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ANGULAR MOMENTUM IN EXTRASOLAR PLANETARY SYSTEMS

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ABSTRACT

As of July, 2008, over 300 extrasolar planets have been discovered. The study of the characteristics of exoplanets and their host stars can provide detailed information about planetary systems beyond our Solar System. This paper investigates the distribution of angular momentum in 28 extrasolar planetary systems. Only exoplanets detected with both transit and radial velocity measurements were included in the study to remove the uncertainty associated with unknown orbital inclination angles. The distribution of angular momentum between an exoplanet and its host star and between different extrasolar planetary systems was determined. It is clear from this study that the angular momentum per unit mass of the host stars is generally less than the average value for main-sequence stars of the same mass and that the angular momentum per unit mass of the complete extrasolar planetary system is generally greater. Also, more than 50% of the angular momentum in these systems resides in the exoplanet and in many cases it is more than 80%. To draw any general conclusions about the role of angular momentum in the planetary formation process will require additional work to understand and quantify the selection effects that result from the detection techniques used.

Subject headings: planetary systems

1. INTRODUCTION

For centuries, humans have been interested in the question of whether planets exist beyond our solar system. As of July, 2008, over 300 extrasolar planets have been discovered with more yet to be confirmed. Studying the characteristics of these planets will lead to a better understanding of the star and planet formation process and give a better understanding of the distribution of planets within the Universe.

There are several techniques for detecting exoplanets. The most prolific method (nearly all exoplanets have been discovered using this method) is the radial velocity method. A star's motion is affected by an orbiting exoplanet, causing both bodies to orbit the center of mass. The orbital motion of the star can be detected as Doppler shifts in its spectral lines, which can be analyzed and, from there, the parameters of the planet can be determined. Measurement of the speed of the star's motion provides an estimate of the exoplanet's mass ($M \sin i$), and the period of its orbit can be used to determine the semi-major axis of its orbit. A large planet orbiting close to its host star will result in a higher orbital speed of the star than a more distant planet; thus the radial velocity technique is biased toward detecting large planets orbiting close to their host star.

Another method used is the transit method. If the inclination of an exoplanet's orbit is very nearly aligned with the observer, a planetary transit can be observed. In a planetary transit, the planet passes between its host star and the observer on Earth causing the star to appear slightly dimmer, producing a dip in the star's light curve. As transit observations do not always conclusively prove an exoplanet's existence, they are used in support of, or are supported by, radial velocity measurements. One advantage provided by the transit method is that the size of the planet and the inclination of its orbit can be determined from the star's light curve, allowing the exoplanet's density to be determined.

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2. DATA SOURCES AND CALCULATIONS

2.1. *Data Sources*

All of the data for this research, except stellar rotational velocities, were taken from the Extrasolar Planets Encyclopedia (Schneider, 2007)[2]. For an object to be classified as an exoplanet its mass must be $\leq 13\ M_J$ (Jupiter masses). However, due to uncertainties in determining the mass of an orbiting secondary, the entries in this data set include secondaries with masses $\leq 20\ M_J$. Only detections published in refereed journals, or announced by astronomers at professional conferences are included in the Extrasolar Planets Encyclopedia.

The Extrasolar Planets Encyclopedia provides information about all confirmed exoplanets; however, for the research presented here, only those that have also been observed by the transit method are included. For this subset of exoplanets, the measured mass can be converted to true mass since the transit observation provides a measurement of the orbital inclination which is very near 90°. This also provides a means to convert the projected rotational velocity of the host star to an actual rotational velocity with the assumption that the inclination of the planet's orbit is aligned with the rotation axis of the star.

[2] This website can be found at http://exoplanet.eu.

