Migrating Planets

N. Murray,* B. Hansen, M. Holman, S. Tremaine

A planet orbiting in a disk of planetesimals can experience an instability in which it migrates to smaller orbital radii. Resonant interactions between the planet and planetesimals remove angular momentum from the planetesimals, increasing their eccentricities. Subsequently, the planetesimals either collide with or are ejected by the planet, reducing the semimajor axis of the planet. If the surface density of the planetesimals exceeds a critical value, corresponding to ~0.03 solar mass of gas inside the orbit of Jupiter, the planet will migrate inward a large distance. This instability may explain the presence of Jupiter-mass objects in small orbits around nearby stars.

In the standard theory of solar system formation, solid material orbiting in a gaseous disk accumulates to form small rocky or icy bodies called planetesimals (*1*). Protoplanets then form by accretion of planetesimals. If a protoplanet accretes roughly 10 Earth masses (10 $M_\oplus$), it can then capture a gas envelope from the protoplanetary disk and become a gas giant such as Jupiter. We now know of a number of Jupiter-mass objects orbiting solar-type stars well inside the radius where rocky material can condense (Table 1) (*2–8*). For example, a planet orbits τ Boötis at a distance of 0.0462 astronomical unit (AU), where the equilibrium temperature of 1550 K is higher than the condensation temperature of the most refractory minerals. Although some of these detections are controversial (*9*), we believe that most or all are real. It is difficult to understand how such planets could form in place.

Although it is difficult to form planets at such small radii, once in place they can survive (*10*). Thus, it is natural to ask whether giant planets can form at orbital radii of a few astronomical units and then migrate inward. One proposed migration mechanism involves the generation by the planet of density waves in the gaseous protoplanetary disk, which cause the planet to spiral inward (*10, 11*). The movement of the planet might be halted by short-range tidal or magnetic effects from the central star (*10*); however, short-range stopping mechanisms cannot easily explain the objects in Table 1 with semimajor axes $a_p \gtrsim 0.2$ AU.

Another migration scenario involves interactions between two or more Jupiter-mass planets (*12, 13*). If two such planets form with a small enough separation, their orbits are unstable, resulting in either a collision or an ejection. The typical outcome is a system with a massive planet in an eccentric orbit at 1 to 2 AU, similar to 70 Virginis or HD 114762 (Table 1). In a tiny fraction of cases, at periapsis one of the planets will come close enough to the star that tidal evolution circularizes the orbit, resulting in a massive planet on a circular orbit inside 0.1 AU. As pointed out in (*13*), this low yield is difficult to reconcile with the observed frequency of such systems, which is roughly a few percent of nearby stars. A second difficulty is the low eccentricity and relatively large a_p of the planet orbiting ρ Coronae Borealis, which would require an additional damping mechanism.

We discuss here a migration mechanism in which the planet exchanges energy and angular momentum with the residual planetesimal disk through resonant gravitational interactions, gravitational scattering, and physical collisions. Long-distance migration is triggered (the "migration instability") if the surface density Σ of planetesimals exceeds a critical value Σ_c derived below. The migration halts when Σ drops below Σ_c or when a significant fraction of scattered planetesimals strike the star. Because planetesimals cannot survive inside a few stellar radii (R_*), the migration is certain to halt. If the mass of the planet is less than about three times the mass of Jupiter (M_J), the eccentricity of the planet's orbit is reduced by the migration; if the mass exceeds this value, the eccentricity may increase.

The orbit of a planetesimal is specified by its semimajor axis a, eccentricity e, and inclination i; the corresponding elements for the planet are a_p, e_p, and i_p. In our analytic work, but not in our numerical work, we assume that the mutual inclination between the orbits of planetesimals and planet is $\lesssim 0.1$ rad. It will also be convenient to use the specific energy $E = -GM_*/2a$ and angular momentum $L = [GM_* a(1 - e^2)]^{1/2}$, where M_* is the mass of the central star and G is the gravitational constant. We shall not distinguish between the total angular momentum L and its normal component $L \cos i$. We assume that the ratio $\mu = M_p/M_*$ of planet mass to stellar mass is much less than unity ($1/\mu = M_\odot/M_J \simeq 1047$ for Jupiter, where $M_\odot$ is the solar mass), as is the ratio of planetesimal mass to planet mass.

