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Forming different planetary systems *

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Abstract With the increasing number of detected exoplanet samples, the statistical properties of planetary systems have become much clearer. In this review, we summarize the major statistical results that have been revealed mainly by radial velocity and transiting observations, and try to interpret them within the scope of the classical core-accretion scenario of planet formation, especially in the formation of different orbital architectures for planetary systems around main sequence stars. Based on the different possible formation routes for different planet systems, we tentatively classify them into three major catalogs: hot Jupiter systems, standard systems and distant giant planet systems. The standard systems can be further categorized into three sub-types under different circumstances: solar-like systems, hot Super-Earth systems, and sub-giant planet systems. We also review the theory of planet detection and formation in binary systems as well as planets in star clusters.

Key words: planetary systems: dynamical evolution and stability — formation — planet-disk interactions — stars: binary: general — clusters: general

1 INTRODUCTION

Since the discovery of a giant planet by radial velocity measurements in 51 Peg by Mayor & Queloz (1995), as well as the planets around 47 UMa and 70 Vir (Butler & Marcy 1996; Marcy & Butler 1996), the new era of detecting exoplanets around main sequence stars was opened at the end of the last century. Now exoplanet detection has become one of the most rapidly developing areas in astronomy. With the development of measurement techniques, the precision of radial velocity (RV) can be better than 0.5 m s^{-1} with the HARPS spectrograph at La Silla Observatory (Mayor et al. 2003), making possible the detection of Earth size planets in close orbits around bright stars. The detection of transiting signals when exoplanets pass in front of their host stars has become another powerful method in searching for planet candidates, especially after the successful launch of CoRoT and Kepler. The unprecedented high precision of photometric observation ($\sim$ 10 ppm) and long-duration continuous observation (up to years) achieved by space missions make transits an ideal tool to detected near-Earth-size planets in the habitable zone of solar type stars.

To date, around 780 exoplanets have been detected mainly by RV measurements, with more than 100 multiple planet systems [1]. The first 16 months' observation of the Kepler mission revealed more

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[1] *http://exoplanet.eu/*, and hereafter for all RV based statistics in the paper.

than 2321 transit candidates, with 54 candidates in the habitable zone of their host stars [2] (Borucki et al. 2011; Batalha et al. 2012; Fabrycky & Kepler Science Team 2012).

The study of planet formation can be traced back to the 18th century, when E. Swedenborg, I. Kant, and P.-S. Laplace developed the nebular hypothesis for the formation of the solar system. At that time the solar system was the only sample of a planetary system. The architecture of the solar system implied that it was formed in a Keplerian disk of gas and dust (for reviews, see Wetherill 1990; Lissauer 1995; Lin & Papaloizou 1996). With the discovery of more exoplanet systems, planet formation theory has developed dramatically. For example, the discovery of hot Jupiters (HJs) stimulated the classical migration theory of planets embedded in the proto-stellar disk (Lin & Papaloizou 1986, 1996), the moderate eccentricities of exoplanet orbits remind us of planet-planet scattering (hereafter, PPS) theory (Rasio & Ford 1996), and the observation of some HJs in retrograde orbits extends the classical Lidov-Kozai mechanism to eccentric cases (Kozai 1962; Lidov 1962; Naoz et al. 2011b). Through population synthesis, N-body and hydrodynamical simulations, the planet formation processes have been well revealed but are still far from fully understood.

In this paper, we focus on recent progress in the theory of detection and formation of solar type stars, either around single stars (Sect. 2), binary stars (Sect. 3), or in star clusters (Sect. 4).

2 PLANETS AROUND SINGLE STARS

2.1 Overview of Observations

2.1.1 Planet occurrence rate

The occurrence rate of gas-giant exoplanets around solar-type stars has been relatively well studied. Tabachnik & Tremaine (2002) fitted 72 planets from different Doppler surveys, and found a mass (M)-period (P) distribution with the form of a double power law,

$$dN \propto M^{\alpha} P^{\beta} d\ln M d\ln P, \tag{1}$$

after accounting for selection effects. They obtained $\alpha = -0.11 \pm 0.1$ and $\beta = 0.27 \pm 0.06$. Recently, Cumming et al. (2008) analyzed eight years of precise RV measurements from the Keck Planet Search, including a sample of 585 chromospherically quiet stars with spectral types from F to M. Such a power-law fit in Equation (1) for planet masses $> 0.3 M_{\rm J}$ (Jupiter mass) and periods < 2000 days was re-derived with $\alpha = -0.31 \pm 0.2$ and $\beta = 0.26 \pm 0.1$. They concluded 10.5% of solar type stars have a planet with mass $> 0.3 M_{\rm J}$ and period $2 - 2000$ days, with an extrapolation of 17%–20% of stars having gas giant planets within 20 AU.

Based on the 8-year high precision RV survey at the La Silla Observatory with the HARPS spectrograph, Mayor et al. (2011) concluded that 50% of solar-type stars harbor at least one planet of any mass and with a period up to 100 days. About 14% of solar-type stars have a planetary companion more massive than $50\,M_{\oplus}$ in an orbit with a period shorter than 10 years. The mass distribution of Super-Earths and Neptune-mass planets is strongly increasing between 30 and $15\,M_{\oplus}$, indicating small mass planets are more frequent around solar type stars.

Howard et al. (2010) calculated the occurrence rate of close planets (with $P < 50$ days), based on precise Doppler measurements of 166 Sun-like stars. They fitted the measurements as a power-law mass distribution,

$$df = 0.39 M^{-0.48} d\log M, \tag{2}$$

indicating an increasing planet occurrence with decreasing planet mass. It also predicts that 23% of stars harbor a close Earth-mass planet, ranging from 0.5 to 2.0 $M_{\oplus}$ (Earth mass).

[2] *http://kepler.nasa.gov/,* and hereafter in the paper

With 12 years of RV data with long-term instrumental precision better than 3 m s^{-1}, the Anglo-Australian Planet Search targets 254 stars, and estimates an occurrence rate of 3.3% of stars hosting Jupiter analogs, and no more than 37% of stars hosting a giant planet between 3 and 6 AU (Wittenmyer et al. 2011a). Their results also reveal that the planet occurrence rate increases sharply with decreasing planetary mass. The results are consistent with those from other surveys: in periods shorter than 50 days, they find that 3.0% of stars host a giant ($m \sin i > 100\, M_\oplus$) planet, and that 17.4% of stars host a planet with ($m \sin i < 10\, M_\oplus$) (Wittenmyer et al. 2011b).

Moreover, the lack of massive planets ($> 8 M_{\rm Jup}$) beyond 4 AU was reported in Boisse et al. (2012), although with less than 20 RV detected candidates at the moment. Such a distribution agrees with population synthesis (Mordasini et al. 2012) , where they showed that a decrease in frequency of massive giant planets at large distance ($\geq$5AU) is a solid prediction of the core-accretion theory.

Transit observations from the Kepler spacecraft give qualitatively similar results. Howard et al. (2012) checked the distribution of planets in close orbits. For $P < 50$ days, the distribution of planet radii (R) is given by a power law,

$$df = k(R/R_\oplus)^\alpha d\log R \tag{3}$$

with $k = 2.9^{+0.5}_{-0.4}$ and $\alpha = -1.92 \pm 0.11$, and $R_\oplus$ is the Earth radius. They find the occurrence of 0.130 ± 0.008, 0.023 ± 0.003, and 0.013 ± 0.002 planets per star for planets with radii $2-4$, $4-8$, and $8-32\, R_\oplus$ respectively.

The rapid increase of planet occurrence with decreasing planet size indicates the presence of Super-Earth and Neptune size cases are quite common. Although this agrees with the prediction of the conventional core-accretion scenario, it conflicts with the results predicted by the population synthesis models that a paucity of extrasolar planets with mass in the range $10-100\, M_\oplus$ and semi-major axis less than 3 AU are expected, the so called 'planet desert' (Ida & Lin 2004).

2.1.2 Stellar masses of planet hosting stars

Kepler results also revealed a correlation between the planet's occurrence with the effective temperature ($T_{\rm eff}$) of host stars (Howard et al. 2012). The occurrence rate f is inversely correlated with $T_{\rm eff}$ for small planets with $R_{\rm p} = 2-4\, R_\oplus$, i.e.,

$$f = f_0 + k(T_{\rm eff} - 5100\ {\rm K})/1000\ {\rm K}, \tag{4}$$

with $f_0 = 0.165 \pm 0.011$ and $k = -0.081 \pm 0.011$. The relation is valid over $T_{\rm eff} = 3600 - 7100$ K, corresponding to stellar spectral types from M ($\leq 0.45\, M_\odot$, solar mass) to F ($1.4\, M_\odot$). This implies that stars with smaller masses tend to have small size planets.

However, the occurrence of planets with radii larger than $4R_\oplus$ from Kepler does not appear to correlate with $T_{\rm eff}$ (Howard et al. 2012). This is in contrast with the observation by RV measurements. In fact, a much lower incidence of Jupiter-mass planets is found around M dwarfs (Butler et al. 2006; Endl et al. 2006; Johnson et al. 2007), and higher mass stars are more likely to host giant planets than lower mass ones (e.g., Lovis & Mayor 2007; Johnson et al. 2007, 2010; Borucki et al. 2011). The result is compatible with the prediction in the core accretion scenario for planet formation (Laughlin et al. 2004; Ida & Lin 2005; Kennedy & Kenyon 2008).

