The Modification of Planetary Orbits in Dense Open Clusters

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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: $\langle\sigma\rangle = (225\ \mathrm{AU})^2$. Combining the numerically determined cross section with typical cluster densities $\langle n \rangle$ and velocity dispersions v, we find a typical interaction rate of $\Gamma = \langle n \rangle \langle \sigma \rangle v \approx 0.12$ disruptive encounters per star per 100 million years. This scattering mechanism naturally accounts for extra-solar systems such as 14 Hercules or 16 Cygni 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 which comprise the bulk of the stellar population.

Subject headings: stars: dynamics, stars: planetary systems

1. Introduction

The detection of planets orbiting nearby solar type stars (e.g., Mayor & Queloz 1995; Marcy & Butler 1998) has revealed that a significant fraction of extra-solar planets lie in unusual orbits. In particular, the planetary companions to 16 Cygni B and 14 Hercules 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 demonstrate the plausibility of the planet migration hypothesis. In one class of theories, giant planets migrate inwards due to tidal interactions with the circumstellar disks (e.g., Takeuchi, Miyama, & Lin 1996; 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 (e.g., Murray et al. 1998; Tremaine 1997). In yet another scenario, interactions between two or more giant planets lead to orbital migration or modification (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.

Consider, for example, a star-planet system which has recently formed in a dense stellar cluster. For the sake of definiteness, we consider the star to be of solar type throughout this discussion. 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

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

where $\langle n \rangle$ is the number density of stellar systems, $\langle \sigma \rangle$ is the cross section for interaction, and v is the relative velocity. The brackets denote effective averages. Our approach 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) determine 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's 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 = few km/s = few pc/Myr (e.g., Binney & Tremaine 1987). Binary separations are often of order 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 on the outside (due to the tidal field of the galaxy). A simple density profile $n(r)$ that exhibits these desired characteristics is

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

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

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

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 percent 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

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

In other words, the effective density $\langle n \rangle$ that determines the interaction rate [1] is a factor 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 paper.

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

$$\langle \sigma \rangle = \int_0^{\infty} f(a) 4a^2 p(a) \, da \, . \tag{5}$$

In the above expression, a is the semi-major axis of the binary orbit and $p(a)$ specifies the probability of encountering a binary system with a given value of a. The function $f(a)$ specifies the fraction of encounters which result in severe orbital disruption (for scattering between a star-Jupiter system and a binary of semi-major 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.

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

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

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 semi-major axes in the range $a \sim$ 200-400 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 semi-major 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 $e_{\rm b}$ 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 which 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 planetary orbit.

To compute the fraction of disruptive encounters $f(a)$, we perform a large number of seperate 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 4-body problems in which the equations of motion are integrated using a fourth-order Runge-Kutta scheme with adaptive step size. During each encounter, we require that overall energy conservation is maintained to an accuracy of one part in 10^5, or better. We obtained nearly identical results using a subset of encounters that were recomputed with an energy accuracy of one part in 10^6.

The initial conditions for each scattering experiment are drawn from the appropriate parameter distributions. Specifically, the distribution of binary eccentricities is sampled in accordance with the observed distribution of Duquennoy & Mayor (1991). The stellar masses of the binary components are separately drawn from the initial mass function 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 seperation) are sampled from a Maxwellian distribution with dispersion $\sigma_v = 1$ km/sec. The initial impact parameters h are chosen randomly within a square of side $2a$ centered on the binary center of mass (necessitating a factor of 4 rather than π in equation [5]).

The integrations are started when the star-planet 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 upon 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 which exceeds 40 free fall times, or (4) three million integration steps. After integration termination, the orbital parameters of all four bodies are computed and stored.

3. Results

We have carried out an initial set of 10,000 scattering experiments using the Monte Carlo approach described above. To provide adequate coverage for determining $f(a)$, we have drawn our binary seperations uniformly within the 0-1000 AU range. In this Letter, we do not consider encounters with binaries having $a > 1000$ AU. Such encounters will certainly cause some 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 the effective cross section for orbital disruption is $\langle\sigma\rangle = 50098$ AU$^2 \sim (225$ AU$)^2$.

