Angular Momentum Distributions for Observed and Modeled Exoplanetary Systems

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Abstract

The distribution of angular momentum of planets and their host stars provides important information on the formation and evolution of the planetary system. However, mysteries still remain, partly due to bias and uncertainty of the current observational data sets and partly due to the fact that theoretical models for the formation and evolution of planetary systems are still underdeveloped. In this study, we calculate the spin angular momentum of host stars and the orbital angular momentum of their planets using data from the NASA Exoplanet Archive along with detailed analysis of observation dependent biases and uncertainty ranges. We also analyze the angular momentum of the planetary system as a function of star age to understand their variation in different evolutionary stages. In addition, we use a population of planets from theoretical model simulations to reexamine the observed patterns and compare the simulated population with the observed samples to assess variations and differences. We found the majority of exoplanets discovered thus far do not have the angular momentum distribution similar to that of planets in our solar system, though this could be due to the observation bias. When filtered by the observational biases, the model simulated angular momentum distributions are comparable to the observed pattern in general. However, the differences between the observation and model simulation in the parameter (angular momentum) space provide more rigorous constraints and insights on the issues that needed future improvement.

Unified Astronomy Thesaurus concepts: Exoplanet dynamics (490); Stellar rotation (1629); Exoplanet evolution (491)

1. Introduction

Technological and scientific advancements have rapidly expanded the field of exoplanets and have allowed us the incredible opportunity to study and compare the over 3200 star systems discovered to date. Using this observational data, we have been able to deduce that the solar system is indeed unique in many ways. For example, the orbits of our planets are nearly circular, and unlike the observations of many systems, our four giant planets are at a much further distance than the Sun, with smaller planets existing closer with highly elliptical orbits (Beer et al. 2004).

It is therefore important to examine how our solar system, and other star systems, vary with respect to angular momentum and look at the distributions between observations versus model for a variety of systems. For this purpose, a combined observational and modeling analysis to compare exoplanetary systems for both the total angular momentum as well as the total orbital angular momentum of the planets is needed.

The distribution of angular momentum between host star and planets provides essential information regarding the formation and evolution of the planetary system. Many planetary formation theories, before the discovery of exoplanets, were based upon our own solar system objects. Early studies by Fish (1967) examined angular momentum densities for the planets and planet-satellite systems including asteroids and the Earth-Moon system. Since then, many studies have been conducted to further our understanding of angular momentum in exoplanetary systems, though it remains an area in which we lack insight into the full picture between theory and observation. A major constraint with any exoplanetary study is the quality and amount of data necessary for meaningful large-scale analysis. Now with the increase in available exoplanet data, we can make comparisons on a much broader scale than ever before with hundreds of data points to elucidate patterns. However, the observational biases related to the different detection techniques (e.g., radial velocity (RV) and transit method, etc.) could mislead us such that any patterns we find might not be linked to the physical meaning we seek.

On the other hand, models for planetary angular momentum have been created to study the orbital mechanics of exoplanets, such as Gurumath et al. (2019), who were able to use real data to estimate orbital angular momentum of known exoplanets. Models are also developed to study the angular momentum for specific ranges of host stars. For example, a theoretical model by Sills et al. (2000) focused on low-mass stars (0.1–0.5 M_☉) and solar analogs (0.6–1.1 M_☉); Gallet & Bouvier (2013) presented specific models for the “rotational evolution of solar-like stars between 1 Myr and 10 Gyr with the aim of reproducing distributions of rotational periods observed for star-forming regions and young open clusters within this age range;” furthermore, Matt et. al. (2015) sought to understand the “observed distributions of rotation rate and magnetic activity of sun-like and low-mass stars.”

Recent advances have been made by Gallet & Bouvier (2013) and Gallet & Bouvier (2015) who parameterize wind braking to include updated results of numerical simulations of magnetized stellar winds. However, they conclude that more measurements of mass-loss rates and magnetic topologies of
young stars are required to fully characterize magnetic wind braking and therefore loss of angular momentum.

In summary, the main gaps that exist in our present understanding of angular momentum in exoplanetary systems are due to (a) bias and uncertainty of the current observational data sets, and (b) theoretical models for the formation and evolution of planetary systems are presently underdeveloped.