2.1.3 Metallicity dependence

It has been well-established that more metal-rich stars have a higher probability of harboring a giant planet than their lower metallicity counterparts (Gonzalez 1997; Santos et al. 2001, 2004; Fischer & Valenti 2005; Udry & Santos 2007; Sozzetti et al. 2009; Sousa et al. 2011). The occurrence rate increases dramatically with increasing metallicity. Based on the CORALIE and HARPS samples, around 25% of the stars with twice the metal content of our Sun are orbited by a giant planet.

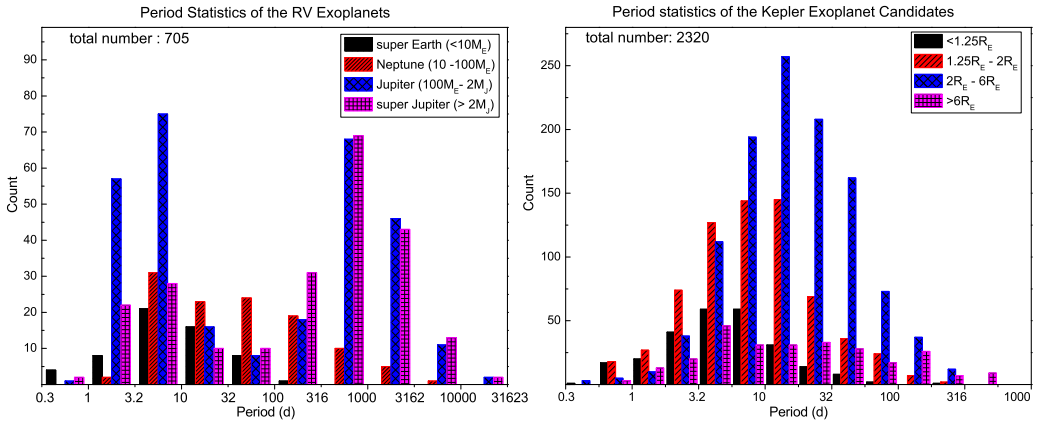

Fig. 1 Distribution of exoplanets detected by RV measurements (*left, http://exoplanet.eu/*), and candidates by the Kepler mission (*right, http://kepler.nasa.gov/*).

This number decreases to $\sim 5\%$ for solar-metallicity cases (Sousa et al. 2011; Mayor et al. 2011). Recently, Mortier et al. (2012) showed the frequency of giant planets is $f = 4.48^{+4.04}_{-1.38}\%$ around stars with [Fe/H] > -0.7, as compared with $f \leq 2.36\%$ around stars with [Fe/H] ≤ -0.7. Curiously, no such correlation between planet host rate and stellar metallicity is observed for the lower mass RV planets, and the stars hosting Neptune-mass planets seem to have a rather flat metallicity distribution (Udry et al. 2006; Sousa et al. 2008, 2011; Mayor et al. 2011).

By re-evaluating the metallicity, Johnson et al. (2009) find that M dwarfs with planets appear to be systematically metal rich, a result that is consistent with the metallicity distribution of FGK dwarfs with planets. Schlaufman & Laughlin (2011) find that stars hosting Kepler exoplanet candidates are preferentially metal-rich, including the low-mass stars that host candidates with small radius, which confirms the correlation between the metallicity of low-mass stars and the presence of low-mass and small-radius exoplanets.

2.1.4 Mass and period distributions

Figure 1 shows the distribution of planetary orbital periods for different mass regimes. 705 planets detected by RV measurement and 2320 candidates revealed by the Kepler mission are included. Several features of the mass-period distribution have been well known and widely discussed in the literatures. However, it seems that the distribution features from RV detected exoplanets *are slightly different* from those of Kepler candidates.

– All kinds of RV planets show a "pile-up" at orbital periods 2–7 days (e.g., Gaudi et al. 2005; Borucki et al. 2011), while Kepler results show that Jupiter-size ($> 6\,R_\oplus$) candidates are more or less flat up to orbits with > 100 days; Neptune-size ($2\,M_\oplus < R_\mathrm{p} < 6\,R_\oplus$) and super-Earth candidates ($1.25\,M_\oplus < R_\mathrm{p} < 2\,R_\oplus$) peak at $10 - 20$ days. Both of them are more abundant relative to Jupiter-size candidates in the period range from one week to one month (Borucki et al. 2011). Extrapolating the distribution by considering the (R_p/a) probability of a transiting exoplanet could extend these peaks to a bit more distant orbits. Earth size or smaller candidates ($< 1.25\,M_\oplus$) show a peak of ~ 3 days.

– RV planets show a paucity of massive planets ($M > 1 M_{\rm J}$) in close orbits (Udry et al. 2002, 2003; Zucker & Mazeh 2002, 2003), and a deficit of planets at intermediate orbital periods of $10 - 100$ days (Jones et al. 2003; Udry et al. 2003; Burkert & Ida 2007). However, this is not obvious as Kepler results show at least several tens of candidates with the radius lying in the $10 - 20 R_\oplus$ line within 10-day orbits, and the distribution extending to 100 days is rather flat (Fig. 1). The lack of all types of planets with orbital periods $\sim 10 - 1000$ days observed by RV is clear, but from Kepler results, the lack of planets with period > 100 days is also shown, possibly due to the observational bias (Fig.1). RV observations from the Anglo-Australian Planet Search indicate that such a lack of giant planets ($M > 100 M_\oplus$) with periods between 10 and 100 days is indeed real. However, for planets in the mass range $10 - 100 M_\oplus$, the results suggest that the deficit of such planets may be a result of selection effects (Wittenmyer et al. 2010).

2.2 Hot Jupiter Systems

The HJ class of extrasolar planets has mass close to or exceeding that of Jupiter ($M_{\rm p} \geq 0.1 M_{\rm J}$, or radius $\geq 8\, R_\oplus$ for densities of $1.4\ {\rm g\ cm^{-3}}$, a typical value of gas giants with small rocky cores), with orbital periods ≤ 10 days (corresponding to $a < 0.1$ AU from their parent stars) (Cumming et al. 2008; Howard et al. 2012; Wright et al. 2012). According to this definition, the RV exoplanets have 202 HJs, while Kepler candidates have 89 HJs. HJs are notable since they are easy to detect either by RV or by transit measurements. For example, the first exoplanet discovered around 51 Peg is such a close giant planet (Mayor & Queloz 1995). Transiting HJs also give us information about their radii, which is crucial for understanding their compositions (e.g., Fortney et al. 2003; Seager & Deming 2010). However, with the increase of RV precision and the number of detected exoplanets, HJs are found to be in fact rare objects (e.g., Cumming et al. 2008; Wright et al. 2012). More interestingly, some HJs were observed in orbits that are retrograde with respect to the spin direction of their host stars (e.g., Winn et al. 2010), indicating that their formation process might have been quite different with that of our solar system.

2.2.1 Occurrence rate and distributions

Marcy et al. (2005) analyzed 1330 stars from the Lick, Keck, and Anglo-Australian Planet Searches, and the rate of HJs among FGK dwarfs surveyed by RV was estimated to be $1.2 \pm 0.1\%$. Mayor et al. (2011) used the HARPS and CORALIE RV planet surveys and found the occurrence rate for planets with $M \sin i > 50\, M_\oplus$ and $P \leq 11$ days is $0.89 \pm 0.36\%$. Recently, Wright et al. (2012) used the California Planet Survey from the Lick and Keck planet searches, and found the rate to be $1.2 \pm 0.38\%$. These numbers are more than double the rate reported by Howard et al. (2012) for Kepler stars ($0.5 \pm 0.1\%$) and the rate of Gould et al. (2006) from the OGLE-III transit search. The difference might be, as pointed out by Wright et al. (2012), that transit surveys like OGLE and Kepler (centered at galactic latitude $b = +13.3°$) probe a lower-metallicity population, on average, than RV surveys.

Previous RV measurements show that there is a sharp inner cutoff in the three day pileup of HJs. They appear to avoid the region inward of twice the Roche radius (Ford & Rasio 2006), where the Roche radius is the distance within which a planet would be tidally shredded. However, recent RV detected exoplanets and Kepler candidates indicate the presence of more than 200 exoplanets and candidates within 3-day orbits, with the inner most orbital period being 0.24 days for system KOI-55, corresponding to a location close to its Roche radius (Fig. 1).

Also, RV detected HJs appear to be less massive than more distant planets (Pätzold & Rauer 2002; Zucker & Mazeh 2002). For planets discovered with the RV method, close planets have projected masses ($M \sin i$) less than twice Jupiter's mass. But numerous planets farther out have $M \sin i > 2 M_{\rm J}$ (Udry & Santos 2007).

2.2.2 Spin-Orbit misalignment

One of the most fascinating features for HJs is that some HJs have orbits that are misaligned with respect to the spin of their host stars (Winn et al. 2010; Triaud et al. 2010). The sky-projected angle between the stellar spin and the planet's orbital motion can be probed with the Rossiter-McLaughlin (RM) effect (Rossiter 1924; McLaughlin 1924). To date, the RM effect has now been measured for at least 47 transiting exoplanets (see Winn et al. 2010, table 1 for a list of 28 planets, and Brown et al. 2012, table 5 for a list of 19 additional planets, and references therein). Only 7 (HAT-P-6b, HAT-P-7b, HAT-P-14b, WASP-8b, WASP-15b, WASP-17b, WASP-33b) of the 47 cases have projected angles above 90°, indicating a ratio of $\sim 15\%$ that are in retrograde motion. It is still not clear what type of stars could host HJs in retrograde orbits. Winn et al. (2010) showed that the stars hosting HJs with retrograde orbits might have high effective temperatures (> 6250 K). The underlying physics remains for further study.

