The Astrophysical Journal, 508:L171–L174, 1998 December 1

THE MODIFICATION OF PLANETARY ORBITS IN DENSE OPEN CLUSTERS

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Received 1998 July 13; accepted 1998 September 11; published 1998 October 23

ABSTRACT

We show that Jovian planets will frequently experience orbital disruption due to interactions with binary stars in their birth clusters. We attack the problem using a Monte Carlo approach and estimate the effective cross section for severe orbital disruption: $\langle\sigma\rangle = (230\ \mathrm{AU})^2$. Combining the numerically determined cross section with typical cluster densities $\langle n\rangle$ and velocity dispersions v, we find a typical interaction rate of $\Gamma = \langle n\rangle\langle\sigma\rangle v \approx 0.13$ disruptive encounters per star per 100 million years. This scattering mechanism naturally accounts for extrasolar systems such as 14 Her or 16 Cyg B, in which a Jovian planet is found in an eccentric and reasonably close orbit. This mechanism can also produce systems with extremely small orbits, such as 51 Peg. However, the efficiency is too low to account for the observed frequency of such close systems, and hence some other mechanism for orbital migration is almost certainly at work. Because of mass segregation within the birth cluster, we predict that higher mass stars will have a larger fraction of planets with eccentric orbits than the low-mass stars that comprise the bulk of the stellar population.

Subject headings: open clusters and associations: general — planetary systems — stars: kinematics

1. INTRODUCTION

The detection of planets orbiting nearby solar-type stars (see, e.g., Mayor & Queloz 1995 and Marcy & Butler 1998) has revealed that a significant fraction of extrasolar planets lie in unusual orbits. In particular, the planetary companions to 16 Cyg B and 14 Her have large orbital eccentricities, while others, such as 51 Peg, υ And, and τ Boo, have alarmingly small orbital radii. The existence of Jupiter-mass planets very close to their primary stars strongly suggests that orbital migration has occurred in these systems. The planets are posited to have formed at large radii, 5–10 AU, where most of the mass resides in the original circumstellar disk. The planets are subsequently transported inward to their new observed locations with new orbital parameters.

Several models of orbital migration have been constructed, and they demonstrate the plausibility of the planet migration hypothesis. In one class of theories, giant planets migrate inward because of tidal interactions with the circumstellar disks (see, e.g., Takeuchi, Miyama, & Lin 1996 and Lin, Bodenheimer, & Richardson 1996). In another mechanism, resonant interactions between the giant planet and an orbiting disk of planetesimals drive the inward migration of the planet (see, e.g., Murray et al. 1998 and Tremaine 1997). In yet another scenario, interactions between two or more giant planets lead to orbital migration or modification (see, e.g., Lin & Ida 1997; Weidenschilling & Marzari 1996; Rasio & Ford 1996); the giant planets form with a relatively small separation, and hence their orbits are unstable, leading to extreme changes in the orbital parameters. In this Letter, we consider an additional dynamical mechanism that operates independently of the existing planetary migration scenarios.

A large fraction of stars are formed within cluster environments (see, e.g., Lada, Strom, & Myers 1993). A Jupiter-like planet born in a conventional circular orbit around a single solar-type star can have its orbit drastically altered by an encounter between the parent star and a binary star within the birth cluster. In this work, we calculate the cross sections and estimate the interaction rates for this mechanism. Our results indicate that over the lifetime of a dense cluster such as the Trapezium, the chances of a given solar system experiencing a disruptive encounter can be in the neighborhood of 50%.

2. THEORETICAL FORMULATION

The orbital disruption problem could in principle be attacked through the direct numerical integration of an entire open cluster. This approach has been taken by de la fuente Marcos & de la fuente Marcos (1997), although they did not investigate the role played by wide binaries. In general, however, the large number of cluster members, combined with the relative scarcity of meaningful encounters, renders a direct approach computationally inefficient. The problem of planetary scattering is best treated as a statistical process. In taking this approach, we separate the problem into two parts: (1) the dynamics of the cluster itself, which ultimately dictates the rate at which a given planetary system encounters other star systems, and (2) the scattering process, which determines what happens to a planetary orbit during an encounter. Since many different types of interactions and outcomes are possible, the results are best calculated and presented statistically.

