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# JUMPING JUPITERS IN BINARY STAR SYSTEMS

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## ABSTRACT

We investigate the outcomes of the dynamical interaction of Jupiter-mass planets orbiting the central star in a binary system. These systems are unstable and lead to the hyperbolic ejection of one or more planets, while the surviving bodies are inserted in inner eccentric orbits. The gravitational perturbations of the companion star, set at an intermediate distance (50 AU) and typically on an eccentric orbit, influence both the development of instability and the outcome of the subsequent chaotic evolution. We compute the statistical properties of the resulting planetary systems when they reach a stable configuration. The binary eccentricity and the number of initial planets (two or three) are strong predictors of the final configuration of the planetary system. Cases of apsidal resonance between two final planets, Kozai resonance between a single surviving planet and the companion star, and retrograde orbits with respect to the binary orbit are naturally produced.

*Subject headings:* planetary systems — planetary systems: formation

## 1. INTRODUCTION

According to Jahreiss & Wielen (2000), the relative frequency of binary stars within 5 pc from the Sun is roughly 50%. Surveys in the Tau-Aur association (Simon et al. 1992; Ghez et al. 1993; Leinert et al. 1993; Richichi et al. 1994) yield a similar frequency. Planetary formation in binary star systems is then a crucial process to estimate the overall frequency and dynamical properties of planets. Our current paradigm for planetary formation is that planets grow from dusty disks, which are remnants of star formation. In recent years, several investigations pointed out that disks are as common in binary systems as in single stars (see Mathieu et al. 2000 for a review). A dusty gaseous disk approximately 200 AU in diameter has been imaged around the primary star of the binary system HR 4796A (Jayawardhana et al. 1998). A large hole in the center of the disk may be an indication of ongoing planetary formation. Interferometric images of L1551 IRS5 (Rodriguez et al. 1998) revealed that each star of this binary system is surrounded by an optically thick disk. Although the disks in binary systems may be reduced in size by the presence of the companion star, the circumstellar disk material may be similar in temperature and surface density to that of disks around single stars. As a consequence, planetary formation may proceed and the spatial distance and final mass of the planets will be determined by the properties of the gas and dust.

At present, 19 extrasolar planets are known within 15 binary systems.[2] In all of these cases the planets orbit one of the stars, with the companion star in a more distant orbit. The closest binary system currently known to have a planet is Gamma Cephei, with a separation of 18 AU and an eccentricity of 0.36 (Hatzes et al. 2003). Recently, two additional binary systems with similar separation, Gl 86 (Eggenberger et al. 2004) and HD 41004 (Santos et al. 2002), have been found to have planets. Detection of planets by radial velocity surveys is more difficult for close binary systems, owing to the light of the companion star and blending of spectral lines; it is not yet clear whether their abundance is similar for single and binary stars. Assuming that planets can form in binary systems with similar properties as around single stars, it is important to understand how the presence of a companion star affects their dynamical evolution. In earlier papers (Weidenschilling & Marzari 1996; Marzari & Weidenschilling 2002), we proposed that observed peculiarities of orbits of extrasolar planets, particularly their large eccentricities and small semimajor axes, were the products of gravitational scattering in multiplanet systems. In this "Jumping Jupiters" model, it is assumed that two or more massive gas giant planets form from the disk around a solar-type star. Mutual perturbations excite the eccentricities of the planets, leading to dynamical instability and crossing orbits. Repeated close encounters between the planets lead to major changes in the orbital configuration. For three initial planets, the most likely outcome is the ejection of one planet on a hyperbolic trajectory, leaving two planets on stable eccentric orbits with some mutual inclination. A lesser fraction of cases results in the ejection of two planets, collisional mergers, or the impact of a planet onto the star. The orbit of the inner (or sole) survivor is closer to the star than the innermost starting orbit, since it supplies orbital energy to the ejected planet(s). The dynamics of Jumping Jupiters may be significantly different in binary star systems.

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The companion star, particularly in systems with separations less than 100 AU, has a strong gravitational influence on planets around the primary star. Holman & Wiegert (1999) have integrated planetary orbits in binary star systems with a range of mass ratios and binary eccentricity. Most of their cases involved a single planet beginning in a circular orbit in the plane of the binary. Their results are presented as an empirical function of the mass ratio and eccentricity of the binary system, which defines the range of semimajor axes of planetary orbits that allow long-term survival ($10^4$ binary periods). However, this criterion is necessary but not sufficient for orbital stability of multiplanet systems, where mutual planetary perturbations are a significant, or even dominant, source of instability, and the orbital evolution involves multiple scattering events in close encounters. The stellar companion may influence the outcomes in the following ways: (1) secular perturbations may affect the range of stable/unstable planetary orbits and the timescale for the building up of their eccentricities that lead to crossing orbits; (2) scattered planets may have encounters with the companion star, possibly affecting the probability of ejection and the final orbital elements of surviving planets; and (3) the survivors may be subject to apsidal or Kozai resonances with the companion. In this paper we adopt a statistical approach to investigate the dynamical evolution and final state of a system of Jumping Jupiters around the primary component of a binary star system. Our results lead to predictions on the final configurations of extrasolar planetary systems around binary stars.

In § 2 we discuss the formation of planets in binary systems. Sections 3 and 4 present results of orbital evolution for systems with three and two initial planets, respectively. In § 5 we discuss these results and draw conclusions.

## 2. PLANETARY FORMATION IN BINARY SYSTEMS

Theoretical calculations of binary-disk interactions predict that a companion star will truncate a circumstellar disk at an outer radius of ~0.1–0.5 times the binary semimajor axis (Artymowicz & Lubow 1994). Truncation reduces the total disk mass, but possibly not the surface density (it may even increase the surface density if the secondary's perturbations remove angular momentum from the outer part of the disk). The observed extrasolar planets, and the test bodies in our simulations, are massive gas giants. Two different mechanisms of formation have been proposed. In the core accretion model (Pollack et al. 1996), planetesimals accrete to form solid cores. Multiple cores will form in adjacent feeding zones, with orbital separations large enough for temporary stability. When cores reach a critical mass, estimated to be $\sim 10\ M_\oplus$, they can capture gas from the circumstellar nebula. The infall of gas increases the masses of the planets by more than an order of magnitude, rendering the multiplanet system dynamically unstable and leading to crossing orbits. Chaotic evolution begins, and the system becomes stable again only after one or more planets are removed by ejection on hyperbolic orbits or mutual collisions (Weidenschilling & Marzari 1996). Depending on the masses and spacing of the cores, the timescale for the orbital instability to develop may vary by orders of magnitude (Marzari & Weidenschilling 2002). Alternatively, in a massive preplanetary disk gravitational instability in the nebular gas may lead to the formation of multiple self-gravitating condensations that collapse into gas giant planets (Boss 1998, 2002; Mayer et al. 2002, 2004; Pickett et al. 2000, 2003). In this context, the formation timescale is rapid, perhaps less than $10^3$ yr. Neither mechanism is well understood, even for the formation of planets around single stars. It is possible that both mechanisms may be effective under different circumstances, e.g., in disks with different masses. The presence of a binary companion introduces further complications. Core accretion would be more effective at distances more than a few AU from the central star, where condensation of water ice would increase the amount of solids available for accretion. A binary companion might affect the temperature distribution in the disk; its influence has not been modeled, but is probably less important than dynamical effects on planetesimal formation and accretion. The presence of a binary companion may affect the dynamics of gas and small grains that are coupled to it, but the effects on planetesimal formation in such an environment have not been studied. Assuming that planetesimals could form, Marzari & Scholl (2000) considered accretion in the binary system Alpha Centauri and found that perturbations by the companion could result in the collisional destruction of planetesimals in the outer disk, although accretion could occur within a few AU of the primary. For the disk instability mechanism, Boss (2003) has suggested that gravitational instabilities might be triggered by the perturbations of a binary companion star, possibly making the formation of gas giant planets more probable in such systems. With either mechanism, dynamical instability might also be triggered by planetary migration, which could decrease mutual separations. Type I migration (Ward 1997) occurs because of an imbalance of tidal torques exerted in the disk by the planet. According to Alibert et al. (2004), this effect can speed the growth of cores in the context of the core accretion model. Type II migration (Goldreich & Tremaine 1979; Lin & Papaloizou 1993) is caused by the viscous evolution of the disk after planetary tides open a gap in the disk. Type II migration might be less effective in binary systems, since the planet may be less able to clear a gap; according to Artymowicz & Lubow (1994), matter may flow through the gap because of the secondary star's perturbations on the disk. In the following sections, we explore the dynamical consequences of orbital instability and gravitational scattering among planets in binary systems. Our results do not depend on the mechanism by which these planets formed; the fact that planets have been detected in systems like Gamma Cephei shows that their formation is possible in such environments.

