Tidal Forces in the Solar System

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Abstract

Tidal forces are a powerful factor in the development of the solar system. This paper summarizes various tidal effects and categorizes them as either direct or secondary, with secondary effects further categorized as strong or weak. Tidally induced heating, as well as the existence of Roche limits, are direct effects of tidal forces. The tidal acceleration effect, which pushes the moon away from Earth, and the tidal deceleration effect, which pulls the Martian satellite Phobos toward Mars, are weak secondary effects, because they depend on a secondary reaction to tides raised by the gravity of the smaller body on the larger body. The tidal locking/despinning effect, which tends to lock one face of a satellite to its planet, and the tidal circularization effect, which tends to produce circular orbits, are strong secondary effects, because they depend on a secondary reaction to tides raised by the gravity of the larger body on the smaller body. A quantification of some of these tidal forces is provided, and a comparative quantification of other tidal effects is made. Some tidal effects are problematic for an old solar system, while other tidal effects appear to place constraints on creation-based models of a young solar system. Further areas of study are suggested.

Introduction

In 1992, tidal forces caused by Jupiter's gravity tore Comet Shoemaker-Levy 9 into pieces. Two years later, the comet retaliated by smacking into the planet. It was not a unique event. Comet Brooks 2 broke into two pieces within Jupiter's Roche limit in 1886 (Luciuk, 2003). Tidal forces from the sun's gravity may have contributed to the breakup of Comet XIV in 1947, Comet Ikeya-Seki in 1965, Comet West in 1976, and Comet Ison in 2012 (Luciuk, 2003). Hartnett describes data from the ESA/NASA Solar Heliospheric Observatory (SOHO), saying, "The SOHO spacecraft has discovered more than 1000 comets that make close approaches to the Sun. In some instances, the comets' orbits cause them to plunge into the Sun" (Hartnett, 2016). Some of these small sun-grazing comets are thought to be remnants of larger ancient comets torn apart by the sun's tidal force (Sekanina and Chodas, 2012). Figure 1 shows Comet Shoemaker-Levy 9 after it was torn apart and before it hit Jupiter.

Tidal Forces

Tidal forces are caused by the force of gravity. Because the gravitational force between two bodies is a function of the distance between the bodies, the gravitational force on the near side of a body is greater than the gravitational force on the far side, and this produces a tidal force. Figure 2 illustrates a tidal force.

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Figure 1. Comet Shoemaker-Levy 9, which was torn apart by tidal forces before crashing into Jupiter. Photo by the Hubble Space Telescope on May 17, 1994. Photo courtesy of NASA and STScl.

The equation for gravitational force is:

$$F_g = GM_p m_s/d^2 \qquad (1)$$

where

- F_g is the gravitational force
- G is the gravitational constant
- M_p is the mass of the primary body
- m_s is the mass of the satellite
- d is the distance between the primary body and the satellite

The equation for tidal force is:

$$F_{tidal} = F_{near} - F_{far} \qquad (2)$$

or

$$F_{tidal} = 2GM_p m_s R_s/d^3 \qquad (3)$$

where

- F_{tidal} is the total tidal force acting on the primary body
- R_s is the radius of the satellite body

