'JUMPING JUPITERS' IN BINARY STAR SYSTEMS. F. Marzari, *Dept. of Physics, University of Padova, Italy, marzari@pd.infn.it*, S. J. Weidenschilling, *PSI, Tucson, USA*, V. Granata, *Dept. of Physics, University of Padova, Italy*, M. Barbieri, *CISAS, University of Padova, Italy*.

Dynamical evolution of multiple–planet systems after their growth may lead to stable configurations after the hyperbolic ejection of one or more planets [1,2]. The surviving planet (or at least one of the surviving planets) at the end of the 'Jumping Jupiter' phase, is moved closer to the star in an orbit with a significant eccentricity. We study the outcomes of such evolution in binary star systems where the companion star can significantly perturb the orbits of the planetary system.

Our current paradigm for planetary formation is centered on the formation of a single star surrounded by a disk of gas and dust, roughly a few hundred AU in size. However, about 2/3 of solar mass stars are part of binary star systems and both numerical simulations and observations (HR4796A [3] and L1551 [4]) suggest that proto-planetary disks around one or both the components of young binary star systems can form as well. The growth of planets within such disks can give origin to a multiple–planet system. Extrasolar planets around binary stars have been already detected in systems where the separation between the stars is larger than some hundreds of AU. The first extrasolar planet in a relatively close stellar binary system has been recently discovered in the gamma Cephei system [5]. The origin and evolution of planets in binary systems with separation less than 50 AU has far-reaching implications since these systems represent more than 50% of all binary systems [6].

We investigate the dynamical evolution and final state of a system of three Jupiter–mass planets that form around the component of a binary star system with separation less than 50 AU. In a dense protoplanetary disk both the conventional core–accretion model [7] or disk instability [8] may lead to the the formation of planets with comparable masses and similar radial spacings. During the final stage of accretion, the stability of the system is affected by the mutual gravitational interactions and the dynamical evolution becomes chaotic with large changes in the orbital elements of the planets. In single star systems the sequence of close encounters among the planets determine the final configuration of the system. The situation is more complex for a system containing a companion star and the 'Jumping Jupiter' phase is strongly affected by the gravitational perturbations of the secondary star.

We performed direct numerical integrations of binary systems with three giant planets initially on orbits within the stability region outlined by [9]. The trajectories have been computed within the full 5–body model with the RA15 version of the RADAU integrator [10]. This is the best choice taking into account the frequency and relevance of close encounters among the planets, and encounters with either of the stars. Due to the chaotic nature of the dynamical evolution, we resorted to a statistical approach and we sampled a large number of initial conditions. We integrated 1000 different systems with the planets initially in orbits with fixed semimajor axes (1,2,3 AU), 0 eccentricity and 0 inclination. The primary star is a 1–$M_\odot$ solar–type star, the companion has a mass typical of an M–type star (0.4 $M_\odot$). We analysed two different orbital configurations for the binary system: in the first case (hereinafter case A) the secondary star has a semimajor axis of 20 AU and an eccentricity of 0.4, in the second (hereinafter case B) it has a semimajor axis of 30 AU and an eccentricity of 0.6. These values of eccentricity are among the most frequent in the observed binary systems [6]. All the initial orbital angles are generated randomly.

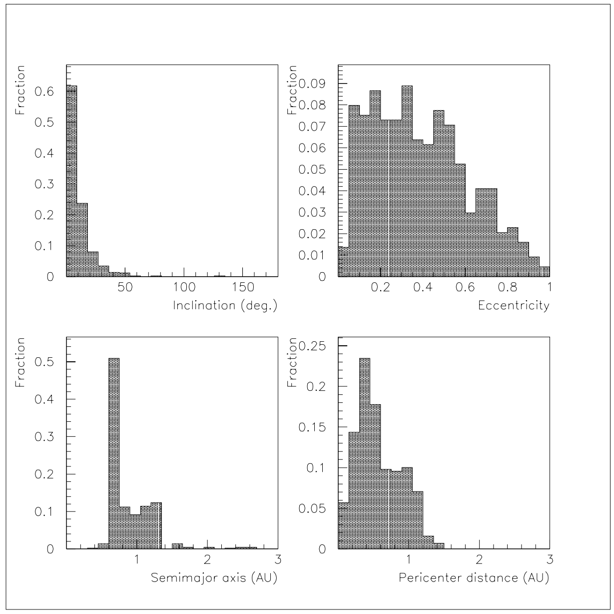

Figure 1: Histograms showing the distribution of the orbital elements of the planet left in the inner orbit after the chaotic phase.