Planet formation remains poorly understood, but we avoid this obstacle by focusing on processes that occur after formation is nearly complete. We shall assume for simplicity that only a single massive planet forms. The newly formed planet is probably surrounded by an annular gap in the planetesimal disk, whose radial extent is ~2.5 times the Hill radius $h = \mu^{1/3} a_p$ (*1*). However, a planet's gravitational reach can exceed its Hill radius grasp by a larger factor, as we now explain.

Consider a planetesimal with orbital period $t = 2\pi(a^3/GM_*)^{1/2}$ and $e \ll 1$, perturbed by an exterior planet with period $t_p > t$, $a_p = a + \Delta a$, and $e_p \sim e$. If the planetesimal is in a mean-motion resonance, so that $(k + q)t \simeq kt_p$, where k and q are positive integers, the planet can force chaotic perturbations of the planetesimal orbit. The value of a is nearly constant, because the planetesimal is in resonance, but e undergoes a random walk, gradually diffusing to larger values. Eventually the planetesimal crosses the planet's orbit, after a time (*14*)

$$t_R \sim \frac{(2\Delta a)^{2q-1}}{\mu} \frac{(e_m e)^{2-\kappa}}{e_p^{2(q-\kappa)}} \qquad (1)$$

where $\kappa \in [0, q]$ and $q \gtrsim 2$. This time is given in units in which G, $M_* + M_p$, and a_p

Table 1. Properties of planets.

Star	Period (days)	a_p (AU)	$M_p \sin i_p$ (M_J)	e_p
τ Boötis (*2*)	3.3128 ± 0.0002	0.0462	3.87	0.018 ± 0.016
51 Pegasi (*3*)	4.229 ± 0.001	0.05	0.47	0.012 ± 0.01
υ Andromedae (*2*)	4.611 ± 0.005	0.057	0.68	0.15 ± 0.04
55 Cancri (*2*)	14.648 ± 0.0009	0.11	0.84	0.051 ± 0.013
ρ Coronae Borealis (*4*)	39.645 ± 0.88	0.23	1.1	0.028 ± 0.04
HD 114762 (*5*)	84.05 ± 0.08	0.3	10 ± 1	0.25 ± 0.06
70 Virginis (*6*)	116.6 ± 0.01	0.43	6.6	0.40 ± 0.01
16 Cygni B (*7*)	800.08 ± 11.7	1.7	1.5	0.634 ± 0.08
47 Ursae Majoris (*8*)	1090 ± 15	2.11	2.39	0.03 ± 0.06

N. Murray, B. Hansen, M. Holman, Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada.
S. Tremaine, Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada, and Canadian Institute for Advanced Research, Program in Cosmology and Gravity, Suite 701, 179 John Street, Toronto, Ontario M5T 1X4, Canada.

*To whom correspondence should be addressed.

are equal to unity, so $t_p = 2\pi$. The minimum e at which the planetesimal can enter the Hill sphere of the planet is $e_m \simeq (a_p - h)/a - 1$ (*15*). For a Jupiter-mass planet at $a_p = 5.2$ AU and a planetesimal in the 7:4 resonance with initial eccentricity $e_0 = 0.05$, we find $t_R \approx 0.5 \times 10^5$ years (*16*).

The orbital phase of a planet-crossing planetesimal at times of conjunction with the planet is effectively random because of resonance overlap. Thus, close encounters between the two objects are common. The first close encounter generally removes the planetesimal from the resonance but leaves it in a planet-crossing orbit. A planet-crossing planetesimal undergoes a random walk in both e and a (or in L and E), but the Jacobi constant $J = E - L$ is roughly constant (*17*). Scaling arguments suggest that the time to random walk out of the system should generally be between t_p/μ and t_p/μ^2, corresponding to a range of 10^4 to 10^7 years for Jupiter. This range is consistent with the median lifetime of Jupiter-family comets of 5×10^5 years (*18*) and with the lifetimes found in our numerical simulations. For example, if we start a planetesimal in the 7:4 resonance, it evolves at roughly constant E or a while e random walks from 0.05 to ~0.3 over ~3.5×10^5 years (Fig. 1). At this point it suffers a close encounter with Jupiter. It then follows curves of constant J until ejected after about 4×10^5 years.