2.2.3 Lack of close companions

Few companion planets have been found in HJ systems within several AU (Wright et al. 2009; Hébrard et al. 2010). To date, only six RV detected planetary systems have multiple planets with the inner one being HJs (HIP 14810, ups And, HAT-P-13, HD 187123, HD 21707, HIP 11952). Compared to the total number of 89 RV detected HJs, the ratio is less than 7%. Interestingly, all these planetary companions are in orbits with periods > 140 days. This relative deficit also shows up in the transit samples, where most attempts at detecting transit timing variations caused by close companions have been unsuccessful (Holman & Murray 2005; Agol et al. 2005; Rabus et al. 2009; Csizmadia et al. 2010; Hrudková et al. 2010; Steffen et al. 2012). Kepler data also revealed the lack of a close companion in HJ systems. Steffen et al. (2012) presented the results of a search for planetary companions orbiting near HJ candidates in the Kepler data. Special emphasis is given to companions between the 2:1 interior and exterior mean motion resonances (MMRs). A photometric transit search excludes the existence of companions with sizes ranging from roughly $2/3$ to 5 times the size of Earth.

2.3 Multiple Planet systems

With the increasing number of exoplanets being detected, the number of multiple planet systems is also steadily increasing. The first 16 months of Kepler data show that, among the 2321 candidates, 896 ones are in multiple planet systems, so that 20% of the stars cataloged have multiple candidates (Borucki et al. 2011; Batalha et al. 2012). Considering the present observation bias toward large mass planets, as well as the increasing occurrence rate of small mass planets, we have a good reason to believe that multiple planets are very common and might occur at a much higher rate. The systems that have been revealed with the most numerous exoplanets are HD 10180 (Lovis et al. 2011, up to seven planets) and Kepler-11 (Lissauer et al. 2011, with six planets). All of them are mainly composed of small mass planets (Super Earth or Neptune mass). Several important signatures have been revealed by the Kepler mission:

- Multiple planets have, on average, smaller masses than single planet systems. Figure 2 shows the paucity of giant planets at short orbital periods in multiple planet systems, and the ratio of giant planets (with radius $> 6\,R_\oplus$) in single and multiple planet systems is roughly 5.7:1, with orbital periods of up to ~ 500 days.
- Many planet pairs are near MMR. The presence of MMR is a type of strong evidence for the migration history of the planet pairs (e.g., Lee & Peale 2002; Zhou et al. 2005). Wright et al. (2011) summarized the data from RV detected planets, and found 20 planetary systems are apparently in MMRs, indicating one-third of the well-characterized RV multiple planet systems

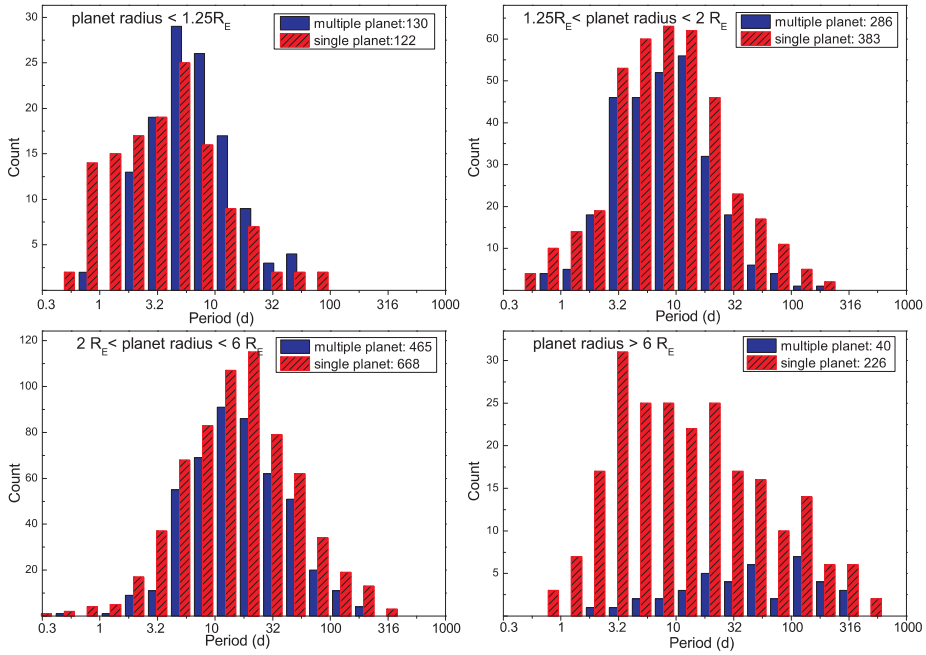

Fig. 2 The distribution of Kepler candidates in single and multiple planet systems for different mass regimes. Data are from *http://kepler.nasa.gov*.

have planet pairs in apparent MMRs. Fabrycky & Kepler Science Team (2012) found the Kepler multiple transiting planet systems show some pile-up for planets pairs near lower order MMRs (especially 3:2 and 2:1 MMRs).

– Multiple planet systems are nearly coplanar. Checking the Kepler multiple-transiting system indicates that these planets are typically coplanar to within a few degrees (Batalha et al. 2012). Also the comparison between the Kepler and RV surveys shows that the mean inclination of multi-planet systems is less than 5° (Tremaine & Dong 2012). Figueira et al. (2012) demonstrated that, in order to match the ratio of single planet systems to the 2-planet ones observed in HARPS and Kepler surveys, the distribution of mutual inclinations of multi-planet systems has to be of the order of 1°.

2.4 Planet Formation Theory

Now it is widely accepted that planets were formed in the protoplanetary disk during the early stage of star formation (e.g., Wetherill 1990; Lissauer 1995; Lin & Papaloizou 1996; Tutukov & Fedorva 2012). According to the conventional core accretion model, planets are formed through the following processes (e.g., Lissauer 1993; Armitage 2007):

(1) grain condensation in the mid-plane of the gas disk, forming kilometer-sized planetesimals (10^{18} – 10^{22} g) on timescales on the order of 10^4 yr, from sticking collisions of dust (Weidenschilling & Cuzzi 1993; Weidenschilling 1997), with gravitational fragmentation of a dense particle sub-disk near the midplane of the protoplanetary disk (Goldreich & Ward 1973; Youdin & Shu 2002). Further growth of planetesimals can be helped by procedures such as the onset of streaming instability (Johansen et al. 2007) or vortices in turbulence (Cuzzi et al. 2008),

or the sweeping of dust with the "snowball" model (Xie et al. 2010; Ormel & Kobayashi 2012; Windmark et al. 2012).

(2) accretion of planetesimals into planetary embryos ($10^{26}-10^{27}$ g, Mercury to Mars size) through a phase of "runaway" and "oligarchic" growth on a timescale of $\sim 10^4-10^5$ yr (Greenberg et al. 1978; Wetherill & Stewart 1989; Aarseth et al. 1993; Kokubo & Ida 1996; Rafikov 2003, 2004).

(3) gas accretion onto solid embryos with mass bigger than a critical mass ($\sim 10\,M_\oplus$) after a $\sim$Myr long quasi-equilibrium stage before gas depletion (Mizuno 1980; Bodenheimer & Pollack 1986; Pollack et al. 1996; Ikoma et al. 2000).

(4) giant impacts between embryos, producing full-sized $(10^{27}-10^{28}$ g) terrestrial planets in about 10^7-10^8 yr (Chambers & Wetherill 1998; Levison & Agnor 2003; Kokubo et al. 2006). Thus the presence of big solid embryos and the lifetime of the gas disk are crucial for the presence of giant plants, while the presence of enough heavy elements determines the mass of solid embryos and terrestrial planets.

According to the above scenario, the correlation between giant stars that host planets and stellar metallicity can be understood. By cosmological assumption, a high stellar metallicity implies a protoplanety disk with more heavy elements, thus a metal-rich protoplanetary disk enables the rapid formation of Earth-mass embryos necessary to form the cores of giant planets before the gaseous disk is dissipated. That correlation might also indicate a lower limit on the amount of solid material necessary to form giant planets. Johnson & Li (2012) estimated a lower limit of the critical abundance necessary for planet formation of $[\mathrm{Fe/H}]_{\mathrm{crit}} \sim -1.5 + \log(r/1\ \mathrm{AU})$, where r is the distance to the star. Another key point may be the correlation between metallicity and the lifetime of the gas disk. There is observational evidence that the lifetime of circumstellar disks is short at lower metallicity, likely due to the great susceptibility to photoevaporation (Yasui et al. 2009).

Although the above procedures for single planet formation are relatively clear, there are some bottleneck questions (see previous listed reviews). Next, we focus on the formation of orbital architectures for different planet systems.

2.4.1 Formation of Hot Jupiter systems

Due to the high temperature that might hinder the accretion of gas in forming giant planets, the HJs were assumed to be formed in distant orbits rather than formed *in situ*. There are mainly three theories that were proposed to explain the formation of HJ systems with the observed configurations.