Let us consider, for example, a star-planet system that has recently formed in a dense stellar cluster. For the sake of definiteness, we consider a solar-type star accompanied by a Jupiter-mass planet on an initially circular 5 AU orbit. The star-planet system will encounter other systems, *most of which are binary stars*, and will experience scattering events. The interaction rate Γ for such scattering events can be written

$$\Gamma = \langle n\sigma v\rangle \approx \langle n\rangle\langle\sigma\rangle v, \tag{1}$$

where n is the number density of stellar systems, σ is the cross section for interaction, and v is the relative velocity. The angle brackets denote effective averages. As defined by the second equality in the above equation, we make the approximation that the number density n can be separated from the cross section.

Our approach thus consists of estimating the proper values of $\langle n \rangle$, $\langle \sigma \rangle$, and v, as well as the appropriate cluster lifetime. The dynamics of the cluster (part 1 of our program) determines the effective density $\langle n \rangle$, the velocity v, and the lifetime. The scattering process itself (part 2) determines the cross section $\langle \sigma \rangle$.

To fix ideas, let us make a rough estimate of the interaction rate. In a very dense cluster, like the Trapezium, the central density is large, $n_0 \approx 5 \times 10^4$ pc^{-3} (McCaughrean & Stauffer 1994). For all open clusters, the velocity dispersion is typically v = a few km s^{-1} = a few pc Myr^{-1} (see, e.g., Binney & Tremaine 1987). Binary separations are often on the order of 100 AU, and hence a reasonable estimate of the cross section is $\langle \sigma \rangle \sim (100 \text{ AU})^2$. With these values, the star-planet system would suffer an interaction with a binary system once every 40 million years. Since open clusters live for at least 100 million years, we expect these interactions to be significant, and hence more precise estimates are indicated.

To obtain a better estimate of the effective number density $\langle n \rangle$, we construct a simple cluster model. Clusters tend to have density profiles that resemble isothermal spheres. However, the number density distribution must be cut off on both the inside (the central density is necessarily finite) and the outside (because of the tidal field of the galaxy). A simple density profile $n(r)$ that exhibits these desired characteristics is

$$n(r) = n_0[1 + (r/r_0)^2]^{-1}[1 - (r/r_T)^2], \qquad (2)$$

where n_0 is the central number density, r_0 is the core radius, and r_T is the tidal radius. For typical open clusters, $r_0 \approx 1$ pc and $r_T \approx 10$ pc (see, e.g., Binney & Tremaine 1987). After some manipulation, this number density distribution can be converted into a probability distribution, i.e., the probability $\mathcal{P}(n)$ that a star in the cluster lives in an environment with background density n. Defining dimensionless variables $z \equiv n/n_0$ and $\alpha \equiv r_0/r_T \approx 0.10$, we can write the probability distribution in the form

$$\mathcal{P}(n) = \frac{dP}{dn} = Cz(1-z)^{1/2}(\alpha^2 + z)^{-5/2}, \qquad (3)$$

where C is a normalization constant that is determined by the value of α.

With this probability distribution, most stars in the cluster spend a disproportionate fraction of their time at large radii and lower densities. This result is expected for any configuration that vaguely resembles an isothermal sphere, which has the mass profile $M(r) \propto r$. The majority of the mass thus resides at large radii within the cluster. For our particular model, only about 4% of the stars live at densities greater than half the central value. The remaining fraction (96%) live at lower density. For this cluster model, with density distribution (3), the mean density is

$$\langle n \rangle = \int_0^{n_0} n\mathcal{P}(n)dn \approx 0.106 n_0. \qquad (4)$$

In other words, the effective density $\langle n \rangle$ that determines the interaction rate (eq. [1]) is a factor of 9.4 smaller than the maximum central density n_0 of the cluster. For a dense cluster such as the Trapezium, the effective number density is thus $\langle n \rangle \approx 5300$ stars pc^{-3}. Since a more modest cluster will have a smaller central density and a correspondingly smaller effective density, we adopt $\langle n \rangle \approx 1000$ stars pc^{-3} as a benchmark for this Letter.