Planetesimals may also suffer fates other than ejection.

1) Collision with the star: If the planetesimal random walks to sufficiently small L (large e), it will be absorbed by the star. This channel can become important once the planet has migrated to $a_p \lesssim 5$ to $10\ R_*$. Planetesimals on resonant orbits with $a \lesssim (a_p - h)/2$ also tend to collide with the star, because these become highly eccentric before they become planet-crossing.

2) Collision with the planet: A planetesimal may collide with the planet before being ejected. The probability is $1 - \exp(-P)$, where

$$P \simeq \frac{2M_* r_p}{M_p a_p} \simeq 2 \times 10^{-3} (\mu^2 \rho)^{-1/3} \times \left(\frac{5.2\ \mathrm{AU}}{a_p}\right) \qquad (2)$$

where r_p is the radius of the planet and ρ is the mean density of the planet. This result shows that about 20% of orbit-crossing planetesimals will strike Jupiter but most will be ejected (*19*).

3) Long-term capture into mean-motion resonances: Planetesimals on planet-crossing orbits can be captured temporarily into resonances; this is the inverse of the process described by Eq. 1, which now gives the typical residence time in the resonance. The median residence time is generally short compared to the age of the solar system. However, a few planetesimals can be trapped for very long times near stable islands (*20*). Such trapping has been seen in numerical integrations of planet-crossing orbits (*21*).

Planetesimals start with negative energy and are ejected with positive energy; thus, the ejection process must remove orbital energy from the planet, which moves closer to the star (*22*). This phenomenon is well known in the context of our solar system: Fernández and Ip (*23*) suggested that the ejection of planetesimals caused the orbit of Jupiter to shrink by 0.1 to 0.2 AU. This shrinkage can account for the depletion of the outer asteroid belt (*14*, *24*). If the surface density of planetesimals is above the critical value Σ_c, this process is unstable. To calculate Σ_c, we let the semimajor axis of the planet shrink by Δa_p, reducing its energy by

$$\Delta E_p \sim \left|\frac{GM_* M_p \Delta a_p}{2a_p^2}\right| \qquad (3)$$

Planetesimals newly captured into chaotic resonances will be removed from the system, either by ejection or by consumption by the planet or the star. The mass of planetesimals affected is

$$\Delta M \simeq 2\pi p_c \alpha a_p \Sigma(\alpha a_p) \,|\, \alpha \Delta a_p | \qquad (4)$$

where $\alpha < 1$ is a measure of the average a/a_p of the affected planetesimals (*25*) and $p_c \approx 1$ is the resonance capture probability. In disposing of a mass ΔM of planetesimals, the planet loses energy

$$\Delta E_\alpha \sim f(a_p)\frac{GM_* \Delta M}{2\alpha a_p} \qquad (5)$$

where f is the fraction of the original planetesimal energy that is taken from the planet's orbit; we expect that $f \approx 1$ for $a_p \gg R_*$ and becomes negative as $a_p \rightarrow R_*$, where the planet perturbs most planetesimals into the star.

The migration process is unstable if $|\Delta E_\alpha| > |\Delta E_p|$, which requires that the density exceed Σ_c

$$\Sigma(\alpha a_p) \gtrsim \Sigma_c = \frac{M_p}{2\pi a_p^2 \alpha f(a_p) p_c} \qquad (6)$$

In other words, if the mass in the planetesimal disk interior to the planet is of order M_p, the planet can migrate nearly to the surface of the star.

The migration halts when either (i) the local surface density of planetesimals falls below the critical value or (ii) a significant fraction of the planetesimals plunges into the star. The local surface density is sure to fall to zero near the star. Solid bodies cannot condense at radii $\lesssim 7R_*$, and existing planetesimals whose orbits might evolve to smaller radii cannot long survive at distances $\lesssim 2R_*$. The minimum semimajor axis achievable by the migration instability is thus a few to 10 stellar radii or ~0.03 to 0.1 AU.