Disk migration model. The earliest model for the formation of HJ systems is the migration theory for planets embedded in protostellar disks (Lin & Papaloizou 1986; Lin et al. 1996). Giant planets formed in distant orbits, then migrated inward under the planet-disk interactions and angular momentum exchanges (Goldreich & Tremaine 1980; Lin & Papaloizou 1986). The so called type II migration will be stalled at the inner disk edge truncated by the stellar magnetic field. The maximum distance of disk truncation is estimated to be ~ 9 stellar radii (Koenigl 1991). Considering the radius of the protostar is generally two–three times larger than their counterpart in the main sequence, the inner disk truncation would occur at ~ 0.1 AU. This might naturally explain the pile-up of orbits with periods of $3-10$ days for HJs. However, as type II migration is effective only in the plane of the disk, and disk's tidal forces try to dampen the inclination of planets (Goldreich & Tremaine 1980), this procedure cannot explain the formation of HJs in orbits with high inclination, as well as the lack of planetary companions in close orbits. Recently, Lai et al. (2011) proposed that stellar-disk interaction may gradually shift the stellar spin axis away from the disk plane, on a time scale up to Gyrs.

Planetary scattering model. Another mechanism that might account for the formation of HJ systems is the PPS model. Close encounters among planets can excite their orbital eccentricities (e). In the extreme case that e is near unity, the orbital periastron will be small enough so that star-planet tidal interactions might be effective and circularize the orbits to become HJs (Rasio & Ford 1996;

Ford et al. 2001; Papaloizou & Terquem 2001; Ford & Rasio 2008). The planetary scattering model can reproduce the observed eccentricity distribution of moderately eccentric ($e \sim 0.1-0.3$), non-HJ extra-solar planets (Zhou et al. 2007; Chatterjee et al. 2008; Jurić & Tremaine 2008). However, the required high eccentricity and the long timescale required for tidal damping to be effective might not be easy to achieve unless some secular effects (e.g. the Lidov-Kozai mechanism) are excited (e.g., Nagasawa et al. 2008).

Secular models. The third class of models relate to the Lidov-Kozai effect (Lidov 1962; Kozai 1962) in the presence of a third body. To account for the high inclination of HJs, Wu & Murray (2003) proposed that a companion star, which is a third body in a high inclination orbit, can induce Kozai oscillations on the planet's evolution, gradually exciting the planet's orbit to an eccentricity near unity so that it can reach a proximity close to the central star, until tidal dissipation circularizes the orbit into an HJ. Fabrycky & Tremaine (2007) found such resulting HJs should be double-peaked with orbital inclinations of $\sim 40^\circ$ and 140°. Such an idea has been extended to brown dwarf companions by Naoz et al. (2011a).

However, the population studies establish that only 10% of HJs can be explained by Kozai migration due to binary companions (Wu et al. 2007; Fabrycky & Tremaine 2007), and most of the HJ systems did not find any stellar or substellar companions. Whether this mechanism can account for the formation of most HJs is not known. Another question is that, in the stellar companion case ($m_{\rm c}$, a star or a brown dwarf), the orbital angular momentum (AM) of $m_{\rm c}$ dominates that of the system and determines an invariant plane, thus the $z-$component of AM (perpendicular to the invariant plane) of the planet ($m_{\rm p}$) is conserved when $m_{\rm c}$ is in a distant orbit. Thus $m_{\rm p}$ can be in an apparent retrograde orbit relative to the spin axis of the main star only when $m_{\rm c}$ has a relatively large inclination with respect to the equator of the main star (Wu et al. 2007; Fabrycky & Tremaine 2007), and this retrograde motion is *not* with respect to the invariant plane determined by the total AM.

To avoid relying on the effects of stars or brown dwarf companions, and also to find the occurrence of retrograde motion relative to the invariant plane, one resorts to the conditions under which the Lidov-Kozai mechanism works for planet mass companions ($m_{\rm c}$). Naoz et al. (2011b) study the mechanism with a general three-body model. Denote $a, a_{\rm c}$ as the semimajor axes of inner planet ($m_{\rm p}$) and companion, respectively, with $e_{\rm c}$ being the eccentricity of $m_{\rm c}$; they find that as long as $(a/a_{\rm c})e_{\rm c}/(1-e_{\rm c}^2)$ is not negligible, the octuple-level of the three-body Hamiltonian would be effective, so that the z-component of $m_{\rm p}$ in AM is no longer conserved, allowing the occurrence of retrograde motion relative to the invariant plane. Thus, to make a retrograde HJ, a companion in a close and eccentric orbit is required, but the mass of the companion is not important.

However, newly-born planets are assumed to be in near circular and coplanar orbits. To generate the required eccentricity, Nagasawa et al. (2008); Nagasawa & Ida (2011) introduced planet scattering into the above pictures. Starting from a relatively compact system ($\sim 3.6\,R_{\rm H}$, where $R_{\rm H}$ is Hill's radius) with three Jupiter-mass planets, the planets scatter one another on a timescale of $\sim 10^3$ years. They found $\sim 30\%$ of the simulations can result in a planet with eccentricity high enough that Kozai excitations from outer planets can become effective, so that it can be either in a close orbit with non-negligible eccentricity, or in a highly inclined (even a retrograde) orbit with relatively small eccentricity over a timescale of 10^9 years. However, it is unclear whether the initial condition of a compact and highly unstable planetary system can exist, as required by this theory (Matsumura et al. 2010). Also the scattered planets can be observed to test the theory.

Another route to generate eccentricities other than through violent PPS is the diffusive chaos arising from a multiple planet system after it forms. The generation of eccentricity in a multiple planet system is a slow, random walk diffusion in the velocity dispersion space, and the timescale increases with the logarithm of the initial orbital separations (Zhou et al. 2007). Recently, Wu & Lithwick (2011) proposed that *secular chaos* may be excited in an orderly space system, and it may lead to natural excitation of the eccentricity and inclination of the inner system, resulting in observed

HJ systems. They inferred that such a theory can also explain the eccentricities and inclinations for distant giant planets. However, to what extent such a mechanism could be effective within the age of planetary systems remains for further study.

To summarize, the Lidov-Kozai mechanism seems to be the most promising mechanism for the formation of HJs. Provided that initial eccentricities of the planet's companion can reach high enough values, interplanetary Kozai oscillations can bring the inner planets into HJ orbits with sufficiently high inclinations.

2.4.2 Formation of multiple planet architectures and a system of classification

What should a 'standard' planet system be like? Before answering this question, let us first check the possible outcome of a planet system after the formation of individuals by the procedure listed at the beginning of Section 2.4.

According to the core accretion scenario, by depleting all the heavy elements in a nearby region (called the feeding zone, roughly 10 Hill radii), an embryo without any migration will be stalled from growing, which is a case called *an isolation mass* (Ida & Lin 2004). In a disk with metallicity $f_{\rm d}$ times the minimum mass solar nebula (MNSN) (Hayashi 1981), the isolation mass can be estimated as (Ida & Lin 2004, eq. (19))

$$M_{\rm iso} \approx 0.16 \eta_{\rm ice}^{3/2} f_{\rm d}^{3/2} \Big(\frac{a}{1\,{\rm AU}}\Big)^{3/4} \Big(\frac{M_*}{M_\odot}\Big)^{-1/2} M_\oplus, \tag{5}$$

where $\eta_{\rm ice}$ is the enhancement factor, with a value of 1 and ~ 4.2 respectively inside and outside the snow line (location with temperature 170 K beyond which water is in the form of ice, ~ 2.7 AU in the solar system). The time required for the core to accrete nearby materials and become isolated is on the order of (Ida & Lin 2004. Eq. (18))

$$\tau \approx 1.2 \times 10^5 \eta_{\rm ice}^{-1} f_{\rm d}^{-1} f_{\rm g}^{-2/5} \Big(\frac{a}{1\,{\rm AU}}\Big)^{27/10} \Big(\frac{M_{\rm iso}}{M_\oplus}\Big)^{1/3} \Big(\frac{M_*}{M_\odot}\Big)^{-1/6} {\rm yr}, \tag{6}$$

where $f_{\rm g}$ is the enhancement factor of the gas disk over MMSN. So for a typical disk with two times the MNSN ($f_{\rm d} = f_{\rm g} = 2$), isolation embryos inside the snow line are small ($< 1\,M_\oplus$), and they cannot develop. Embryos beyond the snow line can grow to $\sim 10\,M_\oplus$ so that they can accrete gas to form gas giants. However, the growth time of embryos with mass $10\,M_\oplus$ in distant orbits (> 20 AU) is long (~ 10 Myr at 10 AU and ~ 70 Myr at 20 AU). Within a disk with a moderate lifetime of ~ 3 Myr for classical T-Tauri stars (Haisch et al. 2001), embryos in distant orbits do not have enough time to accrete gas, thus they will stall their growth at the mass of a sub-giant, like Uranus and Neptune in the solar system.

As the gas disk is depleted, the induced secular resonance sweeps through the inner region of the planetary systems, causing further mergers of cores (Nagasawa et al. 2003). Terrestrial planets are formed after the gas disk was depleted at ~ 200 Myr (Chambers 2001). After the depletion of the gas disk, a debris disk with leftover cores interacts with giant plants, causing small scale migration, as in the Nice model (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005). Thus, assuming no giant migrations occurred, the solar system is the basic "standard" multiple planet system. As all planetary embryos were formed in the region near the mid-plane of the gas disk, without perturbations in the vertical direction, such a standard planet system is nearly coplanar, like many multiple planet systems observed by the Kepler mission.