TABLE 1
ORBITAL PARAMETERS

Name	$m_p(M_J)$	$a(AU)$	e	$i(°)$	$M_*(M_\odot)$	$R_*(R_\odot)$	$V\sin i(km\ s^{-1})$	$\pm(km\ s^{-1})$
GJ 436	0.072	0.02872	0.15	85.8	0.452	0.464	1.0	
WASP-10	3.06	0.0371	0.057	86.8	0.71	0.783	6.0	
HD 189733	1.15	0.0312	0	85.76	0.8	0.788	3.5	1.0
OGLE-TR-111	0.53	0.047	0	88.1	0.82	0.831	5.0	
TrES-1	0.61	0.0393	0	88.4	0.87	0.82	1.08	0.3
WASP-4	1.1215	0.023	0	88.59	0.9	1.15	2.2	1.0
TrES-3	1.92	0.0226	0	82.15	0.924	0.813	2.0	
HAT-P-3	0.599	0.0390	0	87.24	0.936	0.824	0.5	0.5
CoRoT-Exo-1	1.03	0.025	0	85.1	0.95	1.11	1.2	1.0
CoRoT-Exo-2	3.31	0.0281	0	87.84	0.97	0.902	11.5	0.4
WASP-5	1.58	0.02683	0	85	0.972	1.026	3.4	0.7
TrES-2	1.198	0.0367	0	83.9	0.98	1	2	1.5
XO-2	0.57	0.0369	0	88.58	0.98	0.964	1.2	0.3
XO-1	0.9	0.0488	0	89.31	1	0.928	3.0	
HD 209458	0.69	0.045	0.07	86.677	1.01	1.46	3.75	1.25
HAT-P-5	1.06	0.04075	0	86.75	1.16	1.167	2.6	1.5
OGLE-TR-56	1.29	0.0225	0	78.8	1.17	1.32	3.2	1.0
OGLE-TR-10	0.63	0.04162	0	84.5	1.18	1.16	7	1.0
HD 17156	3.111	0.1594	0.6717	88.23	1.2	1.47	2.6	1.1
XO-3	11.79	0.0454	0.26	84.2	1.213	1.377	18.54	0.17
OGLE-TR-132	1.14	0.0306	0	85	1.26	1.34	5.0	
WASP-7	0.96	0.0618	0	89.6	1.28	1.236	17	2.0
HAT-P-2	8.62	0.0677	0.5163	90	1.298	1.416	19.8	1.6
HD 149026	0.36	0.0432	0	85.3	1.3	1.497	6	0.5
WASP-14	7.725	0.037	0.095	84.79	1.319	1.297	4.9	1.0
XO-4	1.72	0.0555	0	88.7	1.32	1.55	8.8	0.5
TrES-4	0.84	0.0488	0	82.81	1.384	1.81	9.5	1.0
HAT-P-7	1.776	0.0377	0	85.7	1.47	1.84	3.8	0.5

The projected rotational velocity measurements and error estimations for each of the host stars were taken from various papers. Measurements for six stars were given without measured errors (OGLE-TR-111 and OGLE-TR-132, Melo et al. 2006; TrES-3, O'Donovan et al. 2007; XO-1, McCullough et al. 2006; GJ 436, Maness et al. 2007; WASP-10, Christian et al. 2008). The remaining measurements for projected rotational velocities for host stars were taken from the following papers: HD 17156, Fischer et al. 2007; XO-4, McCullougoh et al. 2008; WASP-7, Hellier et al. 2008; HAT-P-5, Bakos et al. 2007b; HAT-P-3, Torres et al. 2007; XO-2, Burk et al. 2007; HAT-P-2, Bakos et al. 2007a; XO-3, Winn et al. 2008; HAT-P-7, Pal et al. 2008; TrES-4, Mandushev et al. 2007; TrES-1, OGLE-TR-10, OGLE-TR-56, HD 149026, and HD 189733, Melo et al. 2006; WASP-14, Joshi 2008; HD 209458, Queloz et al. 2000; CoRoT-Exo-2, Bouchy et al. 2008; WASP-5 Anderson et al. 2008; WASP-4, Wilson et al. 2008; CoRoT-Exo-1, Barge et al. 2008; and TrES-2 O'Donovan et al. 2006.

Not all entries in the Extrasolar Planets Encyclopedia whose transits have been observed are included in this research. There are two reasons for this: First, several entries lacked a complete data set. Any entry without measurements for the planet mass, semi-major axis, or host star mass were excluded. Several entries listed no value of the eccentricity; these were assumed to have eccentricities of zero. Second, no value for the star's rotational velocity could be found in the literature. This narrowed the list down to the 28 entries included in this research. The data for this study are shown in Table 1. Again, six of the 28 entries have no error estimates for the stellar rotational velocity.