## 3. MODELING SYSTEMS WITH THREE INITIAL PLANETS

The frequency of binaries among solar-type stars peaks at semimajor axes on the order of 50 AU and any value of eccentricity may be found (Duquennoy & Mayor 1991). The same authors show that the mass ratio distribution has a peak between 0.2 and 0.4. We model the dynamical evolution and final state of a system of three equal-mass planets with masses equal to that of Jupiter around the more massive component of a binary star system. The trajectories of the planet and that of the companion star have been numerically integrated with the RADAU integrator (Everhart 1985), which is particularly suited for modeling close encounters between massive bodies. The central star is assumed to be a solar-type star, in common with the majority of stars with planets discovered so far (Santos et al. 2004). The semimajor axis of the secondary star is fixed to 50 AU, the most frequent separation encountered among binary systems (Duquennoy & Mayor 1991). In different simulations we vary both the eccentricity $e_B$ and the mass ratio $\mu$ of the system. The initial semimajor axes of the three planets are $a_1 = 3$ AU, $a_2 = 4$ AU, and $a_3 = 5$ AU, while their initial eccentricities and inclinations are less than $10^{-3}$. All the $a_i$ values are within the limits of stability for single-planet orbits outlined by Holman & Wiegert (1999) for $e_B \leq 0.6$. The initial spacing among the planets grant that when they are still in the embryo stage with a mass of ~10 $M_\oplus$, they are stable at least for 10 Myr when $e_B \leq 0.4$. For larger values of $e_B$, the timescale for the onset of instability reduces to $10^4$–$10^5$ yr even if larger spacings are assumed for the cores. The perturbations of the companion star destabilize a system of three 10 $M_\oplus$ bodies even if the external planet is set at the edge of the stable region outlined by Holman & Wiegert (1999). Only a strong dynamical friction due to the gravitational interactions between the planet core and the planetesimals (Stewart and Wetherill 1988) or caused by tidal interaction of the core with the gaseous disk (Ward 1998) might prevent the onset of chaotic behavior prior to the gas infall for $e_B > 0.4$. For large values of $e_B$, the disk instability mechanism is more appealing as a way to form a multiplanet system around the central star. Large eccentricities destabilize orbits of potential planetary cores. This might prevent them from accreting gas from the disk and prevent them from becoming gas giants. The formation of gas giants as a result of fragmentation may take only $10^2$–$10^3$ yr. After their formation, the planets would enter the chaotic phase and end up with a different orbital configuration.

In Figure 1 we show the evolution of a typical system with $e_B = 0.3$ and $\mu = 0.4$. During the chaotic evolution one of the planets is set into a temporary highly eccentric circumbinary orbit after ~$6.9 \times 10^4$ yr, and is finally ejected out of the system after $1.5 \times 10^5$ yr by a close encounter with the companion star. When the planet orbits both the stars the orbital elements, computed with respect to the primary star, are not well defined and they are not shown in the figure. The two surviving planets are left on orbits with semimajor axes ~2 and 5.3 AU; the escaping planet has taken energy from the system, moving the inner survivor closer to the star. Further integration shows that the orbits of the survivors are stable for at least 10 Myr. The final eccentricities of the two planets are encompassed between 0.2 and 0.4. When a system evolves chaotically, the best way to characterize its behavior is through a statistical approach. To explore the range of all the possible final dynamical configurations of the system, for each given value of $e_B$ and $\mu$ we randomly sample the initial orbital angles of the three planets between 0° and 360°. For any given $e_B$ and $\mu$, we perform 200 simulations and analyze the final orbits of the planets. The numerical integrations are stopped whenever one of these conditions are met: (1) no planets are left in orbit around the primary star; (2) a single planet survives in a stable orbit (i.e., within the critical semimajor axis defined by Holman & Wiegert 1999); or (3) two planets are retained on orbits inside the critical semimajor axis for stability (Holman & Wiegert 1999), and their orbits do not cross because of mutual perturbations for at least 10 Myr.

In Figure 2 we show the statistical distribution of the orbital elements of the inner surviving planet (not necessarily the one that started in the innermost orbit) when the two stars have $e_B = 0.3$ and $\mu = 0.4$. The final distribution of the semimajor axis has a peak around 1.6 AU (<10 AU, the inner edge of unstable region by Holman & Wiegert 1999). This is not the minimum semimajor axis (≈1.3 AU) that could be reached by a single planet by scattering the other two out of the system (Marzari & Weidenschilling 2002). The companion star contributes a fraction of the orbital energy needed for planetary escape, and the star tends to migrate inward slightly. A second, smaller peak is visible around 2.9 AU and corresponds to the cases in which two planets collide and form a single larger body in an inner orbit. In the code, a collision occurs when the mutual distance between two planets is less than the sum of their physical radii. All the planets in our simulations have the same initial radii equal to Jupiter's, and when they collide they merge into a single body whose radius is updated by using the Jupiter bulk density. Figure 2 shows that the eccentricity has a broad distribution with a maximum around 0.4. A few planets end up in orbits with periastra close to the star and their orbital evolution may be affected by tidal evolution. Hot Jupiter-like planets may be produced by circularization of orbits at the periastron distance.