This study aims to provide a quantitative assessment of spin angular momentum of host stars and the orbital angular momentum of their planets using observational data. In order to understand variation of angular momentum in different evolutionary stages of stars, we bin the observational data according to the known age of the stars and use a model simulation to analyze changes in angular momentum of planetary systems over their lifetime. The angular momentum generated by the model simulation is filtered by the observational biases, in order to reexamine the correlations and compare the simulated population with the observed samples. In doing so, we can examine planetary formation. Do the exoplanetary systems discovered thus far have an angular momentum distribution similar to our solar system planets? We hope our analyses will bring us closer to determining just how special or perhaps ordinary, we really are.

The organization of the paper is as follows: Section 2 describes the data set used in this study, the methodologies for calculating the angular momentum from the observational data, estimating the observational biases, model simulations and the corresponding parameters to compare with the observations. Section 3 analyzes (a) the distribution of angular momentum of the exoplanet systems from observed data and compares them with our solar system; (b) the comparison between observation and model simulations at different time stages of star and planetary systems. From this, we can then draw conclusions and suggest improvements that are needed for a robust analysis in the future.

2. Data and Methodology

2.1. Observational Data

The data set for this study was downloaded from the NASA Exoplanet Archive (https://exoplanetarchive.ipac.caltech.edu/), which currently contains data for more than 4500 confirmed exoplanets in over 3200 planetary systems. The measurement as well as the uncertainties of orbital parameters, planetary parameters, and stellar parameters are archived from more than 800 reference papers. We selected a subset of exoplanets with the full information of planetary mass, orbital parameters (semimajor axis, eccentricity, inclination), stellar mass, stellar radius, and stellar rotational velocity, in order to calculate the orbital angular momentum of planets and the rotational angular momentum of host stars following the method introduced in the next section. The subset only includes the data with stellar mass < 1.4 $R_\odot$, of which the moment of inertia can be determined according to the stellar evolutionary model from Baraffe et al. (2015). The archive also includes more than 150 exoplanets orbiting binary or multi-star systems (e.g., Kong et al. 2021). For simplicity, however, the data from binary and multi-star systems are not included in our study. The uncertainties of the angular momentum are also calculated, which are propagated from the measurement uncertainties. To ensure the reliability of the statistical results, we exclude the data with relative uncertainties of the rotational angular momentum larger than 1. The final sample contains 247 exoplanets in 227 planetary systems.

2.2. Calculating the Angular Momenta from Observational Data

The angular momentum in a planetary system includes both the orbital angular momentum of the planets and the rotational angular momentum of the star (here we neglect the spin angular momentum of the planets as well as the orbital angular momentum of their possible satellites). These can be computed from the systems when the mass and rotation of the host star, and the mass, semimajor axis, eccentricity, and inclination of the planets are known. Due to the limit of observable parameters, we only consider the component of both orbital and spin angular momentum perpendicular to the line of sight.

The total orbital angular momentum of all the planets in a system are

$$ L_p = \sum_{n=1}^{N_s} \sqrt{G M_{st} m_n^2 a_n (1 - e_n^2) \cos(i_n)} $$

where $G$ is the gravitational constant, $M_{st}$ is the mass of the star, $N_s$ is the total number of planets in the system, subscript $n$ denotes the $n$th planet in the system with mass $m_n$, semimajor axis $a_n$, eccentricity $e_n$, and inclination angle of the orbital plane with the line of sight $i_n$.

The spin angular momentum of the host star, $L_{st}$, is estimated with the following equation as used by Gurumath et al. (2019), which only takes radial rotational velocity into account:

$$ L_{st} = \frac{v \sin i}{R_{st}} l_{st}, $$

where $i$ is the inclination angle of the rotation axis with the line of sight, $v$ is the rotational velocity of the star, $R_{st}$ is the radius of the star, and then

$$ l_{st} = k^2 M_{st} R_{st}^2 $$

is the moment of inertia of the star calculated with a reasonable assumption of having uniform density, where $k$ is the radius of gyration that accounts for the variation of density in the stellar interior. Thus, Equation (2) can be rewritten as

$$ L_{st} = k^2 v \sin i M_{st} R_{st}. $$

Let $\sigma_x$ be the measurement uncertainty of a parameter $x$ listed in the NASA Exoplanet Archive. According to the propagation of uncertainties, the relative uncertainty of orbital angular momentum of planet $n$ is

$$ \sigma_{L_{pn}} = L_{pn} \sqrt{\sum_{x \in m, a, e, i} \left( \frac{\sigma_{x_{pn}}}{x_{pn}} \right)^2 + \left( \frac{\sigma_{\gamma_{pn}}}{\gamma_{pn}} \right)^2 + \left( \frac{\sigma_{\epsilon_{pn}}}{\epsilon_{pn}} \right)^2} $$