2.2. *Angular Momentum Calculations*

The angular momentum per unit mass for an exoplanet of mass m_p in a Keplerian orbit about a star of mass M_* (assuming $m_p << M_*$) is given by the following equation:

$$l_p = \frac{L_p}{m_p} = \sqrt{GM_* a\left(1-e^2\right)} \tag{1}$$

where G is the gravitational constant, a is the semi-major axis of the orbit, and e is the orbital eccentricity. The exoplanet masses given in Table 1 are lower limits since the quantity deduced from radial velocity measurements is $m_p \sin i$ where i is the orbital inclination with respect to the obsrever's line of sight. For the transiting exoplanets used here, i is measured (and always near 90°) so accurate exoplanet masses are used.

The angular momentum per unit mass of the host star is given by the following equation:

$$l_* = \frac{L_*}{M_*} = \gamma R_* \left(\frac{V\sin i}{\sin i}\right) \tag{2}$$

where R_* is the stellar radius, γ is the moment of inertia ratio $\left(I/M_* R_*^2\right)$, V is the star's equatorial rotational velocity, and i is the inclination angle of the star's spin axis. Here it is assumed that the stellar spin axis is aligned with the exoplanet's orbital inclination. The moment of inertia ratio for a uniform density, rigid sphere is 2/5 but for centrally condensed stars it can be much smaller. The moment of inertia ratio for the Sun has been determined from measurements to be $\gamma = 0.06$ and is the value used for all the calculations presented here.

To compare the angular momentum content of different planetary systems, the angular momentum per unit mass of the entire system is calculated using the following equation:

$$l_{sys} = \frac{L_* + L_p}{M_* + m_p} \quad (3)$$

To study the angular momentum distribution within a planetary system, the percentage of the angular momentum that resides in the exoplanet is calculated using the following equation:

$$\%L = \frac{L_p}{L_p + L_*} \quad (4)$$

2.3. *Error Estimates*

Errors were propagated through the above calculations to determine the total error for each quantity. Errors were available for most of the parameters in Table 1. Errors in e and i were not used since they were either not given or were too small to have much effect. Errors in the stellar rotational velocity dominate the other errors in the calculations and are thus listed separately in Table 1. As previously mentioned, six of the stars in this research had no error listed for $V \sin i$ so for those systems no errors are calculated and their errors are unknown.

Stellar rotational velocities can be determined a number of ways, including Doppler broadening of narrow spectral lines, Fourier transform methods, Doppler imaging, and interferometry. Our literature search found that Doppler broadening was the technique used for most of the stars in this study. In this method, the width (FWHM) of He I lines in the stellar spectra are measured and, using a relationships between line width and the projected rotational velocity, $V \sin i$ can be determined. With this method, aspects such as gravity, temperature, and turbulence must be accounted for (De Medeiros et al. 2006, Pace & Pasquini, 2004).

3. RESULTS AND DISCUSSIONS

A study performed by McNally (1965) showed that more massive main-sequence stars rotate more rapidly and contain more specific angular momentum than less massive ones. A plot of McNally's results is shown in Figure 1. Each of the crosses gives the average angular momentum per unit mass for a given spectral class. There is a definite break in this trend at spectral class A5, where the slope of decreasing specific angular momentum with decreasing mass becomes steeper. The two solid lines are least squares fits to the data above and below the break. Also included are the angular momentum per unit mass of the Sun (lower box) and the angular momentum per unit mass of the entire solar system (upper box). It has been suggested that if the angular momentum of the planets were included in specific angular momentum measurements, the trend in specific angular momentum with system mass might continue with the same slope as for more massive stars and that this might indicate planet formation. It has also been pointed out that it is risky to extrapolate with only one data point.

To compare the exoplanetary systems studied here with this trend in angular momentum, Figure 2 plots the angular momentum per unit mass of the host stars (asterisks) and the angular momentum per unit mass of the complete systems (triangles) as a function of stellar mass. The average angular momentum per unit mass of the various spectral types provided by the data from McNally (1965) are also shown with crosses and the Sun and

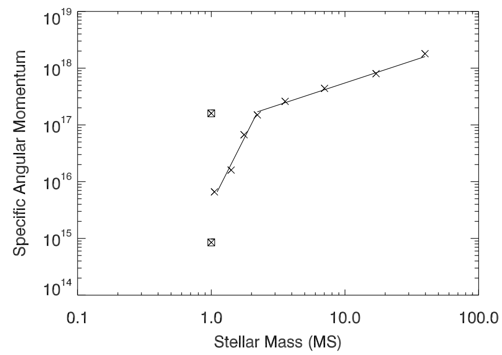

FIG. 1.— Plot of the average angular momentum per unit mass of main-sequence stars for eight spectral classes ranging from O5 in the upper right corner to G0 near the bottom left (McNally, 1965). Also included are the angular momentum per unit mass of the Sun (lower box) and the angular momentum per unit mass of the entire solar system (upper box).

