

Chapter 2

Evolution History of Extrasolar Planetary Systems

Abstract In this chapter, we review the basics on the detection and characterization of exoplanetary systems. We first focus on the two leading techniques (the radial velocity and transit methods), deriving the basic quantities that can be extracted from observations with each technique. We then see the distributions of planetary parameters, and introduce various “planetary migrations” in order to account for the presence of close-in giant planets. Finally, we describe the measurements of the Rossiter-McLaughlin (RM) effect for probing the angle between the host star’s spin axis and planetary orbital axis. We show that measurements of the RM effect are an important key to confirm or refute the theoretical models regarding the planetary migrations. A summary and the current status of RM measurements are presented together with possible mechanisms to explain the observed distribution of the spin-orbit angle.

Keywords Hot Jupiters · Radial velocity · Transits · Planetary migration

2.1 Detection and Orbital Diversity of Exoplanets

According to “the Extrasolar Planet Encyclopedia”,¹ 941 planets have been discovered as of August, 2013. Most of them were detected by the radial velocity (RV) technique, which measures Doppler-shifts of the central star due to gravitational pull by planetary companion(s). Another leading technique to detect exoplanets is the transit method. This method simply finds a periodic flux decrease of a star when an exoplanet passes in front of it. It has recently become feasible to hunt planets by “direct imaging” and “microlensing”. The latter detects a weak signal of gravitational lensing of the light from a background star when a lensing object accompanied by planetary companion(s) changes the light path. These methods (direct imaging

¹ <http://exoplanet.eu/catalog/>.

and microlensing) are complementary to the RV and transit methods; while RV and transit methods are sensitive to close-in planets with edge-on orbits (the orbital axis is perpendicular to the line-of-sight), direct imaging and microlensing methods both have higher sensitivities to planets with distant, face-on orbits.

In this section, we review the RV and transit methods and present a set of basic equations and quantities that we can extract from observations of RVs (Sect. 2.1.1) and transits (Sect. 2.1.2). These basic equations and notations will be used throughout this thesis. Below we do not describe the details of planet-huntings using direct imaging or microlensing since there have been many good reviews on these techniques (e.g., [7, 17]) and we do not refer to these methods in the rest of the present thesis. We also show the distributions of the variety of physical quantities for the discovered exoplanets (e.g., mass, semi-major axis, and eccentricity) and their implications to formation and evolution of planetary systems in Sect. 2.1.3.

2.1.1 Radial Velocity Method

The RV method has been the most successful and productive technique to discover exoplanets. Thanks to the great progress in both high dispersion spectroscopy (hardware) and RV analysis pipeline (software), leading spectrographs (e.g., ESO/HARPS and Keck/HIRES) are now able to achieve the RV precision of $\lesssim 1 \text{ m s}^{-1}$, and as of July 2013, approximately 500 planets have been discovered by the RV technique. The set of information that we can learn from such precise RV measurements includes the mass (lower limit), eccentricity, and argument of periastron of the planet. In what follows, we show several equations that describe the orbital motion of the system and its relation to the observed quantities (RVs). We basically follow the formulation by Murray and Correia [12].

The goal here is to derive the expression for RV variations as a function of time t and show the quantities that can be extracted from RV observation. Figure 2.1 shows the stellar orbit around the center-of-mass at the origin. In this figure, the Z -axis is along the line-of-sight and pointing toward the observer and the X -axis is along a reference direction (arbitrary). The orbital plane of the star, denoted by the blue ellipse, is inclined by I_o (orbital inclination) with respect to the X - Y plane (sky plane) and both the planet and its host star are known to orbit the center-of-mass with the same orbital period P and eccentricity e . From the definition of the center-of-mass, when the star is located at $\mathbf{R}_\star$, the position of the planet $\mathbf{R}_p$ is

$$\mathbf{R}_p = -\frac{M_\star}{M_p} \mathbf{R}_\star, \quad (2.1)$$

where $M_\star$ and M_p are the stellar and planet masses, respectively.

The angle Ω is defined as the angle between this reference direction and “line of nodes” (which is along the intersection between the X - Y plane and orbital plane). The argument of periastron (the angle between the stellar periastron and line of node) and

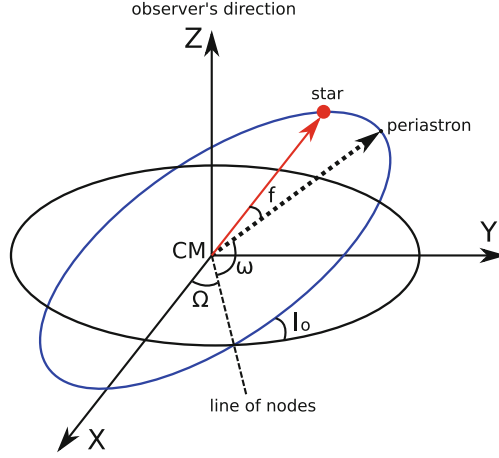


Fig. 2.1 Definition of the angles in a planet-star system. The origin is set at the center-of-mass (CM). The Z-axis points toward the observer and the X-Y plane is the sky plane. Figure based on Murray and Correia [12]

true anomaly (the argument of star in its orbital plane measured from the periastron) are denoted by ω_* and f , respectively. Using these quantities, the position of the star $\mathbf{R}_*$ in this coordinate is computed as

