total material in a cross-section of a ring. Optical depth (= optical thickness) is a measure of the amount of light absorbed in passage through a ring and is indicated as the natural logarithm of the ratio of the intensity of the incident light to that of the emerging light. In simple terms, a ring (or other semi-transparent sheet of material) is said to have an optical depth of 1 if the incident light is reduced by a factor of e (= 2.718). The optical depth is 2 if the reduction is a factor of e^2 (= 7.389), and so forth. Vertical (or normalized) optical depth is the measured optical depth multiplied by the trigonometric sine of the viewing angle. (The viewing angle is the angle between the observing direction and the perpendicular to the ring plane.) Normalized optical depth is therefore an approximation of the optical depth of the rings for vertical illumination and viewing. In mathematical terms,

$$I = I_0\, e^{-\tau} \quad \text{[or alternatively expressed as } \tau = \ln(I_0/I)],$$

where I_0 is the incident light intensity, I is the emerging light intensity, e is the base of natural logarithms, ln is the natural logarithm, and τ is the optical depth,

$$\tau_n = \tau \sin B,$$

where B is the viewing angle just described and τ_n is the normalized optical depth, and

$$A = W\tau_n,$$

where A is the equivalent depth and W is the physical width. For the rings of Uranus, equivalent depth tends to be relatively constant around the narrow rings, even when their physical widths vary. Equivalent depth is, in a sense, a measure of the amount of ring material in a cross-section of the ring.

Now back to our discussion of the stellar occultation measurements of the Neptune rings by Voyager 2. To reduce the noise in the data, the photopolarimeter, with a sampling interval of 1.5 km, was smoothed to an effective resolution of 5 km. The equivalent depth of the Adams ring as measured by the Voyager photopolarimeter [7] was determined to be 0.77 ± 0.13 km. The ultraviolet spectrometer, with a radial resolution of 2.3 km, measured an Adams ring equivalent depth [8] of 0.66 ± 0.12 km. The two numbers are statistically identical, an indication that there are few ring particles in a size range near 0.1-micrometer radius in that part of the Adams ring, which fortuitously corresponds to the leading edge of the Liberté arc within the Adams ring. The Liberté arc is much brighter than those portions of the Adams ring sampled by the radio occultation experiment (60° and 90° from the arc region); therefore, no conclusions can be drawn about the relative numbers of larger ring particles in the Adams ring.

The ultraviolet spectrometer detected no Neptune ring features other than the Adams ring. A statistical analysis of the photopolarimeter data [9] indicated that the Adams ring occultation was the only unambiguous non-random event detected during the occultation experiment. However, there is a slight dip in the starlight intensity near the radial distance of the Le Verrier ring, which may indicate a near detection of that ring. Otherwise, the most useful data on the radial positions of the six Neptune rings listed in Table 5.3 are those from the Voyager imaging data.

Beyond the rings seen by the imaging system, Voyager detected dust particles near the ring plane both inbound and outbound. The detections were made by the plasma wave [10] and planetary radio astronomy [11] investigations. The inbound equatorial crossing of Neptune was at a radial distance of 85,290 km and the outbound was at a radial distance of 103,950 km [12]. On the inbound leg, both investigations found a maximum in the numbers of dust particles at a radial distance of 85,400 km and a vertical height above the ring plane of +146 to +160 km. The numbers of particles dropped off smoothly above and below that point, reaching half the maximum number density at a distance of about ±140 km. The two investigations differed slightly in their derived numbers for the outbound ring crossing. The plasma wave investigation found the maximum numbers near a radial distance of 104,000 km and near a vertical distance of −948 km below Neptune's equatorial plane; the vertical width of the dust distribution was more than ±500 km at half maximum. The planetary radio astronomy investigation found a maximum at a slightly larger radial distance of 105,500 km and a little closer to Neptune's equator (−700 km); they found a much narrower dust distribution with a thickness of about ±115 km.

8.3 RING AZIMUTHAL VARIATIONS

No significant azimuthal inhomogeneity has been noted in Neptune's inner four rings. The unnamed ring that shares its orbit with the satellite Galatea is not visible in most Voyager images of the rings; for those in which it is discernible, it appears to be discontinuous, but the existing data are insufficient to quantify any azimuthal variability. The only ring for which azimuthal variability is clearly and measurably present is the Adams ring.