Using the numerically determined cross section $\langle\sigma\rangle$, we can estimate the scattering rate [1]. With a typical number density $\langle n\rangle = 1000$ stars/pc^3 and velocity v=1 km/sec, the total disruption frequency becomes $\Gamma = 0.12$ 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., $e_{final} < 0.5$) 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 further orbital modification not considered here.

Within the aggregate of 10,000 scattering experiments, we have found a total of 493 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 five percent of Jovian planets can be ejected by the scattering process. We have also obtained 455 unresolved encounters, which are largely the result of the three million time-step criteria being exceeded. A more powerful integrator will help to alleviate this problem and will also speed up the overall pace of results. However, since we are considering here only the *net* cross section, a faster code will have little effect on this overall result. The unresolved experiments are found disproportionately among the wider binary encounters. These encounters in turn have a smaller chance of perturbing a Jovian orbit.

In Figure 1, we plot the distribution of periods and semi-major axes of the Jovian planets resulting from 4468 experiments. The subset of experiments shown in this plot were drawn from the full set of 10,000 encounters, so that the distribution of binary separations conforms to the distribution $4p(a)a^2$. In other words, encounters with binaries of given a are presented with the relative frequency at which they occur. There are thus 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. The role of this mechanism has not been previously explored, but 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 semi major axes $a \leq 1000$ AU: $\langle\sigma\rangle \approx (225\ \mathrm{AU})^2$. This cross section, combined with typical cluster densities and velocities, implies an interaction rate $\Gamma = 0.12$ disruptions per star per 100 million years. In other words, during the typical lifetime of an open cluster (about 100 million years), 12% of the star-Jupiter systems will experience serious orbital disruption. The distribution of the resulting orbital parameters for these disrupted systems is illustrated by 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 also at work. 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 4-body scattering.

This Letter represents an initial exploration of planetary scattering. A number of further issues will be addressed in more detailed forthcoming work. One important 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.

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 very respectable 5th out of 50 among the fifty 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 1998), which harbor planets with large eccentricities (i.e., $e \sim 0.4$) and relatively small semi-major axes ($a < 1$ AU).

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REFERENCES

Adams, F.C. & Fatuzzo, M. 1996, ApJ, 464, 256

Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)

de la Fuente Marcos C., & de la Fuente Marcos R. 1997, A & A, 326, L21

Duquennoy, A. & Mayor M. 1991, A & A, 248, 485

Hut, P. & Bahcall, J.N. 1983, ApJ, 268, 319

Kroupa, P. 1995, MNRAS, 277, 1507

Lada, E. A., Strom, K. M., & Myers, P. C. 1993, in Protostars and Planets III, ed. E. H. Levy and J. I. Lunine (Tucson: Univ. Arizona Press), p. 245

Lin, D.N.C., Bodenheimer, P., & Richardson D. C. 1996, Nature, 380, 606L

Lin, D.N.C. & Ida, S. 1997, ApJ, 477, 781

Marcy, G. W. & Butler, R. P. 1998, ARAA, 36, 57

Mayor, M., & Queloz, D. 1995, Nature, 378, 355

McCaughrean, M. J., & Stauffer, J. R. 1994, AJ, 108, 1382

McMillan, S.L.W., & Hut, P. 1996, ApJ, 467, 348

Murray, N., Hansen, B., Holman, M., & Tremaine, S. 1998, Science, 279, 69

Rasio, F. A., & Ford, E. B. 1996, Science, 274, 954

Takeuchi, T., Miyama, S. M., & Lin, D.N.C. 1996, ApJ, 460, 832

Tremaine, S. 1997, BAAS, 191, 201

Weidenschilling, S. J., & Marzari, F. 1996, Nature, 384, 619

Figure Captions

Fig. 1.— Distribution of the final periods and eccentricities of Jovian planets resulting from 4468 scattering experiments. All of the experiments began with the Jovian planet in a circular orbit (zero eccentricity) with a semi-major axis of 5 AU. The radial size of the circle marking each experiment is in proportion to the semi-major axis, a of the impinging binary. Planets falling above the solid line have a periapse of 0.1 AU or less, and are thus likely experience significant tidal circularization. In addition to the points plotted, there were 160 planetary escapes within the set of 4468 experiments.

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