The uncertainty of the total angular momentum of the planetary system is

$$ \sigma_{L_p} = \sqrt{\sum_{n} \sigma_{L_{pn}}^2}. $$

The uncertainty of the spin angular momentum of the host star is

$$ \sigma_{L_{st}} = L_{st} \sqrt{\left( \frac{\sigma_{v \sin i}}{v \sin i} \right)^2 + \left( \frac{\sigma_{R_{st}}}{R_{st}} \right)^2}. $$

To ensure suitable quality of observational data used in this study, we only accept data satisfying $\sigma_{L_p} / L_p < 1$ and $\sigma_{L_{st}} / L_{st} < 1$. 

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The transit method is highly biased toward planets on very short period orbits (approximately days) and closer to the host star (<1 au) because they transit more frequently (e.g., Jiang et al. 2019). The transit method is also biased toward discovering large planets because larger planets block more light and are thus easier to detect, and biased toward finding big planets around small stars for the same reason. The RV method is biased toward finding massive exoplanets since the Doppler effect is more noticeable with large planets orbiting close to its host star (e.g., Zakamska et al. 2011). Microlensing and direct imaging methods are most sensitive to detecting planets that are more than 1 au away from Sun-like stars (e.g., Tsapras 2018). Another consideration is that the total angular momentum in a planetary system will vary due to the number of planets in the system. There might be planets undiscovered in the systems especially those further away from the host, likely being the case for Kepler and TESS. Furthermore, the observational data sets are also highly heterogeneous in terms of relative precision on the measurements and types of host stars.

Due to limitations of the observation methods, the angular momentum are mostly calculated using data from two observational methods, transit and RV, each having different pros and cons. The exoplanet radius is calculated by the depth of the transit, and the exoplanet mass is calculated using RV based measurements of velocity along line of sight. In the NASA Exoplanet Archives, almost all the planet radius data are discovered via transit method, and planet mass is often obtained first by the transit discovery of planet, e.g., with transit timing variation or using a mass–radius relationship (Agol et al. 2005; Holfman & Murray 2005), and then subsequently estimated with follow-up RV observations.

Most of the exoplanets in our angular momentum analyses were discovered via the transit method, specifically by the Kepler telescope, and it requires more than two transits to confirm a planet, which limited the orbital period of detectable planets. As Kepler worked for 4 yr, the planets with orbital period larger than ∼730 days cannot be detected by Kepler, which further limited the detectable angular momentum.

The masses of these planets were later determined by RV after the transit discovery. The amplitude $K_1$ for RV detection is in terms of eccentricity ($e$), planet mass ($M_p$), stellar mass ($M_\star$), and orbital period ($P$) is expressed as (Lovis & Fischer 2010)

$$K_1 = \frac{28.4329 \text{ m s}^{-1}}{\sqrt{1 - e^2}} M_\star \sin i \left( \frac{M_\star + M_p}{M_\odot} \right)^{1/2} \left( \frac{P}{1 \text{ yr}} \right)^{-1/2},$$

where $M_\odot$ is mass of Jupiter and $M_\odot$ is solar mass.

Our analysis found that almost all of the scaled amplitudes of the detected planets are $K_1 > 10 \text{ m s}^{-1}$. We therefore adopt this as the detection threshold. Assuming the inclination is close to 90° and eccentricity is close to zero, $K_1$ can be written in terms of

$$K_1 \propto \frac{M_p^2 M_\star^{5/3}}{L^4} \left(1 + \frac{M_\star}{M_p} \sin i\right)^{5/6}.$$