We have simulated the evolution of a Jupiter-mass body in a planetesimal disk, using the Öpik approximation (*26*) (see Fig. 2). The simulations assume that the surface density in planetesimals varies as $\Sigma(r) = \Sigma_\odot(1\ \mathrm{AU}/r)^{1.5}$, where $\Sigma_\odot$, the surface density at 1 AU, is a free parameter. The total mass in the planetesimal disk within radius r is then

$$M_D \simeq 1.4 \times 10^{-3} M_\odot \times (\Sigma_\odot/10^3\ \mathrm{g\ cm^{-2}})(r/\mathrm{AU})^{0.5} \qquad (7)$$

and, if we assume solar metal abundance $Z = 0.02$, the disk mass in gas interior to Jupiter's orbit is $0.16 M_\odot(\Sigma_\odot/10^3\ \mathrm{g\ cm^{-2}})$.

The energy transfer from planet to planetesimal is approximated as a succession of close encounters until the planetesimal is ejected, strikes the planet, or strikes the star. Summing over many encounters, we derive the average efficiency of energy transfer from the planet to planetesimals in a given resonance. These efficiency factors are then used to calculate the evolution of the planet in a disk of a given initial mass profile. For the case where the planet interacts with the 2:1, 3:2, 2:3, and 1:2 resonances, as well as a broad resonance zone in the immediate vicinity of the planet, the onset of the migration instability is at $\Sigma_\odot \approx 200$ g cm^{-2} (Fig. 2). Equation 6, evaluated with $a_p = 5.2$ AU, $\alpha = 0.7$, $p_c = 1$, and $f = 1$, gives $\Sigma_c \approx 70$ g cm^{-2}, corresponding to $\Sigma_\odot \approx 160$ g cm^{-2}, in good agreement with our numerical estimate. A much higher

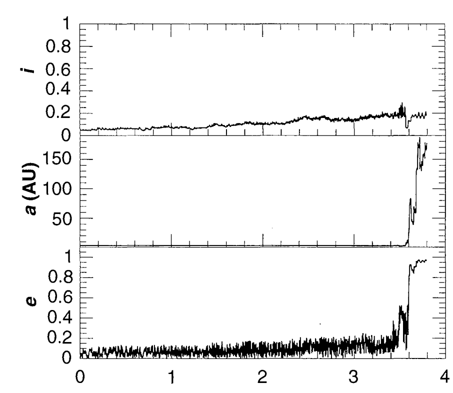

Fig. 1. The evolution of the $i(t)$, $a(t)$, and $e(t)$ values of a planetesimal having a mass 10^{-2} that of Jupiter. The planetesimal was initially placed in the 7:4 resonance with $e = 0.05$ and $i = 0.05$. The perturbing planet had mass $\mu = 10^{-3}$ and $e_p = 0.05$. The planetesimal suffers its first close encounter with the planet after 3.5×10^5 years and is ejected after about 3.8×10^5 years.

density ($\Sigma_\odot \simeq 8000$ g cm^{-2}) is required for the instability to persist until the planet reaches 0.03 AU.

In some cases a gas disk with the surface density required for the migration instability may be nearly gravitationally unstable. The criterion for local gravitational instability of a thin disk is $Q = c\Omega/(\pi G\Sigma) < 1$, where c is the speed of sound and Ω is the angular speed (27). Replacing Σ by Σ_c from Eq. 6, we find

$$Q = 1.2\left(\frac{r}{1\ \mathrm{AU}}\right)^{1/2}\left(\frac{T}{300\ \mathrm{K}}\right)^{1/2} \times \left(\frac{Z}{0.02}\right)\left(\frac{M_*}{M_\odot}\right)^{1/2}\left(\frac{M_J}{M_p}\right) \quad (8)$$

where T is the disk temperature.

