34. J. J. Schneider, D. Wolf, C. W. Lehmann, *Inorg. Chim. Acta* **350**, 625 (2003).
35. M. A. Petrukhina, K. W. Andreini, L. Peng, L. T. Scott, *Angew. Chem. Int. Ed. Engl.* **43**, 5477 (2004).
36. T. Murahashi, T. Nagai, T. Okuno, T. Matsutani, H. Kurosawa, *Chem. Commun.* **2000**, 1689 (2000).
37. E. L. Muetterties, T. N. Rhodin, E. Band, C. F. Brucker, W. R. Pretzer, *Chem. Rev.* **79**, 91 (1979).
38. T. Murahashi, H. Kurosawa, *Coord. Chem. Rev.* **231**, 207 (2002).

39. Supported by the Japan Science and Technology Agency (JST) through PRESTO (Structure Control and Function) program; grants-in-aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan; and Frontier Research Center (FRC), Osaka University. Metrical parameters for the crystal structures of **1** and **4-toluene** are available from the Cambridge Crystallographic Data Centre under reference numbers CCDC-602060 and CCDC-602061, respectively.

**Supporting Online Material**
www.sciencemag.org/cgi/content/full/313/5790/1104/DC1
Materials and Methods
Figs. S1 to S7
Schemes S1 and S2
Tables S1 to S9
References

23 January 2006; accepted 20 July 2006
10.1126/science.1125245

---

# Forced Resonant Migration of Pluto's Outer Satellites by Charon

**William R. Ward* and Robin M. Canup**

**Two small moons of Pluto have been discovered in low-eccentricity orbits exterior to Pluto's large satellite, Charon. All three satellite orbits are nearly coplanar, implying a common origin. It has been argued that Charon formed as a result of a giant impact with primordial Pluto. The orbital periods of the two new moons are nearly integer multiples of Charon's period, suggesting that they were driven outward by resonant interactions with Charon during its tidal orbital expansion. This could have been accomplished if Charon's orbit was eccentric during most of this orbital evolution, with the small moons originating as debris from the collision that produced Charon.**

Hubble Space Telescope observations in May 2005 revealed two previously undetected satellites of Pluto, S/2005 P1 and S/2005 P2 (P1 and P2) (*1*–*3*). The diameters of P1 and P2 are respectively ~160 km and ~120 km if they are as dark as cometary nuclei, but only ~35 km and ~30 km for a Charon-like reflectivity, with each object containing ≤0.2% of Charon's mass. The orbital period, $P$, of P1 is 38.2065 ± 0.0014 days, whereas that of P2 is 24.8562 ± 0.00013 days. This implies that P1 and P2 have periods of about six and four times the 6.38723-day orbital period of Charon (*1*–*3*), and a nearly 3:2 mutual ratio. Such orbital period ratios are referred to as mean motion commensurabilities, where the mean motion is $n = 2\pi/P$. The moons orbit in the same sense and plane as Charon (*1*), consistent with all three having formed by a common process rather than, for example, through sequential capture events (*4*, *5*).

The favored explanation for Charon's origin is a large impact (*6*, *7*) similar to that believed to have produced Earth's Moon. Charon appears most likely to have formed intact, on an eccentric orbit (*7*). It seems plausible that the impact generated some accompanying orbiting debris as source material for the outer small satellites. However, the present orbital distances of P2 at 41.9 $R_P$ and P1 at 54.8 $R_P$, where $R_P$ = 1180 ± 15 km is Pluto's radius, are far outside where debris from the type of collision favored for Charon's origin would be expected [e.g., typically within 15 $R_P$ (*7*, *8*)].

Charon occupies a tidal end-state with an orbital period synchronous with Pluto's day and has likely undergone considerable outward tidal migration, perhaps by a factor of ~4, to arrive at its current distance of 16.6 $R_P$ (*9*). The near 6:1 and 4:1 commensurabilities of P1 and P2 naturally lead to the supposition that they were driven outward by resonant torques from Charon (*2*). However, the required degree of expansion is large, and most observed solar system resonant configurations (e.g., that between Neptune and Pluto itself) act to excite the eccentricity of the resonantly perturbed object as the orbital radius of the perturbing object approaches it. This would have led to large, destabilizing eccentricities for P2 and P1. We propose instead that Pluto's small moons were captured into exterior corotation resonances with an eccentrically orbiting Charon. This is the same general type of resonance thought to confine the Neptune ring arcs (*10*, *11*) and does not excite eccentricities, thus providing an explanation for how Pluto's distant new moons could have originated from the same impact event as Charon.