This shows that for a given star, the RV amplitude limits the possible angular momentum of a detectable planet with mass $M_p$. To simplify this problem, we look at the observational bias for single-planet systems and focus on potential bias in the distribution of orbital angular momentum. We assume that the stellar mass ranges from 0.2–2 $M_\odot$, and planetary mass ranges from 0.1–10$^5$ $M_\oplus$. We then compute the limits caused by the detection methods of RV and transit separately, as shown in Figure 1. It suggests that only if the planetary mass is $<1 M_\oplus$, will it suffer the RV bias. Figure 2 shows the histogram of $L_p$ of the planets with only $M_p \sin i$ information, which can be thought of as those without transit follow-up observation. We still found the drop, e.g., at $\sim 10^{52}$ g cm$^2$ s$^{-1}$, although there are more planets with higher $L_p$. As $M_p \sin i$ is the minimum mass, the true $L_p$ could be higher. Whether or not it is a physical drop, however, is unclear, as we already know their masses and most
of them are beyond $1 M_\oplus$. We would argue it is because almost all of the RV detected planets have an orbital period $<10^6$ days, which is 28 yr (equivalent to $\sim8$ au when orbiting the Sun), and a Jupiter-mass planet at 10 au is $2 \times 10^{50}$ g cm$^2$ s$^{-1}$. Therefore, it is limited by the maximum detectable orbital period.

Also, Figure 1 demonstrates that at the same time, all of the planets in our sample suffer from transit bias, but at varying levels for different planetary masses. Analyzing the observational biases as discussed above will help us to better understand the current data sample and help infer the true distribution of the physical parameters.

In addition, we noted that potential tidal angular momentum exchange or transfer from the planets to the star could lead to a different rotational evolution (e.g., Poppenhaeger & Wolk 2014; Benbakoura et al. 2019). For simplicity, we did not include such process in our calculation or the model that is used below.

2.4. Angular Momenta from Model Simulations

Angular momentum of planetary systems can be simulated by means of a planetary population synthesis model. This approach relies on observed distributions of protoplanetary disk properties (i.e., mass, metallicity, inner edge, and lifetime) to then compute a population of synthetic planets (Ida & Lin 2004; Mordasini et al. 2009; Benz et al. 2014; Mordasini 2018). Emsenhuber et al. (2021b) and Burn et al. (2021) utilize a recently updated planetary synthesis model (Emsenhuber et al. 2021a) to simulate the angular momentum of planetary systems.

Here, we briefly outline a number of key ingredients to this model. The gaseous disk evolves $\alpha$ viscously (Shakura & Sunyaev 1973) and the midplane temperature is analytically approximated (Nakamoto & Nakagawa 1994). It depends on irradiation from the star (Hueso & Guillot 2005) and viscous heating as well as the mean opacity (Bell & Lin 1994).

The modeled growth of a protoplanet starts at the stage of a lunar-mass embryo, which is assumed to have grown in a stage of runaway planetesimal accretion (Kokubo & Ida 1998). Multiple such protoplanets are injected at random locations in the disk consisting of gas and planetesimals. Then, the accretion rates of planetesimal (Fortier et al. 2013) and gas, as well as the gravitational interactions between the multiple growing protoplanets using the MERCURY N-body code (Chambers 1999) are calculated. To derive realistic accretion rates of gas, the standard equations governing the evolution of the gaseous envelope (Bodenheimer & Pollack 1986) are solved. In addition to that, protoplanet migration in the type I (Paardekooper et al. 2010, 2011) or type II (Dittkrist et al. 2014) regime is considered.

The gaseous disk is observed to disperse quite rapidly (Haisch et al. 2001), which is achieved in the models by including internal and external disk photoevaporation (Clarke & Bishnoi 2001; Matsuyama et al. 2003). The latter is scaled with a stochastic parameter to reproduce the observed lifetime distribution of disks.

After the dissipation of the gas disk, the planets are able to lose their accretional energy over Gyr timescales. For that, the model continues to solve the internal structure of the protoplanets including stellar irradiation and photoevaporation of the atmospheres (Jin et al. 2014). During this late stage of the evolution, the star also significantly evolves. In the model, during all stages, the stellar temperature, luminosity, and radius follows the evolutionary tracks of Baraffe et al. (2015). This is not the case for the rotation period of the star $P_\ast$, which is key to this endeavor. We therefore parameterize the evolution of $P_\ast$ to match reasonably well with the resulting surface rotation periods of Eggenberger et al. (2019), Amard et al. (2019), and Amard & Matt (2020):

$$P_\ast(t) = \begin{cases} P_{\text{ini}} \left( \frac{t}{t_{\text{disk}}} \right)^{-0.435} & \text{for } t = t_{\text{disk}} \\ \frac{1}{P_{\ast}(\text{PMS})} - \frac{a}{P_{\ast}(\text{PMS})} \left( \frac{t}{t_{\text{PMS}}} \right)^b & \text{for } t_{\text{disk}} < t \leq t_{\text{PMS}} \\ P_{\ast}(\text{PMS}) \left( \frac{t}{t_{\text{PMS}} - t_{\text{disk}}} \right)^{0.3} \times 10^{1.236 \left( \text{Fe/H} \right)} & \text{for } t > t_{\text{con}} \end{cases}$$