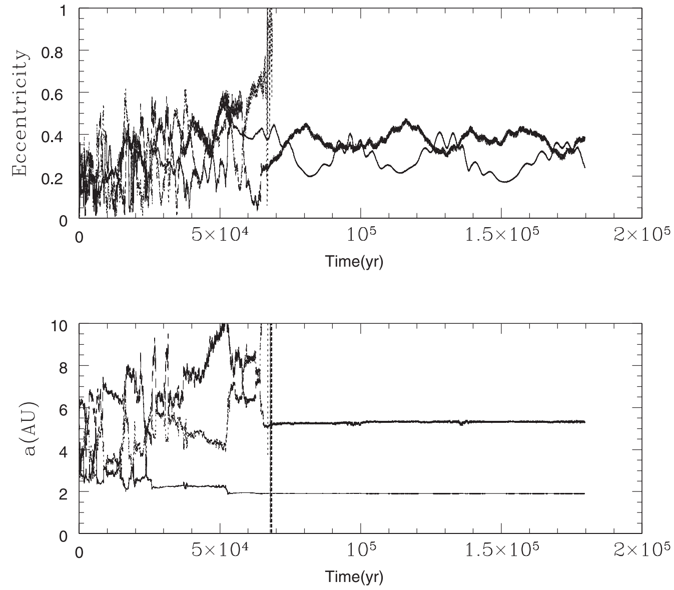


Fig. 1.—Evolution of three Jupiter-size planets in a binary star system with $e_B = 0.3$ and $\mu = 0.4$. At the end of the chaotic phase, two planets survive on stable orbits with oscillating eccentricities. The third planet is ejected out of the system after a period of circumbinary orbiting.

The orbital integrations were carried out in three dimensions. Although the initial inclinations of the planetary orbits were assumed to be small (~$10^{-3}$), gravitational scattering during close encounters can cause large changes in the mutual inclinations of the planets, and consequently with respect to the plane of the binary. The final inclination distribution show that we may find systems in which the mutual inclination between the planet and the companion star is significantly different from 0°, an indication that the system has dynamically evolved from a state in which the disk and the secondary star were coplanar. Even retrograde orbits are produced at the end of the chaotic phase. In Figure 3 we summarize the statistical outcomes for different values of $e_B$ by assembling in three-dimensional histograms the orbital element distributions, normalized to unity, of the inner planet. The plots suggest that the binary eccentricity has little influence on the final orbit of the inner planet. The mutual encounters between the planets and, possibly, with the companion star determine the final orbital configuration of the planet close to the star. The three-dimensional distribution of the semimajor axis of the inner planet, with two dominant peaks at ~1.6 and 3.0 AU, is a direct consequence of the choice of the initial orbits of the three planets with $a_i = 3, 4, 5$ AU. The chaotic evolution and the final ejection of one (or often two) planet tends to leave the inner survivor at a fixed fraction of the distance of the innermost starting orbit. The companion star exchanges some energy with the planets during the scattering phase and this explains why the two peaks in Figure 3 are broader compared to the single-star case (Marzari & Weidenschilling 2002). In real planetary systems in binaries we do not expect that the planets grow exactly at 3, 4, and 5 AU. Their initial location depends on the formation process and on

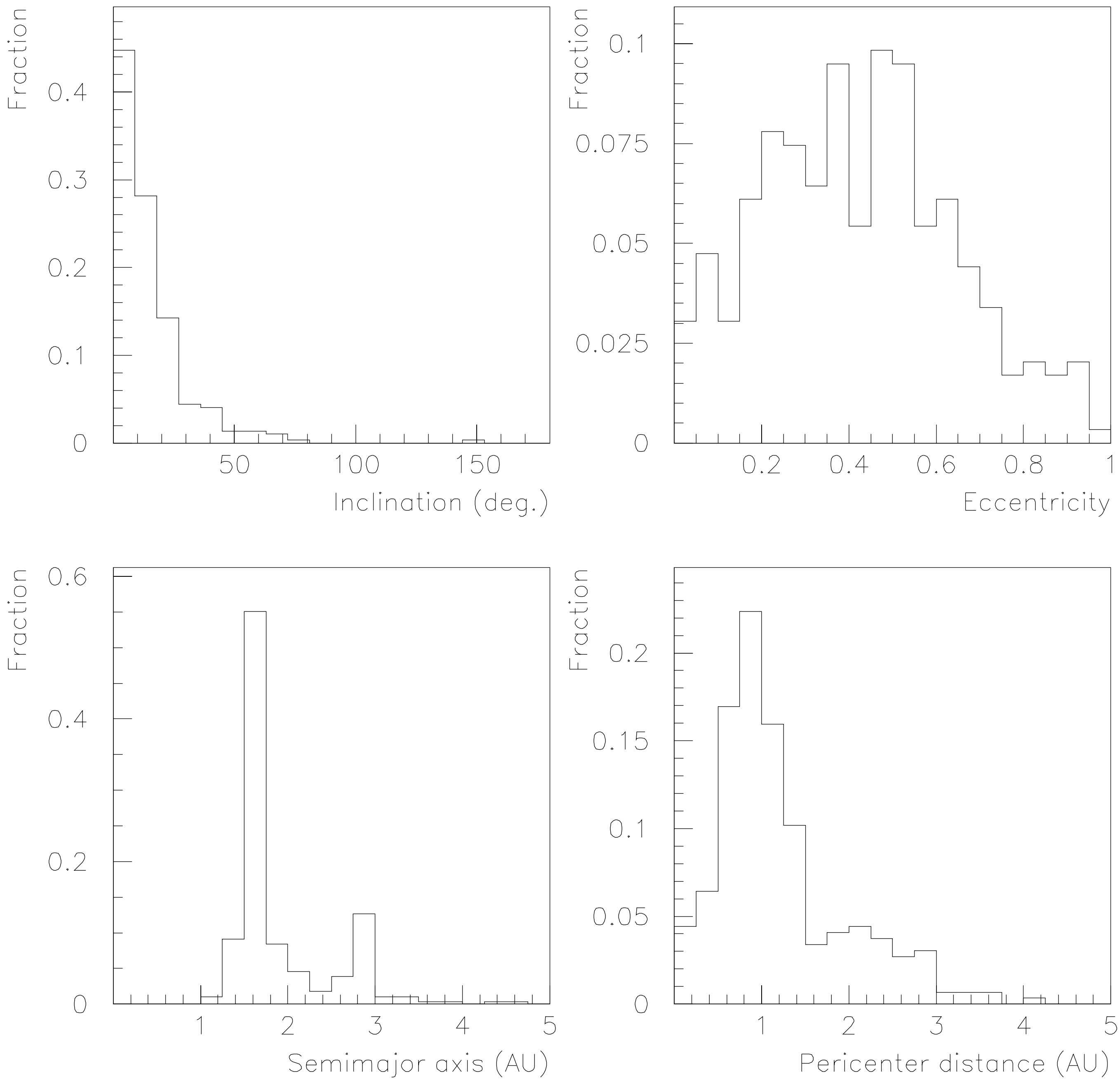


FIG. 2.—Histograms showing the distributions of the orbital elements of the inner surviving planet. The inclination is computed with respect to the orbital plane of the stars. The binary system has $e_B = 0.3$ and $\mu = 0.4$.

the physical parameters of the accretion disk, which are possibly truncated not far beyond 5 AU because of the companion star's gravitational perturbations. The real distribution of the semimajor axis is then expected to be broader. Note that in all cases of Figure 3, the planet remaining in the innermost orbit has a semimajor axis lower than 5 AU, the value of the critical semimajor axis for long-term orbital stability $a_c$ (Holman & Wiegert 1999) computed for $e_B = 0.6$ and $\mu = 0.4$.

