Dynamical Instabilities and the Formation of Extrasolar Planetary Systems

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The existence of a dominant massive planet, Jupiter, in our solar system, although perhaps essential for long-term dynamical stability and the development of life, may not be typical of planetary systems that form around other stars. In a system containing two Jupiter-like planets, the possibility exists that a dynamical instability will develop. Computer simulations suggest that in many cases this instability leads to the ejection of one planet while the other is left in a smaller, eccentric orbit. In extreme cases, the eccentric orbit has a small enough periastron distance that it may circularize at an orbital period as short as a few days through tidal dissipation. This may explain the recently detected Jupiter-mass planets in very tight circular orbits and wider eccentric orbits around nearby stars.

In current models of planet formation (*1*), the minimum distance at which a Jupiter-type planet can form around a solar-like star is several astronomical units (AU). The minimum distance for the formation of a rocky planet is ~0.4 AU (Mercury's distance to the sun), corresponding to a period of about 90 days. In addition, all planets should be found on nearly circular orbits. Our models of planetary system formation are at odds with observations (*2, 3*) of extrasolar planets (Table 1). With one exception, 47 Ursae Majoris B, these Jupiter-mass objects are all at distances smaller than 1 AU from the central star. Three planets, 51 Pegasi B (51 Peg), τBootes B (τ Boo), and υ Andromedae B, are in extremely tight circular orbits with periods of only 3 to 5 days. Two planets with somewhat longer periods, HD114762 and 70 Virginis B (70 Vir), have orbits with large eccentricities.

If the 51-Peg-type planets had formed, like Jupiter, at a large distance from the central star, they must have been brought in through some angular-momentum-loss mechanism. Any dissipative mechanism, such as friction in the protostellar nebula or interaction with a protoplanetary disk, would tend to increase rapidly with decreasing separation. The dissipation would have had to switch off at a critical moment for the planets to end up so close to the star without being disrupted. Alternatively, tidal interaction with a rapidly spinning central star can be invoked to provide a barrier at some small radius (*4, 5*).

Here we explore an alternative mechanism for angular momentum loss: two or more Jupiter-like planets that initially formed at a large distance from the central star and later interacted. This could happen if the planets' orbits evolved secularly at different rates (*6*) or if their masses increased by accretion (*1*), resulting in a dynamical instability of the orbits and a close interaction between two planets (*7, 8*). The interaction can lead to the ejection of one planet, leaving the other in a highly eccentric orbit. If the pericenter distance of the inner planet is sufficiently small, its orbit can later circularize at an orbital separation of a few stellar radii (*5*).

We performed ~ 10^3 numerical integrations of the orbital dynamics following the onset of instability in a two-planet system (*9*). We started our calculations with two planets just inside the Hill stability limit, which, for nearly circular orbits, is given approximately by the condition $\Delta < \Delta_{crit} \simeq 2.40\,(\mu_1 + \mu_2)^{1/3}$, where $\Delta = (a_2 - a_1)/a_1 > 0$ is the fractional separation between the two planets ($\mu_i = m_i/M_*$ is the ratio of the mass of each planet to that of the central star and a_i is the radius of the planet's orbit). For $\mu_1 = \mu_2 = 10^{-3}$ (two identical Jupiter-mass objects around a solar-like star) we get $\Delta_{crit} = 0.30$. For comparison, our numerical integrations give $\Delta_{crit} \simeq 0.298$. Because the stability boundary is so sharply defined (*7*) and the evolution of an unstable system is strongly chaotic, we do not need to specify how the system actually evolved to this point. In the subsequent dynamical evolution the system quickly loses any memory of the initial conditions and the final outcome depends only on the masses and radii of the two planets, with statistical variations due to small differences in the initial conditions. In our simulations, we varied the initial phases of the two planets and Δ between 0.295 and 0.298 randomly. The results illustrated here were obtained for the case of two identical planets with $\mu_1 = \mu_2 = 10^{-3}$ and $R_1 = R_2 = 10^{-4}\,a_1$, where R_i is the radius of the planet (Jupiter would be at 4.8 AU if it were the inner planet in this system).