When the period ratio of two satellites is nearly that of two integers, resonant forcing of their orbits acts to maintain the locations of their orbital conjunctions relative to the pericenter of one or both of their orbits. Their mutual gravitational potential can be expanded as a Fourier series (*12*), but near a commensurability, the motion will be dominated by only a few resonant terms. An exterior moon with a period relative to Charon's of $P/P_C \sim (m+1)$, with $m = 3$ for P2 or $m = 5$ for P1, will be subject to multiple resonant terms of the form $\Phi_{ml}(a, a_c, e, e_c)\cos\phi_{ml}$, with

$$\phi_{ml} = (m+1)\lambda - \lambda_C - (m-l)\tilde{\varpi} - l\tilde{\varpi}_C \qquad (1)$$

and $0 \le l \le m$ (*13*). Here, $\lambda$ and $\tilde{\varpi}$ are the longitudes of the satellite and its orbital pericenter. Subscripts C refer to Charon, whereas unsubscripted quantities refer to a moon. Resonance capture causes the argument, $\phi_{ml}$, of the resonance to librate about some fixed value. The amplitude of a resonant term has the form

$$\Phi_{ml} = -f_{ml}(\alpha)e^{m-l}e_C^l GM_C/a \;;\; \alpha \equiv a_C/a \qquad (2)$$

where $a$ and $e$ are semi-major axis and eccentricity, the quantity $f_{ml}(\alpha)$ is a combination of Laplace coefficients and their derivatives (*12*), and $M_C$ is Charon's mass. For any single resonance, the equations of motion admit two constants (*14*–*16*): the Brouwer integral

$$B = a^2 n[(m+1)(1-e^2)^{1/2} - (l+1)] \qquad (3)$$

and the Jacobi integral

$$C = -\tfrac{1}{2}a^2n^2 - \frac{1}{m+1}a^2 n n_c + \Phi_{ml}\cos\phi \qquad (4)$$

If an exterior moon were forced to migrate as Charon tidally evolved, Eq. 3 gives the moon's eccentricity, $e(t)$, as a function of $a(t)$. For resonances with $l \ne m$, the resonant argument in Eq. 1 contains the moon's longitude of pericenter, $\tilde{\varpi}$, and evolution in resonance increases the moon's eccentricity as $a$ increases. Even for an initially zero eccentricity, a fourfold expansion of semi-major axis excites an eccentricity

$$e_{ml} \rightarrow [1 - (2+l+m)^2/4(m+1)^2]^{1/2} \qquad (5)$$

For $m = 3$ (i.e., the 4:1), the $l \ne m$ resonances would produce $e_{30} = 0.781$, $e_{31} = 0.661$, and $e_{32} = 0.484$. Eccentricities for $m = 5$ (the 6:1) are also substantial ($e \ge 0.4$) for all $l \ne m$ terms. Because objects in the 6:1 and 4:1 resonances are separated in semi-major axis by

---

Department of Space Studies, Southwest Research Institute, Boulder, CO 80302, USA.

*To whom correspondence should be addressed. E-mail: ward@boulder.swri.edu

only $a_1 - a_2 \approx 0.31a_2 \approx 0.24a_1$, crossing orbits and instability between such objects would be expected for $e \geq 0.3$. However, for the special case of $l = m$, the resonance argument becomes $\phi_{mm} = (m+1)\lambda - \lambda_C - m\tilde{\omega}_C$, which does not contain the outer moon's pericenter longitude nor excite its eccentricity. Because the resonant amplitude, $\Phi_{mm}$, is proportional to $e_C{}^m$ (Eq. 2), corotation resonances with $m \geq 1$ require an eccentric perturber.