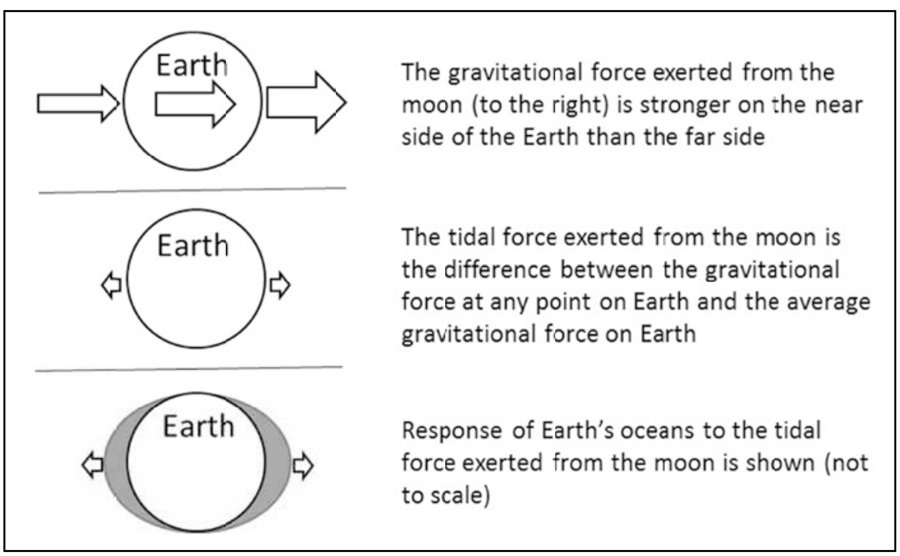

Figure 2. Tidal Forces – Earth/moon example. The moon exerts a gravitational force on Earth, as illustrated by the large arrows in the top drawing. Because it depends on distance, the gravitational force on the near side of Earth is greater than the gravitational force on the far side, producing a residual tidal force, shown by the small arrows on the center drawing. The bottom drawing illustrates how Earth's oceans are raised by the tidal force due to the gravity of the moon.

As equation (1) shows, the gravitational force between two bodies varies based on the distance between the bodies squared, while the tidal force in equation (3) varies based on the distance cubed. Therefore, tidal forces are more sensitive to distance than gravitational forces. Table 1 uses equations (1) and (3) along with well-known physical parameters in the solar system[1] to give a summary of gravitational and tidal forces for the Earth-moon system and for the sun with each planet.

Table 1 shows in a quantifiable form that tidal forces between two bodies are much weaker than the gravitational forces. It also illustrates the sensitivity to

[1] Physical and orbital parameters for bodies in the solar system are from the NASA Jet Propulsion Laboratory Solar System Dynamics web page, ssd.jpl.nasa.gov.

Table 1. Gravitational and Tidal Forces in the Solar System.

	Gravitational Force on Satellite (meters/sec^2)	Tidal Force on Satellite (meters/sec^2)	Gravitational Force on Primary (meters/sec^2)	Tidal Force on Primary (meters/sec^2)
Earth – Moon	2.70E-03	2.44E-05	3.32E-05	1.10E-06
Sun – Mercury	3.96E-02	3.33E-06	6.57E-09	1.58E-10
Sun – Venus	1.13E-02	1.27E-06	2.77E-08	3.57E-10
Sun – Earth	5.93E-03	5.06E-07	1.78E-08	1.66E-10
Sun – Mars	2.56E-03	7.61E-08	8.25E-10	5.03E-12
Sun – Jupiter	2.19E-04	4.03E-08	2.09E-07	3.74E-10
Sun – Saturn	6.50E-05	5.48E-09	1.86E-08	1.81E-11
Sun – Uranus	1.61E-05	2.85E-10	7.01E-10	3.39E-13
Sun – Neptune	6.54E-06	7.19E-11	3.37E-10	1.04E-13

distance for tidal forces, in that although the sun's gravitational force on earth is 180 times greater than the moon's, the moon's tidal force on Earth is twice that of the sun. The gravitational and tidal forces of the planets on the sun are weak. In fact, the moon's gravitational pull on Earth is about 100 times greater than all the planets' gravitational pull on the sun summed together. Their tidal force is much weaker still. For this reason, theories that arise from time to time about the effect of planets lining up, affecting the sunspot cycle or even astrology, should be discounted.

Roche Limits

The comets mentioned in the introduction were torn apart by tidal forces because they crossed within their Roche limit with a larger body. The Roche limit is the distance within which a body, held together only by its own gravity, will disintegrate due to a second body's tidal forces exceeding the first body's gravitational self-attraction (Weisstein, 2007). Comets Shoemaker-Levy 9 and Brooks 2 made the mistake of encroaching within their Roche limit with Jupiter, while comets Ikeya-Seki and Ison entered their Roche limit with the sun.