Direct collisions between the two planets occurred in about one half of the simulations. We identified a collision and terminated our calculations whenever the separation between the two planets became less than the sum of the radii, $r_{12} < R_1 + R_2$. The collisions typically occurred within $\sim 10^3$ to 10^4 orbits following the onset of instability. The relative velocity at infinity for these collisions is $v_r \lesssim (GM_*/a_1)^{1/2}$ where G is the gravitational constant, and therefore we have $(v_r/v_e)^2 \lesssim 0.1$, where $v_e = (2Gm_1/R_1)^{1/2}$ is the escape speed from the planet's surface. Since $(v_r/v_e)^2 \ll 1$, we

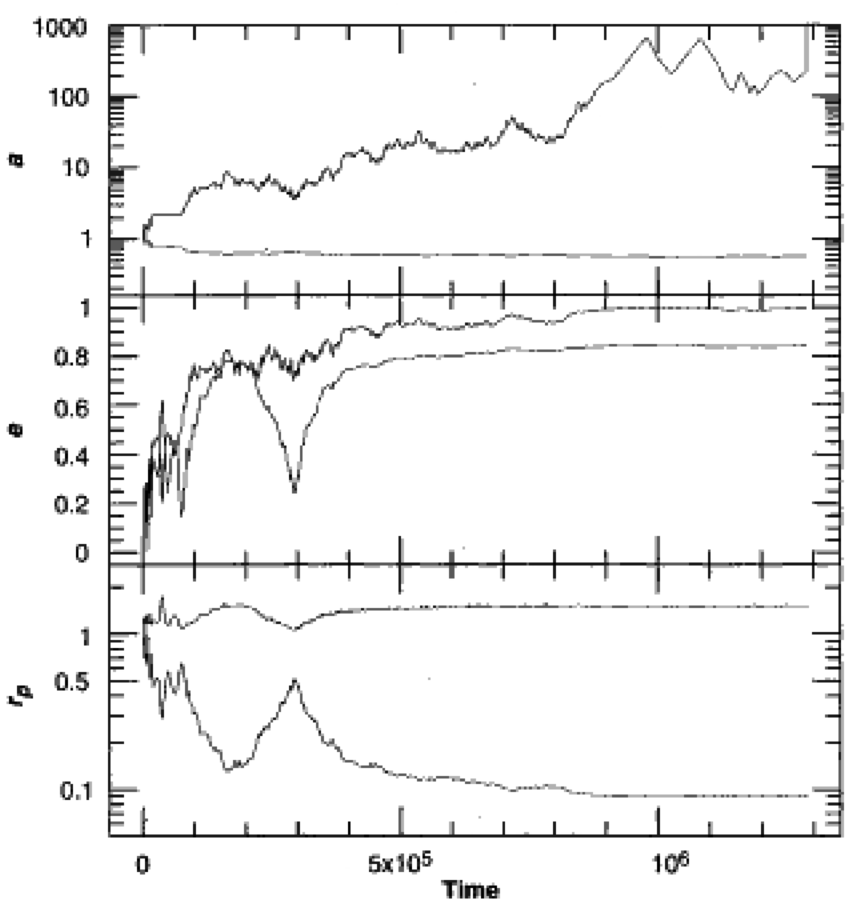

Fig. 1. Results of a typical simulation leading to the ejection of the outer planet. Here *a* is the semi-major axis, *e* is the orbital eccentricity, and $r_p = a(1 - e)$ is the periastron distance, all calculated for the osculating Keplerian orbits of the two planets. Units are such that $G = M_* = a_1 = 1$ (the initial orbital period of the inner planet is about 2π in these units).

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Table 1. Properties of the planets from (2, 3).