$$\mathbf{R}_* = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = r_* \begin{pmatrix} \cos \Omega \cos(\omega_* + f_*) - \sin \Omega \sin(\omega_* + f_*) \cos I_o \\ \sin \Omega \cos(\omega_* + f_*) + \cos \Omega \sin(\omega_* + f_*) \cos I_o \\ \sin(\omega_* + f_*) \sin I_o \end{pmatrix}, \quad (2.2)$$

where r_* is the distance between the center-of-mass and the star. Since the stellar orbit is expressed by an ellipse with the center-of-mass being its focal point, r_* is associated with the true anomaly f_* by

$$r_* = \frac{a_*(1 - e^2)}{1 + e \cos f_*}, \quad (2.3)$$

where a_* is the semi-major axis of the star around the center-of-mass. The conventional semi-major axis a , which is defined from Kepler's third law via

$$P^2 = \frac{4\pi^2}{G(M_* + M_p)} a^3. \quad (2.4)$$

Through Eq. (2.1), a can be easily translated into a_* as

$$a_* = \frac{M_p}{M_* + M_p} a. \quad (2.5)$$

Given these quantities, the relative velocity of the star along the line-of-sight (RV) is computed as the time derivative of Z in Eq. (2.2)

$$\dot{Z} = \dot{r}_\star \sin(\omega_\star + f_\star) \sin I_o + r_\star \dot{f}_\star \cos(\omega_\star + f_\star) \sin I_o. \quad (2.6)$$

To proceed further, we differentiate Eq. (2.3) with respect to time t :

$$\dot{r}_\star = \frac{r_\star \dot{f}_\star e \sin f_\star}{1 + e \cos f_\star}, \quad (2.7)$$

and the conservation of angular momentum around the center-of-mass gives

$$r_\star^2 \dot{f}_\star = n a_\star^2 \sqrt{1 - e^2}, \quad (2.8)$$

where $n \equiv 2\pi/P$ is “the mean motion”. Substituting Eqs. (2.3), (2.7), and (2.8) into Eq. (2.6) with some algebra, we obtain the following expression for the relative RV of the star V_r :

$$\begin{aligned} V_r \equiv -\dot{Z} &= -\frac{n a_\star \sin I_o}{\sqrt{1 - e^2}} (\cos(\omega_\star + f_\star) + e \cos \omega_\star) \\ &= -\frac{M_p}{M_\star + M_p} \frac{n a \sin I_o}{\sqrt{1 - e^2}} (\cos(\omega_\star + f_\star) + e \cos \omega_\star). \end{aligned} \quad (2.9)$$

Defining the RV “semi-amplitude” K as $(V_{r,\max} - V_{r,\min})/2$, the above expression is rewritten as

$$\begin{aligned} V_r &= -K (\cos(\omega_\star + f_\star) + e \cos \omega_\star), \\ &= K (\cos(\omega + f) + e \cos \omega), \end{aligned} \quad (2.10)$$

where $\omega = \omega_\star + \pi$ and $f = f_\star$ are the argument of periastron and true anomaly of the “planet”, and

$$\begin{aligned} K &= \frac{M_p}{M_\star + M_p} \frac{n a \sin I_o}{\sqrt{1 - e^2}} \\ &= \sqrt{\frac{G}{a(1 - e^2)}} \frac{M_p \sin I_o}{\sqrt{M_\star + M_p}} \\ &= \frac{M_p \sin I_o}{\sqrt{1 - e^2}} \left\{ \frac{2\pi G}{P(M_\star + M_p)^2} \right\}^{1/3}. \end{aligned} \quad (2.11)$$

Note that we have used Eq. (2.4) for the last derivation. Also, we should keep in mind that the quantity V_r is the relative RV around the center-of-mass of the system. The center-of-mass in general has a constant velocity seen from our direction (peculiar velocity) in the absence of outer bodies that perturb the two-body system. In real RV

measurements, the peculiar velocity appears as a constant offset in observed RVs that needs to be optimized, but is usually unimportant as long as we are interested in the orbital elements of the system.

Equation (2.10) is the observed RV as a function f . The true anomaly f is related to time t through the eccentric anomaly E by

$$\frac{2\pi}{P}(t - T_0) = E - e \sin E \quad (2.12)$$

$$\tan \frac{f}{2} = \sqrt{\frac{1+e}{1-e}} \tan \frac{E}{2}, \quad (2.13)$$

where T_0 is the time of planet's periastron passage. Equation (2.12) is so-called "Kepler's equation" and its solution has been discussed in literatures (e.g., [4]).

Equations (2.10)–(2.13) are the set of equations that we need to solve from the observed RV V_r as a function of time t ; observed RVs are fitted with three free parameters K , e , and ω , and the projected mass of the planet is estimated via Eq. (2.11). In many cases, the mass ratio of planet to its host star is sufficiently small ($\sim 10^{-3}$). Then the projected mass of the planet is well approximated as

$$M_p \sin I_o \simeq \left(\frac{P}{2\pi G} \right)^{1/3} K M_\star^{2/3} \sqrt{1 - e^2}. \quad (2.14)$$

Note that the mass of the star, which is the only unknown parameter in the above equations, is usually estimated from spectroscopy based on some isochrone model (e.g., [22]).

2.1.2 Transit Method

Observations of planetary transits provide us invaluable information on the internal structure, surface environment, and evolution history of exoplanets. Thanks to many dedicated surveys, 288 transiting planets have been confirmed as of August 2013, and more than 2000 planet candidates are alleged to have been detected by the *Kepler* mission. The recent rapid progress in transit observations has also enabled the discovery of many super-Earths, and their characterization is now an interesting field in the exoplanetary science.