However, several procedures make the above picture more complicated. One of the most difficult tasks is to understand the migration of embryos or planets embedded in the gas disk before depletion. For a sub-Earth protoplanet, the exchanges of AM between it and the nearby gas disk will cause a net momentum loss, which results in a so-called type I migration over a timescale on the order of < 0.1 Myr (Goldreich & Tremaine 1979; Ward 1986, 1997; Tanaka et al. 2002). If the protoplanet

can avoid such disastrous inward migration, and successfully grow massive enough to accrete gas and become a gas giant, the viscous evolution of the disk may cause the giant planet to undergo a type II migration, with a timescale of Myrs (Lin & Papaloizou 1986). Recent studies infer that, under more real conditions, the migration speeds of both types can be reduced or even, with their direction being reversed, lead to an even rarer outcome (see a recent review, Kley & Nelson 2012).

The evidence for planet migration is the observed systems in MMR. Since 2:1 MMR has the widest resonance width, especially for planetesimals in nearly circular orbits (Murray & Dermott 1999), many planet pairs are expected to show 2:1 MMRs if they had a history of convergent migration (e.g. Zhou 2010; Wang et al. 2012). However, Kepler data show many planets with their orbital conditions near but not in MMRs. This can be understood by the phenomenon that later stage planetesimal and planet interactions may cause further migrations but with smaller extensions, causing strict commensurability to be lost (Terquem & Papaloizou 2007). Giant planets in MMR might be strong enough and survive under such perturbations, like the GJ 876 system (Lee & Peale 2002). Hydrodynamical simulations show that different disk geometries might lead the planet pair to either convergent migration (thus possibly to the trap of different MMRs), or sometimes to divergent migrations (Zhang & Zhou 2010a,b). However, planet pairs may not necessarily lead to MMR configurations for some dynamical configurations (Batygin & Morbidelli 2012), e.g. the resonant repulsion of planet pairs is discussed by Lithwick & Wu (2012).

The orbital configurations of multiple planet systems incorporating planetary migration have been studied extensively by population syntheses (e.g., Ida & Lin 2008, 2010; Mordasini et al. 2009a,b) and N-body simulations (e.g., Thommes et al. 2008; Liu et al. 2011). Thommes et al. (2008) found that for giant planet formation, two timescales are crucial: the lifetime of the gas disk $\tau_{\rm disk}$ and the time to form the first gas giant $\tau_{\rm giant}$. In cases with $\tau_{\rm giant} > \tau_{\rm disk}$, the gas is removed before any gas giant has a chance to form, leaving behind systems consisting solely of rocky-icy bodies. In cases with $\tau_{\rm giant} < \tau_{\rm disk}$, such systems generally produced a number of gas giants that migrated inward a considerable distance. Liu et al. (2011) also showed that $\tau_{\rm disk}$ is crucial for forming planet systems, as large τ_{disk} tends to form more giant planets in close and nearly circular orbits, while small $\tau_{\rm disk}$ favors forming planets with small masses in distant and eccentric orbits.

According to the above theories as well as currently available observations, the planet systems around solar type stars can be roughly classified into the following categories. A detailed classification will be presented later (Zhou et al., in preparation).

(1) *Class I: Hot Jupiter systems*. These might be formed through some secular mechanisms such as Lidov-Kozai cycling, as discussed previously. Typical example: 51 Peg b.

(2) *Class II: Standard systems*. They are formed either through processes similar to our solar system, or by undergoing some large scale migrations, as mentioned perviously. According to whether the planets had a migration history, or whether the disks had sufficient heavy elements, they can be further classified as,

- *Subclass II-1: Solar-like systems.* These have planetary configurations similar to the solar system: terrestrial planets in the inner part, two–three gas giant planets in middle orbits, and Neptune-size sub-giants in outer orbits, due to insufficient gas accretion. Typical examples: Mu Arae, ups And and HD 125612 systems.
- *Subclass II-2: Hot super-Earth systems.* With the migration of giant planets, the sweeping of inward MMRs or secular resonances will trap the isolated masses ($0.1 - 1\,M_{\oplus}$) and excite their eccentricities, causing further mergers, which result in the formation of hot super Earths, like GJ 876d (Zhou et al. 2005; Raymond et al. 2006, 2008). Other formation scenarios, see a review of Haghighipour (2011). Typical examples: GJ 876 and Kepler-9 systems.
- *Subclass II-3: Sub-giant planet systems*. Due to the low disk mass or low metallicity, planet embryos around some stars (especially M dwarfs) might not grow massive enough to accrete

sufficient gas to become a gas giant, thus planets in these systems are generally sub-giants, like most of the systems discovered in Mayor et al. (2011). Typical example: the Kepler-11 system.

(3) *Class III: Distant giant systems*. Through direct imaging, a type of system was detected with many massive companions (up to several times the mass of Jupiter) in distant orbits, such as Fomalhaut b (Kalas et al. 2008), the HR 8799 system (Marois et al. 2008), and beta Pic b (Lagrange et al. 2009). Interestingly, all these stars have short ages ($\sim 100-300$ Myr). Whether the planets were formed in situ through gravitational instability (Boss 1997), or formed through outward migration or scattering, is still not clear. Typical examples: Fomalhaut, HR 8799 and beta Pic systems.

3 PLANETS IN BINARY STAR SYSTEMS

3.1 Overview of Observations

Planets in binaries are of particular interest as most stars are believed to be born not alone but in a group, e.g., binaries and multiple stellar systems. Currently, the multiplicity rate of solar like stars is $\sim 44\% - 46\%$, including $\sim 34\% - 38\%$ for only binaries (Duquennoy & Mayor 1991; Raghavan et al. 2010). Different resulting values of the multiplicity rate of planet-bearing stars (compared to all the planet hosts) were found to be 23% (Raghavan et al. 2006) and $\sim 17\%$ (Mugrauer & Neuhäuser 2009), and most recently $\sim 12\%$ (Roell et al. 2012). The decreasing multiplicity rate is mainly because of the quickly increasing number of transiting planets discovered in recent years. For example, Kepler has discovered more than 60 planets since 2010, however, follow up multiplicity studies on such planet hosts are usually postponed or even considered impracticable. In any case, the multiplicity rate of a planet host is significantly less than the multiplicity rate of stars. This may be because of selection biases in planet detection against binary systems and/or because of impacts of binarity on planet formation and evolution (Eggenberger et al. 2011).

Depending on the orbital configuration, planets in binaries are usually divided into two categories (Haghighipour et al. 2010), S type for planets orbiting around one of the stellar binary components, i.e., the circumprimary case, and P type for those orbiting around both the stellar binary components, i.e., the circumbinary case. Currently, most of them are S type, and only a few are found in P type, including NN Ser (Beuermann et al. 2010), HW Vir (Lee et al. 2009), DP Leo (Qian et al. 2010), HU Aqr (Qian et al. 2010; Hinse et al. 2012), UZ For (Dai et al. 2010; Potter et al. 2011), Kepler-16 (AB)b, Kepler-34 (AB)b, and Kepler-35 (AB)b (Doyle et al. 2011; Welsh et al. 2012). In the following, we will focus more on the former, and a binary system, hereafter refers to S type unless explicitly noted otherwise.

According to the most recent summary of observations (Roell et al. 2012), there are 57 S type planet-bearing binary systems [3], which, as a subsample of extra-solar planetary systems, may provide some significant statistics. Here we summarize several points worth noting.

(1) *Binary separation (or orbital semimajor axis, $a_{\rm B}$).* Most S type systems have an $a_{\rm B}$ larger than 100 AU. However, there seems to be a pileup at $a_{\rm B} \sim 20$ AU with four systems: γ Cephei (Hatzes et al. 2003), Gl 86 (Queloz et al. 2000), HD 41004 (Zucker et al. 2004), and HD 196885 (Correia et al. 2008; Chauvin et al. 2011). Planets are slightly less frequent in binaries with $a_{\rm B}$ between 35 and 100 AU (Eggenberger et al. 2011). No planet has been found in binaries with $a_{\rm B} < 10$ AU (excluding P type).

(2) *Planetary mass.* Planets in wide binaries ($a_{\rm B} > 100$ AU) have a mass range ($0.01 - 10 M_{\rm J}$) that is close to those in single star systems but is much more extended than those ($0.1 - 10 M_{\rm J}$) in close binaries ($a_{\rm B} < 100$ AU) (Roell et al. 2012).

[3] In fact, 10 of them are triple stellar systems, but with the third star being very far away and thus exerting less effects on the binaries with planets.

(3) *Planetary multiplicity*. Planets in close binaries ($a_{\rm B} < 100$ AU) are all singletons, while those in wide binaries are diverse (fig. 3 of Roell et al. (2012)). The occurrence rate of multiple planets in wide binaries is close to that in single star systems (Desidera & Barbieri 2007).
(4) *Planetary orbit*. Most extremely eccentric planets are found in wider binaries (e.g., $e = 0.935$ for HD 80606 b and $e = 0.925$ for HD 20782 b). The distribution of planetary eccentricity in binaries also seems to be different compared to those in single star systems (Kaib et al. 2012). Planetary orbital periods are slightly smaller in close binaries as compared to those in wide binaries and single star systems (Desidera & Barbieri 2007).