Star	Period (days)	a (AU)	m sin i (M_J)	e
51 Pegasi	4.229	0.05	0.46	0
τ Bootes	3.313	0.046	3.87	0
υ Andromedae	4.6	0.057	0.60	0
55 Cancri	14.76	0.11	0.8	0
HD114762	84.02	0.38	10	0.33
70 Virginis	116.6	0.45	6.6	0.40
47 Ursae Majoris	1090	2.11	2.39	0.03

do not expect these collisions to be very disruptive. They should leave an object of mass $\lesssim (m_1 + m_2)$ in a moderately eccentric orbit at a distance comparable to the initial separation a_1. The debris of the collisions may provide the seeds for further planet or satellite formation in these systems. When a collision does not occur, one planet is typically ejected to infinity (10), leaving the other in a tighter eccentric orbit (Fig. 1). We find that the ejection of the outer planet always takes place after a succession of many weak interactions rather than a single strong one. As a consequence, the ejected planet leaves with a positive but small energy (compared to the binding energy of the other). Conservation of total energy therefore gives us the final semi-major axis of the retained planet as $a_f \simeq a_1[1 + [\mu_2/\mu_1 (1 + \Delta)]]$, implying $a_f \simeq 0.56\, a_1$ for $\mu_1 = \mu_2$ and $\Delta \simeq \Delta_{crit}$. Our numerical integrations give final configurations that always agree with this estimate to within about 1%. We are tempted to identify an outcome of the type illustrated in Fig. 1 with eccentric orbits like that of the planet in 70 Vir. However, the final orbital period in this case should always be $\gtrsim$0.4 year if the initial semi-major axis $a_1 \gtrsim 1$ AU. The orbital period for 70 Vir is slightly shorter, about 117 days. Thus, a dynamical instability can explain the eccentricity of the orbit in this case, but it would still require the formation of Jupiter-type planets at somewhat smaller distances than expected from our current models.

The eccentricity of the inner planet's orbit can become close to unity in some systems, and we have obtained periastron distances as small as $r_p \sim 10^{-3}\, a_1$ (Fig. 2). If $a_1 \sim 5$ AU, then r_p is comparable to the radius of a solar-type star. Tidal dissipation will then circularize this inner orbit and the final semi-major axis will be about $2r_p$. A system like 51 Peg or τ Boo could result. The dissipation could take place in the star, especially if it is still in the pre–main-sequence phase and has a massive outer convective zone (4), or in the planet itself (5). For example, if the planet had an initial spin period ~10 hours and a dissipation factor $Q \sim 10^5$ like that of Jupiter (11) then the orbit of the 51 Peg system could have circularized in $\sim 10^8$ years (5, 12). In all systems where the periastron separation of the inner orbit became $< 10^{-2}\, a_1$ we found that the outer planet was not ejected to infinity, but rather drifted out to a wider elliptical orbit. Thus we predict that a 51 Peg–like system formed through a dynamical instability of the type described here should have another planet of comparable mass in a much wider, eccentric orbit. Some evidence for such a second object has been reported recently for 55 Cancri (3). Although in principle possible, we did not find any system in which the outer planet was ejected to infinity and the inner orbit was eccentric enough to circularize in $\lesssim 10^9$ years.

Other, less massive planets that may have formed in the same system are likely to be lost as a result of the dynamical instability. We have repeated a small number of simulations adding four inner planets initially on circular orbits, assuming masses and semi-major axes scaled from our solar system as if the inner of the two massive planets were Jupiter. In all cases, large eccentricities are induced in the orbits of these inner planets, eventually causing them to escape from the system or to collide with the central star.