The effective cross section $\langle \sigma \rangle$ for the disruption of planetary orbits can be defined through the relation

$$\langle \sigma \rangle = \int_0^{\infty} f(a)(B\pi a^2)p(a)da. \qquad (5)$$

In the above expression, a is the semimajor axis of the binary orbit, and $p(a)$ specifies the probability of encountering a binary system with a given value of a. For a given value of a, we include only those scattering interactions within the area $B\pi a^2$, where B is a dimensionless factor. The function $f(a)$ specifies the fraction of encounters that result in severe orbital disruption (for scattering between a star-Jupiter system and a binary of semimajor axis a). We define a severe orbital disruption to be an encounter in which the planet is either (1) given a large eccentricity, $e > 0.5$, (2) ejected, or (3) captured by one of the impinging stars. Notice that we neglect the contribution to the cross section from scattering interactions outside the area $B\pi a^2$, so that equation (5) thus provides a lower limit to the true cross section.

The distribution $p(a)$ is determined by the observed distribution of binary periods and by the normalization condition

$$\int_0^{\infty} p(a)da = 1. \qquad (6)$$

We model the observed distribution, and hence obtain $p(a)$, by making a simple fit to the results of Kroupa (1995). The observed binary period distribution peaks at a period of $P = 10^5$ days, and significant numbers of binaries have periods longer than 10^7 days. In practice, we find that encounters with systems having semimajor axes $a \geq 200$ AU are statistically the most important contributors to the overall effective cross section for significant orbital disruption.

An infinite number of possible encounters can occur between a star-Jupiter system and a field binary of semimajor axis a. This class of events is described by 12 input parameters, including the stellar masses, m_1 and m_2, of the binary pair, the eccentricity e_b and the initial phase angle l of the binary orbit, the asymptotic incoming velocity v of the star-Jupiter system with respect to the center of mass of the binary pair, the angles θ, ψ, and ϕ that describe the impact direction and orientation, the impact parameter h, as well as three parameters describing the angular momentum vector and initial phase of the initially circular 5 AU Jovian orbit.

To compute the fraction of disruptive encounters $f(a)$, we perform a large number of separate scattering experiments using a Monte Carlo scheme to select the input parameters. Our approach is similar to the program used for studying binary–single-star interactions in a cluster setting (see the series of papers from Hut & Bahcall 1983 to McMillan & Hut 1996). Individual encounters are treated as four-body problems in which the equations of motion are integrated using a Bulirsch-Stoer scheme. During each encounter, we require that overall energy conservation be maintained to an accuracy of at least one part in 10^6. For most experiments, both energy and angular momentum are conserved to better than one part in 10^8. Nearly identical results were obtained when a subset of encounters was recomputed with a Runge-Kutta integrator and an energy accuracy of one part in 10^5.

The initial conditions for each scattering experiment are drawn from the appropriate parameter distributions. Specifically, the distribution of binary eccentricities is sampled in