How are these planets formed with double suns? Are they behaving in a similar way as our solar system or other single star systems? In the following, we review some important effects on planet formation and evolution in a binary system as compared to those in a single star system, which may provide some clues to answer these questions.

3.2 Binary Effects on a Protoplanetary Disk

3.2.1 Disk truncation

Planets are considered to be born in a protoplanetary disk. Such a disk, in the solar system, could be extended to the location of the Kuiper belt, e.g., 30–50 AU from the Sun. But in a binary system, the disk could be severely truncated by the companion star. For the S type case, the typical radial size of a truncated disk is about $20\% - 40\%$ of the binary's separation distance, depending on the mass ratio and orbital eccentricity of the binary. For the P type case, the binary truncates the circumbinary disk by opening a gap in the inner region. The typical radial size of the gap is about two–five times the binary's separation. Various empirical formulas for estimating the boundary of the truncated disk are given by Artymowicz & Lubow (1994); Holman & Wiegert (1999); Pichardo et al. (2005)[4]. The size range of the truncated disk puts the first strict constraint on planet formation, determining where planets are allowed to reside and how much material is available for their formation. The reason why no S-type planet has been found in binaries with $a_{\rm B} < 10$ AU could be that the truncated protoplanetary disk was too small to have enough material for formation of a giant planet (Jang-Condell 2007).

3.2.2 Disk distortion

After the violent truncation process, the left-over, truncated disk is still subject to strong perturbations from the companion star, and thus it is not as dynamically quiet as disks around single stars. First, a binary in an eccentric orbit can also cause the disk to be eccentric (Paardekooper et al. 2008; Kley & Nelson 2008; Müller & Kley 2012). Second, if the binary orbital plane is misaligned with respect to the disk plane, then binary perturbations can cause the disk to become warped, twisted or even disrupted (Larwood et al. 1996; Fragner & Nelson 2010). Third, the eccentric, warped disk is precessing. All the above effects cause planet formation in binary systems to be more complicated than that in single star systems.

3.2.3 Disk lifetime

Estimating the lifetime of the protoplanetary disk is crucial as it provides a strong constraint on the timescale of planet formation. Observations of disks around single stars show that the typical disk lifetime is in the range 1–10 Myr (Haisch et al. 2001). Although disks around wide binaries show a similar lifetime, those in close binaries ($a_{\rm B} < 40$ AU) show evidence of shorter lifetime, i.e.,

[4] The boundaries given by Holman & Wiegert (1999) and Pichardo et al. (2005) are actually the boundaries of stable orbits of a test particle.

$\sim 0.1 - 1$ Myr (Cieza et al. 2009). Such results are not unexpected as disks in close binaries are truncated to a much smaller size and thus have much smaller timescales of viscous evolution. In any case, such a short disk lifetime requires that planets in close binaries (such as γ Cephei) should form quickly, probably on a timescale less than 1 Myr.

3.3 Binary Effects on Planet Formation

We consider planet formation based on the core accretion scenario (Lissauer 1993; Chambers 2004)[5], starting from planetesimals (usually having a radius on the scale of kilometers) embedded in a protoplanetary disk. This is the standard way that people consider planet formation in single star systems, though planetesimal formation itself is still unclear (Blum & Wurm 2008; Chiang & Youdin 2010). Nevertheless, some observational indications imply that the first stages of planet formation, i.e., dust settling and growing to planetesimals, could proceed in binaries as well as in single star systems (Pascucci et al. 2008).

3.3.1 Growing planetesimals

One straightforward way for growing planetesimals is via mutual collisions and mergers, as long as the collisional velocity $V_{\rm col}$ is low enough. For a protoplanetary disk around a single star system, if the disk turbulence is weak, e.g., in a dead zone, growth by mutual collisions could be efficient, and it is thought that planetesimals have undergone a runaway and oligarchic phase of growth to become planetary embryos or protoplanets (Kokubo & Ida 1996, 1998). However, the situation becomes less clear in binary systems. On one hand, the outcome of planetesimal-planetesimal collision is highly sensitive to $V_{\rm col}$ (Benz & Asphaug 1999; Stewart & Leinhardt 2009). On the other hand, perturbations from a close binary companion can excite planetesimal orbits and increase their mutual impact velocities, $V_{\rm col}$, to values that might exceed their escape velocities or even the critical velocities for the onset of eroding collisions (Heppenheimer 1978; Whitmire et al. 1998). This is a thorny problem for those binaries with separation of only ~ 20 AU, such as γ Cephei and HD 196885. Recently, many studies have been performed to address this issue.

An earlier investigation by Marzari & Scholl (2000) found that the combination of binary perturbations and local gas damping could force a strong orbital alignment between planetesimal orbits, which significantly reduced $V_{\rm col}$ despite relatively high planetesimal eccentricities. This mechanism was thought to solve the problem of planetesimal growth until Thébault et al. (2006) found the orbital alignment is size-dependent. Planetesimals of different sizes align their orbits to different orientations, thus $V_{\rm col}$ values between different sized planetesimals are still high enough to inhibit planetesimal growth (Thébault et al. 2008, 2009 for S-type, and Meschiari 2012 for P type). Moreover, the situation would become much more complicated (probably unfavorable) for planetesimal growth if the eccentricity, inclination and precession of the gas disk are also considered (Ciecielä G et al. 2007; Paardekooper et al. 2008; Marzari et al. 2009; Beaugé et al. 2010; Xie et al. 2011; Fragner et al. 2011; Batygin et al. 2011; Zhao et al. 2012). Nevertheless, the problem could be somewhat simplified if the effects of a dissipating gas disk are taken into account (Xie & Zhou 2008) and/or a smaller inclination ($i_{\rm B} < 10^\circ$) between the binary orbit and the plane of the protoplanetary disk is considered (Xie & Zhou 2009). Optimistically, planetesimals may undergo a delayed runaway growth mode (called Type II runaway) towards planets (Kortenkamp et al. 2001). In any case, however, it seems that planetesimal-planetesimal collision is not an efficient way for growing planetesimals in close binary systems.

An alternative way of growing planetesimals could be via accretion of dust that they pass through in the disk. Both analytical studies and simulations (Xie et al. 2010; Paardekooper & Leinhardt

[5] Gravitational instability is another candidate scenario for planet formation in binaries (see Mayer et al. (2010) for a review).

2010; Windmark et al. 2012) have shown this could be promising to solve the problem of growing planetesimals not only in binaries but also in single star systems (e.g., the well known "meter-barrier" puzzle). For an efficient dust accretion to occur, one needs, first, a source of dust, which could be either from the primordial protoplanetary disk or from fragmentation of planetesimal-planetesimal collisions, and second, weak disk turbulence to maintain a high volume density of dust (Johansen et al. 2008).

3.3.2 Formation of terrestrial and gaseous planets

Once planetesimals grow to 100–1000 km in radius (usually called planetary embryos or protoplanets), they are no longer as fragile as before. Their own gravity is strong enough to prevent them from fragmenting by mutual collisions. In such a case, most collisions lead to mergers and thus growth of planetesimals. Hence, one way to speed up growth is by increasing $V_{\rm col}$, which is readily available in a binary star system. For close binaries, such as α Centauri AB, simulations (Barbieri et al. 2002; Quintana 2004; Quintana & Lissauer 2006; Quintana et al. 2007; Guedes et al. 2008) have shown that habitable Earth-like planets could be formed in 10–100 Myr.

If a protoplanet reaches several Earth masses, the critical mass for triggering a runway gas accretion, before the gas disk is depleted, then it could accrete the surrounding gas to become a gaseous planet. Generally, planets would stop gas accretion after they have cleared all the surrounding gas and opened a gap. However, because of the binary perturbation, gas could be pushed inward to refill the gap and finally accreted by the planet (Kley 2001), leading to a higher gas accretion rate and more massive gaseous planets. Such an effect could partially explain one of the observed facts: gaseous planets in close binaries are slightly more massive than those in single star systems.

3.4 Binary Effects on Planetary Dynamical Evolution

3.4.1 With a gas disk

Due to the complication of the problem itself, the studies of this aspect mainly rely on numerical simulations. Kley & Nelson (2008) considered the evolution of a low mass planet (30 Earth masses) embedded in a gas disk of the γ Cephei system (S type). They found that the planet would rapidly migrate inward and accrete a large fraction of the disk's gas to become a gas giant planet, which is similar to the observed planet. For the circumbinary case, i.e., P type, simulations (Pierens & Nelson 2007, 2008a,b) showed the results were sensitive to planet mass. Low mass planets (tens of Earth masses) would successively migrate inward to the inner edge of the gas disk and subsequently merge, scatter, and/or lock into an MMR. A high mass planet ($>$ Jupiter mass) would enter a 4:1 resonance with the binary, which pumped up the eccentricity of the planet and probably led to instability. The model favoring the low mass planet from the simulation is consistent with the recent observation: the masses of the three confirmed circumbinary planets (Kepler-16b,-34b,-35b) are all $\leq$ Saturn's mass.

3.4.2 Without a gas disk

As the lifetime of the disk, typically ≤ 10 Myr, is only less than 1% that of a planet (typically on the order of Gyr), the subsequent gas free phase could dominate the evolution of planets after they have formed. In fact, several mechanisms are found to play an important role in shaping the final structure of planetary systems in binaries.