Ejecting a planetesimal removes energy ΔE and angular momentum ΔL from the planet. If $|\Delta E/\Delta L| > 1$, then e_p decreases, whereas e_p increases if $|\Delta E/\Delta L| < 1$. For a planet with $M_p \lesssim 3M_J$, $|\Delta E/\Delta L| > 1$ because the planetesimal must approach within a few Hill radii of the planet to be ejected, and the Hill sphere does not extend into the region where $|\Delta E/\Delta L| < 1$ when $E \approx 0$. In this case, the ejection of small planetesimals tends to reduce e_p and a_p. However, the planet is immersed in a bath of planetesimals, many of which have substantial masses. Interactions between the planet and these objects will tend to produce equipartition between the energy in radial motion of the planet and the planetesimals. If most of the planetesimal mass is in objects of mass near m_0, the expected equilibrium eccentricity of the planet is $e_{eq} \approx (m_0/M_p)^{1/2}$. This e_{eq} ranges from 0.06 to 0.006 for m_0 between an Earth mass and a lunar mass.

Seven objects in Table 1 have $a_p < 1$ AU and probably did not form in their present orbits. We suggest that at least four of these seven—51 Pegasis, 55 Cancri, ρ Coronae Borealis, and τ Boötis—migrated to their present semimajor axes through the process described here. The planet around υ Andromedae is puzzling because of its rather high eccentricity, $e_p = 0.15 \pm 0.04$. Such an eccentricity could arise from an encounter with an object of a few $M_\oplus$, or the measured eccentricity could be in error. The last two short-period objects on the list—70 Virginis with $M = 6.6\ M_J$ and HD 114762 with $M = 10 \pm 1\ M_J$—are sufficiently massive that planetesimals scattered from their Hill sphere can be ejected with $|\Delta L| > |\Delta E|$. If so, their large eccentricities could arise from the migration instability. Their relatively large a_p values might reflect the difficulty of satisfying the instability criterion (Eq. 6) at small radii when M_p is large.

The planet orbiting 47 Ursae Majoris could have formed at its present location; however, we think it more likely that it migrated inward a few astronomical units and halted because $\Sigma(r)$ dropped below Σ_c. The companion to 16 Cygni B is also likely to have migrated inward; its large e_p could be due to interactions with the stellar companion to 16 Cygni B (28).

Equation 7 shows that a planetesimal disk mass of $\sim 6 \times 10^{-4}\ M_\odot$ within the planetary orbit is required to initiate the migration instability for a planet with Jupiter's mass and radius, whereas a much larger mass of $\sim 2 \times 10^{-2}\ M_\odot$ is required to move the planet to 0.03 AU. Infrared observations of solar-mass T Tauri stars suggest that disks at the upper end of this mass range are rare, but they do occur (29). These observations were designed to measure the total mass in particulate matter at $r < 100$ AU, with results in the range 10^{-5} to $10^{-2}\ M_*$ (30). The mass in planetesimals would be similar if the efficiency of conversion of dust particles to planetesimals is high, and even higher if the observed disks already hide most of their solid material in planetesimal-sized objects.

There is observational evidence for a correlation between the presence of short-period planets and high stellar metallicity (31). We note two possible explanations for this correlation. (i) For a fixed mass of gas, enhancing the metallicity increases the surface density of planetesimals, increasing the chances for planet migration. (ii) If migration is halted by planetesimals hitting the star, then the planetesimals can pollute the surface layers of the star.

When several planets are present, migration becomes more complex. For example, in the solar system Uranus and Neptune migrate outward rather than inward because Jupiter acts like an inner absorbing boundary similar to a nearby stellar surface (23). In such a system, the migration instability is triggered at a lower surface density, because the outer planets effectively push the inner planet toward the star. The migration of a massive planet will reduce the surface density of planetesimals substantially; as a result, it is unlikely that two massive planets can independently migrate to short-period orbits. It is also unlikely that any other planets in the migration path can survive; thus, a short-period Jupiter-mass planet should have no sister planets with orbital radii less than a few astronomical units.