To describe the character of libration in a corotation resonance, we define the corotation distance as where $n(a_{cr}) = \Omega_{ps}$ with $\Omega_{ps} = n_C/(m+1) + m(d\tilde{\omega}_C/dt)/(m+1)$ being the so-called pattern speed, and consider a perturbation in $a$, i.e., $a = a_{cr} + \Delta a$, $\Delta a \ll a_{cr}$. The trajectory is found from the Jacobi integral, which can be recast as (*16*)

$$C + {}^3\!/_2 a_{cr}^2 n_{cr}^2 - \Phi_{mm} = -{}^3\!/_8 n_{cr}^2 \Delta a^2 - {}^1\!/_2 \Phi_{mm}\phi^2 = -{}^1\!/_2 \Phi_{mm}\phi_{\max}^2 \qquad (6)$$

and describes an ellipse with major axis $a\phi_{\max}/m$ and minor axis $\Delta a_{\max} = (4\Phi_{mm}/3n_{cr}^2)^{1/2}\phi_{\max}$, as shown in Fig. 1. The maximum radial width of the librating region is $w = 4(\Phi_{mm}/3n_{cr}^2)^{1/2} = 4(e_C^m|f_{mm}|\mu_C/3)^{1/2}a_{cr}$, where $\mu_C \equiv M_C/M_P = 0.116$ and $M_P$ is Pluto's mass (*3*, *17*). Thus, for example, with a Charon eccentricity of $e_C \sim 0.2$, moons librating in the 4:1 and 6:1 corotation resonances would have a $\Delta a/a_{cr} \leq w/a_{cr} \sim 0.03$ and 0.002, respectively. The libration period $2\pi/\omega_{lib}$, with $\omega_{lib} = (m+1)(3\Phi_{mm}/a_{cr}^2)^{1/2}$ (*16*), is much longer than the orbital period, so that over multiple orbits in inertial space a moon completes a single libration, as seen in the frame rotating with the resonant term (Fig. 2) (*18*).

Now consider the response of a trapped moon to a slow tidal expansion of Charon's orbit according to (*9*)

$$\frac{da_C}{dt} = 3\frac{k_p}{Q_p}\frac{M_C}{M_P}\left(\frac{R_P}{a_C}\right)^5 a_C n_C\ ; \qquad \frac{dn_C}{dt} = -{}^3\!/_2 n_C \frac{\dot{a}_C}{a_C} \qquad (7)$$

where $Q_P \sim 10^2$ is Pluto's tidal dissipation parameter, and $k_P \sim 0.055$ is its tidal Love number (*9*). Objects remain trapped in a moving resonance so long as the time, $w/\dot{a}_{cr} = w/\dot{a}_C(m+1)^{2/3}$, that it takes for Charon to migrate a distance comparable to the libration zone half-width $w$, is much longer than the libration period (*13*, *16*). This yields an adiabatic condition, $e_C^m f(\alpha) \gg (3\pi)(k_P/Q_P)(R_P/a_C)^5$. Adopting $a_C(0) \approx 4R_P$ leads to a threshold value for Charon's initial eccentricity $e_{crit} \approx (5 \times 10^{-6}/f_{mm})^{1/m}$ (*19*). This requires $e_C \approx 0.2$ for capture of P1, the more difficult to capture moon. Simulations of Charon's intact formation by impact (*7*) find cases with initial eccentricities and semi-major axes comparable to these values. Early resonant trapping of P1 and P2 would allow for them to have originated from impact debris extending only to ~13 $R_P$, which is reasonable given results of impact simulations (*7*, *8*).

We are interested in the evolution of $e_c$ as Charon's orbit tidally expands, which is given by (*20*)

$$\frac{1}{e_C}\frac{de_C}{dt} \approx {}^{19}\!/_8[sgn\sigma - {}^{28}\!/_{19}A]\frac{\dot{a_C}}{a_C} \qquad (8)$$

where $\dot{a}_C$ is the expansion rate due only to Pluto tides, $\sigma \equiv 2\omega_P - 3n_C$, with $\omega_P$ being the spin frequency of Pluto, and $A \approx (k_C/k_P)(Q_p/Q_C)(R_P/R_C)$ where similar densities have been assumed for Pluto and Charon. The first term on the right side of Eq. 8 is due to tides raised on Pluto, whereas the second term is due to tidal dissipation in Charon. Assuming that the $k$'s are dominated by similar rigidities, then $k_C/k_P \sim (R_C/R_P)^2$, $A \sim R_C Q_P/R_P Q_C$, and $e_c$ increases if $Q_P/Q_C \leq {}^{19}\!/_{28} R_P/R_C \approx 1.3$. Given the uncertainties, Charon's eccentricity could have either grown or decayed during most of its orbital expansion. However, once $\omega_P \leq 3n/2$ toward the end of its expansion, $\sigma$ reversed sign and $e_C$ decayed.