A different story is the final orbit of the second outer planet. Its orbital distribution is significantly different with respect to the single-star case, and the eccentricity of the binary is a strong predictor of both its survival and location with respect to the primary star. In Figure 4 we illustrate the distribution of the semimajor axis of the outer planet compared to that of the inner planet for a binary system with $e_B = 0.3$ and $\mu = 0.4$. The maximum observed semimajor axis is 10 AU, the outer edge of dynamical stability of single planet orbits according to Holman & Wiegert (1999). Compared with the Jumping Jupiters mechanism around a single star (Marzari & Weidenschilling 2002), the distance of the second planet is consistently decreased. This effect is due to the contribution of the companion star to the chaotic evolution of the planets. The companion star is involved in the dynamical evolution, and it can exchange orbital energy with the planets (particularly with the escaping body), and it is often shifted from its initial orbit. The maximum observed change in its semimajor axis is +1, −2 AU. In Table 1 we report a summary of the statistical outcomes of all the simulations for different values of $e_B$ up to 0.6. In the last line of the table we also give the percentages of similar outcomes for single-star planetary systems with three initial planets. In this reference case the planets are given the same initial semimajor axes (3, 4, and 5 AU) as the planets in the binary systems. The other orbital

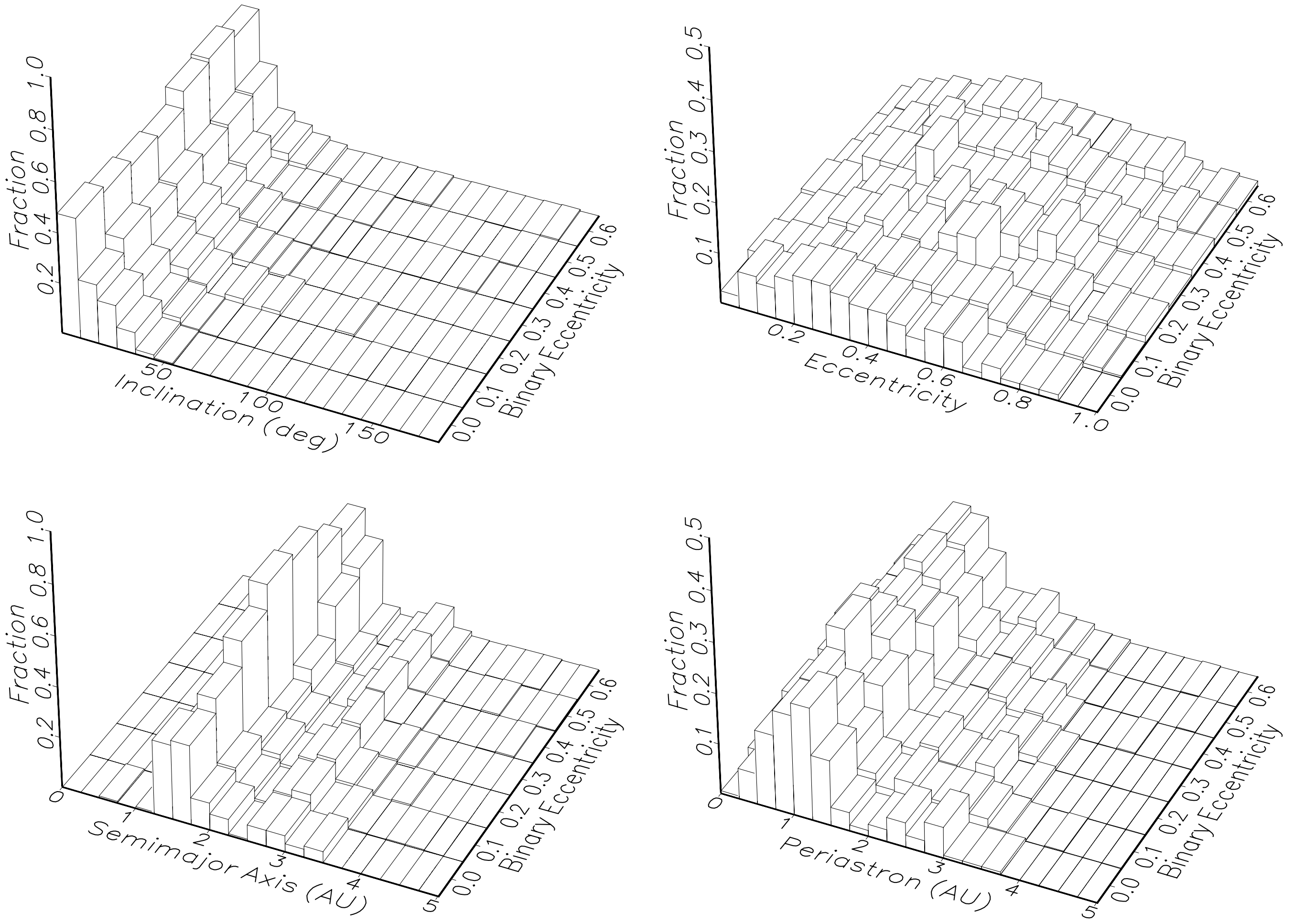


FIG. 3.—Three-dimensional histograms showing the distributions of the orbital elements of the inner surviving planet as a function of $e_B$. The mass ratio of the binary system is $\mu = 0.4$.

elements are randomly chosen within the same intervals. In comparison with the single-star reference case, we see that the fraction of systems ending up with two planets on a stable configuration is lower in the presence of a companion star and it decreases almost linearly with the binary eccentricity. For large values of $e_B$ the percentage of systems ending up with two planets is reduced to only 9%, while in the single-star case it is 80%. This is partly due to the shrinking of the stable region around the central star (Holman & Wiegert 1999), but the dominant mechanism for planetary ejection is the strong interaction with the secondary star during the scattering phase. The random changes of the semimajor axis of the planets lead them into crossing orbits with the companion star and they are ejected out of the system by a close encounter. Another interesting aspect is that in the single-star case, 4% of planets end up in retrograde orbits (mutual inclination larger than 90°), while for the binary systems never more than 1% of the planets are inclined more than 90° to the orbital plane of the two stars.

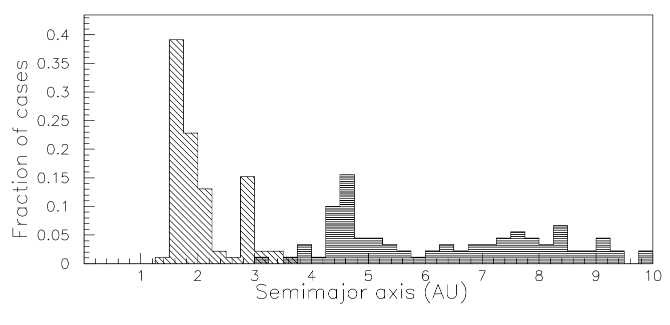


FIG. 4.—Distribution of the semimajor axis of the inner (*diagonal shading*) and outer (*horizontal shading*) surviving planets after the chaotic phase in the case with $e_B = 0.3$ and $\mu = 0.4$. The critical semimajor axis for single-planet orbital stability is 10 AU (Holman & Wiegert 1999).