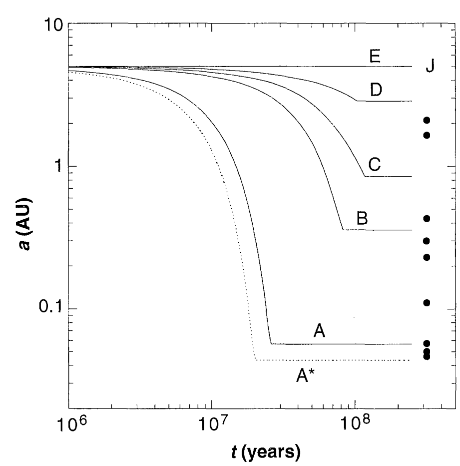

Fig. 2. The solid curves show the evolution of a 1-Jupiter-mass planet in a disk with planetesimal surface density $\Sigma(r) = \Sigma_\odot\,(1\ \mathrm{AU}/r)^{3/2}$. We take initial elements as follows: the plane has $a_p = 5.2$ AU and $e_p = 0.048$, whereas the planetesimals have a ranging from 0.03 to 4 AU, e in the range (e_m to $e_m + 0.2$), and i between 0 and 0.5 rad. The labeled curves correspond to the following values of $\Sigma_\odot$ in units of grams per square centimeter: A, 8000; B, 2000; C, 1200; D, 600; and E, 40 (the nominal value for the minimum solar nebula). The corresponding gas surface densities in grams per square centimeter, if we assume solar metallicity $Z = 0.02$, are: A, 4×10^5; B, 1×10^5; C, 6×10^4; D, 3×10^4; and E, 2×10^3. There is a critical value of $\Sigma_\odot$ at $\sim$200 g cm^{-2} (between curves D and E), below which there is very little movement. The solid circles indicate the positions of the various extrasolar planets (Table 1); J indicates the location of Jupiter. The dotted line (labeled A*) corresponds to the case for which we replaced the 2:1 resonance with the 3:1 resonance, in which the planetesimals are not strictly orbit-crossing unless one takes into account the finite Hill sphere radius. This indicates the approximate range of uncertainty in the final position in this idealized model. The time for the migration to occur is very model-dependent; inclusion of more resonances will reduce the migration time.

REFERENCES AND NOTES

1. J. J. Lissauer, *Annu. Rev. Astron. Astrophys.* **31**, 129 (1993).
2. R. P. Butler, G. W. Marcy, E. Williams, H. Hauser, P. Shirts, *Astrophys. J.* **474**, L115 (1997).
3. M. Mayor and D. Queloz, *Nature* **378**, 355 (1995).
4. R. W. Noyes *et al.*, *Astrophys. J.* **483**, L111 (1997); see also erratum, *ibid.* **487**, L195 (1997).
5. D. W. Latham, R. P. Stefanik, T. Mazeh, M. Mayor, G. Burki, *Nature* **339**, 38 (1989).
6. G. W. Marcy and R. P. Butler, *Astrophys. J.* **464**, L147 (1996).
7. W. D. Cochran, A. P. Hatzes, R. P. Butler, G. W. Marcy, *ibid.* **483**, 457 (1997).
8. R. P. Butler and G. W. Marcy, *ibid.* **464**, L153 (1996). See also the extrasolar planets catalog at http://www.obspm.fr:80/departement/darc/planets/catalog.html.
9. D. Gray, *Nature* **385**, 795 (1996); G. Marcy *et al.*, *Astrophys. J.* **481**, 926 (1997).
10. D. N. C. Lin, P. Bodenheimer, D. C. Richardson, *Nature* **380**, 606 (1996).
11. P. Goldreich and S. Tremaine, *Astrophys. J.* **241**, 425 (1980).
12. F. A. Rasio and E. B. Ford, *Science* **274**, 954 (1996).
13. S. J. Weidenschilling and F. Marzari, *Nature* **384**, 619 (1996).
14. M. Holman and N. Murray, *Astron. J.* **112**, 1278 (1996); N. Murray and M. Holman, *ibid.* **114**, 1246 (1997); The presence of a massive planetesimal disk can change both the location and the amount of overlap relative to a Keplerian potential. The change in location will not affect the dynamics, and our calculations show that the change in the amount of overlap is generally small.
15. For resonances with $q \leq 2$, e_m is replaced by e, but this expression must be used with caution when the resonances are strong, because the dynamics are more complicated [see (14)].