As we have noted, RV measurements are a very powerful tool to estimate their projected masses ($M_p \sin I_o$) and verify the presence of exoplanets. However, true (non-projected) masses are usually not available with RV measurements alone, and statistical treatments are required in order to discuss the mass distribution and orbital evolution of the system. On the other hand, what we can learn from a transit involves the radius (R_p), orbital inclination (I_o), and hence the true mass (M_p) and mean density of the planet.

If we combine transit observations with spectroscopy, we can learn more about the formation and evolution history of exoplanets. For instance, a high resolution spectroscopy during a transit tells us about the atmospheric composition of the planet surface. This is because during a transit, the light emitted from the central star is partially absorbed by the outer atmosphere of the transiting planet, and hence an additional absorption should be imprinted in the spectral lines. This technique to probe the planetary atmosphere is called “transmission spectroscopy”. Also, during a transit the measured RV must show an anomaly due to the Rossiter-McLaughlin effect, which is caused by a partial occultation of the rotating stellar surface. We describe this phenomenon in detail in Sect. 2.3. But before combining the RV technique with transit observations, we present the basics in transit photometry for the rest of this subsection, following Winn [19].

In Sect. 2.1.1, we have derived the expression for observed RVs as a function of time. We set the origin at the center-of-mass, since what we can observe is the relative RVs of the star around the center-of-mass. For the case of planetary transits, however, the relative location of planet with respect to star’s center is more important and intuitive in describing transit light-curves. Making use of Eqs. (2.1) and (2.2), the position of planet relative to the host star is

$$\begin{aligned}
 \mathbf{R}_p - \mathbf{R}_\star &= -\frac{M_\star + M_p}{M_p} \mathbf{R}_\star \\
 &= -r \begin{pmatrix} \cos \Omega \cos(\omega_\star + f_\star) - \sin \Omega \sin(\omega_\star + f_\star) \cos I_o \\ \sin \Omega \cos(\omega_\star + f_\star) + \cos \Omega \sin(\omega_\star + f_\star) \cos I_o \\ \sin(\omega_\star + f_\star) \sin I_o \end{pmatrix}, \\
 &= r \begin{pmatrix} \cos \Omega \cos(\omega + f) - \sin \Omega \sin(\omega + f) \cos I_o \\ \sin \Omega \cos(\omega + f) + \cos \Omega \sin(\omega + f) \cos I_o \\ \sin(\omega + f) \sin I_o \end{pmatrix}, \quad (2.15)
 \end{aligned}$$

where

$$r = \frac{M_\star + M_p}{M_p} r_\star = \frac{a(1 - e^2)}{1 + e \cos f} \quad (2.16)$$

is the distance between the star and planet. Since the X -axis is an arbitrary reference direction and the actual direction in the sky plane (e.g., RA and Dec) is usually not so important in discussing planetary transits, we set $\Omega = \pi$. Then, Eq. (2.15) reduces to

$$\mathbf{R}_p - \mathbf{R}_\star \equiv \begin{pmatrix} X_{\text{rel}} \\ Y_{\text{rel}} \\ Z_{\text{rel}} \end{pmatrix} = r \begin{pmatrix} -\cos(\omega + f) \\ -\sin(\omega + f) \cos I_o \\ \sin(\omega + f) \sin I_o \end{pmatrix}. \quad (2.17)$$

In this case, the distance between the planet and star in the sky plane r_{sky} is written as

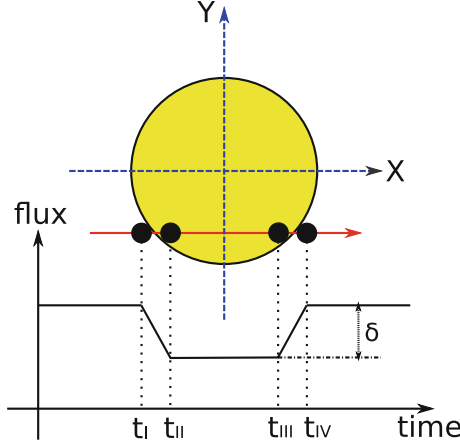


Fig. 2.2 Schematic illustration of a planetary transit. The planetary orbit is shown by the *red arrow*. Figure based on Winn [19]

$$r_{\text{sky}} \equiv \sqrt{X_{\text{rel}}^2 + Y_{\text{rel}}^2} = \frac{a(1 - e^2)}{1 + e \cos f} \sqrt{1 - \sin^2(\omega + f) \sin^2 I_o}. \quad (2.18)$$

The inferior and superior conjunctions are defined by the condition $X_{\text{rel}} = 0$, which is translated as

$$f = +\frac{\pi}{2} - \omega \quad (\text{inferior}) \quad (2.19)$$

$$f = -\frac{\pi}{2} - \omega \quad (\text{superior}). \quad (2.20)$$

Except for very eccentric, close-in orbits, the inferior (superior) conjunction corresponds to almost the center of transit (secondary eclipse), where r_{sky} takes its minimum. The impact parameter b of transit is defined as the star-planet distance in the sky plane at the inferior conjunction normalized by the stellar radius $R_{\star}$:

$$b = \frac{a \cos I_o}{R_{\star}} \left(\frac{1 - e^2}{1 + e \sin \omega} \right). \quad (2.21)$$

Next, we move on to the quantities that can be extracted from a transit observation. Figure 2.2 shows the schematic illustration of a planetary transit, where the impact of stellar limb-darkening is neglected in the light-curve. We show the first to fourth contacts of transit, whose times are denoted by t_I , t_{II} , t_{III} , and t_{IV} , respectively. The total duration is usually referred to as $T_{\text{tot}} \equiv t_{IV} - t_I$, and the full duration is also defined by $T_{\text{full}} \equiv t_{III} - t_{II}$. The transit depth δ is equivalent to $(R_p/R_{\star})^2$ in the absence of stellar limb-darkening and thermal emission from the planet's nightside.