The equation for the Roche limit between two bodies (Luciuk, 2003) is:

$$d = 2.44R_p(\rho_p/\rho_s)^{1/3} \qquad (4)$$

where

- d is the Roche limit distance
- R_p is the radius of the primary body
- ρ_p is the density of the primary body
- ρ_s is the density of the satellite body

The equation indicates that if the density of a satellite and a primary body are the same, the satellite body will reach its Roche limit at a distance of 2.44 times the radius of the primary body. If the satellite body has no tensile strength, it will be torn apart by tidal forces at that distance. This limit is sometimes called the "liquid" Roche limit, since a rigid body within the limit may hold together for some time due to tensile strength. Earth's moon is far beyond its Roche limit, but a number of satellites in the solar system are close to or even within the limit. The Martian satellite Phobos is at a distance of 88%, or within its limit, and ten other satellites in the solar system (Pan, Daphnis, Atlas, Prometheus, Pandora, Cordelia, Ophelia, Naiad, Thalassa, and Despina) are farther inside the Roche limit with their respective planets, in percentage terms, than Phobos. Figure 3 shows the proximity of selected satellites to their Roche limit.

Phobos is slowly moving toward Mars due to tidal deceleration (which will be discussed later). Estimates for the time of Phobos's collision with Mars range from 30–50 million years, with one estimate pegged at 43 million years (Efroimsky and Lainey, 2007). However, as Phobos approaches Mars, the tidal stress will increase, and it may be torn apart by tidal forces before it gets there. Some of the rings around the gas giant planets may be the remains of satellites that disintegrated due to tidal forces within their Roche limits with their planets (Henry, 2008), and the breakup of Phobos may form a ring around Mars. The surface of Phobos already shows "stretch marks," as shown in Figure 4, which may indicate the tidal stress that will one day destroy the satellite (Howell, 2015).

Does the subject of Roche limits have any bearing on the question of the age of the solar system? A 43-million-year time frame for the end of Phobos would