(9)

For this parameterization, $t_{\text{disk}}$ is the lifetime of the protoplanetary disk, which varies for each simulation, but ultimately samples the distribution of observed disk lifetimes (e.g., Haisch et al. 2001; Richert et al. 2018). $P_{\text{ini}}$ is the initial rotation period chosen to sample the measured distribution by Venuti et al. (2017), specifically for young objects with disk signatures in the open cluster NGC 2264. This quantity is also used to describe the inner edge of the disk in the planetary population synthesis model. The parameter $b$ is set to the value 6 and $a$ is chosen to get a continuous evolution function. The rest of the parameter choices for the fit are listed in Table 1 and vary for different stellar masses. In particular, the pre-main-sequence time $t_{\text{PMS}}$ significantly varies for different masses. We note that for late-type M dwarfs ($<0.5 M_\odot$), $t_{\text{PMS}}$ should be instead considered as a time of maximum rotation. For the discussion, we note that late-stage rotation of similar stars is almost indistinguishable despite different initial rotation periods (Eggenberger et al. 2019) and results converge toward the classical result of a power law with a slope of 0.5 (Skumanich 1972). In the left panel of Figure 3, we compare the evolution of stellar surface angular velocity to measured data.
collected by Gallet & Bouvier (2015) and theoretical values from the model of Eggenberger et al. (2019). For our purposes, we find good agreement, especially at late and early times.

To finally get the angular momentum of the modeled stars, we use the radii of gyration and the stellar radii from the tables of Baraffe et al. (2015). The resulting stellar angular momenta are shown in the right panel of Figure 3.

Because exoplanets are frequently discovered around stars with sub-solar masses, we include in the synthetic data set the results of Burn et al. (2021) who discuss the synthetic planetary population for K and M dwarfs in addition to the nominal solar-like case. To achieve this, the initial conditions for the protoplanetary disks need to be scaled. An important quantity that gives the initial mass content available for planets to accrete from is the mass of the protoplanetary disk. It is assumed to depend linearly on the stellar mass as discussed in Burn et al. (2021) and disks around solar mass stars are distributed according to the Very Large Array measurements of Class I disks by Tychoniec et al. (2018). The measured, young T tauri stars with spectral signatures of an envelope, are found to be surrounded by disks that are an order of magnitude more massive (median dust mass is $96 M_\oplus$) than the older, more common Class II objects ($\sim 10 M_\oplus$). We note that more recent works find lower disk masses for the same class of objects (i.e., Williams et al. 2019). However, there is the additional constraint of measured gas accretion rates onto the stars (e.g., Hartmann & Bae 2018), which favor larger disks. Therefore, we sample initial disk masses from the distributions found by Tychoniec et al. (2018) in this work.

In addition to initial masses, dust-to-gas ratios are distributed equally for all stellar masses following the measurements of Santos et al. (2003). Initial locations of protoplanets are drawn from a log-uniform distribution of semimajor axis spanning from the inner edge to separations corresponding to orbital periods of 253.2 yr. Model parameters that are fixed for all simulation runs can be found in Table 2. Additionally, references and further discussion can be found in Burn et al. (2021).

### 3. Results and Discussion

#### 3.1. Angular Momentum from Observational Data

We first analyze the distribution of angular momentum of the exoplanet systems from observed data and compare them with our own solar system. Figure 4 shows scatter plots of orbital (left panel) and total (middle panel) angular momentum of confirmed exoplanetary systems (x-axis) versus the ratio of spin angular momentum of the host stars divided by the total orbital angular momentum of all the planets (y-axis). A red curve

![Figure 3](Image 88x559 to 525x739)