Using the conservation of angular momentum of the planet around the central star:

$$r^2 \dot{f} = \frac{2\pi}{P} a^2 \sqrt{1 - e^2}, \quad (2.22)$$

the total and full durations are respectively expressed as

$$T_{\text{tot}} \equiv t_{\text{IV}} - t_{\text{I}} = \frac{P}{2\pi\sqrt{1 - e^2}} \int_{f_{\text{I}}}^{f_{\text{IV}}} \left[\frac{r(f)}{a} \right]^2 df \quad (2.23)$$

$$T_{\text{full}} \equiv t_{\text{III}} - t_{\text{II}} = \frac{P}{2\pi\sqrt{1 - e^2}} \int_{f_{\text{II}}}^{f_{\text{III}}} \left[\frac{r(f)}{a} \right]^2 df. \quad (2.24)$$

In the case of a circular orbit ($e = 0$), the above equations reduce to

$$T_{\text{tot}} = \frac{P}{\pi} \sin^{-1} \left[\frac{\sqrt{(1 + k)^2 (R_{\star}/a)^2 - \cos^2 I_o}}{\sin I_o} \right], \quad (2.25)$$

$$T_{\text{full}} = \frac{P}{\pi} \sin^{-1} \left[\frac{\sqrt{(1 - k)^2 (R_{\star}/a)^2 - \cos^2 I_o}}{\sin I_o} \right], \quad (2.26)$$

where $k \equiv R_p/R_{\star}$ is the planet-to-star radius ratio, which is estimated from the transit depth. Even for an eccentric orbit, it has been shown that multiplying the above expressions by the following factor τ gives good approximations for T_{total} and T_{full} :

$$\tau = \frac{\sqrt{1 - e^2}}{1 + e \sin \omega}. \quad (2.27)$$

Equations (2.25)–(2.27) imply that an observation of a planetary transit gives the orbital inclination I_o as well as the semi-major axis a normalized by the stellar radius $R_{\star}$.

$$b^2 \approx \frac{(1 - k)^2 - (T_{\text{full}}/T_{\text{tot}})^2(1 + k)^2}{1 - (T_{\text{full}}/T_{\text{tot}})^2} \quad (2.28)$$

$$\frac{R_{\star}}{a} \approx \frac{\pi}{2\sqrt{k}} \frac{\sqrt{T_{\text{tot}}^2 - T_{\text{full}}^2}}{P} \left(\frac{1 + e \cos \omega}{\sqrt{1 - e^2}} \right). \quad (2.29)$$

In summary, an analysis of a transit light-curve lets us learn the important orbital and planetary parameters: planet-to-star size ratio k , semi-major axis in unit of stellar radius $a/R_{\star}$, and orbital inclination I_o . Considering that we can measure the projected planet mass $M_p \sin I_o$ as well as the orbital eccentricity e , and argument of periastron ω from RV measurements, we obtain the real mass M_p from the combination of the two methods. The relative size of planet radius k is converted to the real planetary radius R_p given the stellar radius usually estimated from spectroscopy. Therefore,

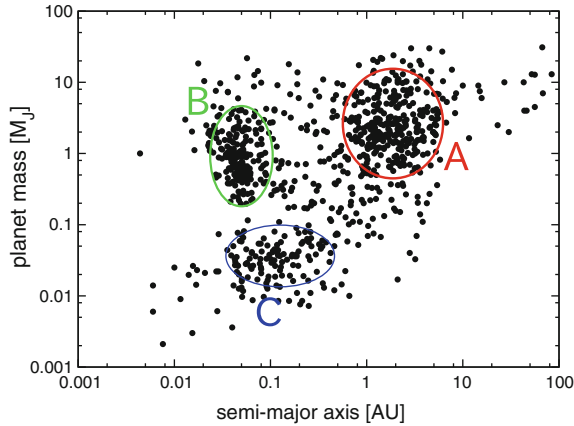


Fig. 2.3 Correlation diagram between semi-major axis and mass for the planets detected by the RV, transit, microlensing, and direct imaging techniques (as of 2013 August). Figure based on the data at <http://exoplanet.eu/catalog/>

all of these quantities combined, the mean density of planet can be inferred, which enables us to discuss the internal structure and composition of the planet.

2.1.3 Correlations of Planetary Parameters

It is well known that those planets discovered by the above-described techniques have diverse distributions in terms of their orbits, and internal parameters such as masses and radii. Here, we describe diverse distributions of planetary parameters.

First, we describe on the planetary mass. Figure 2.3 plots the correlation diagram between the planet mass and semi-major axis. From this diagram, the distribution of planets is basically divided into three categories. The first category “A”, which is surrounded by the red ellipse, indicates jovian planets located beyond ~ 1 AU. The presence of these planets is consistent with the standard planet formation scenario that jovian planets form beyond the “snow line” that determines the boundary between liquid water and solid water (ice) in the proto-planetary disk. On the other hand, we also see many giant planets in the proximity of central stars whose semi-major axes are less than 0.1 AU (category “B” in green). The origin of these close-in giants (hot Jupiters or hot Neptunes) has been an enduring problem since the discovery of the first exoplanet 51 Pegasi b [11]. We revisit this issue in the next section. Note that the paucity of planets between the categories “A” and “B” should be real, since the observation bias (both in RV and transit techniques) always reduces the number of outer planets, which have been abundantly detected beyond ~ 1 AU.