In Fig. 1 we show the histograms of the orbital elements of the planet injected in the inner orbit of case A. The semimajor axes are concentrated in between 0.65–0.7 AU. This is not the minimum value achievable by conservation of energy when two planets are ejected ($a_m = 0.55AU$) since a fraction of the planetary orbital energy is gained by the companion star. The eccentricity distribution is peaked at about 0.3 and high values are less frequent. This is in contrast with the single–star case [2] where high eccentricities are easily obtained by the inner planet. In Table I we report the significant statistics of the scattering phase. In 84% of cases a single planet survives and in 26% of cases the inner planet is the outcome of a collision between two of the initial planets. When two planets survive at the end of the chaotic phase and are both within the stable region, a few cases exhibit secular apsidal resonance [11]. Those in which the relative apsidal longitude $\Delta\tilde{\omega} = \tilde{\omega}_1 - \tilde{\omega}_2$ librates

0 pl.	1 pl.	2 pl.	Inner Mas.	Imp. S1	Imp S2	Aps. Res.
1.3%	84.0%	14.8%	26.0%	26.5%	4.7%	0.9%
2.6%	68.3%	29.1%	13.2%	21.0%	4.1%	2.2%

Table 1: Percentages of different outcomes of the gravitational scattering phase. The first line is relative to case A, the second to case B. The first three columns indicate a final system with 0, 1, or 2 planets left in the system. The fourth column gives the fraction of systems where the inner planet is more massive, being the outcome of a collision between two planets. The fifth and sixth columns give the percentage of impacts on the primary star (S1) or secondary star (S2), respectively. The last column reports the percentage of cases where the two planets left are in apsidal resonance.

around $0°$ are stable (Fig. 2) while those showing libration around $180°$ are unstable and end up with the impact of one of the two planets on the primary star. The inclination relative to the binary orbital plane is pumped up and sometimes it exceeds $50°$ possibly leading to Kozai resonances. In a minority of cases (1.3%) all the planets are ejected and the companion star is injected in an inner orbit. In some cases a planet is set into a temporary circumbinary orbit, but it becomes unstable and it escapes on a hyperbolic orbit over a timescale of a few 10^4 yr. However, it might perturb a potential circumbinary planetary system and cause its destabilization.

In case B, there is a larger fraction of systems with two planets compared to case A, and a higher number of apsidal resonances (Table I). The distributions of the orbital elements for the inner planet are similar in the two cases, while there is a slight increase in the number of highly inclined planets.

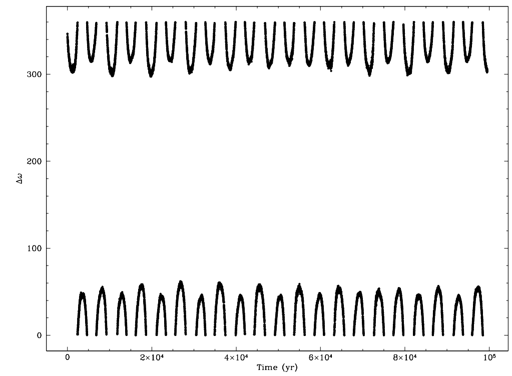

Figure 2: Evolution with time of $\Delta\omega$ for a system where the planets are in apsidal resonance.

REFERENCES: [1] Weidenschilling S.J. and F. Marzari, Nature, 384, 619 (1996). [2] Marzari F. and S.J. Weidenschilling, Icarus, 156, 570 (2002). [3] Jayawardhana, R. et al., ApJL 503, L79 (1998). [4] Rodriguez L.F. et al., Nature, 395, 355 (1998). [5] Cochran W.D. et al., DPS 34th Meeting, (2002). [6] Duquennoy A:, Mayor M., A&A 248, 485 (1991). [7] Bodenheimer, P., Hubickyj, O., Lissauer, J.J., Icarus, 143, 2 (2000). [8] Boss A.P. ApJ, 551, L167 (2001). [9] Holman M.J., and P.A. Wiegert, AJ 117, 621 (1999). [10] Everhart E., In Dynamics of Comets: Their Origin and Evolution. 185 (1985). [11] Malhotra R., ApJL, 575, 33 (2002).