Figure 5 shows that the value of $e_B$ is predictive of the number of planets we may find orbiting the central star after a Jumping Jupiter phase in which one or two planets are lost by ejection and/or collision with a star. When $e_B$ is larger than 0.5, a small fraction of the systems (1%–2%) may also be totally disrupted with all the planets ejected out of the system in hyperbolic orbits and contributing to the population of "ghost" floating planets. The fraction of systems in which a planet collides with the central star does not depend on $e_B$ and is ~15%–20%. This may lead to the pollution of the outer envelope of the star if the planet has a core of rock and ice, such that it is significantly enriched in heavy elements relative to the stellar composition. Of course, the degree of such a pollution would depend on several factors, including the masses of the planet and star, whether the planet is enriched in heavy elements relative to the stellar composition, and the depth of the star's convective zone. If there is such a pollution, it would affect only one star, and it may be significant that the majority of collisions are with the primary rather than the secondary star. Impacts on the secondary star are rare and occur in only 1% of cases on

TABLE 1

Percentages of Different Outcomes of the Gravitational Scattering Phase for Different Values of $e_B$ and for $\mu = 0.4$

| $e_B$ (1) | s1 (%) (2) | s2 (%) (3) | M (%) (4) | Apsidal (%) (5) | $1_p$ (%) (6) | $2_p$ (%) (7) | $0_p$ (%) (8) | Retrograde (%) (9) | Kozai (%) (10) | $e_{\rm med}$ (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 5 | 1 | 13 | 16 | 44 | 56 | 0 | 0 | 1 | 0.34 |
| 0.1 | 8 | 1 | 16 | 14 | 52 | 47 | 1 | 1 | 2 | 0.40 |
| 0.2 | 15 | 3 | 16 | 12 | 60 | 39 | 1 | 0 | 0 | 0.43 |
| 0.3 | 9 | 0 | 13 | 15 | 68 | 32 | 0 | 0 | 2 | 0.47 |
| 0.4 | 12 | 3 | 16 | 7 | 70 | 30 | 0 | 1 | 1 | 0.45 |
| 0.5 | 14 | 3 | 16 | 3 | 79 | 19 | 2 | 1 | 2 | 0.44 |
| 0.6 | 12 | 3 | 14 | 4 | 89 | 9 | 2 | 1 | 1 | 0.47 |
| Single[a] | 18 | ... | 16 | 15 | 20 | 80 | 0 | 5 | ... | 0.47 |

Notes.—Percentages of different outcomes of the gravitational scattering phase for different values of $e_B$ and for $\mu = 0.4$. Col. (2): Fraction of final configurations in which one planet impacted on the central star. Col. (3): Impact on the secondary star. Col. (4): Percentage of systems in which the inner planet is more massive, being the outcome of a collision between two planets of the system. Col. (5): Fraction of cases in which two final planets are in apsidal resonance with the critical argument librating around either 90° or 180°. Cols. (6)–(8): Systems in which the final configuration has one, two, or zero surviving planets, respectively. Col. (9): Planets injected into retrograde orbits. Col. (10): Systems in which one planet is in a Kozai resonance with the companion star. For planets in binary systems, retrograde is intended with respect to the binary orbit, while for planets around single star retrograde is the orbit of one planet with respect to that of the other survivor. Col. (11): $e_{\rm med}$ is the median of the eccentricity distribution of the inner surviving planet.

[a] The last row shows the outcome of the Jumping Jupiter model in a reference single-star case.

average. The median of the eccentricity distribution of the inner surviving planet appears to depend only weakly on $e_B$. The semimajor axis and eccentricity of the inner survivor tends to be set by gravitational scattering by one of the other planets (usually the one that is ejected from the system). The binary companion has relatively little effect, since the scattering takes place rather close to the primary star. The forced component of the eccentricity is in fact rather small, between 1 and 2 AU, where most of the inner planets are clustered at the end of the chaotic phase. According to Heppenheimer (1978), the forced eccentricity has an approximate value of 0.045 at 2 AU from the central star when $e_B = 0.6$, and this may account for the small difference between the median value of the eccentricity when $e_B = 0$ compared with the case where $e_B = 0.6$.

In Table 2 we report the statistical outcomes of Jumping Jupiters when the mass ratio is reduced to $\mu = 0.2$. The perturbations of the secondary star are less strong and, in fact, the fraction of systems ending up with two planets is significantly higher when compared to the cases with $\mu = 0.4$.

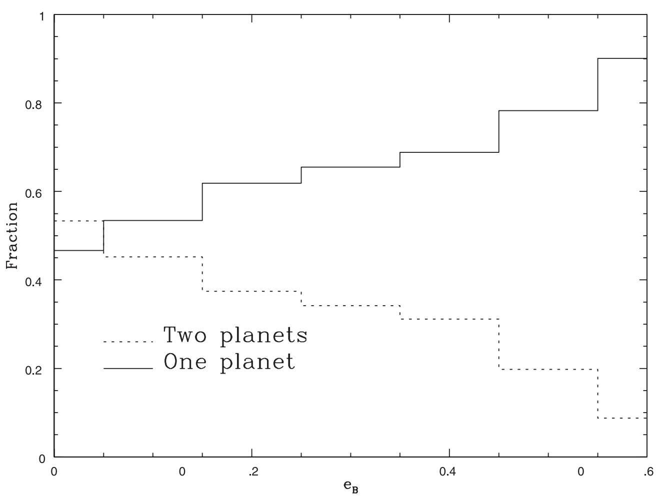


Fig. 5.—Number of systems with one (*solid line*) or two (*dotted line*) surviving planets against the binary eccentricity $e_B$.

Among the final systems with two surviving planets, a few cases exhibit secular apsidal resonance (Malhotra 2002). The fraction of systems in resonance does not depend on the mass ratio $\mu$ but decreases from ~16%–17% for $e_B = 0$ to only 2%–3% for $e_B = 0.6$. Those systems in which the relative apsidal longitude $\Delta\tilde{\omega} = \tilde{\omega}_1 - \tilde{\omega}_2$ librates around 0° are stable, while those showing libration around 180° are sometimes unstable within 1 Myr and end up with the impact of one of the two planets on the primary star. When only one planet survives at the end of the chaotic phase, in a fraction of cases the planet is in Kozai resonance with the companion star, as in the case of 16 Cyg B (Holman et al. 1997). In Figure 6 we show the critical argument of two resonant cases, drawn from the simulations where $e_B = 0.3$ and $\mu = 0.4$. The apsidal resonance has the critical argument librating around 180° and the biplanet system is stable over 5 Myr. The critical argument of the Kozai resonance librates around 90°, but we also found cases librating around 270°. The inclination with respect to the orbital plane of the companion star for entering the resonance is gained during the chaotic phase and on average it is higher than 40°.