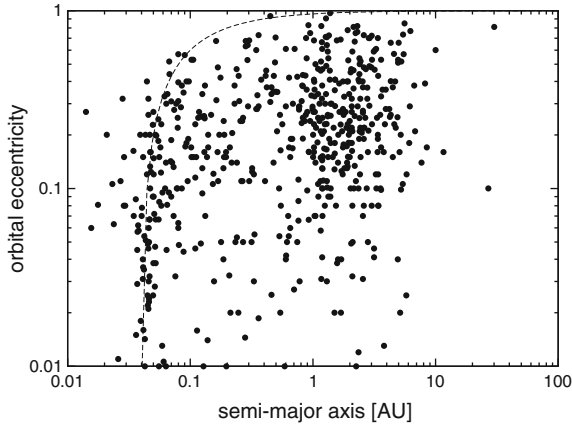


Fig. 2.4 Correlation diagram between semi-major axis and eccentricity (as of 2013 August). The dashed line represents the constant pericenter distance ($a(1 - e) = 0.04$ AU). Figure based on the data at <http://exoplanet.eu/catalog/>

The recent improvements in the RV and transit techniques have enabled the detection of less massive exoplanets including “super-Earths”.² The category “C” in Fig. 2.3 (blue ellipse) represents the population of such smaller planets with a wide range of semi-major axis. While this population only extends up to ~ 1 AU due to the limitation of the observational precision, the lack of planets between the categories “B” and “C” is also clear. This may suggest different formation channels for jovian and other smaller planets. The origin and internal (surface) structure of super-Earths are still under debate but would be an interesting topic in the next decade.

Another remarkable feature of exoplanets is the orbital eccentricity. In our solar system, all the planets except Mercury have small eccentricities ($e < 0.1$), which suggests that the solar system has evolved quiescently since the formation of proto-planets in the disk. Meanwhile, as we plot in Fig. 2.4, the orbital eccentricities of exoplanets exhibit a broad distribution. Exoplanets with eccentricities higher than 0.1 are called “eccentric planets”. Specifically, outer jovian planets ($a \gtrsim 1.0$ AU) are mostly eccentric planets with e up to unity. This is also a remarkable difference from our solar system.

It should be emphasized that, as opposed to outer jovian planets, most of close-in planets have smaller orbital eccentricities. In particular, most of the planets orbiting at $a \lesssim 0.05$ AU have small eccentricities ($e < 0.1$). This clear trend strongly implies the damping of eccentricities due to tidal force from the central stars. Indeed, as we show by the dashed line in Fig. 2.4, many close-in exoplanets have been discovered along the line with a constant pericenter distance, suggesting the presence of a tidal interaction between the star and planet. As we describe in the next section,

² There has been no clear definition of “super-Earth” but it is usually referred to the planets with mass ranging between $\sim 1 - 10M_{\oplus}$.

a tidal interaction between the host star and highly eccentric planet leads to energy dissipation around the periastron, and consequently damps the orbital eccentricity and semi-major axis while keeping the periastron distance constant.

2.2 Planetary Migration Scenarios

According to the standard planetary formation scenario, giant planets can only form beyond the snow line (a few AU away from the central (Sun-like) star), where the planets can collect abundant solid materials (e.g., ice) to grow up into giant planets. Thus, the presence of close-in giant planets implies that many of exoplanetary systems have undergone planetary migrations. Several migration scenarios have been proposed, and they are different in their predictions for orbital parameters (e.g., eccentricity). Here we introduce some of the major migration channels suggested thus far, and describe their outcomes that could be distinguished by observations.

2.2.1 Disk Migration

Until recently the prevailing migration theory was “disk migration,” in which the planet forms beyond the snow line and then spirals inward due to a tidal interaction with the proto-planetary gas disk (e.g., [2, 8, 9]). Depending on the planet mass and gas surface density, variants of this theory are called Type I, Type II, and Type III migration. Type I migration refers to a migration of small planets caused by a dynamical friction from surrounding disk materials. On the other hand, type II migration occurs to a larger planet, which is massive enough to create a gap in the proto-planetary disk by accreting the surrounding gases. When a gap forms in the disk, the massive planet is captured within the gap, which is then gradually dragged toward the host star as the disk undergoes a viscosity dissipation. The disk migration is supposed to have ended when the migrating planet reaches the inner edge of the disk, or due to the magnetospheric cavity.

The best evidence for this theory is the existence of mean motion resonances observed in many exoplanetary systems; these seem likely to have been formed through resonance capture while multiple planets were spiraling inward at different rates. But, this scenario has become suddenly vulnerable, as it predicts that isolated close-in planets should have very circular orbits that are well-aligned with the stellar rotation, which is often not the case.