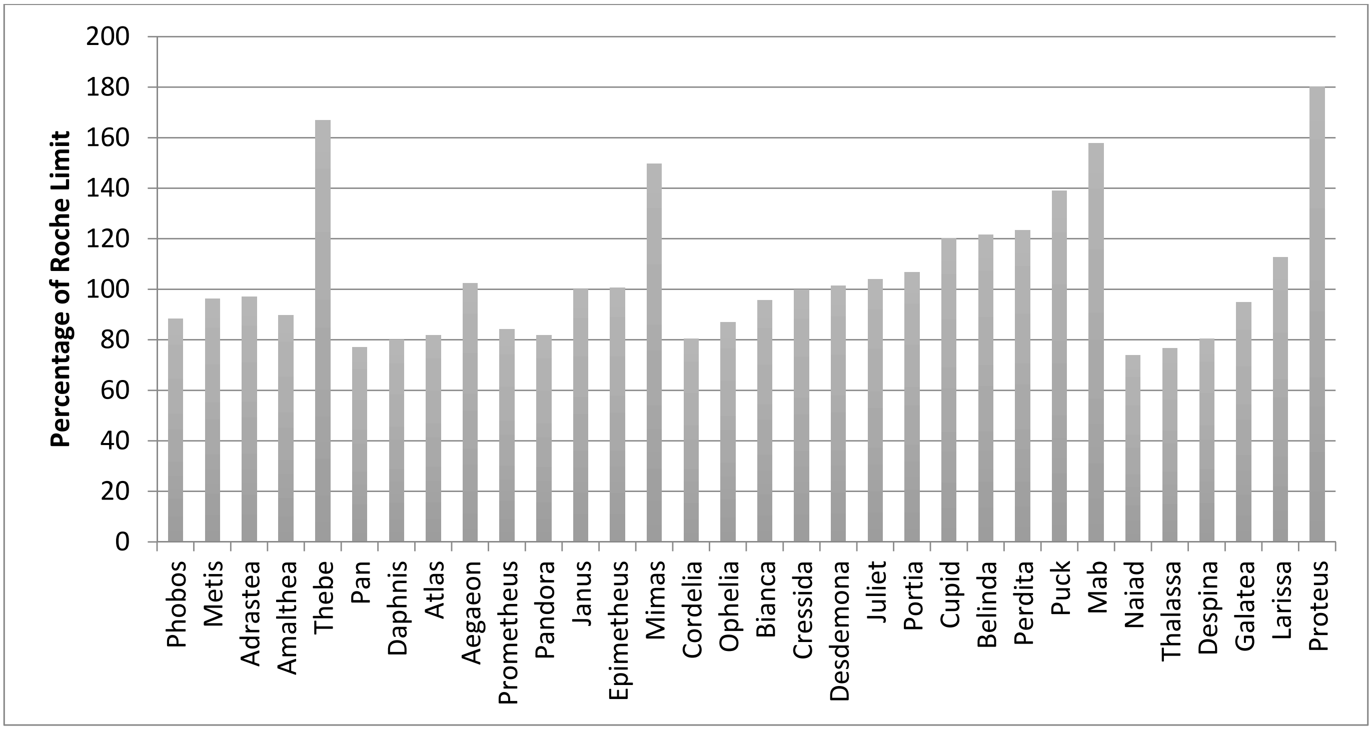

Figure 3. Roche Limits. The chart shows the semimajor axis of satellites as a percentage of their Roche limit. For example, the first satellite shown, Phobos, is at 88% of its Roche limit, so Phobos is within it. All known satellites in the solar system with a value of 200% or less are shown.

be within the last 1% of the age of an old, 4.6-billion-year solar system. If Phobos and the ten satellites farther inside their Roche limit than Phobos were all to break up in the next 43 million years, that would mean that 11 of the solar system's 64 currently known regular satellites would be destroyed during 1% of the solar system's age, which would not seem plausible. However, it is not known whether any of the other ten satellites are decelerating at a significant rate, because neither high-resolution photographs nor measurements of changes in the orbits for the other ten satellites are available yet, so there are no reliable estimates on breakup times for them. The tidal deceleration effect that is moving Phobos closer to Mars is so weak it can scarcely budge any of the other satellites closer to their gas giant planets. Tidal deceleration due to interaction with outer satellites, which will be discussed later, will also not be significant. However, drag can be a factor on satellites close to a planetary body. Drag lowers the orbit of the International Space Station, at an altitude of about 400 km, by 1 km every month or two, depending on variations in Earth's atmosphere. Jupiter's interior satellites Metis, Amalthea, and Thebe show different coloring on their leading and trailing sides, indicating that they are hitting matter as they orbit (Simonella et al., 2000) and encountering some drag. Pan, Daphnis and Atlas are walnut shaped, apparently from gathering material from Saturn's rings and therefore are also encountering drag. Hopefully, future accurate measurements of changes in these orbits will shed more light on the subject.

The continued existence of short-period comets has long been used as an argument for a young solar system, since each time a comet approaches the sun, its ice is heated and some matter is lost (Steidl, 1983). The fact that three comets in the last 25 years have been destroyed by tidal forces, while others discovered by SOHO have plunged into the sun, is anecdotal evidence for another way comets are eliminated and could be factored into the argument.

Secondary Tidal Effects

Tidal forces produce secondary effects, including tidal acceleration, tidal deceleration, tidal circularization, and tidal locking. These effects are secondary in that they first involve the raising of tides on a body due to tidal forces, then those tides act or are acted upon by other gravitational or tidal forces. The secondary application of gravitational or tidal