## 4. MODELING SYSTEMS WITH TWO INITIAL PLANETS

We determine here the statistical properties of systems containing two initial planets in a configuration that becomes unstable once the planets reach their final mass. Both core accretion and disk fragmentation, possibly assisted by planetary migration, may lead to such an initial configuration. The expected outcome of the dynamical instability would be a single planet in an eccentric orbit. The initial separation leading to chaos is larger compared with similar scenarios around single stars (Rasio & Ford 1996) owing to the presence of the perturbing companion star. For $e_B < 0.3$ the initial semimajor axes of the planets are set to $a_1 = 3.0$ AU and $a_2 = 3.6$ AU, while for $e_B \geq 0.3$ the semimajor axis of the external planet is shifted to $a_2 = 4$ AU so that the instability onset is delayed by $10^4$–$10^5$ yr. The value of 4 AU is still within the stability region of Holman & Wiegert (1999) and it allows the planets to evolve without mutual encounters for ~$10^4$–$10^5$ yr.

In Figure 7 we show the typical evolution of a system of two initial Jupiter-mass planets with $e_B = 0.3$ and $\mu = 0.4$. After a

TABLE 2

Percentages of Different Outcomes of the Gravitational Scattering Phase for Different Values of $e_B$ and for $\mu = 0.2$

| $e_B$ (1) | s1 (%) (2) | s2 (%) (3) | M (%) (4) | Apsidal (%) (5) | $1_p$ (%) (6) | $2_p$ (%) (7) | $0_p$ (%) (8) | Retrograde (%) (9) | Kozai (%) (10) | $e_{med}$ (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0.................. | 6 | 1 | 16 | 17 | 27 | 73 | 0 | 1 | 3 | 0.43 |
| 0.1.................. | 7 | 1 | 16 | 18 | 32 | 67 | 1 | 0 | 1 | 0.38 |
| 0.2.................. | 7 | 2 | 11 | 12 | 33 | 66 | 1 | 0 | 1 | 0.38 |
| 0.3.................. | 13 | 2 | 13 | 8 | 33 | 63 | 3 | 1 | 3 | 0.44 |
| 0.4.................. | 8 | 1 | 15 | 5 | 38 | 60 | 2 | 2 | 1 | 0.43 |
| 0.5.................. | 11 | 3 | 16 | 5 | 41 | 57 | 2 | 3 | 2 | 0.46 |
| 0.6.................. | 10 | 1 | 19 | 2 | 43 | 53 | 4 | 1 | 1 | 0.45 |

Notes.—Percentages of different outcomes of the gravitational scattering phase for different values of $e_B$ and for $\mu = 0.2$. Col. (2): Fraction of final configurations in which one planet impacted on the central star. Col. (3): Impact on the secondary star. Col. (4): Percentage of systems in which the inner planet is more massive, being the outcome of a collision between two planets of the system. Col. (5): Fraction of cases in which two final planets are in apsidal resonance with the critical argument librating around either 90° or 180°. Cols. (6)–(8): Systems in which the final configuration has one, two, or zero surviving planets, respectively. Col. (9): Planets injected into retrograde orbits. Col. (10): Systems in which one planet is in a Kozai resonance with the companion star. For planets in binary systems, retrograde is intended with respect to the binary orbit, while for planets around single star, retrograde is the orbit of one planet with respect to that of the other survivor. Col. (11): $e_{med}$ is the median of the eccentricity distribution of the inner surviving planet.

period of orbital stability lasting approximately $5 \times 10^5$ yr, the system evolves chaotically until one planet is ejected.

In Figure 8 we illustrate the orbital distribution of the surviving planet in the system for $e_B = 0.3$ and $\mu = 0.4$, to be compared to Figure 2 where three planets are formed prior to the chaotic phase. The chief feature in the semimajor axis distribution is the presence of two peaks, one at ~2 AU and the other at ~3.4 AU. The first peak is due to the ejection of one planet out of the system and the consequent inward migration of the second planet. The second peak corresponds to systems in which the two planets collide and form a bigger body in an intermediate orbit. Nearly always the impact occurs in the initial phases of instability when the eccentricities of the two planets are still low. One body catches the other traveling on a close orbit and the merged body has a low eccentricity. This behavior is marked by a sharp rise around zero in the eccentricity distribution. The bimodal distribution is also retrieved in the periastron distribution, in which the peak of the merged bodies is sharp and centered around 3 AU.

In Table 3 we present the relevant statistics for biplanet systems. For low values of $e_B$ almost 50% of the systems lead to a

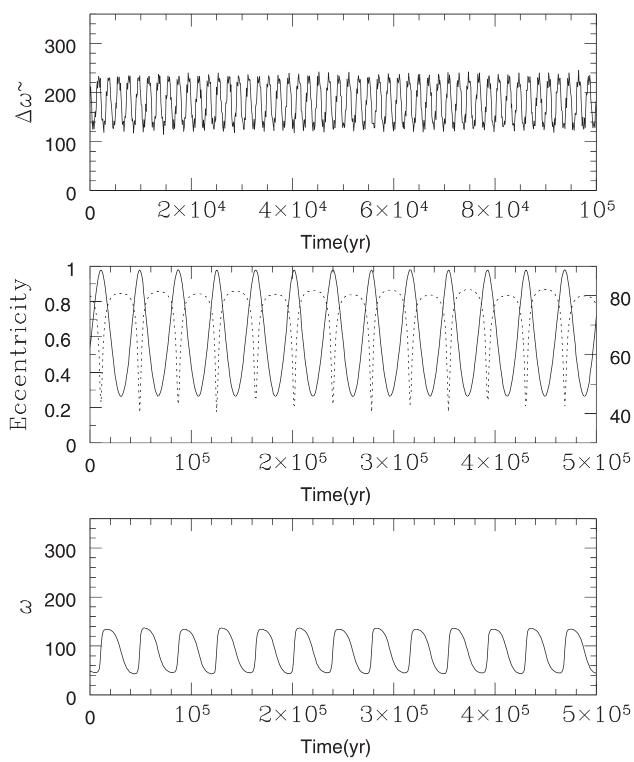


Fig. 6.—Two cases of secular resonances. The upper plot shows the critical argument of an apsidal resonance among two planets surviving after the chaotic phase. It librates around 180°. The middle and bottom plots illustrate the evolution of the eccentricity, inclination, and the perihelion argument of a planet in a Kozai resonance with the companion star. The average value of inclination is 60° and that of eccentricity is 0.6.

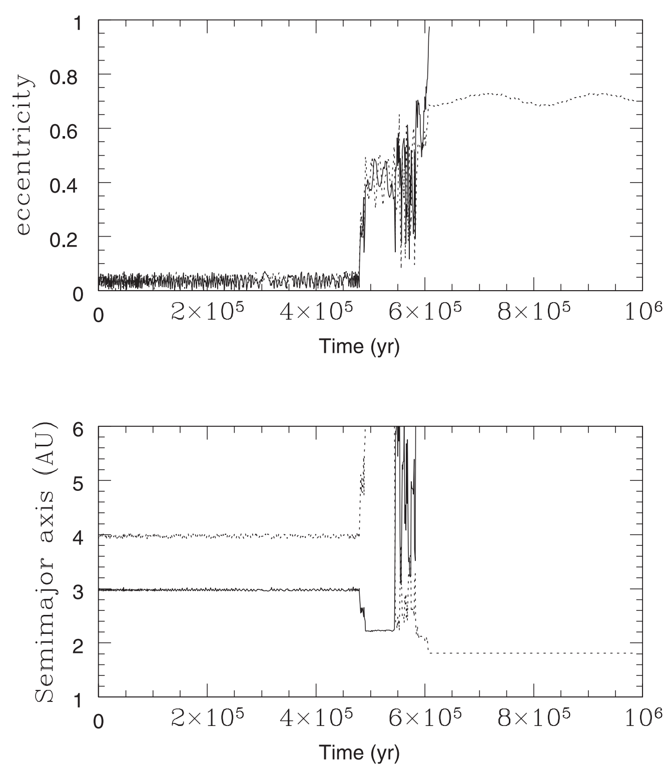


Fig. 7.—Chaotic evolution of a system of two Jovian-mass planets. The surviving planet is left on a highly eccentric orbit. To compare with Fig. 1, we used the same values of $e_B = 0.3$ and $\mu = 0.4$.