2.2.2 Planet-Planet Scattering

Another major migration theory involves mutual gravitational interactions among multiple giant planets, followed by tidal interactions with the parent star (e.g.,

[3, 13, 16]). Mutual interactions among multiple planets lead to large eccentricities and inclinations of planetary orbits, and sometimes collisions among planets also occur. As a result of these dynamical interactions, the orbits of the planets often cross, even if the initial orbits of the planets are circular (the orbital instability). According to numerical simulations, systems with more than 3 planets finally cause orbital crossings in finite time, regardless of their initial orbits (e.g., [13]). The time needed for the orbital crossing in the case of three Jupiter-mass planets with $a_1 \simeq 5$ AU, $a_2 = a_1 + bR_H(1, 2)$, and $a_3 = a_2 + bR_H(2, 3)$ around a solar-type $1M_\odot$ star is estimated as

$$T_{\text{cross}} \simeq \exp[2.47b - 4.62] \text{ years}, \quad (2.30)$$

where $R_H(k, j)$ is the mutual Hill radius of planets k and j [10]. It is possible that T_{cross} is longer than the timescale of planetary formation ($\sim 10^5$ – 10^7 years) and is shorter than the lifetime of the host star ($\sim 10^{10}$ years). In this case, the orbits are stable during the planetary formation epoch, and subsequently become unstable after the proto-planetary gas disk is gone. As a result of orbital crossing, one of the planets is often removed from the system while the others are left but with large eccentricities. If the orbit is eccentric enough, the periastron distance will be very small, and tidal effects become important. Tidal dissipation causes the orbit to shrink its semi-major axis and circularize, while keeping the planet's periastron distance nearly constant. This may partly explain the observational fact that orbital eccentricities of close-in planets pile up along the constant periastron distance (see Fig. 2.4). It also causes the star and orbit to come back into alignment, but this process is expected to be much slower than the orbital circularization. Therefore, in contrast to disk migration, planet-planet scattering is expected to produce occasionally large spin-orbit misalignments.

2.2.3 Kozai Migration

A variation of the “planet-planet scattering model” is possible if the star has another massive companion (another star, or a giant planet) besides an inner planet. In this case, if the companion's orbit is initially inclined relative to the transiting planet's orbit, then the inner planet's orbit will undergo oscillations in eccentricity and inclination, due to the secular perturbations by the companion. This phenomenon is called “Kozai cycles”. When we denote the eccentricities of the inner planet and the outer companion by e_1 and e_2 , and the orbital inclinations by i_1 and i_2 , respectively, the conservations of the time averaged Hamiltonian and angular momentum conservation result in the following equations [13]:

$$(1 - e_1^2) \cos^2 i_1 \equiv h = \text{const.}, \quad (2.31)$$

$$(2 + 3e_1^2) \left(\frac{3h}{1 - e_1^2} - 1 \right) + 15e_1^2 \left(1 - \frac{h}{1 - e_1^2} \right) \cos(2\eta) = \text{const.}, \quad (2.32)$$

where η represents the difference between the arguments of pericenters of the two interacting bodies. Equation (2.31) implies that a small inclination angle i_1 leads to a high eccentricity of the inner planet, which means the small pericenter distance.

During the high-eccentricity phases of these cycles, tidal interactions may lead to energy dissipation, orbit shrinkage, and circularization, as in the case of planet-planet scatterings. Thus there is another possible channel for producing hot Jupiters. The combination of the Kozai cycles to raise eccentricities and subsequent tidal circularizations is called “Kozai migration” [21]. The Kozai migration theory also predicts a very broad range of spin-orbit angles, even broader than planet-planet scattering alone, and in starker contrast to disk migration (e.g., [5]).

All the migration theories described above seem physically plausible as explanations for the formation of close-in giants, so it is difficult to distinguish among these theories and tell which (if any) is the dominant channel. The measurements of the RM effect, described below, are a promising route to solving this problem. The observed distribution of the spin-orbit misalignment angle λ and its host star dependence (such as stellar types) have already provided crucial clues and generated new hypotheses, which can be tested and clarified with the future measurements.

2.3 Measurements of the Rossiter-McLaughlin Effect

2.3.1 Introduction

In order to distinguish the possible migration scenarios stated in the previous section, observations of the relation between the planetary orbital and stellar spin axes proved to be a powerful tool. Quiescent migrations due to disk-planet interactions (Type I and II) result in small spin-orbit angles since the whole system preserves the initial direction of angular momenta for both of planetary orbits and stellar spin. In contrast, planet-planet scatterings and/or Kozai migrations can produce significant spin-orbit misalignments as we discussed in Sect. 2.2.

A spectroscopic observation during a planetary transit provides us an unique opportunity to measure the spin-orbit angle. During a planetary transit, a portion on the rotating stellar disk is occulted by the planet. This partial occultation produces a distortion in the spectral lines. When we measure RVs during the transit, the distortion is manifested as an apparent RV anomaly; we see an apparent red-shift if a blue-shifted part on the stellar surface is blocked by the planet, and the reverse occurs in case the planet blocks the red-shifted portion. The pattern of the RV anomaly determines the angle λ , which is defined as the sky-projected angle between the planetary orbital axis and stellar spin axis (see Fig. 2.5). In Fig. 2.6, we show the schematic plots for the RM effect. In case of $\lambda = 0^\circ$, the RV anomaly due to the RM