Because the current eccentricity of Charon is very low as a result of tidal damping, P1 and P2 are probably not now in corotation resonances. On the other hand, it is unlikely they escaped simultaneously. At present $4n_2 - n_C = 3.14 \times 10^{-7}s^{-1}$ (*3*), so that P2 lies slightly inside the nominal positions of the $m = 3$ terms given by $n_2 \approx n_C/4 + (3 - l)\omega_2^C/4$, where $\omega_2^C = \approx 3.87 \times 10^{-8}s^{-1}$ is Charon's contribution to P2's apse precession (*16*). This suggests that P2 escaped from corotation first (perhaps because of a larger libration amplitude), just before Charon's orbital migration halted. Continued occupancy of the 3:2 resonance could have protected P2 from the remaining $m = 3$ resonances by controlling the rate of apse precession, $d\tilde{\omega}_2/dt \approx 3n_1 - 2n_2$. This would have caused the resonance variable $\phi_{33}$ to circulate, and as Charon continued to migrate outward, the other $\phi_{ml}$ resonances variables would circulate as well (*16*). Finding P2 in 3:2 libration currently (*21*) would be strong support for this notion, although it is also possible that a small free eccentricity could have caused a transition from libration to circulation as P1 and P2 separated somewhat.

Because most resonances excite large eccentricities, much of the original impact-produced debris may have been destabilized

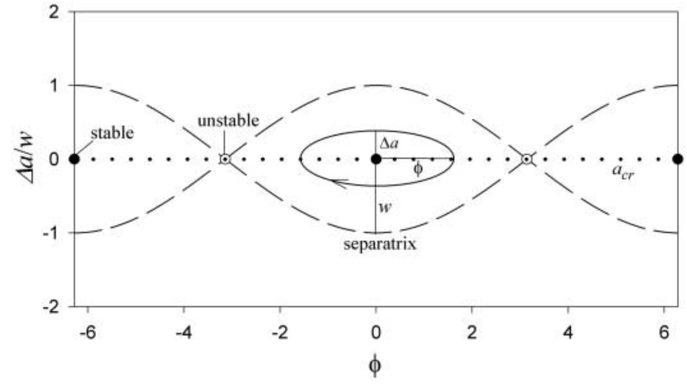

**Fig. 1.** Schematic of a corotation resonance island, shown in a frame rotating with the resonant pattern speed, $\Omega_{ps}$. Dashed curve indicates the separatrix, dotted line is the corotation distance, and the primary is in the negative *y*-axis direction. The separatrix separates resonantly librating orbits from nonresonant circulating orbits. Particle trajectories displaced from a stable equilibrium point (filled circles) librate about the point, with each island of libration separated by unstable equilibrium points (open circles).

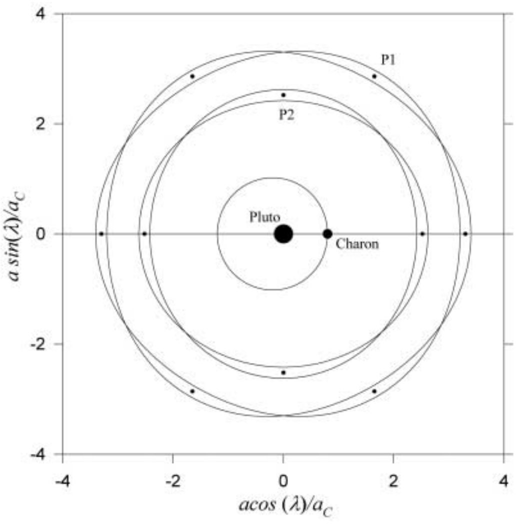

**Fig. 2.** The $m + 1 = 4$ and $m + 1 = 6$ stability islands for the corotation resonances near P2 and P1, shown when Charon is at pericenter. For each resonance, the $(m + 1)$ islands are confined by a separatrix. The island widths are arbitrarily set to 0.1 for clarity; the actual widths are a function of Charon's eccentricity. The solid point contained in each island is a stable equilibrium about which trajectories librate. Each pattern rotates counter-clockwise at the pattern speed $\Omega_{ps} \approx n_C/(m + 1)$, so for each Charon orbit, a new stable equilibrium point is brought to conjunction at pericenter.

by mutual collisions or scattering into Charon or Pluto. Debris captured into some corotation islands could also have been dislodged through encounters with other high-eccentricity material. Nevertheless, it seems plausible that a fraction comparable to the tiny masses of P1 and P2 might have survived such stochastic removal processes.