The primary azimuthal structure noted in the Adams ring is associated with the ring arcs. A radially averaged longitudinal scan of a Voyager 2 wide-angle image that includes all the arcs is shown in Figure 8.2, taken from Porco *et al.* [13]. The arcs, from leading to trailing, are Courage, Liberté, Egalité 1, Egalité 2, and Fraternité. Their relative positions and respective lengths were given in Table 5.4. Internal brightness variations within the ring arcs, clearly evident from Figure 8.2, are real and exist in each of the arcs. These variations are likely due to clumpiness within the arcs. They may be the result of accumulation of dust-sized particles around larger than average bodies within the arcs. The larger bodies in turn may be the source bodies for the smaller material in the arcs [14].

In addition to the fine-scale brightness variations within the ring arcs, the non-arc regions of the Adams ring seem to vary by about a factor of 3; the background ring is brightest near and between the ring arcs and faintest well away from the longitude of the arcs [15].

Recent observations of the Adams ring arcs from the Keck Telescope, utilizing its adaptive optics capability, show that there have been substantial changes in the ring arcs since the Voyager 2 encounter in 1989 [16]. The trailing arc, Fraternité, seems to be the only well-behaved arc within the ring. It continues to be essentially unchanged in appearance and to circle Neptune at the same rate measured during the Voyager era (820.1118 deg/day). Egalité 1 and Egalité 2 appear to have reversed in relative intensity, perhaps the result of material migrating between the two resonance sites. Courage appears to be approximately 8° ahead of its prior position relative to Fraternité, perhaps an indication that it has shifted one resonance site ahead of its prior position. In earlier data, Liberté seemed to be migrating between resonance sites; in the latest data it has all but disappeared.

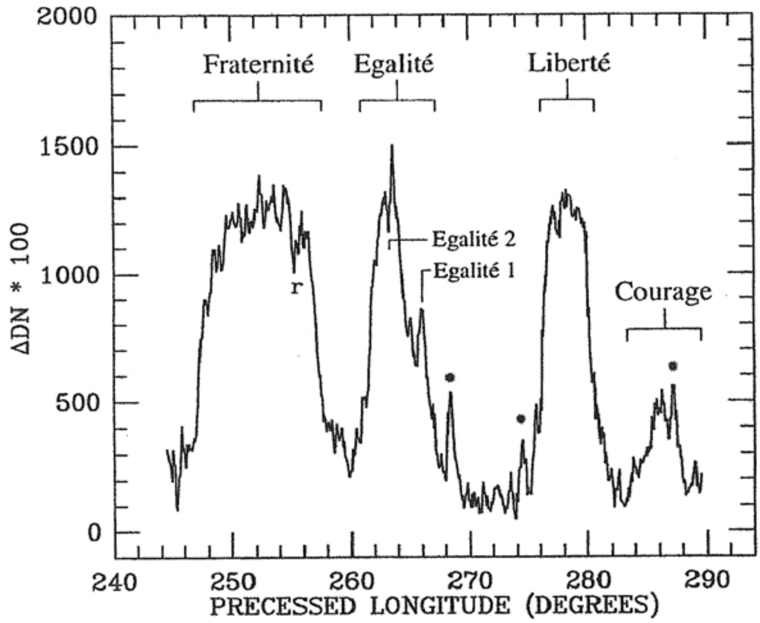

Figure 8.2. In a wide-angle image obtained 20.5 hr after Voyager 2's closest approach to Neptune, all the Adams ring arcs were captured. A radially averaged azimuthal scan of the Adams ring depicts the relative sizes and positions of the five ring arcs. The longitude system is one for which the rings are fixed as of August 18, 1989. Adjustment to that date was accomplished by precession of the observed position backwards at a rate of 820.1185 deg/day, the observed rotational rate of the A ring arcs. The three asterisks in the figure indicate the positions of background stars. The "r" in the Fraternité arc shows the position of an incompletely removed black reseau mark from the camera; reseau marks are used for geometric reconstruction of Voyager images.

8.4 SMALL SATELLITES NEAR THE RINGS

Four known satellites orbit near or within the Neptune ring system (see Table 8.1). These include Naiad, Thalassa, Despina, and Galatea. Naiad, Thalassa, and Despina are all between the Galle and Le Verrier rings. Galatea seems to circle Neptune precisely 43 times for every 42 circuits of particles in the Adams ring. In scientific terms, that means that the Adams ring and its ring arcs are located at a 42:43 *outer Lindblad resonance* [17] of Galatea. Galatea may therefore be partly responsible for the narrowness of the Adams ring. It may also play a role in the azimuthal confinement of the ring arcs. Over time, its gravitational influence will create 42 nodes in the Adams ring which may inhibit the azimuthal motion of ring particles past those nodes, which would be separated by 8.57° of ring longitude. Six nodes would span a longitudinal range of about 42.85°, very nearly the same as the longitude span covered by the five known arcs.