Figure 3. Parameterized surface angular velocity (left) in units of the solar value and stellar angular momentum (right) evolution for different stellar masses and initial rotations. Observations of angular velocities of different star-forming regions and open clusters compiled by Gallet & Bouvier (2015) are shown for comparison observational data for $0.5 M_\odot$ are shifted back in time by 10% for better visibility. The error bars, respectively, fast and slow cases, denote the 25th–90th percentile range. The simple fit does not capture all transition phases accurately, but a good agreement in early and late stages is visible. Shaded bands at late times show the 1σ scatter due to different (Fe/H).

| $M_*$: $1.0 M_\odot$ | $M_*$: $0.7 M_\odot$ | $M_*$: $0.5 M_\odot$ | $M_*$: $0.3 M_\odot$ | $M_*$: $0.1 M_\odot$ |
|-------------------|-------------------|-------------------|-------------------|-------------------|
| $t_{\text{FAD}}$ | $4.0 \times 10^7$ yr | $7.9 \times 10^7$ yr | $1.2 \times 10^8$ yr | $3.2 \times 10^8$ yr | $6.3 \times 10^8$ yr |
| $P_{\text{disk}}$ | $0.082 P_\odot$ | $0.0185 P_\odot$ | $0.294 P_\odot$ | $0.312 P_\odot$ | $0.312 P_\odot$ |
| $t_{\text{conv}}$ | $10^8$ yr | $3.6 \times 10^8$ yr | $8.3 \times 10^8$ yr | $1.3 \times 10^9$ yr | $1.6 \times 10^9$ yr |

| Parameter | Value |
|-----------|-------|
| Gas disk viscosity parameter | $2 \times 10^{-3}$ |
| Slope of the initial gas disk | -0.9 |
| Exponential cutoff radius of the gas disk | $\approx M_\text{disk}$ |
| Slope of the initial planetesimal disk | -1.5 |
| Planetesimal radius | 300 m |
| Initial number of protoplanets | 50 (100 for 1 $M_\text{\odot}$) |
| Initial mass of protoplanets | 0.01 $M_\text{\odot}$ |
| Opacity reduction in the planetary envelope | 0.003 |
| N-body integration time | 20 Myr |
across the figure moves from the top to the lower portion illustrating the path of a set of virtual planetary systems with the Sun as the host star, but containing one, two, three, and so forth, planets at the same masses, sizes, and orbits of our solar system planets: Mercury (M), Venus (V), Earth (E), Mars (M), Jupiter (J), Saturn (S), Uranus (U), and Neptune (N). The positions of such virtual systems are indicated by the black dots on the red curve. For reference, the positions of angular momentum that are related to Earth, Jupiter, and Neptune, and an imaginary position of angular momentum of Jupiter as if it were in the location of Mercury, are also shown in the left- and middle panels. It is interesting to see that if Jupiter were in Mercury’s orbit, its angular momentum position would be like that of an exoplanet, e.g., the hot-Jupiter case.

The original idea of Figure 4 (left panel and middle panel) is that if the distribution of angular momentum in our solar system is typical, then we could produce a prediction curve of what the angular momentum distribution might look like if more outer exoplanets further away from the host stars were discovered in the future. Interestingly, there is a gap: the position of angular momentum in such solar systems is at either the high end or low end compared to the angular momentum computed with the population of currently discovered exoplanets. This is further highlighted by the histogram in the right panel of Figure 4, in which the x-axis is the ratio of spin angular momentum of stars divided by the orbital angular momentum of the planets and the y-axis is the total count of confirmed exoplanet systems with available data. The gap can be attributed to the presence of a giant planet—Jupiter for the case of the solar system—and will be discussed in more detail in Section 3.2.

It is clear that the majority of exoplanets discovered so far do not have the angular momentum distribution similar to our solar system planets. In the solar system, planets within Mars’ orbit and closer, are small terrestrial planets, each with a radius of thousands of kilometers, and have a rocky surface. The planets outside Mars’ orbit are gas giant planets, with masses ranging from Neptune’s 15 $M_{\oplus}$ to Jupiter’s 318 $M_{\oplus}$. The gap between the angular momentum distribution for our solar system in Figure 4 reflects the large separation between the small terrestrial inner planets and gaseous outer giants. Many exoplanets and solar system planets have obvious differences. For example, hot Jupiters have been found with a mass and volume similar to Jupiter; they are giant planets but with orbital distances less than that of Mercury, and their revolution periods are as short as days and hours. Such objects do not exist in the solar system.