Solar System with boxes. The scale has been expanded somewhat to emphasize the exoplanetary data by leaving off the more massive stars in the McNally data. The dashed line is an extension of the slope from the O5 to A5 data that is included to guide the eye. Errors are not shown for these data because they clutter the figure; a typical value is ≈ 0.1 decade.

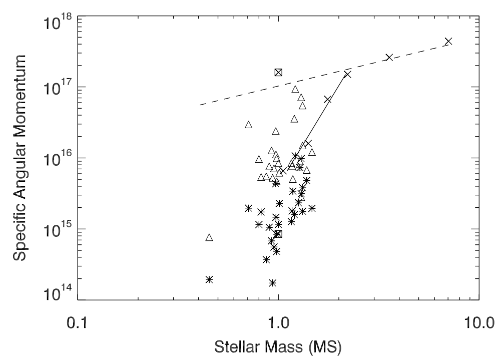

FIG. 2.— Plot of the angular momentum per unit mass of the host stars (asterisks) and the angular momentum per unit mass of the complete systems (triangles) as a function of stellar mass. The average angular momentum per unit mass of the various spectral types from McNally (1965) are also shown with crosses and the Sun and Solar System with boxes.

It is clear from this plot that the host stars have angular momentum per unit mass at or below the slope for stars in this mass range and that the angular momentum per unit mass of the complete systems (star + planets) fall above this slope. It is also clear from this that the angular momentum per unit mass of the complete systems fall below the extended slope of the more massive stars. Thus the conjecture that the specific angular momentum of the complete system might continue with the same slope as the O5 to A5 data is not supported; however, since the specific angular momentum of a planet scales like $l_p \propto \sqrt{a}$, a Jupiter mass planet in a Jupiter like orbit would have ≈ 10 times greater l_p than the planets in this study. Both radial velocity and transit methods are biased toward planets in small orbits. It seems reasonable that there could be undetected

Jovian planets in much larger orbits so the system specific angular momenta given here should be considered lower limits.

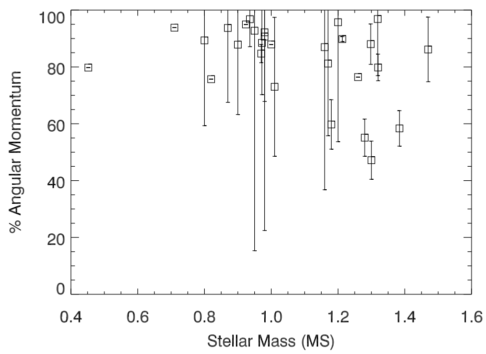

FIG. 3.— Plot showing the percentage of the total angular momentum of the extrasolar planetary system that resides in the exoplanet. Errors are given for all the systems where an error in $V \sin i$ was available.

To further investigate the distribution of angular momentum in exoplanetary systems, Figure 3 shows the percentage of the system's angular momentum that resides in the exoplanet. For this plot, errors in the percentage of planetary angular momentum are given. As indicated before the major uncertainty is in the stellar rotation rates. All of the exoplanets shown here have greater than 50% of the angular momentum contained in the system and many are consistent with 80% or more.

4. CONCLUSIONS

In this paper, we have calculated the angular momentum distribution in 28 extrasolar planetary systems. The distribution of angular momentum between an exoplanet and its host star and between different extrasolar systems systems was determined. Comparing these calculations to the work of McNally (1965), a clear trend is apparent; the angular momentum per unit mass of the host stars is generally less than the average value for main-sequence stars of the same mass and the angular momentum per unit mass of the complete extrasolar planetary system is generally greater. Also, more than 50% of the angular momentum in these systems resides in the exoplanet and in many cases it is more than 80%. To draw any general conclusions about the role of angular momentum in the planetary formation process, however, will require additional work to understand and quantify the selection effects that result from the detection methods.

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