Table 8.1. Neptune ring dimensions ($1R_N = 24{,}674$ km, $1M_N = 10.246 \times 10^{25}$ kg).

Ring region	Boundary (km)	Boundary (R_N)	Velocity, (km/s)	Period (hr)	Mass (M_N)
Galle ring	~40,900	1.66	12.94	5.518	??
	~42,900	1.74	12.63	5.927	
(Naiad	*48,227*	*1.95*	*11.914*	*7.065*	*2×10^{-9})*
(Thalassa	*50,075*	*2.02*	*11.690*	*7.476*	*4×10^{-9})*
(Despina	*52,526*	*2.12*	*11.414*	*8.032*	*20×10^{-9})*
Le Verrier ring	$53{,}200 \pm 20$	2.15	11.35	8.187	??
Lassell ring	53,200	2.15	11.35	8.187	??
	57,200	2.31	10.92	9.129	
Arago ring	57,200	2.31	10.92	9.129	??
Unnamed ring	~61,950	2.50	10.50	10.290	??
(Galatea	*61,953*	*2.50*	*10.508*	*10.290*	*37×10^{-9})*
Adams ring	$62{,}932 \pm 2$	2.54	10.42	10.535	??
(Larissa	*73,548*	*2.97*	*9.643*	*13.312*	*48×10^{-9})*

Note: Widths of the narrow rings (in km) are: Le Verrier ~110; Arago and Unnamed <100; Adams 15–50.

Despina is relatively close to the Le Verrier ring, but its gravitational force seems to have no effect on that ring. The center of the ring is only a few kilometers from the position of a potential 53:52 outer Lindblad resonance, but the 54:53 resonance is only 13.1 km closer to the planet, and the Le Verrier ring has a width of about 110 km. Furthermore, the absence of azimuthal inhomogeneity or internal radial structure would seem to rule out substantial gravitational effects from Despina. If the Le Verrier ring's width is affected by a Lindblad resonance, it does not appear to be that of Despina.

Galatea seems also to be subject to bombardment by meteoroids that have blasted material from its surface. That is probably the source of the tenuous and possibly intermittent ring that shares its orbit. Little more is known about this tenuous ring that has yet to garner an official name from the International Astronomical Union's Nomenclature Commission.

8.5 POSSIBLE ELECTROMAGNETIC EFFECTS

The presence of an extended disk of dust well beyond the visible ring system was discussed in Section 8.3. The plasma wave and planetary radio astronomy investigations also detected dust particles at all latitudes, albeit at levels that were several orders of magnitude smaller than observed near the equator. Neptune's magnetic equator is highly tilted (by 47°!) with respect to Neptune's rotation equator, so if tiny dust particles in the extended dust disk become electrically charged, they can perhaps be rapidly moved out of the equatorial plane near Lorentz resonance positions, as discussed for the Halo ring of Jupiter in Chapter 6. Lorentz resonances occur at radial distances where the orbital period of the dust particles is a simple integer ratio of the rotation period of Neptune. Neptune's rotation period is 16.108 ± 0.006 hr [18]. By inspection of Table 8.1, it is clear that the co-rotation radius (where the natural orbital period is equal to the rotation period of Neptune) is well outside the rings. It falls at a radial distance of 3.22 R_N (79,740 km) from Neptune's center, between the orbits of Larissa and Proteus. The 3:2 Lorentz resonance radial distance is outside the Adams ring and the 2:1 resonance is interior to the Le Verrier ring. Any electrically charged sub-micrometer-sized particles that wander planetward at those two radial distances will quickly be perturbed to high inclinations, possibly ending up as a part of the high-latitude dust population observed.

Ring particles in the main rings and the dust disk, except at the co-rotation radius near 79,740 km, will have trapped radiation in the Neptune magnetosphere swept back and forth across them. The resultant collisions are expected to remove some of that plasma from the magnetosphere, resulting in reduced plasma levels above and below the rings. However, the passage of Voyager 2 over the pole of Neptune did not take the spacecraft through those portions of the Neptune magnetosphere that might enable such depletions to be measured directly.

8.6 PHYSICAL PROPERTIES OF THE RINGS

The absence of a detection of the Adams ring (away from the arc region) implies that the material in that portion of the ring is much smaller than a few centimeters in radius. This is in sharp contrast to similar measurements of the rings of Saturn and Uranus, where dust-sized particles apparently constitute 1% or less of particle population. The brightness of the six Neptune rings at high phase angle in Voyager 2 images leads to a similar conclusion: that a high percentage of the particles in the rings must be micrometer-sized. Similarly, from the greater contrast between the arcs in the Adams ring and particles in the remainder of the ring in high-phase images, the ring arcs have an even higher percentage of micrometer-sized particles than the rest of the Adams ring. The Le Verrier ring particles are similar to those of the non-arc regions of the Adams ring.