What about corotation resonances other than the 4:1 and 6:1? For an eccentric Charon, the 3:1 corotation resonance is nearly overlapped by its Hill sphere at apocenter and was likely not a stable niche. Corotation resonances also occur when $(m + p)n \approx pn_C$ for $p > 1$, but these fall at distances $a_{\mathrm{cr}} = (m/p + 1)^{2/3}$ and are shifted inward. Thus, those that fall in the vicinity of P1 and P2 have amplitudes that are dependent on a higher power of Charon's eccentricity (i.e., $\sim e_C^{3p}$, $e_C^{5p}$) and are weaker. Although transient forced eccentricities may interfere with the stability of adjacent $p = 1$ resonances, it remains an intriguing possibility that smaller, yet undetected moons may orbit Pluto near the 5:1.

Because the corotation resonances we invoke no longer exist, direct diagnostic evidence of this mechanism is elusive. However, a circumstantial case can be made by considering the alternatives. Although there are capture mechanisms (*4*, *5*) to create well-separated secondaries such as some Kuiper belt binaries, they do not select a common orbital plane or direction. In addition, the subsequent hardening of these configurations tends to produce large eccentricities that could not be damped by tidal forces given the small masses of P1 and P2 (*2*). Alternatively, if a protosatellite disk were to extend to sufficient distance to allow the accretion of P1 and P2 in situ, there is no obvious reason why they should be found in near-resonant orbits, because tidal torques are also too weak to migrate them into such configurations. A final unanswered question is how the moons were initially trapped in corotation resonances. One possibility is that a small amount of vapor and/or small particles extended past the location of the 6:1 resonance ($\sim 3.3\ a_C$) and their free eccentricities damped by collisional viscosity. This could have initially populated many resonance sites, but most would be later cleared as eccentricities were excited by resonant migration. Indeed, material comprising P1 and P2 may have begun as ring arcs, except that by lying external to Pluto's Roche limit, single moons were able to accumulate.

### References and Notes

1. H. A. Weaver *et al.*, *Nature* **439**, 943 (2006).
2. S. A. Stern *et al.*, *Nature* **439**, 946 (2006).
3. M. W. Buie, W. M. Grundy, E. F. Young, L. A. Young, S. A. Stern, *Astron. J.* **132**, 290 (2006).
4. P. Goldreich, Y. Lithwick, R. Sari, *Nature* **420**, 643 (2002).
5. S. J. Weidenschilling, *Icarus* **160**, 212 (2002).
6. W. B. McKinnon, *Astrophys. J.* **344**, L41 (1989).
7. R. M. Canup, *Science* **307**, 546 (2005).
8. R. M. Canup, *Ann. Rev. Astron. Astrophys.* **42**, 441 (2004).
9. A. R. Dobrovolskis, S. J. Peale, A. W. Harris, in *Pluto and Charon*, S. A. Stern, D. J. Tholen, Eds. (Univ. Arizona Press, Tucson, AZ, 1997), pp. 193–219.
10. P. Goldreich, S. Tremaine, N. Borderies, *Astron. J.* **92**, 490 (1986).
11. F. Namouni, C. Porco, *Nature* **417**, 45 (2002).
12. C. D. Murray, S. F. Dermott, *Solar System Dynamics* (Cambridge Univ. Press, Cambridge, 2001).
13. S. Dermott, R. Malhotra, C. D. Murray, *Icarus* **76**, 295 (1988).
14. D. Brouwer, *Astron. J.* **68**, 152 (1963).
15. P. Goldreich, S. Tremaine, *Astrophys. J.* **243**, 1062 (1981).
16. Methods are available as supporting material on *Science* Online.
17. C. B. Olkin, L. H. Wasserman, O. G. Franz, *Icarus* **164**, 254 (2003).
18. The libration period is $2\pi/\omega_{\mathrm{lib}} = T_{\mathrm{orb}}(3e_C^m f_m(\alpha)\mu_C)^{-1/2}/(m + 1)$. With $e_C = 0.2$, the libration periods for the 4:1 and 6:1 are ~11 and ~112 times the local orbit periods, $T_{\mathrm{orb}}$, respectively.
19. Because the tidal expansion rate (Eq. 7) decreases strongly as $a_C^{-11/2}$, the critical $e_C$ value decreases with orbital radius as well, i.e., $e_{\mathrm{crit}} \propto (R_P/a_{cr})^{5/m}$, so that the adiabatic constraint on $e_C$ eases as Charon's orbit expands.
20. P. Goldreich, S. Soter, *Icarus* **5**, 375 (1966).
21. M. H. Lee, S. J. Peale, 2006. Preprint available at http://arxiv.org/abs/astro-ph/0603214.
22. This work was supported by NASA's Planetary Geology and Geophysics Program (W.R.W.) and NSF's Planetary Astronomy Program (R.M.C.). We thank S. A. Stern for communicating discovery results of Pluto's new moons just before publication and the referees for thoughtful comments.