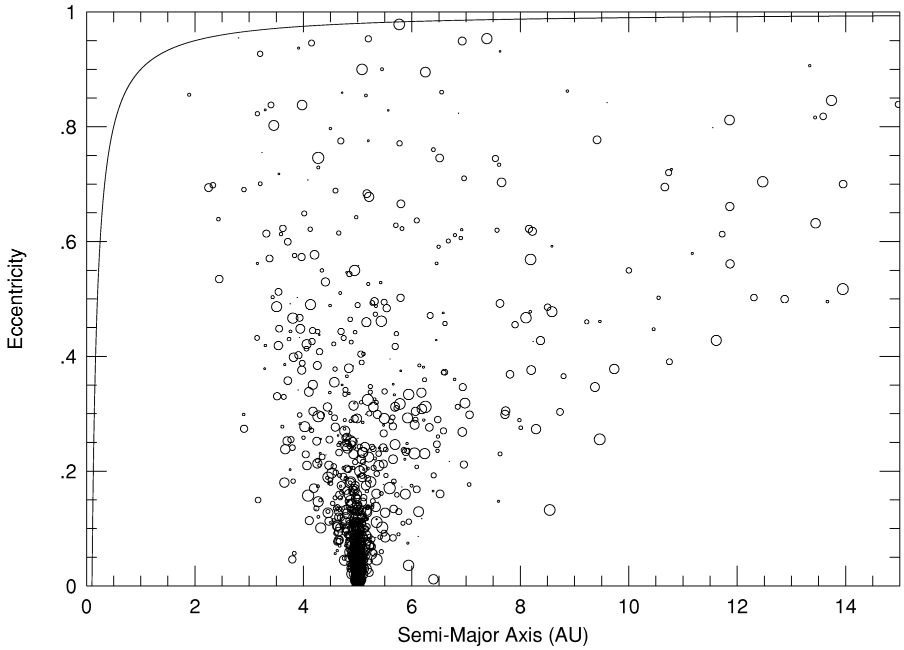

FIG. 1.—Distribution of the final periods and eccentricities of Jovian planets resulting from 19,742 scattering experiments. All of the experiments began with the Jovian planet in a circular orbit (zero eccentricity) with a semimajor axis of 5 AU. The radial size of the circle marking each experiment is in proportion to the semimajor axis, a, of the impinging binary. Planets falling above the solid line have a periapse of 0.1 AU or less and thus are likely to experience significant tidal circularization. In addition to the points plotted, there were 148 planetary escapes within the subset of 19,742 experiments.

accordance with the observed distribution of Duquennoy & Mayor (1991). The stellar masses of the binary components are drawn separately from the initial mass function (IMF) advocated by Adams & Fatuzzo (1996). This IMF is consistent with the observed distribution of stellar masses and is slowly declining in the brown dwarf regime. The impact velocities (at infinite separation) are sampled from a Maxwellian distribution with dispersion $\sigma_v = 1$ km s^{-1}. The initial impact parameters h are chosen randomly within a circle of radius $2a$ centered on the binary center of mass. (Note that the use of a circular target of radius $2a$ requires that we adopt $B = 4$ in eq. [5]).

The integrations are started when the star-Jupiter system has fallen to a distance corresponding to either 85 AU or $10a$ (whichever is larger) from the binary center of mass. Up to this point, the joint motion of the solar-type star and the impinging binary is assumed to conform to the Keplerian approximation. The numerical integration is terminated automatically on the receipt of any one of several flags. These include (1) the escape of the planet from the system, (2) the escape of any one star from the system, (3) an integration time that exceeds 40 free-fall times, or (4) 2.5×10^5 integration steps. After integration termination, the orbital parameters of all four bodies are computed and stored.

3. RESULTS

We have computed 40,000 scattering experiments using the Monte Carlo approach described above. To provide adequate coverage for determining $f(a)$, we have drawn our binary separations uniformly within the 0–1000 AU range. In this Letter, we do not consider encounters with binaries having $a > 1000$ AU, and we do not consider encounters with impact parameter $h > 2a$. Such encounters will cause additional scattering, an estimate of which we will compute in a forthcoming paper. Integrating equation (5) over our numerically determined function $f(a)$, we find that the effective cross section for orbital disruption is $\langle\sigma\rangle = 53167$ AU$^2 \sim (230$ AU$)^2$.

Using the numerically determined cross section $\langle\sigma\rangle$, we can estimate the scattering rate (eq. [1]). With a typical number density $\langle n\rangle = 1000$ stars pc^{-3} and velocity $v = 1$ km s^{-1}, the total disruption frequency becomes $\Gamma = 0.13$ disruptions per star per 100 million years. Since cluster lifetimes are typically longer than 100 million years, we expect this mechanism to drive a significant number of drastic orbital modifications. A considerably larger number of Jovian planets will receive moderate (i.e., $e_{\rm final} < 0.5$) increases in their orbital eccentricity. For cases in which the overall energy of the encounter is negative, two of the stellar components tend to emerge in a bound orbit, while the third star is dispatched to infinity. In such cases, the planet will often be subject to a further orbital modification that is not considered here.

Within the aggregate of 40,000 scattering experiments, we have found a total of 148 captures and 995 escapes, indicating that ejection is a fate shared by many planets. Using this result in conjunction with the interaction rate found above, we find that approximately 5% of Jovian planets can be ejected by the scattering process. We have also obtained 371 unresolved encounters, which occur when the 2.5×10^5 time-step criteria is exceeded.