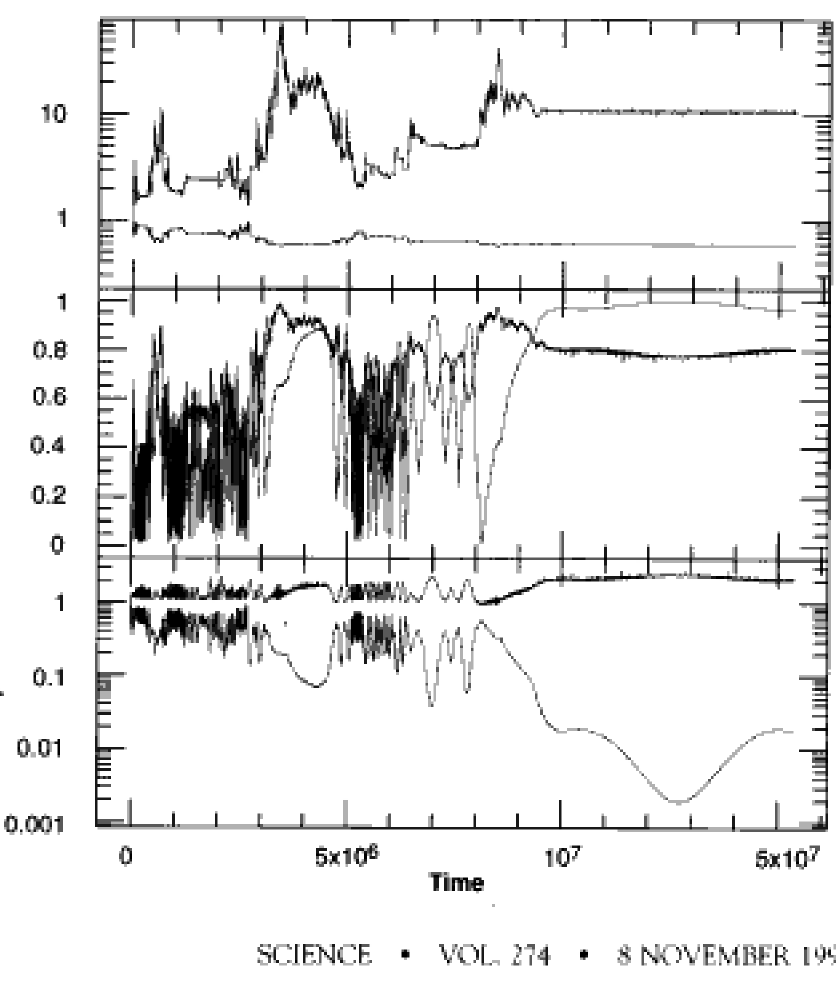

Fig. 2. Results of a typical simulation leading to the formation of a 51 Peg-type system. Conventions are as in Fig. 1. Note that the outer planet remains in a bound eccentric orbit.

REFERENCES AND NOTES

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6. The orbit of Jupiter may have evolved significantly by interaction with the protoplanetary disk during the formation of our solar system; P. Goldreich and S. Tremaine, *Astrophys. J.* **241**, 425 (1980).
7. See B. Gladman, *Icarus* **106**, 247 (1993) for a very thorough discussion of this instability.
8. J. E. Chambers, G. W. Wetherill, A. P. Boss, *Icarus* **119**, 261 (1996) have studied the generalization to more than two planets. Alternatively, chaotic evolution of two or more planets well outside the Hill stability limit could also lead to instabilities and strong interactions on much longer time scales; G. D. Quinlan, in *Proceedings of the 152nd Symposium of the International Astronomical Union*, Angra dos Reis, Brazil, 15 to 19 July 1991, S. Ferraz-Mello, Ed. (Kluwer, Dordrecht, Netherlands, 1992), p. 25.
9. The numerical integrations were done using the standard Bulirsch-Stoer algorithm, following W. H. Press, S. A. Teukolsky, W. T. Vetterling, B. P. Flannery, *Numerical Recipes* (Cambridge Univ. Press, 2nd ed., 1992). The CPU time is about 1 hour per 10^5 orbits on an IBM SP-2 supercomputer. Our longest integrations conserved total energy to about 1 part in 10^6 and total angular momentum to 1 part in 10^9.
10. The ejected planet is usually the one that was initially