Looking at particle sizes in the broader Galle and Lassell rings, the Galle ring also appears to have high dust content. The Lassell ring, of comparable optical depth, appears significantly less dusty (although still more than ten times as dusty as the main rings of Saturn or Uranus).

One characteristic common to the rings of Uranus and Neptune is their low reflectivity. Both are characterized by particles that reflect less than 5% of the light incident on their surfaces. This low reflectivity is certainly uncharacteristic of water ice particles. Perhaps both ring systems have particles coated with black elemental carbon, possibly produced by the bombardment of methane by magnetospheric plasma.

The masses of the rings of Neptune (listed as '??' in Table 8.1) were not determined, but they are estimated to be 10,000 times less massive than the rings of Uranus.

If dedicated searches for such rings had not been conducted, either from Earth or from Voyager 2, they might never have been seen in images taken for other purposes. Neptune has more satellites within its ring system (Naiad, Thalassa, Despina, and Galatea) than Uranus (only Cordelia resides within the ring system), so the smaller mass of the Neptune rings is not a consequence of less available source material. The reasons for the differences between the two ring systems are not understood, but they imply significant differences in the evolution of these two ring systems.

8.7 NOTES AND REFERENCES

[1] Porco, C. C., Nicholson, P. D., Cuzzi, J. N., Lissauer, J. L., Esposito, L. W., 1995, "Neptune's ring system", in *Neptune and Triton*, edited by D. P. Cruikshank, pp. 703–804.

[2] Miner, E. D., Wessen, R. R., 2002, *Neptune: The planet, rings and satellites*, chapters 3 ("Speculation about Neptune's rings", pp. 27–34) and 11 ("The rings of Neptune", pp. 237–246).

[3] Image reproduced from fig. 3 of Porco *et al.* [1], provided originally by M. Showalter.

[4] Tyler, G. L., Sweetnam, D. N., Anderson, J. D., Borutzki, S. E., Campbell, J. K., Eshleman, V. R., Gresh, D. L., Gurrola, E. M., Hinson, D. P., Kawashima, N., Kursinski, E. R., Levy, G. S., Lindal, G. F., Lyons, J. R., Marouf, E. A., Rosen, P. A., Simpson, R. A., Wood, G. E., 1989, "Voyager radio science observations at Neptune and Triton", *Science* **246**, 1466–1473.

[5] Lane, A. L., West, R. A., Hord, C. W., Nelson, R. M., Simmons, K. E., Pryor, W. R., Esposito, L. E., Horn, L. J., Wallis, B. D., Buratti, B. J., Brophy, T. G., Yanamandra-Fisher, P., Colwell, J. E., Bliss, D. A., Mayo, M. J., Smythe, W. D., 1989, "Photometry from Voyager 2: Initial results from the Neptunian atmosphere, satellites and rings", *Science* **246**, 1450–1454.

[6] Broadfoot, A. L., Atreya, S. K., Bertaux, J. L., Blamont, J. E., Dessler, A. J., Donahue, T. M., Forrester, W. T., Hall, D. T., Herbert, F., Holberg, J. B., Hunten, D. M., Krasnopolsky, V. A., Linick, S., Lunine, J. L., McConnell, J. C., Moos, H. W., Sandel, B. R., Schneider, N. M., Shemansky, D. E., Smith, G. R., Strobel, D. F., Yelle, R. V., 1989, "Ultraviolet spectrometer observations of Neptune and Triton", *Science* **246**, 1459–1465.

[7] Horn, L. J., Hui, J., Lane, A. L., Colwell, J. E., 1990, "Observations of neptunian rings by Voyager photopolarimeter experiment", *Geophysical Research Letters* **17**, 1745–1748.

[8] Broadfoot *et al.*, 1989, [6].

[9] Horn *et al.*, 1990, [7].

[10] Gurnett, D. A., Kurth, W. S., Granroth, L. J., Allendorf, S. C., Poynter, R. L., 1991, "Micron-sized particles detected near Neptune by the Voyager 2 Plasma Wave Instrument", *Journal of Geophysical Research* **96**, 19177–19186.