In Figure 1, we plot the eccentricities and semimajor axes of the Jovian planets resulting from 19,742 experiments. The subset of experiments shown in this plot were drawn from the full set of 40,000 encounters, so that the distribution of binary separations conforms to the distribution $p(a)a^2$. In other words, encounters with binaries of given a are presented with the relative frequency at which they occur. Thus, there are considerably more large a encounters plotted than small a encounters.

4. DISCUSSION AND SUMMARY

In this Letter, we have demonstrated the importance of planetary scattering in dense open clusters. This previously unexplored mechanism can potentially have a great impact on the evolution of planetary systems. Using a Monte Carlo scheme to perform a series of scattering experiments, we calculated the effective cross section of interaction between a star-Jupiter system and field binaries with semimajor axes $a \leq 1000$ AU: $\langle\sigma\rangle \approx (230\ \mathrm{AU})^2$. This cross section, combined with typical cluster densities and velocities, implies an interaction rate of $\Gamma = 0.13$ disruptions per star per 100 million years. In other words, during the typical lifetime of an open cluster (about 100 million years), 13% of the star-Jupiter systems will experience severe orbital disruption. The distribution of the resulting orbital parameters for these disrupted systems is illustrated in Figure 1. Roughly 5% of the planets in a typical cluster can be ejected

Although the scattering mechanism developed here imparts an important influence on the final distribution of planetary orbits, other planetary migration mechanisms are very likely at work as well. Simple estimates suggest that at least 1%–2% of all stars contain Jovian planets in extremely close orbits, as in the 51 Pegasus system; this percentage is too large to be explained by four-body scattering.

Among the planetary systems discovered to date, the 16 Cyg system is an excellent candidate for having experienced disruptive scattering in the birth aggregate. In the 16 Cyg system, two G dwarf stars are separated by 835 AU. The $1.67M_{\mathrm{JUP}}$ companion to 16 Cyg B has a 2.2 yr orbit with an eccentricity of $e = 0.69$. The G dwarfs display very different lithium abundances. For 16 Cyg A, the photospheric Li abundance is log $N(\mathrm{Li}) = 1.27$, whereas for 16 Cyg B, the photospheric Li abundance is log $N(\mathrm{Li}) = 0.48$ (Marcy & Butler 1998). This situation implies different angular momentum histories for the stars, which is consistent with a separate formation in the birth aggregate followed by a scattering encounter of the type described here.

This Letter represents an initial exploration of planetary scattering. A number of further issues will be addressed in detail in a forthcoming work. One interesting issue is the gravitational settling of heavy stars. Within an open cluster, the more massive stars tend to sink to the central regions where the density is larger. Higher mass stars thus have an appreciably greater chance of experiencing planetary scattering than low-mass stars do. On average, the planetary orbits associated with higher mass stars should have greater eccentricity than orbits in systems with low-mass stars. In this context, solar-type stars are among the heavier objects (recall that the Sun ranks a respectable fifth among the 50 nearest stars). With a more comprehensive dynamical analysis, this effect can be quantified to obtain testable predictions of the planetary eccentricity distribution as a function of stellar mass.

A second important issue is the subsequent dynamical stability of planetary systems after a scattering event has taken place. So far, we have calculated the cross section for the orbital disruption of a single planet in a Jovian orbit. However, it is reasonable to expect that many systems contain more than one planet. Interactions between planets, both during and after scattering events, can lead to a rich variety of further orbital modifications. Such activity may account for observed planetary systems such as Gleise 876 (Marcy & Butler 1998), which harbor planets with large eccentricities (i.e., $e \sim 0.4$) and relatively small semimajor axes ($a < 1$ AU). Indeed, further work on this topic should elucidate the wide range of complicated dynamics displayed by scattering planetary systems.

We thank Sverre Aarseth for useful comments on the manuscript. G. L. is supported by a NASA astrophysics theory program that supports a joint Center for Star Formation Studies at NASA Ames Research Center, UC Berkeley, and UC Santa Cruz. F. C. A. is supported by NASA grant NAG 5-2869 and by funds from the Department of Physics at the University of Michigan. This work was completed at the Institute for Theoretical Physics, UC Santa Barbara, and we acknowledge additional support from NSF grant PHY94-07194.

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