outside in the equal-mass case studied here, otherwise we expect the less massive one to be ejected preferentially.
11. See P. J. Ioannou and R. S. Lindzen, *Astrophys. J.* **406**, 266 (1993) and references therein.
12. The time scale for the initial *e* to decrease significantly, say from ~1 to 0.5, is determined by the dissipation of dynamical tides in the star and is likely to be considerably shorter. The evolution of the system during this early phase will be similar to that of a tidal-capture binary; R. A. Mardling, *Astrophys. J.* **450**, 732 (1995). Once dissipation in the equilibrium tide becomes dominant, the circularization can be studied using the standard weak-friction model; P. Hut [*Astron. Astrophys.* **99**, 126 (1981)], provides the needed generalization to high-eccentricity orbits. The outer planet is not expected to play a significant role during the circularization, since its dynamical coupling to the inner orbit is now very weak. This weak coupling is already evident at the end of the simulation (Fig. 2), which shows that the system has entered a quasi-periodic regime (*7*).
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Controlled Deposition of Size-Selected Silver Nanoclusters

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Variable-temperature scanning tunneling microscopy was used to study the effect of kinetic cluster energy and rare-gas buffer layers on the deposition process of size-selected silver nanoclusters on a platinum(111) surface. Clusters with impact energies of ≤1 electron volt per atom could be landed nondestructively on the bare substrate, whereas at higher kinetic energies fragmentation and substrate damage were observed. Clusters with elevated impact energy could be soft-landed via an argon buffer layer on the platinum substrate, which efficiently dissipated the kinetic energy. Nondestructive cluster deposition represents a promising method to produce monodispersed nanostructures at surfaces.

Nanostructure formation at surfaces has been studied extensively both because of the intrinsic interest in structures with reduced dimensions and because of potential technological applications. The most advanced techniques for the synthesis of nanostructured surfaces are atomic manipulation with scanning-probe methods (*1*, *2*) and self-organized growth (*3*). A promising alternative route is the controlled deposition of nanoclusters from the gas phase (*4*, *5*). The deposition of clusters on a solid substrate is characterized by a number of important physical phenomena. When a cluster impinges on the surface, it must transfer its kinetic energy and the energy of condensation to the substrate crystal lattice to ensure efficient sticking. The energy dissipation depends primarily on the relation between cluster surface and internal cluster binding strength and on the cluster impact energy. At high impact energies, the condensation energy is negligible, and a large amount of energy can be delivered to a localized region of the surface during the collision, resulting in substantial cluster fragmentation, substrate damage, and even implantation. The extreme nonequilibrium conditions in energetic cluster surface collisions have been exploited to grow smooth films at low temperatures (*6*). In contrast, the synthesis of nanostructured surfaces requires low kinetic energies to be released during the impact to ensure a nondestructive deposition in which the nanoclusters maintain their individual characteristics.

Despite considerable recent effort in studying cluster surface interactions (*5*, *7–12*), the effect of the impact parameters on the result of the deposition process has not been characterized in situ on the microscopic scale to date. We now report the investigation of the deposition of size-selected Ag_n clusters (n = 1, 7, and 19) of varying kinetic energy (1 to 14 eV per cluster atom) onto a Pt(111) substrate in ultrahigh vacuum (UHV). Deposition took place either onto the bare surface at 80 or 90 K or into a preadsorbed Ar buffer layer at 26 K, which was subsequently evaporated at 90 K (*13*). The surface and cluster morphologies were characterized in situ in the same UHV chamber by variable-temperature scanning tunneling microscopy (STM) (Fig. 1) before and after annealing to 300 K. Our study was motivated by the hope of obtaining controlled soft landing through