[11] Pedersen, B. M., Meyer-Vernet, N., Aubier, M. G., Zarka, P., 1991, "Dust distribution around Neptune: Grain impacts near the ring plane measured by the Voyager Planetary Radio Astronomy experiment", *Journal of Geophysical Research* **96**, 19187–19196.

[12] Stone, E. C., Miner, E. D., 1991, "The Voyager encounter with Neptune", *Journal of Geophysical Research* **96**, 18903–18906.

[13] Fig. 5 of Porco *et al.*, 1995, [1], found on p. 715 of that article.

[14] Smith, B. A., Soderblom, L. A., Banfield, D., Barnet, C., Basilevsky, A. T., Beebe, R. F., Bollinger, K., Boyce, J. M., Brahic, A., Briggs, G. A., Brown, R. H., Chyba, C., Collins, S. A., Colvin, T., Cook, A. F. H., Crisp, D., Croft, S. K., Cruikshank, D., Cuzzi, J. N.,

Danielson, G. E., Davies, M. E., De Jong, E., Dones, L., Godfrey, D., Goguen, J., Grenier, I., Haemmerle, V. R., Hammel, H., Hansen, C. J., Helfenstein, C. P., Howell, C., Hunt, G. E., Ingersoll, A. P., Johnson, T. V., Kargel, J., Kirk, R., Kuehn, D. I., Limaye, S., Masursky, H., McEwen, A., Morrison, D., Owen, T., Owen, W., Pollack, J. B., Porco, C. C., Rages, K., Showalter, M., Sicardy, B., Simonelli, D., Spencer, J., Sromovsky, B., Stoker, C., Strom, R. G., Suomi, V. E., Synott, S. P., Terrile, R. J., Thomas, P., Thompson, W. R., Verbiscer, A., Veverka, J., 1989, "Voyager 2 at Neptune: Imaging science results", *Science* **246**, 1422–1449.

[15] Showalter, M. R., Cuzzi, J. N., 1992, "Physical properties of Neptune's ring system", *Bulletin of the American Astronomical Society* **24**, 1029 (abstract); quoted in Porco *et al.*, 1995, [1], p. 715.

[16] De Pater, I., Gibbard, S. G., Chiang, E., Hammel, H. B., Macintosh, B., Marchis, F., Martin, S. C., Roe, H. G., Showalter, M., 2005, "The dynamic Neptunian ring arcs: Evidence for a gradual disappearance of Liberté and resonant jump of Courage", *Icarus* **174**, 263–272.

[17] Lindblad resonances are named for Swedish astronomer Bertil Lindblad (1895–1965). He was the first to recognize that galactic spiral structure could be attributed to the gravitational influence of a perturbing body on a disk of smaller bodies if the two orbited around a common center in periods that are related by relative small integers. For the purposes of this chapter, the three bodies involved in Lindblad resonances are the planet, a perturbing satellite of sufficient mass, and a ring. For example, if a satellite orbits a planet interior to a planetary ring and completes two orbits of the planet for every single orbit of some of the particles in the ring, and if the satellite is large enough to exert a measurable gravitational force from that distance, those particles in the ring will be perturbed by a 1:2 outer Lindblad resonance due to repeated gravitational tugs in the same direction. If the satellite is exterior to the ring and orbits the planet three times for every four orbits of the ring material, it might exert a perturbing force on the ring material at the 4:3 inner Lindblad resonance. In general, the smaller the satellite, the closer it must be to the ring and the higher the order of the Lindblad resonance. In the case of Galatea and the Adams ring, the latter is at a 42:43 outer Lindblad resonance radius of the former.

[18] Zarka, P., Pedersen, B. M., Lecacheux, A., Kaiser, M. L., Desch, M. D., Kurth, W. S., 1995, "Radio emissions from Neptune", in *Neptune and Triton*, edited by D. P. Cruikshank, pp. 341–387.

8.8 BIBLIOGRAPHY

Miner, E. D., Wessen, R. R., 2002, *Neptune: The planet, rings and satellites*, Springer-Praxis (note especially chapters 3 ("Speculation about Neptune's rings", pp. 27–33), 11 ("The rings of Neptune", pp. 237–246), and 14 ("Comparative planetology of the four giant planets", pp. 273–288).

Porco, C. C., Nicholson, P. D., Cuzzi, J. N., Lissauer, J. L., Esposito, L. W., 1995, "Neptune's ring system", in *Neptune and Triton*, edited by D. P. Cruikshank, pp. 703–804.

8.9 PICTURES AND DIAGRAMS

Figure 8.1 Fig. 3 of Porco *et al.* [1].
Figure 8.2 Fig. 5 of Porco *et al.* [1].