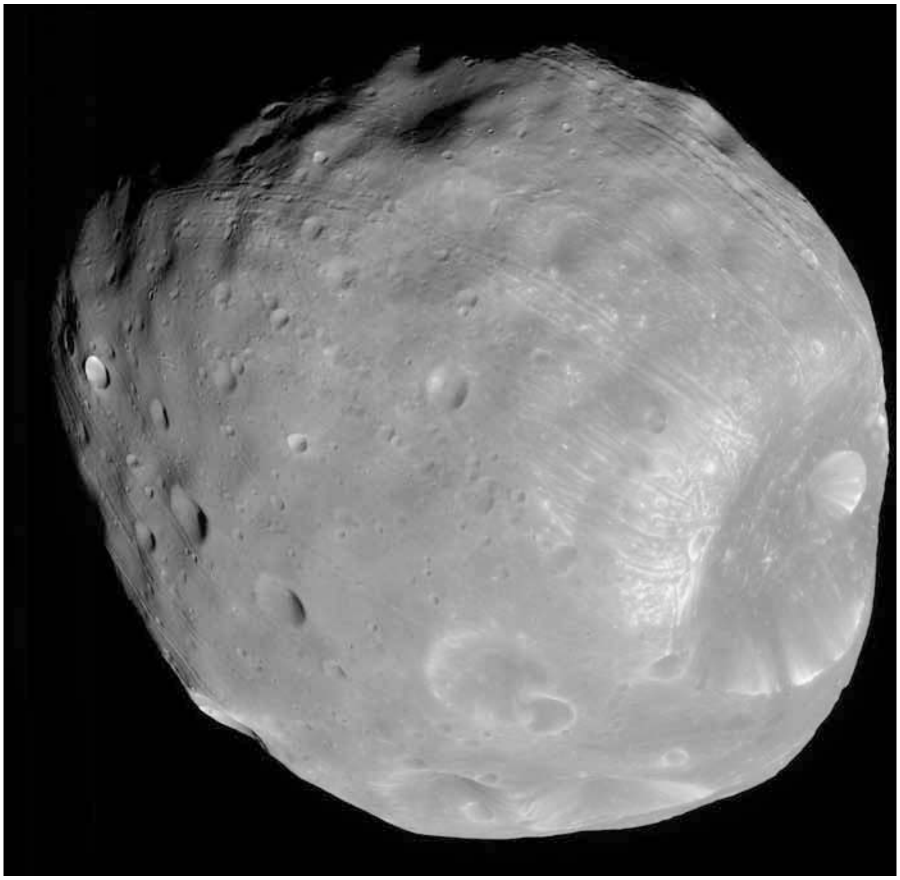

Figure 4. Photo of Phobos taken by NASA's Mars Reconnaissance Orbiter on March 23, 2008. The lines may be stretch marks caused by tidal forces. Photo courtesy of NASA/JPL-Caltech.

forces means that these effects are even more sensitive to distance than direct tidal forces; the strength of the forces between two bodies varies inversely based on the distance between them raised to the fifth or sixth power. Table 2 summarizes the tidal interactions in the solar system.

Tidal Acceleration and Deceleration

A satellite will raise tides on a planet, leading to either tidal acceleration or tidal deceleration of the satellite. (These unfortunate terms can be confusing, since a body that undergoes tidal acceleration ends up moving slower at a higher orbit, while a body that undergoes tidal deceleration ends up moving faster at a lower orbit.) Because tidal acceleration from tides on a planet involves tides raised by the smaller body's gravity on a larger body, tidal acceleration can be considered a *weak* secondary tidal effect.

The best-known example of a satellite raising tides on a planet is on Earth, where the moon causes high and low

Table 2. Possible Tidal Interactions.

Tides Raised on	Tides Raised by	Raises or Lowers Orbit of	Changes Rotation of	Heating Due to Friction	Orbit Eccentricity
planet	satellite	satellite	planet	planet	increases
satellite	planet	neither[6]	satellite	satellite	decreases
satellite	satellite	both[7]	negligible[8]	both	varies
Sun	planet	negligible	negligible	negligible	negligible
Sun	satellite	negligible	negligible	negligible	negligible
planet	Sun	negligible	inner satellites	negligible	negligible
satellite	Sun	negligible	negligible	negligible	negligible

[6] Assuming the satellite is tidally locked and has low eccentricity.