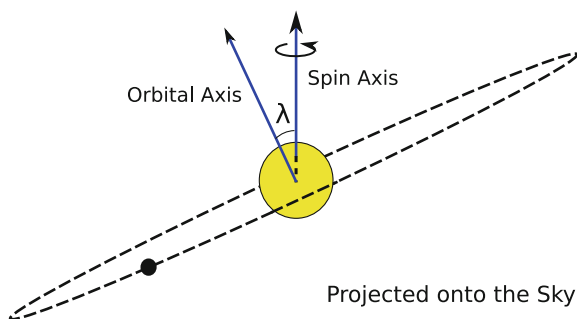


Fig. 2.5 Definition of the spin-orbit angle λ

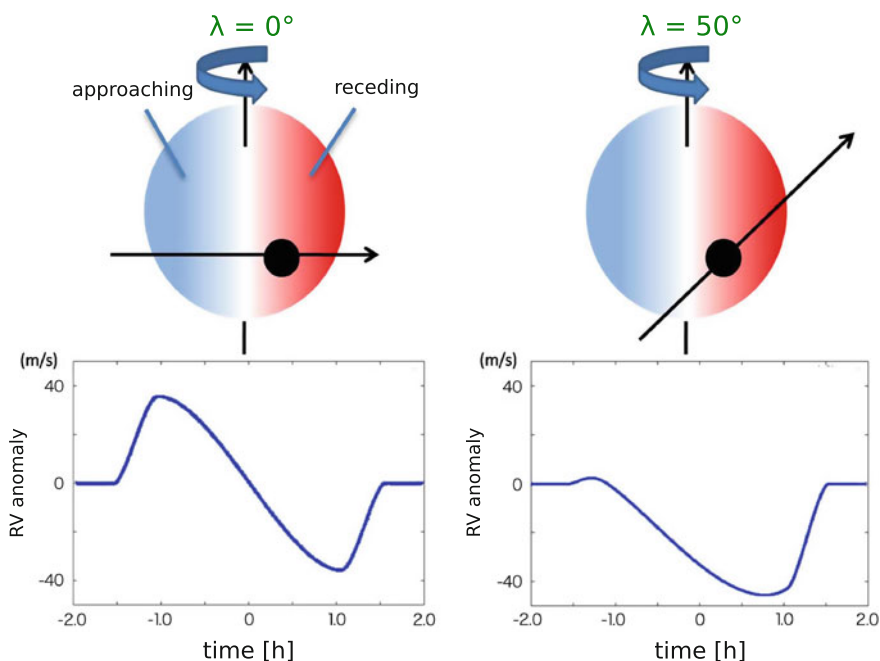


Fig. 2.6 Schematic description of the RM effect: The *upper* two figures show two different planetary transits that produce the same photometric signal—but they have different spin-orbit angles ($\lambda = 0^\circ$ and $\lambda = 50^\circ$), and therefore produce different RM signals, shown in the *lower* figures. In each case, the *left* half of the stellar disk is approaching due to stellar rotation, while the *right* half is receding. Note that time = 0 means “mid-transit”. When the planet blocks a portion of the approaching half, the net starlight is observed to be blueshifted, and when the planet is on the receding half, the starlight is redshifted. The shape of velocity anomaly curve depends on the trajectory of the planet relative to the pattern of stellar rotation

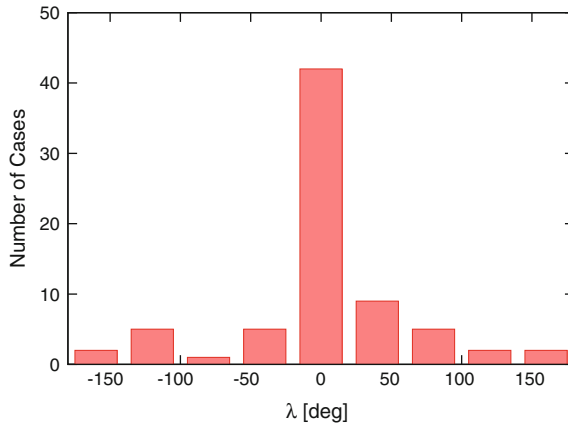


Fig. 2.7 Histogram of the observed spin-orbit angle λ . We have divided the range of λ into nine bins, each having the bin width of 40° . According to the summary of RM measurements at http://ooo.aip.de/People/rheller/content/main_spinorbit.html, 71 systems have been investigated, many of which have more than one RM measurement. In that case, the latest result is adopted to make the histogram. If RM measurements for the same system are published in the same year, the measurement with the best precision (the smallest error for λ) is adopted

effect is symmetrical with respect to the transit center as shown on the left, while it becomes asymmetrical for a non-zero λ (on the right). Thus, the time variation of the anomalous RVs during a transit enables us to measure the spin-orbit angle λ . Although the qualitative interpretation of this velocity “anomaly” is intuitively easy, its quantitative description is not straightforward. We discuss this point in Chap. 3 in detail.

2.3.2 Observational Results

Historically, the RM effect for a transiting planet was first detected in 2000 for the first transiting system HD 209458b [15]. Since then many systems have been observed for measurements of the RM effect, and so far there are more than 70 systems with RM measurements.³ In Fig. 2.7, we show the histogram of the spin-orbit angle λ observed so far. While many systems show a spin-orbit alignment, a significant fraction of the systems with close-in giants are now believed to have large spin-orbit misalignments. As Fabrycky and Winn [6] pointed out, the distribution of the spin-orbit angles can be described as a combination of two different populations: one in which the two axes are very well-aligned, and one in which the two axes have no correlation with each other. An intriguing hypothesis is that the former population

³ List of RM measurements are summarized at the following website: http://ooo.aip.de/People/rheller/content/main_spinorbit.html.