3.2. Angular Momentum from Model Simulations and Comparison with Observations

We now use a population of simulated planets to reexamine angular momentum distributions found in the observed samples. To filter the simulated data with observational bias, only the simulated exoplanets with a transit depth >0.0004, orbital period $P > 2$ yr, and with $K_1 > 10$ m s$^{-1}$ are counted as the detectable exoplanets.

Angular momentum is a function of the star age. Figure 5 shows that when time goes by, the observed rotational angular momentum of stars decreases continuously following $10^{-0.02} \frac{g \text{ cm}^2 \text{ s}^{-1}}{\text{gyr}}$ based on least-squares fitting (Figure 5, left panel) of the observed data. The modeled stellar spin evolution follows Equation (9) and is shown as a black line. It is interesting to see that our Sun has relatively smaller spin angular momentum compared to most stars of the sample. We note that the Sun does spin faster than what the usual models predict but so are stars with the same mass and age (e.g., van Saders et al. 2016; Hall et al. 2021). The fact that most stars of the sample have a higher spin angular momentum can be an indicator of (1) the youth of these stars which then have not lost their angular momentum yet, (2) stars of the sample are more massive, thus lose less angular momentum overall and typically have a higher initial content, or (3) they have had a different evolution than other planet-less stars.

The planet’s observed orbital angular momentum also declines with time but at higher rate of $10^{-0.04} \frac{g \text{ cm}^2 \text{ s}^{-1}}{\text{gyr}}$ (Figure 5, middle panel). The total angular momentum of the system from observation (Figure 5, right panel), which is the sum of planetary orbital angular momentum and stellar-rotation angular momentum, decreases at a rate of $10^{-0.02} \frac{g \text{ cm}^2 \text{ s}^{-1}}{\text{gyr}}$. Compared to most exoplanetary systems, both the total orbital angular momentum of the planets and the total angular momentum of our solar system are among the largest in the observed sample that are similar to the simulations.

Figure 5 shows that the time dependency of the observed planetary angular momentum is not reproduced by the population synthesis model. While the model does include the removal of planets due to tides, as well as atmospheric mass...
loss, those processes are not efficient at removing angular momentum. This is because they act on low-angular momentum planets (tides, following Benítez-Llambay et al. 2011) or remove relatively little mass (photoevaporation of atmospheres; Jin et al. 2014). Potential effects on the angular momentum of observable exoplanets that are not included in the model are dynamical self-interactions of the planets after 20 Myr as well as close encounters with other stars. Both of these should be explored in future work to understand the slightly decreasing trend of planetary angular momentum with time. In particular, encounters were shown to be efficient in removing ∼10% of the outer solar system planets (Stock et al. 2020).

Figure 6 and Figure 7 show scatter plots of orbital angular momentum (Figure 6) and total angular momentum (Figure 7) of exoplanetary systems versus the ratio of spin angular momentum divided by orbital angular momentum, respectively. The red curve across the figure moving from top to bottom illustrates the path of a set of virtual planetary systems discussed previously. The purple dots are the observed data, other colored dots are the simulated data with different host star masses. The simulation results at different time stages (0 yr, 100 Kyr, 1, 100 Myr, 1 Gyr, and 5 Gyr) are shown, respectively. For both Figures 6 and 7, only those simulated data filtered by the observational biases are shown, i.e., only the simulated exoplanets with a transit depth >0.0004, orbital period $P > 2$ yr and with $K_1 > 10$ m s$^{-1}$ are counted as detectable exoplanets.

After the initial stage (0 yr), the number of observables, simulated planets in the protoplanetary disk starts to grow. In both Figures 6 and 7, we see that the angular momentum distribution for the planets forming at each time stage appears to line up along the red curve and also groups according to the mass of the host star.

During the stages embedded in the protoplanetary disks (0–1 Myr), orbital angular momentum can still increase due to growing protoplanets. In the second column of panels (100 Myr–5 Gyr), the stellar evolution described in Section 2.3 is found to be the dominating factor. Although the Bern model includes evolutionary processes for planets, it does not significantly alter the angular momentum.

In contrast, stars converge in terms of their spin angular momentum and reach the Skumanich (1972) relation after their pre-main-sequence phase. The scatter due to different metallicities is considered here (see Section 2.3) but estimated to be of a small magnitude following modern braking law cases (van Saders & Pinsonneault 2013; Matt et al. 2015) investigated by Amard & Matt (2020). In Figure 4, we see that in our samples, the Sun, is a relatively slow rotator. This is not recovered in Figure 2, comparing the Sun to open clusters where the Sun is found to be average. Therefore, there might be a significant selection effect in the exoplanetary data used here. Indeed, it is easier to measure fast rotation rates due to the decreased observational time needed.