[7] Inner satellites move lower and outer satellites move higher.

[8] The tendency of the planet to tidally despin/lock a satellite will overwhelm the interaction between satellites.

tides on the ocean. High tides typically raise the ocean by about one meter and raise the continental crust by about 30 centimeters (Pogge, 2007). However, because the earth is rotating more rapidly than the moon is orbiting, the highest tides are constantly being rotated a little ahead of a direct line to the moon; the axis of highest tides is not on a straight line to the moon, but about 10 minutes of time ahead of it (Goldreich and Soder, 1966). Because the gravitational pull on the moon is greater from the near side of the planet than from the far side, the advanced tidal bulge accelerates the moon forward a little bit and tends to raise its orbit. The effect is strongest at perigee, the point in the moon's orbit when it is nearest to the planet, so this effect also tends to increase the orbit's eccentricity. The effect, known as tidal acceleration, is illustrated in Figure 5 and applies to any planet-satellite system in which the planet rotates faster than the satellite orbits. Because the total angular momentum in the overall planet-satellite system must be preserved, there is an opposite effect on the planet known as tidal braking, tidal locking, or tidal despinning. Tidal braking slows the rotation of the planet and will be discussed later. Some angular momentum is also lost to friction inside the planet. The effect is analogous to placing a hand on a spinning wheel: the wheel tends to accelerate the hand, the hand tends to brake the wheel, and there is some heat due to friction.

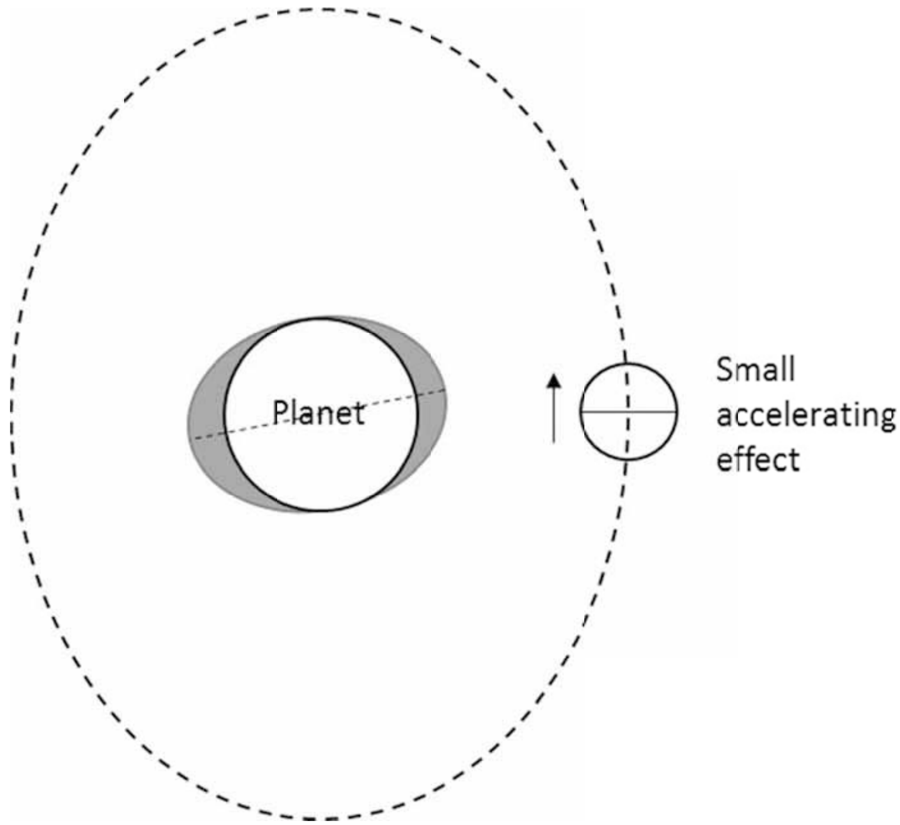

Figure 5. Tidal Acceleration (not to scale). Because the planet rotates faster than the satellite orbits, the tides raised on the planet are rotated a little ahead of a direct line to the satellite. The gravitational pull on the satellite from the near side high tide is greater than the pull from the far side high tide, causing the satellite to accelerate slightly and the planet to slow its rotation slightly.