– *Planet-planet scattering*. Multiple planets could form in a protoplanetary disk, and because of damping from the gas disk, planets could maintain their near circular orbits and thus avoid close encounters. Once the gas disk dissipated, planet-planet interaction would excite the eccentric-

ities of planets, leading to close encounters and finally instability of the systems; e.g., merger and/or ejection. Such a mechanism (usually called PPS) is thought to explain the eccentricity distribution of observed giant planets (Ford & Rasio 2008; Nagasawa et al. 2008; Chatterjee et al. 2008). In a binary system, PPS would be more violent because of the additional perturbation from the binary stars (Malmberg et al. 2007a). In S type binaries (especially those with close separations and highly inclined and/or eccentric orbits), simulations (Marzari et al. 2005, Xie et al. in prep.) have shown that PPS often causes the system to finally have only a single planet, and the remaining planet is usually the most massive one. Such results may explain one observed fact: planets in close binaries are single and massive. In P type binaries, PPS again favors a single planet. In addition, it predicts a positive correlation between the planet's orbital semimajor axis and eccentricity (Gong et al. in prep.), which currently fit well to the three confirmed circumbinary planets (Kepler-16b,-34b,-35b). More P type planets detected in the future will further test this correlation.

– *Lidov-Kozai Effect*. In an S type binary, if a planet is on a highly inclined orbit[6], then it could undergo the Lidov-Kozai effect (Kozai 1962; Lidov 1962). One of the most striking features of the effect is that the planet's eccentricity could be pumped to a very high value and oscillate with its inclination out of phase. Recently, it has also been found that the planet could flip its orbit back and forth when its eccentricity approaches unity (Lithwick & Naoz 2011; Naoz et al. 2011a) if the binary orbit is eccentric, hence exhibiting the so called eccentric Lidov-Kozai effect. One application of this effect is that it could produce an HJ; when the planet oscillates to very high eccentricity, with a very small periastron, tides from the central star kick in and dampen its orbits to form a close planet (Wu & Murray 2003; Fabrycky & Tremaine 2007). Recently, there have been examples of such candidates showing evidence that they are on the way to being HJs via the Lidov-Kozai effect (Socrates et al. 2012; Dawson & Johnson 2012). In addition, as the planet could flip during the Lidov-Kozai evolution, there are significant chances to form an HJ in a retrograde orbit (Naoz et al. 2011a), which has been observed in some extrasolar systems (Triaud et al. 2010). Nevertheless, depending on specific conditions, e.g, if general relativistic effects and/or perturbation by another planet is relevant, the Lidov-Kozai effect can be suppressed (Takeda et al. 2008; Saleh & Rasio 2009).

3.5 Non-Primordial Scenario

There is another possibility that a currently observed planet-bearing binary was not the original one when the planet was born, namely the non-primordial scenario. Various mechanisms can lead to such a result, and we briefly summarize these two kinds as follows.

– *Encounters with other stars and/or planets.* A binary star system has a larger collisional cross section than a single star and thus a larger chance to have a close encounter with other stars, during which they could have their planets lost and/or exchanged (Pfahl 2005; Marti & Beauge 2012). In the end, the binaries probably dramatically changed their orbits, and the surviving planets were probably excited to highly eccentric and/or inclined orbits (Malmberg et al. 2007b; Spurzem et al. 2009; Malmberg et al. 2011). In addition, free floating planets (FFPs) could be recaptured by flyby binary stellar systems (Perets & Kouwenhoven 2012).
– *Steller Evolution.* If one of the binary component stars evolves away from the main sequence, it could induce instabilities in the planetary system in the binary. Planets could bounce back and be forced between the space around the two component binary stars (Kratter & Perets 2012). If a close binary star evolves to some phase to have mass transfer, the mass lost from the donor star could form a circumbinary disk, which could potentially harbor new planets (Perets 2010).

[6] This could be either primordial or induced by PPS.

4 PLANETS IN STAR CLUSTERS

Almost all the planets found now are around field stars. However the normal theory of star formation predicts that most field stars are formed from a molecular cloud, having the same initial mass function (IMF) as stars ($< 3\,M_{\odot}$) in an open cluster, indicating that these field stars initially formed in clusters, e.g. our solar system's initial birth environment was reviewed by Adams (2010). According to the chemical composition of our solar system, our Sun may have formed in an environment with thousands of stars, i.e. a star cluster or association. Thus scientists are very interested in focusing on planet detection in clusters which would be more effective than that around field stars due to many more objects existing in the same size of a telescope's field of view.

To survey planets around stars in a cluster, we have some advantages in obtaining more effective and credible results. Some correlations between planet occurrences as well as their properties and characteristics of their host stars are not very clear due to the bias of measurements for these field stars, such as age, mass, [Fe/H] etc. Large differences among these field stars, especially the type of environment in the early stage, is a problem for surveying the correlations. However, in one cluster, most of its members have homogeneous physical parameters, i.e. age and [Fe/H]. The comparative study of planets in clusters will provide more valid, credible correlations.

Unfortunately, except for some FFPs, few planets are found to be bounded around members of either globular clusters (GCs) or open clusters (OCs). The following sections will introduce the observational results and theoretical works in both GCs and OCs.

4.1 Planets in Globular Clusters

Because of the fruitful observation results of GCs and the huge number of stars in GCs, especially main sequence stars (MSSs), people naturally expect to find planets around these MSSs in GCs. As these stars are, on average about 50 times denser than field stars near the Sun, GCs have advantages for planet searching. For example, in the two brightest GCs: ω Cen and 47 Tuc, there are more than 60 000 MSSs, approximately half of the total number of Kepler targets. However, the extreme star density near the center of GCs (10^5 stars within a few arcmin) requires an extremely high precision of photometry. Until now, it has been hard to individually distinguish two nearby stars in the core of GCs. The stars in the outer region of GCs are more widely separated from each other, therefore they are more suitable for planet searches.

The first planet system was found in the nearest GC: M4. It was PSR B1620–26 b (Backer et al. 1993), a $2.5\,M_{\rm J}$ planet around a binary radio pulsar composed of a $1.35M_{\odot}$ pulsar and a $0.6\,M_{\odot}$ white dwarf. However, if we focus on sun-like stars in GCs, no planets have been confirmed until now.

To search for bounded planets around MSSs, some efforts have been made by several groups. As the brightest GCs in the sky, 47 Tucanae and ω Centauri are good targets for planet searching by transiting. Using HST to find planets in the core of 47 Tucanae, Gilliland et al. (2000) provided a null result. In the outer halo, the same result was obtained by Weldrake et al. (2005). Furthermore, Weldrake et al. (2007) found no bounded planets by transiting in both of the two clusters, under the precision of $P < 7$ day, $1.3 - 1.6\,R_{\rm J}$. The most recent work to find planets in the nearby globular cluster NGC 6397 is contributed by Nascimbeni et al. (2012), but still no highly-significant planetary candidates have been detected for early-M type cluster members.

Do the null results in GCs indicate the low occurrence of planets? For some dense star environments, the stability of planets is crucial. Although planets at 1 AU in the core of 47 Tuc can only survive around 10^8 yr in such a violent dynamical environment (Davies & Sigurdsson 2001), planets at 10 AU in the uncrowded halo of GCs can be preserved for several Gyrs (Bonnell et al. 2001). Therefore HJs with periods around a few days can survive much longer in the halo. If HJs formed near these cluster members, they have a chance to be detected in GCs (Fregeau et al. 2006).

The null results are mainly attributed to the low metallicity of these GCs. Fischer & Valenti (2005) surveyed planet systems not far from the Sun, and pointed out that the occurrence of gas giants depends on the metallicity of their host stars. The most recent work by Mortier et al. (2012) found a frequency of HJs $< 1\%$ around metal-poor stars, while the frequency of gas giants is $< 2.36\%$ around stars with [Fe/H] < -0.7. Both 47 Tuc and ω Cen have a low [Fe/H] (respectively -0.78 and < -1, from data collected by Harris (1996)). Hence, these two GCs contain few HJs. Higher frequencies of giant planets are expected in GCs with higher [Fe/H].

Additionally, different properties of a circumstellar gas disk, especially its structure, might influence the final architecture of planet systems, e.g. if the gas disk in GCs is depleted much faster due to Extreme-Ultraviolet (EUV) and Far-Ultraviolet (FUV) evaporation from nearby massive stars (Matsuyama et al. 2003), formation of gas giants may be unlikely, as well as the formation of a hot planet. The different structure of a gas disk might not force the planet to migrate inward enough to form hot planets, and naturally they are hard to detect using transits.

In these old GCs, mass segregation is obvious due to energy equipartition, i.e. massive objects concentrate in the center of the cluster while small objects are easily ejected outside. Energy equipartition results in FFPs, which might be ejected to become unbound by some mechanisms (Parker & Quanz 2012; Veras & Raymond 2012) and have a lower mass than stars. It is hard for FFPs to stay in old GCs.