A prominent feature in the angular momentum distribution of synthetic planets is the planetary desert (Ida & Lin 2004). It separates systems where no planet was reaching critical core masses to trigger runaway gas accretion (e.g., Pollack et al. 1996) with those where at least one planet was able to accrete a significant amount of gas. Given the presence of two orders of magnitude more gas than solids, planets able to accrete gas have the potential to dominate the orbital angular momentum of the system. In Figure 5, the planetary desert is located at angular momentum below Jupiter’s corresponding to $10^{50}$ g cm$^2$ s$^{-1}$. Burn et al. (2021) found that giant planets form around stars with masses of $0.5 M_\odot$ or larger, which is why the large orbital angular momentum systems are absent in Figures 5 and 6 for stellar masses of 0.1 and 0.3 $M_\odot$.

However, this feature is not discernible in the observed distribution of angular momentum. Indeed, this agrees with the finding of Suzuki et al. (2018) based on microlensing surveys; they did not find a drop in planetary occurrences at the theoretically predicted location of the planetary desert (or sub-Saturn-mass desert). When looking at transit (Thompson et al. 2018) and RV (Mayor et al. 2011) data sets the interpretation is less conclusive, but the desert cannot be confirmed (Bennett et al. 2021). Numerical simulations also show that the 1D accretion treatment used in the Bern model (Mordasini et al. 2012) is not able to accurately capture the three-dimensional accretion process in all mass regimes (Szulágyi et al. 2014; Moldenhauer et al. 2021). This might be especially relevant if a circumplanetary disk forms instead of an envelope (Szulágyi et al. 2016).

Therefore, we retrieve here in a different parameter space—orbital angular momentum instead of mass—the discrepancy of 1D theoretical accretion and observations. Our analysis is not yielding more rigorous constraints on the issue since we take a
simple approach to modeling observational biases and we ignore sampling effects.

4. Summary

The angular momentum distributions of planetary systems are examined using data from the NASA Exoplanet Archive as well as by a model simulation using planetary population synthesis. We found that a majority of exoplanets discovered so far do not have the angular momentum distribution similar to that of our solar system planets. The total orbital angular momentum distributions of the exoplanets are considerably smaller than that of the solar system planets.

When the host star ages over time, the total angular momentum of the exoplanetary system from observation decreases at a rate about $10^{-0.02} \, \text{Gyr}^{-1}$. This is contributed from declines of angular momentum both from the spin of the star ($10^{-0.04} \, \text{Gyr}^{-1}$) and the orbiting of the exoplanets ($10^{-0.02} \, \text{Gyr}^{-1}$). The decrease of observed stellar angular momentum is consistent with the model simulation; however, time dependency of orbital angular momentum of the exoplanets is not reproduced by the models.

The simulated planetary angular momentum distributions at each evolutionary stage appear to line up and could be grouped according to the mass of the host star. Moreover, the planetary

Figure 6. Scatter plots of orbital angular momentum of exoplanetary systems vs. the ratio of spin angular momentum divided by orbital angular momentum. A red curve across the figure moving from top to bottom illustrates the path of a set of the virtual planetary systems discussed in the text. The black dots are the observed data, other colored dots are the simulated data with different host star masses. The numbers at the lower left corner show the number of detectable systems around the star with different mass showing with the same color code. The simulations results are outputted at different time stages (0 yr, 100 Kyr, 1, 100 Myr, 1 Gyr, and 5 Gyr), respectively.
desert feature in the synthetic planets is not perceptible in the observed distribution of angular momentum. These comparisons between observation and model simulation in angular momentum for exoplanetary systems provide significant insights into the gaps in both data and understanding that need future improvement in this field.

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Data Statement

The data underlying this article are described in the article and in a deposit on Zenodo: doi:10.5281/zenodo.5590784, in which the codes to plot all the figures, as well as the original data are included. The codes are well written and can be run anywhere to reproduce all of the figures. For additional questions regarding the data sharing, please contact the corresponding author at Jonathan.H.Jiang@jpl.nasa.gov.
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