The current rate at which the moon moves away from Earth has been accurately measured by lunar laser ranging at 38.3 mm per year, or 3.8 meters per century. The lunar perigee is increasing at a rate of 30.4 mm per year, while the apogee is increasing by 46.2 mm per year, illustrating the tendency to increase the orbit's eccentricity (Williams, Boggs, and Ratcliff, 2016). Lisle and others have argued that this lunar recession due to tidal acceleration places an upper bound on the age of the Earth-moon system that is lower than the 4.6 billion years usually assumed for the solar system (Lisle, 2006).

If a satellite is orbiting a planet faster than the planet rotates, the effect is reversed: the satellite is pulled closer to the planet (tidal deceleration), and the planet rotates faster. The effect is analogous to pushing on a spinning wheel to try to make it go faster: the wheel tends to decelerate the hand, and the hand tends to speed up the wheel. There are 19 known satellites in the solar system that orbit very close to their planet such that their orbital rate is faster than their planet's rotation rate. The best studied case, due to its proximity to Earth, is Phobos, the interior satellite of Mars. Phobos completes an orbit of Mars every 7 hours and 39 minutes, while Mars rotates once every 24 hours and 37 minutes. Measurements indicate that the orbit of Phobos is decreasing by 2 meters every 100 years, which will cause its eventual breakup, as discussed earlier (Beatty, 2015).

The Earth-moon system and the Mars-Phobos system are the only instances in the solar system in which changes in a satellite's orbit have been directly measured with a high degree of confidence, although some effort has been made to quantify this effect mathematically. The tidal equation for

Table 3. Tidal Acceleration/Deceleration of Selected Satellites by Equation (6).

Satellite	Tidal Quality Factor Q of Planet[9]	Love Number k_2 of Planet	Current Semi-Major Axis (1000 km)	100 Year Change (meters)
Moon	12	0.302	384.4	3.73
Phobos	99.5	0.164	9.4	-3.50
Deimos	99.5	0.164	23.5	0.004
Io	35600	0.37	421.8	11.2
Europa	35600	0.37	671.1	0.47
Mimas	2453	0.39	185.6	5.13
Enceladus	2453	0.39	238.0	3.76
Tethys	2453	0.39	294.7	6.64
Dione	2453	0.39	377.4	3.02
Rhea	2453	0.39	527.1	1.01
Titan	2453	0.39	1221.9	0.58
Miranda	500	0.104	129.9	2.94
Ariel	500	0.104	190.9	7.27
Umbriel	500	0.104	266.0	1.02

9 Values of Q and K_2 for Mars, Jupiter, Saturn, and Uranus are taken from Lainey (2016).

change in a satellite's semimajor axis[2] first developed by William Kaula is (Efroimsky and Lainey, 2007):

$$da/dt = -3k_2R^5Gm \; / \; Q\,(\mathrm{sqrt}(G(M_0 + m))a^{11/2} \qquad (6)$$

where

- da/dt is the change in the semimajor axis of the motion of the satellite around the planet in meters per second
- k_2 is the tidal Love number of the planet, a measure of its rigidity
- R is the radius of the planet
- G is the gravitational constant, 6.674×10^{-11} N·m²/kg²
- m is the mass of the satellite
- Q is the dissipation function of the planet, or tidal quality factor = half the rate at which energy is dissipated through friction
- M_0 is the mass of the planet
- a is the semimajor axis; the distance between the planet and the satellite

Table 3 uses equation (6) to calculate the change in the semimajor axis of selected satellites.