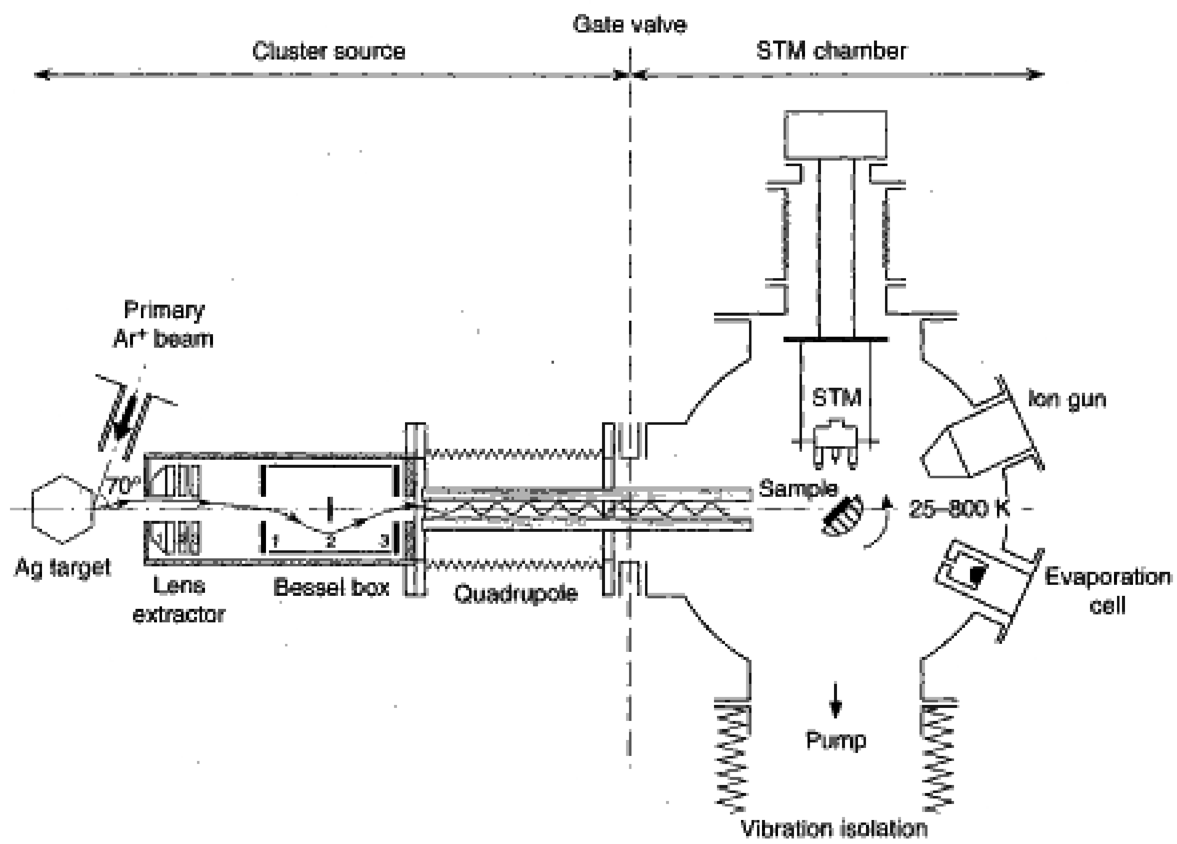

Fig. 1. The apparatus for the cluster deposition experiment consists of two UHV chambers separated by a gate valve. The Ag clusters were produced by sputtering of a Ag target in a differentially pumped secondary ion source, energy-filtered (Bessel box), and mass-selected by a quadrupole (*5*). During deposition, the non–rare gas background pressure was held in the 10^{-10} mbar range. Cluster current densities were on the order of several 10^{11} atoms cm^{-2} s^{-1}, the equivalent to deposition of 0.1 monolayer in about 10 min. After deposition onto the Pt(111) crystal, the resulting structures can be examined by variable-temperature STM (25 to 800 K) (*25*). All STM images were measured in constant-current mode, with a typical tunneling resistance of 10^8 ohm.

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