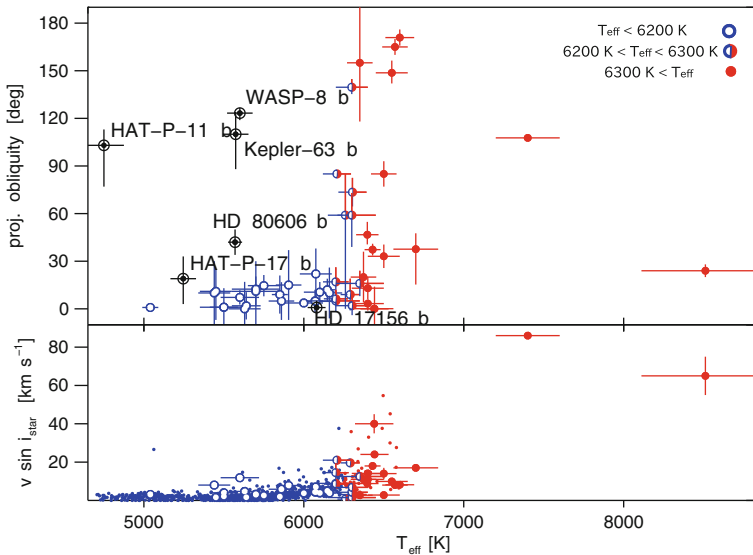


Fig. 2.8 Correlations of the projected spin-orbit angle $|\lambda|$ (*upper*) and projected stellar rotational velocity $V \sin I_s$ (*lower*) with stellar effective temperature T_{eff} [1]

corresponds to disk migration, while the latter population represents those planets that migrated through dynamical interactions (planet-planet scattering and/or Kozai cycles).

Regarding the dependence of the spin-orbit angle on host stars' property, an interesting pattern was pointed out by Winn et al. [20]. Namely, spin-orbit misalignments are found around hot stars having isolated hot Jupiters. In the top panel of Fig. 2.8, we plot the spin-orbit angle λ as a function of host star's effective temperature [1]. Cool stars with $T_{\text{eff}} < 6200$ K, are likely to be slowly rotating and show good spin-orbit alignment, while hot stars ($T_{\text{eff}} \geq 6300$ K) tend to be rapid rotators and have spin-orbit misalignments. The half-blue, half-red systems have moderately hot host stars with $6200 \text{ K} \leq T_{\text{eff}} < 6300$ K. This possible dependence that spin-orbit misalignments are preferentially seen for hot (massive) stars was surprising, but reinforced later by Albrecht et al. [1] along with more samples of RM measurements.

Winn et al. [20] suggested that this empirical finding is evidence that *all* isolated hot Jupiters begin with initially misaligned orbits (due to planet-planet scattering or Kozai migration). The reason why good alignment is observed today among systems with low-mass host stars is due to tidal interactions; low-mass stars have stronger tidal dissipation than high-mass stars, due to their thicker outer convective zones. It is widely believed that convective envelopes drastically grow as the stars become cooler ($T_{\text{eff}} \lesssim 6250$ K) [14]. The transition from mostly-aligned to mostly-misaligned systems occurs where the convective mass becomes negligible.

There are some systems which show spin-orbit misalignments even though the stars have thick convective zones: HD 80606, WASP-8, HAT-P-11, Kepler-63, and

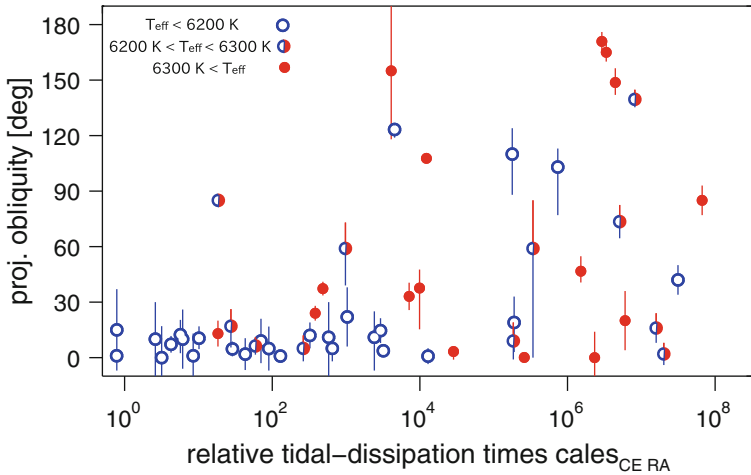


Fig. 2.9 The spin-orbit angle $|\lambda|$ as a function of the relative tidal-dissipation timescales τ . See Albrecht et al. [1] for detail

HAT-P-17. However, these systems also have unusually large orbital semi-major axes and/or small planet sizes, and therefore their tidal interactions are expected to be especially weak. Albrecht et al. [1] further investigated this point and estimated the typical timescales for the stellar spin axis to “realign” with the planetary orbit based on the empirical equations for the tidal interaction by Zahn [23]. Figure 2.9 indicates the “relative” timescale τ needed for a spin-orbit realignment for each of the systems with RM measurements, estimated by the mass and orbit of the planet along with host star’s property. Although these timescales for the spin-orbit realignment were computed by simple relations originally derived for binary star systems, the result points to a trend; the longer τ is, the more likely we observe a spin-orbit misalignment. This hypothesis to interpret the dependence of λ on T_{eff} is also consistent with another interesting pattern of λ , suggested by Triaud [18], that massive, younger stars (with ages $\lesssim 2.5$ Gyr) are likely to show spin-orbit misalignments. These patterns should be confirmed by further observations together with an improved theoretical modeling of the tidal interaction for star-planet systems.

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Exoplanets

Hirano, T.

2014, XV, 134 p. 45 illus., 25 illus. in color., Hardcover

ISBN: 978-4-431-54585-9