**Supporting Online Material**
www.sciencemag.org/cgi/content/full/1127293/DC1
SOM Text

13 January 2006; accepted 23 June 2006
Published online 6 July 2006;
10.1126/science.1127293
Include this information when citing this paper.

---

# Ice Record of $\delta^{13}$C for Atmospheric $CH_4$ Across the Younger Dryas–Preboreal Transition

Hinrich Schaefer,[1,2]* Michael J. Whiticar,[1] Edward J. Brook,[2] Vasilii V. Petrenko,[3] Dominic F. Ferretti,[4,5] Jeffrey P. Severinghaus[3]

**We report atmospheric methane carbon isotope ratios ($\delta^{13}CH_4$) from the Western Greenland ice margin spanning the Younger Dryas–to–Preboreal (YD-PB) transition. Over the recorded ~800 years, $\delta^{13}CH_4$ was around –46 per mil (‰); that is, ~1‰ higher than in the modern atmosphere and ~5.5‰ higher than would be expected from budgets without $^{13}$C-rich anthropogenic emissions. This requires higher natural $^{13}$C-rich emissions or stronger sink fractionation than conventionally assumed. Constant $\delta^{13}CH_4$ during the rise in methane concentration at the YD-PB transition is consistent with additional emissions from tropical wetlands, or aerobic plant $CH_4$ production, or with a multisource scenario. A marine clathrate source is unlikely.**

Ice core records reveal prominent changes in atmospheric methane concentration $[CH_4]$ associated with abrupt climate change (*1*) but the causes, including source and sink changes, remain controversial (*1*, *2*). Modern contributions from individual sources or sinks have been constrained by the $^{13}$C/$^{12}$C ratio of atmospheric methane ($\delta^{13}CH_4$) (*3*, *4*). New analytical techniques extend this approach to air samples from gas occlusions in polar ice. Using ice samples from the Pakitsoq outcrop (Western Greenland) (*5*), we measured $\delta^{13}CH_4$ in air dating between 11,360 and 12,220 years before the present (yr B.P.) (*6*). The record covers the transition between the Younger Dryas (YD) and Preboreal Holocene (PB), when temperature (*7*) and $[CH_4]$ (*1*) increased rapidly at the termination of the last ice age (Fig. 1).

The suitability of Pakitsoq ice for paleostudies has been demonstrated by the agreement of $[CH_4]$ and other geochemical tracers with records from the Greenland Ice Sheet Project 2 (GISP2) ice core (*5*). Samples were collected during three field campaigns (2001 to 2003) by means of oil-free chainsaws and shipped frozen to the University of Victoria. The main data set was measured after wet extraction by gas chromatography–isotope ratio mass spectrometry (GC-IRMS) (*8*). $[CH_4]$ measurements were duplicated at Washington State University. Six samples from three time periods were analyzed for $\delta^{13}CH_4$ at the National Institute of Water and Atmospheric Research (NIWA) using ~100-liter air samples extracted in the field (*8*) (Fig. 1). All samples were dated with a gas age scale derived by comparison of geochemical records from Pakitsoq and GISP2 (*8*). Results are consistent throughout the three field seasons and form a composite data set (Fig. 1).

---

[1]School of Earth and Ocean Sciences, University of Victoria, Post Office Box 3055, V8W 3P6, Canada. [2]Department of Geosciences, Oregon State University, 104 Wilkinson Hall, Corvallis, OR 97331, USA. [3]Scripps Institution of Oceanography, University of California, San Diego, Mail Code 0244, La Jolla, CA 92093, USA. [4]Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309, USA. [5]National Institute of Water and Atmospheric Research Limited, Post Office Box 14901, Wellington, New Zealand.

*To whom correspondence should be addressed. E-mail: schaefeh@geo.oregonstate.edu

Science

# Forced Resonant Migration of Pluto's Outer Satellites by Charon

William R. Ward and Robin M. Canup

*Science* **313** (5790), 1107-1109.
DOI: 10.1126/science.1127293originally published online July 6, 2006

*Science* (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.