16. Somewhat longer times apply in other low-order, mean-motion resonances. Similar results apply if the planet orbits inside the planetesimal.
17. If e_p is nonzero, there is a random walk in J, but this is much slower (by a factor of order e_p) than the random walk in E or L.
18. H. F. Levison and M. Duncan, *Icarus* **108**, 18 (1994). The lifetimes of Centaurs are similar [see L. Dones, H. F. Levison, M. Duncan, in *Completing the Inventory of the Solar System*, T. W. Rettig and J. M. Hahn, Eds. (Astronomical Society of the Pacific, San Francisco, CA, 1996), p. 233].
19. Equation 2 holds for planets the mass and size of Jupiter with orbital periods larger than about 50 days.
20. B. V. Chirikov, *Chaotic Dynamics in Hamiltonian Systems with Divided Phase Space* (Springer, Berlin, 1983); C. F. F. Karney, *Physica D* **8**, 360 (1983); N. Murray, *ibid.* **52**, 220 (1991).
21. H. F. Levison and M. Duncan, *Icarus* **127**, 13 (1997); M. J. Duncan and H. F. Levison, *Science* **276**, 1670 (1997).
22. By similar arguments, orbit-crossing planetesimals that collide with the star add energy to the planet; however, consumption by the star is much less common than ejection for planets at semimajor axes larger than a few stellar radii.
23. J. A. Fernández and W.-H. Ip, *Icarus* **58**, 109 (1984).
24. J.-C. Liou and R. Malhotra, *Science* **275**, 375 (1997).
25. The average radius $\alpha = \langle a/a_p \rangle = (7/4)^{-2/3} \simeq 0.7$ if the inner 7:4 resonance is the only relevant one.
26. E. J. Öpik, *Interplanetary Encounters* (Elsevier Scientific, Amsterdam, 1976).
27. A. Toomre, *Astrophys. J.* **139**, 1217 (1964); V. S. Safronov, *Ann. Astrophys.* **23**, 979 (1960); J. Binney and S. Tremaine, *Galactic Dynamics* (Princeton Univ. Press, Princeton, NJ, 1987).
28. M. Holman, J. Touma, S. Tremaine, *Nature* **386**, 254 (1997); K. A. Innanen, J. Q. Zheng, S. Mikkola, M. J. Valtonen *Astron. J.* **113**, 1915 (1997); T. Mazeh, Y. Krymolowski, G. Rosenfeld, *Astrophys. J.* **477**, L103 (1997).
29. S. V. W. Beckwith, A. I. Sargent, R. S. Chini, R. Güsten, *Astron. J.* **99**, 924 (1990).
30. A possible concern with the interpretation of these observations is that the gas surface density may imply gravitational instability if the disk extends out to 100 AU. See the references in (*27*).
31. R. P. Butler, G. W. Marcy, E. Williams, H. Hauser, P. Shirts, *Astrophys. J.* **474**, L115 (1997); S. L. Baliunas, G. W. Henry, R. A. Donahue, F. C. Fekel, W. H. Soon, *ibid.*, p. L119; G. Gonzalez, *Mon. Not. R. Astron. Soc.* **285**, 403 (1997); G. Laughlin and F. C. Adams, http://xxx.lanl.gov/abs/astro-ph/9710110. "Planet swallowing" as a source of abundance anomalies in stellar atmospheres was first discussed by J. B. Alexander [*Observatory* **87**, 238 (1967)].
32. We acknowledge useful conversations with R. Malhotra and B. Paczyński. This research was supported by the Natural Sciences and Engineering Research Council of Canada and the Canadian Institute for Advanced Research.

26 August 1997; accepted 11 November 1997

Magnetic Properties of Hexagonal Closed-Packed Iron Deduced from Direct Observations in a Diamond Anvil Cell

Stuart Gilder* and Jonathan Glen†

The attraction of hexagonal closed packed (hcp) iron to a magnet at 16.9 gigapascals and 261 degrees centigrade suggests that hcp iron is either paramagnetic or ferromagnetic with susceptibilities from 0.15 to 0.001 and magnetizations from 1800 to 15 amperes per meter. If dominant in Earth's inner core, paramagnetic hcp iron could stabilize the geodynamo.