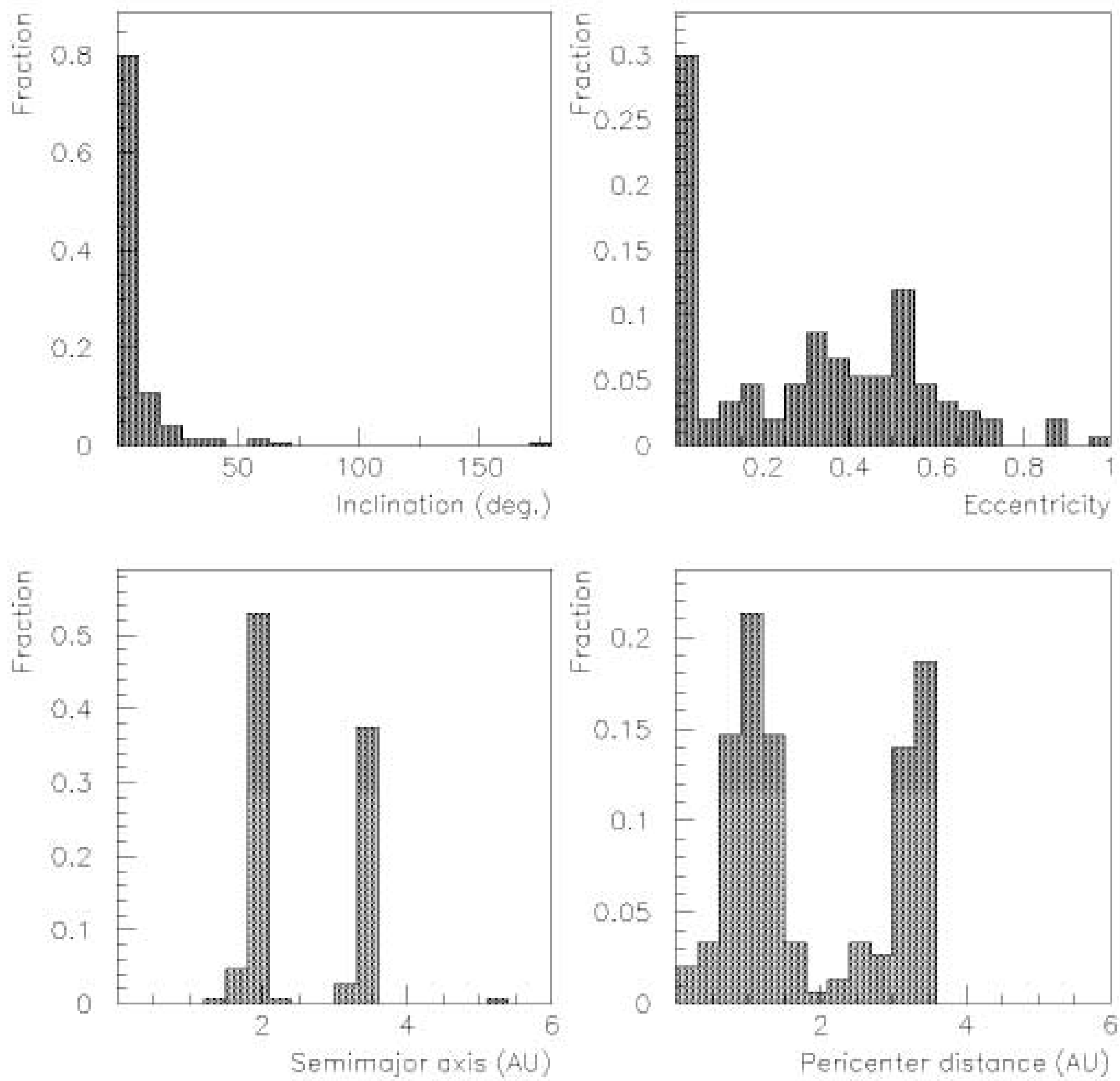


FIG. 8.—Same as Fig. 2, but for systems with two initial planets and $e_B = 0.3$ and $\mu = 0.4$.

single more massive planet given by the merging of the two original Jovian-mass planets, a percentage comparable to that for systems around single stars. The median eccentricity is low, being dominated by impact events. As $e_B$ increases, the number of collisions diminishes and the ejection of one planet is the preferred outcome. The median eccentricity rises to values comparable with those observed in the scattering of three planets. The decrease in the collision frequency with $e_B$ is also manifest in the three-dimensional histograms of Figure 9. The peak at low eccentricity and at a perihelion distance of ~3 AU, indicating that the two planets merged, slopes down for larger $e_B$. An additional effect related to the binary eccentricity is the rise with $e_B$ of the frequency with which one of the planets impacts on the central star (Table 3).

## 5. DISCUSSION AND CONCLUSIONS

Planet-planet scattering might be a common evolutionary stage of planetary systems. We know that, for single stars, the Jumping Jupiter model leads to highly eccentric orbits consistent with those observed for extrasolar planets. If tidal dissipation is effective, the model can also account for a fraction of "hot Jupiters" in circular orbits close to the star. For planets orbiting the central star of a binary system, a Jumping Jupiter phase is favored by the gravitational perturbation of the companion star. The initial spacing among adjacent planets leading to dynamical instability is increased compared to the single-star case, and the whole process appears more plausible from the point of view of planetary formation, in particular for systems containing only two planets. The planets have large feeding zones for accretion before the onset of orbital crossings.