4.2 Planets in Open Clusters and Associations

None of the planets around solar-like stars are found in GCs, because of the reasons mentioned before. OCs and associations, which still contain lots of MSSs, are also useful for planet searching. The main dissimilarities between OCs and GCs are the following:

(1) *Cluster ages*. OCs and associations are much younger than GCs, and have a much larger [Fe/H], probably leading to more planets being formed around the cluster members.
(2) *The dynamical environments*. The dynamical environment in OCs and associations is still less violent than that in GCs because of lower star density, which can preserve the two-body systems more easily than in GCs.
(3) *Binary fraction*. The much larger fraction of binary systems in OCs than GCs is a good way to understand the formation of planet systems in binary stars.

Additionally, many more OCs and associations (~ 1200) are observed than GCs (~ 160) in our galaxy. Due to these dissimilarities, a higher probability of planet detection is expected.

As for the different properties of OCs, surveyed planets in OCs have their own values. Some OCs are only a few Myr old, e.g. NGC 6611 (Bonatto et al. 2006) and NGC 2244 (Bonatto & Bica 2009). Their ages are comparable with the timescale of planet formation. Surveying planets and circumstellar disks in these very young clusters will provide valuable samples to check and enhance the current theories of planet formation, particularly the influences via different environments, in clusters during the early stages of planet formation.

4.2.1 Bounded planets and debris disks

Many groups have made efforts to search for planets by transits in OCs: e.g. Bruntt et al. (2003) in NGC 6791, Bramich et al. (2005) in NGC 7789, Rosvick & Robb (2006) in NGC 7086, Mochejska et al. (2006) in NGC 2158, etc. Only few candidates were found but none were confirmed. The most significant progresses were made in 2007. In NGC 2423, a gas giant with a minimum mass of $10.6\,M_{\rm J}$ around a $2.4\,M_{\odot}$ red giant was found by Lovis & Mayor (2007) using RV. Another planet was found soon afterwards by RV around the giant star ϵ Tauri (Sato et al. 2007) in the Hyades, the nearest OC, with a minimum mass of $\sim 7.6\,M_{\rm J}$ and a period of ~ 595 days. Using transiting, some

Table 1 Parameters of the planets and their host stars in OCs, as well as their host cluster. Data are from Lovis & Mayor (2007); Sato et al. (2007); Harris (1996); Quinn et al. (2012)

$M_{\rm p}\sin i$ ($M_{\rm J}$)	Period (d)	Semi-major axis (AU)	ecc	$M_{\rm star}$ ($M_{\odot}$)	Host cluster	Age (Gyr)	[Fe/H]	Dist (pc)
10.6	714.3	2.1	0.21	2.4	NGC 2423	0.74	0.14	766
7.6	594.9	1.93	0.15	2.7	Hyades	0.6	0.19	47
0.54	4.42	0.09	0	1.23	Praesepe	0.578	0.187	177
1.84	2.14	0.04	0	0.95	Praesepe	0.578	0.187	177

smaller candidates have also been found without RV confirmation, e.g. a single transit of a candidate $\sim 1.81\,M_{\rm J}$ in NGC 7789 found by Bramich et al. (2005), which may indicate another exoplanet with a long period. Most recent work by Quinn et al. (2012) claims that they found two HJs by RV: Pr0201b and Pr0211b in Praesepe. These planets are the first known HJs in OCs. Parameters describing these planets are listed in Table 1 as well as properties of their host cluster.

Compared with the null results in GCs, the encouraging results of planet searching in OCs confirm the formation and survival ability of planets in a cluster environment, especially observations of the circumstellar disk in young OCs, which is related to the occurrence of planet formation.

Haisch et al. (2001) showed the fraction of disks in OCs decayed with their ages. Some recent results verify this correlation: $30\% - 35\%$ of T-Tauri stars have a disk in the σ Orionis cluster with ages ~ 3 Myr (Hernández et al. 2007). Using the Chandra X-ray Observatory, Wang et al. (2011) found a K-excess disk frequency of $3.8 \pm 0.7\%$ in the $5 \sim 10$ Myr old cluster: Trumpler 15.

Although the disk structures around cluster members are not well known, the large fraction of gas disks in very young OCs makes the formation of planets possible, especially for gas giants. The first two confirmed planets found were not HJs, but another two planets found most recently are HJs. However, lack of more samples is a big problem in making a credible conclusion and surveying the statistical characteristics of planet formation and evolution in OCs.

4.2.2 Free-floating planets

Ages, metallicity and star density are the main dissimilarities between OCs and GCs. The formation of planets in OCs is thought to be common, but few planets bounded around stars have been observed. However, a population of FFPs has been found in OCs. In 2000, Lucas & Roche (2000) found a population of FFPs in Orion. Bihain et al. (2009) also found three additional FFPs with $4-6\,M_{\rm J}$ in the ~ 3 Myr old OC σ Orionis. A huge number (nearly twice the number around MSSs) of unbounded planets have been found in the direction of the Galactic Bulge (Sumi et al. 2011).

These planets have multiple origins. One of them is that they may form around some cluster members, but were ejected out of the original systems and cruise into clusters (Sumi et al. 2011). Because of their young ages, energy equipartition in OCs is less effective than that in GCs. The dissolution timescale for objects to escape from a cluster is $t_{\rm dis} \sim 2\,{\rm Myr} \times \frac{N}{\ln(0.4N)} \times \frac{R_{\rm G}}{\rm kpc}$ (Baumgardt & Makino 2003). For a typical OC, with $N = 1000$ stars at distance $R_{\rm G} = 1\,$kpc, $t_{\rm dis} \sim 0.1\,$Gyr and therefore FFPs can still stay in their host clusters for most young OCs. It is hard to find the original host stars of these FFPs, but surveying them is still useful for evaluating the frequency of planet formation in OCs and GCs.

4.3 Planetary systems in clusters: theoretic work

The planet occurrent rate, including formation rate and stability related with the cluster environment, is very important for predicting the rate of further observations. From their respective dynamics, the

large distinctions between OCs and GCs generally predict more planets in OCs and HJs in halos of GCs.

Dynamical works focus on the stability and orbital architecture of planetary systems in a cluster. Considering a fly-by event, the previous works show the stability of planet systems depends on the bounded energy of planetary systems, fly-by parameters as well as the star density of the environment, which decides the occurrent rate of a fly-by event ($t_{\rm enc} \propto 1/n$, Binney & Tremaine 1987). Spurzem et al. (2009) used a strict N-body simulation as well as a Monte Carlo method to survey the dynamical characteristics, especially the effective cross section of planetary systems with different orbital elements in a cluster's gravity field. Adding substructure of a young OC by Parker & Quanz (2012), the fraction of liberated planets depends on the initial semi-major axis and virial parameter. The planet systems in binary systems were also be surveyed by Malmberg et al. (2007a,b); Malmberg & Davies (2009). They considered encounters between a binary system and a single star. After obvious changes of the inclination, a fraction of planets will suffer the Kozai effect after encounters and consequently show instabilities.

The stability and orbital architecture of multi-planet systems in clusters still need to be surveyed in further works, because planet-planet interactions play an important role in deciding the final configuration of a planet system after fly-bys. The dynamical evolution in clusters is much more complex than in a single fly-by. In some very open clusters, the tidal effect can also disrupt planet systems in the outer region. The effect of interstellar gas in very young OCs is still uncertain. The fine structure of the circumstellar disks still needs to be investigated during the formation of planet systems.

Planet formation in star clusters must have a strong dependence on the physical and dynamical environments of their host stars. The environments in clusters are very different from that around field stars, or binary pairs, e.g. the different properties of the circumstellar disk, dynamical instabilities in different stages during planet formation, as well as the stability of a planetary system after the planets were formed. The protoplanetary gas disk plays a very important role in the formation of gas giant planets. A comparison between the timescale of gas disk dispersion and that of gas giant formation is a crucial clue to judge the formation rate of giant planets. On the other hand, the observation of circumstellar disks and giant planets (including FFPs) in some very young OCs can also give a limit on the rate that a planetary gas disk is preserved, which is related to the planet formation rate in a cluster environment. The distinctions in the different environments for OCs and small bounded planet samples in OCs have limited our knowledge about the formation of planets in clusters.

5 CONCLUSIONS

With the increasing data of observed exoplanets, the study of orbital architectures for multiple planet systems becomes timely. Unlike the relatively mature theory for formation of a single planet (except for some bottleneck problems), the properties of planet's architecture are relatively far from clear. Dynamical factors, such as interactions among planets, tidal interactions with the host star and protostellar disk, or in some cases perturbations from a third companion (a star or brown dwarf), etc., tend to affect the orbital evolution and sculpt the final architectures of the planet systems.

According to our present knowledge, we tentatively classify the planet systems around single stars into three major catalogs: HJ systems, standard systems and distant giant planet systems. The standard systems can be further categorized into three sub-types under different circumstances: solar-like systems, hot super-Earth systems and sub-giant planet systems. The classification is based on the major process that occurred in their history. It may help to predict unseen planets, as well as to understand the possible composition of planets, since through the history of their evolution, we can judge whether large orbital mixing has occurred.

Due to the presence of a third companion, planet formation in a binary environment has raised some more challenging problems, especially for the stage of planetesimal formation. Anyway, the

observed exoplanets around binary stars, especially the circumbinary exoplanets like Kepler-34b and 35b, indicate that planet formation is a robust procedure around solar type stars.

Planets in clusters will provide a useful clue for understanding the formation of planets in a cluster environment. Although only very limited observational results have been obtained, theories can still predict some properties of exoplanets in clusters. Planet samples in some young OCs might be especially interesting for revealing the difference between planet formation around field stars and members of clusters.

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