Fluid motion in Earth's liquid outer core generates a magnetic field that, when observed at the surface over several tens of thousands of years, resembles a dipole whose axis parallels Earth's rotational axis. However, the time-averaged field geometry may not depend on the fluid dynamics in the outer core alone. Recent numerical models suggest that a finitely conducting solid inner core stabilizes the geodynamo (*1*, *2*). Deviations of the mean field from that of a geocentric dipole, such as the far-sided effect (*3*), could be explained if the inner core is composed of an aggregate of preferentially oriented hcp iron crystals (*4*). Such an aggregate could also explain why seismic waves traveling parallel to the rotational axis appear 1 to 4% faster than those traversing equatorial paths (*5*).

Although the phase of iron in the inner core is unknown, several studies conclude that the hcp (ε) phase is the best candidate (*6*–*8*). Some work has suggested that convective flow in the inner core is sufficient to give ε-Fe a crystallographically preferred orientation (*9*, *10*). Karato (*11*) proposed that the toroidal component of the field could give ε-Fe a preferred orientation such that its crystallographic *c* axis grows parallel to the rotation axis if the metal is paramagnetic with a certain degree of crystalline anisotropy of magnetic susceptibility (AMS) (*12*). The link between AMS in ε-Fe and field behavior was addressed by Clement and Stixrude (*4*), who assumed that magnetic susceptibilities of hcp metals other than Fe served as analogs for ε-Fe (*9*, *13*). On the basis of this assumption, they assigned the magnetic susceptibility of ε-Fe to be 10^{-3} to 10^{-4} (SI units).

We used a nickel chromium alloy Merrill-Bassett diamond anvil cell (DAC). Iron (>99.9%) particles, generally spherical in shape with diameters of 1 to 5 μm, were loaded together with ruby chips and a pressure medium of methanol, ethanol, and water (16:3:1) into a ~100-μm-diameter hole formed in a Re gasket. The cell was bolted to an insulating plate, which was in turn bolted to a motorized *xy* stage. A thermocouple was fixed in direct contact with the lower diamond. Three other thermocouples surrounded the diamonds. An alternating current was applied to these thermocouples so that they functioned as resistive heaters. Pressure was measured several times during each experiment using the shift in the ruby R_1 peak (*14*) and temperature was measured continuously. Uniform melting of the pressure medium at low pressures suggests that no temperature gradient existed. The transparent pressure medium allowed the iron particles to be imaged with an optical microscope.

The DAC was heated in order to reduce the viscosity of the pressure medium so that the particles could move. A rare earth element magnet (measured magnetic moment M_1 = 1.2 A·m^2) was held 25 mm from the sample region with a pole pointed toward the cell, inclined 35° ± 10° with respect to a horizontal plane. The magnet was held stationary or moved back and forth through an angle of ~100° about a horizontal plane to elicit a response from the particles. At a distance of 25 mm, fields measuring 1.2 × 10^{-4} A/m were induced in the sample region. The Inconel cell, stainless steel bolts, and Re gasket had negligible magnetizations. We assumed that the field of the magnet accounted for the total field in the sample region.

Particle motion was defined as either rotation or translation (Fig. 1). Motion of various particles was observed over a range of pressure and temperature during run 94.2.1 (Fig. 2). No motion was observed at 130°C and 9.7 GPa (Fig. 2A). At 140°C and 10.0 GPa, particle *a* migrated toward and collided with particle *b* (Fig. 2B). Between 155° to 160°C at 10.1 GPa, the combined particle (*a*+*b*) and particle *c* moved in response to the magnet. Particle *a*+*b* migrated to the gasket wall at 165°C and 15.3 GPa (Fig. 2C). Between 166° to 366°C and 15.3 to 18.8 GPa, particles *c* and *d* (and others) responded to the magnet. Sometimes separate particles moved in concert with the motion of

S. Gilder, Institut de Physique du Globe de Paris, Laboratoire de Paléomagnétisme, 4 place Jussieu, 75252 Paris Cedex 05, France. E-mail: gilder@ipgp.jussieu.fr
J. Glen, Berkeley Geochronology Center, Berkeley, CA 94709, USA. E-mail: jglen@bgc.org

*Also at Institute of Tectonics, University of California, Santa Cruz, CA 95064, USA.
†Also at Earth Sciences Department, University of California, Santa Cruz, CA 95064, USA.