Inspection of Tables 1–3 shows that the presence of a stellar companion aids the ejection of planets during chaotic orbital evolution. Compared with the single-star case, systems with three initial planets are more likely to leave a single survivor (or none), although two-planet systems are still a significant outcome. All surviving planets have stable orbits according to the Holman-Wiegert criterion, at least in those cases in which the mutual inclination between the planet and the secondary star is

TABLE 3

Percentages of Different Outcomes of the Gravitational Scattering Phase for Different Values of $e_B$ and for $\mu = 0.4$ for Systems with Two Initial Planets

| $e_B$ (1) | s1 (%) (2) | s2 (%) (3) | M (%) (4) | $1_p$ (%) (5) | $0_p$ (%) (6) | Retrograde (%) (7) | Kozai (%) (8) | $e_{med}$ (9) |
|---|---|---|---|---|---|---|---|---|
| 0.0 | 3 | 1 | 58 | 100 | 1 | 0 | 0 | 0.10 |
| 0.1 | 9 | 1 | 40 | 99 | 1 | 1 | 1 | 0.22 |
| 0.2 | 6 | 1 | 53 | 99 | 1 | 0 | 0 | 0.14 |
| 0.3 | 9 | 1 | 40 | 99 | 1 | 1 | 1 | 0.16 |
| 0.4 | 10 | 2 | 34 | 98 | 2 | 2 | 0 | 0.27 |
| 0.5 | 9 | 2 | 18 | 98 | 2 | 0 | 0 | 0.34 |
| 0.6 | 8 | 3 | 13 | 97 | 3 | 1 | 0 | 0.31 |
| Single[a] | 0 | ... | 60 | 100 | 0 | 3 | ... | 0.16 |

Notes.—Percentages of different outcomes of the gravitational scattering phase for different values of $e_B$ and for $\mu = 0.4$. Col. (2): Fraction of final configurations in which one planet impacted on the central star. Col. (3): Impact on the secondary star. Col. (4): Percentage of systems in which the inner planet is more massive, being the outcome of a collision between two planets of the system. Cols. (5) and (6): Systems in which the final configuration has one or zero surviving planets, respectively. Col. (7): Planets injected into retrograde orbits. Col. (8): Systems in which one planet is in a Kozai resonance with the companion star. For planets in binary systems, retrograde is intended with respect to the binary orbit, while for planets around single star, retrograde is the orbit of one planet with respect to that of the other survivor. Col. (9): $e_{med}$ is the median of the eccentricity distribution of the inner surviving planet.

[a] The last row shows the outcome of the Jumping Jupiter model in a reference single-star case.

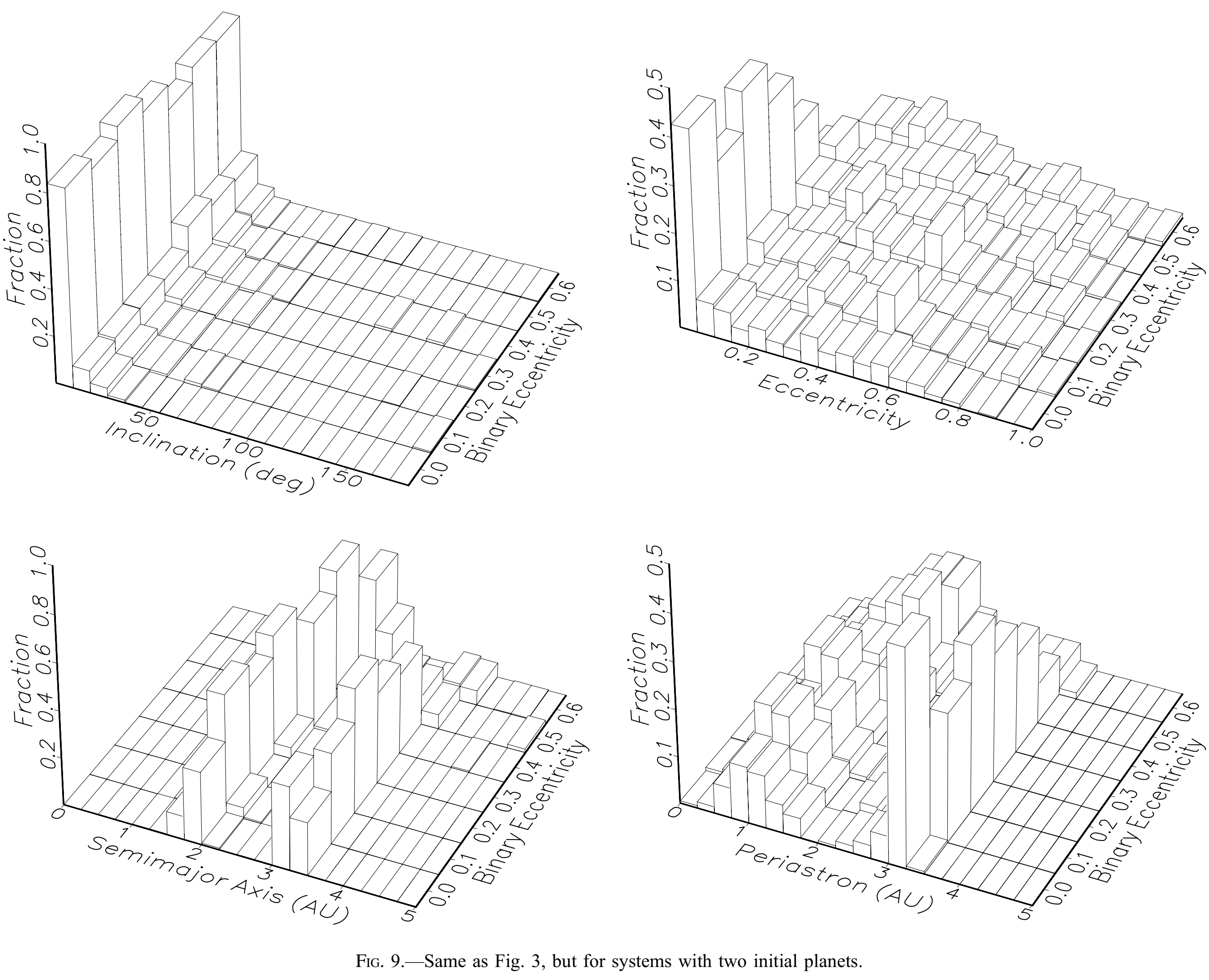


Fig. 9.—Same as Fig. 3, but for systems with two initial planets.

small (the criterion was derived for the planar case). From Figures 3 and 9 it can be seen that all the planets left in inner orbits have semimajor axes less than 5 AU, the critical semimajor axis $a_c$ of Holman & Wiegert (1999) computed in the least favorable case when $e_B = 0.6$ and $\mu = 0.4$. For those systems in which two planets remain, in more than 95% of cases both planets have semimajor axes lower than $a_c$ (cf. Fig. 4 where $a_c = 10$ AU). However, the Holman-Wiegert criterion refers to a single planet. When two planets are orbiting the primary star the situation is dynamically different owing to the mutual gravitational perturbations between the planets and between the planets and the companion star. The long-term stability of these systems may be affected, but its study is beyond the scope of this paper.

The chaotic phase that ends up with the ejection of one or more planets on hyperbolic orbits strongly depends on the eccentricity of the binary system. Moreover, there is a significant difference between the evolution of a system of three initial planets compared to that of only two planets. This difference can be exploited to cast predictions when we detect a planet (or planets) in a binary system. When $e_B$ is low and the planet is massive and on a low-eccentricity and low-inclination orbit, it possibly comes from the merging of two Jupiter-size planets after a short period of gravitational scattering. On the other hand, a single planet on a highly eccentric orbit close to the star is possibly produced by a more complex dynamical evolution involving three initial planets. An observed biplanet system may either be primordial or the result of a Jumping Jupiter phase. In the latter case, the planets would be in eccentric orbits and, in ~15% of cases, they would be in apsidal resonance.

More rare events include a single planet in a stable orbit around the central star and in a Kozai resonance with the companion star, a planet in a temporary circumbinary orbit, and a single planet in a retrograde orbit (with respect to the binary system).

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