Equation (6) gives a result that roughly matches the measured results for the moon and Phobos, though the given deceleration of Phobos is higher (3.6 meters) than what has been measured (2 meters). Earth's tidal quality factor Q value of 12 is lower than any other planet because of the presence of liquid oceans on the surface, and this is an important factor in the recession of the moon. For other bodies in the solar system, any conclusions should be tentative, since k_2 and Q are not usually well known now and may have changed over time. Also, for gas giant planets, the presence of multiple satellites may introduce other factors that overwhelm the effects of tidal acceleration or deceleration. Jupiter's satellite Io would be moving away from Jupiter at 11 meters per 100 years, but there is reason to believe that is not occurring, perhaps due to Io's resonance with other Jovian satellites (Lainey, 2009).

Based on equation (6), some of the satellites of Saturn and Uranus show significant acceleration. The larger satellites of Saturn inside of Titan (Mimas, Enceladus, Tethys, and Dione) accelerate at rates similar to the moon (5.1, 3.8, 6.6, and 3.0 meters per 100 years, respectively). Because all these satellites are closer to Saturn than the moon is to Earth, they present the same dilemma for an old solar system model as the recession of the moon. "The present quantification of Saturnian tidal dissipation is incompatible with a satellite formation scenario in Saturn's subnebulae for all moons below Titan" (Lainey et al., 2012). In the Uranus system, Ariel and Umbriel, both closer to the planet than the moon is to Earth, move away from the planet at rates of 2.9 and 7.3 meters per 100 years.

The tidal acceleration numbers for the satellites of Saturn and Uranus are large enough to constitute a new argument against an old solar system model. This analysis is new, since until recently, the tidal quality factor Q of the gas giant planets was assumed to be much larger. The assumption was made partly to preserve an old solar system, as Goldreich and Soder write, "For if Q_p were too small, the orbits' evolution would be

2 The semimajor axis is the average orbital distance.

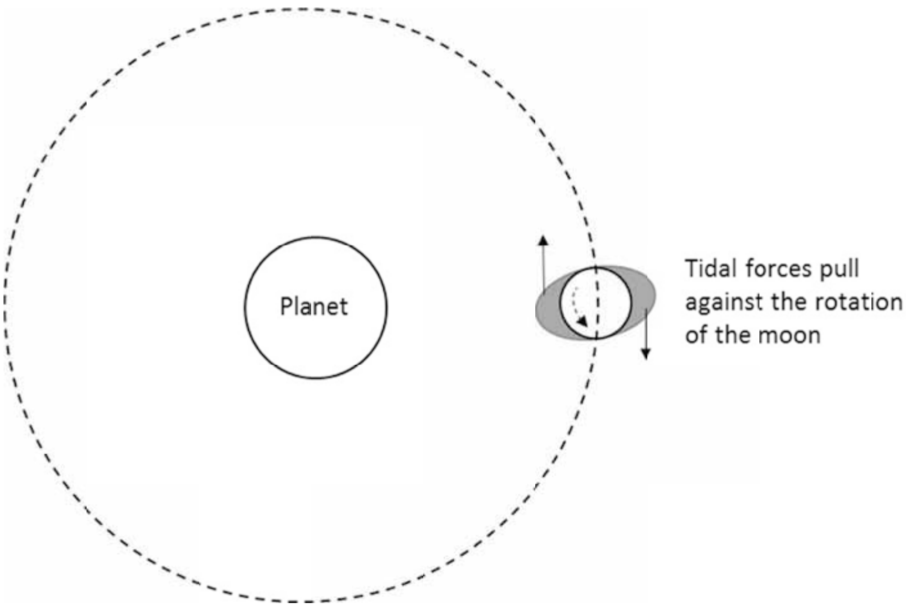

Figure 6. Tidal Locking applies to a satellite that rotates faster than it orbits. The tides raised on the satellite are rotated forward, a little ahead of a direct line to the planet. The planet's gravity pulls forward on the near side high tide and pulls back on the far side high tide, slowing the rotation and eventually locking the satellite into a spin-synchronous orbit in which the same side of the satellite always faces the planet.

too rapid and, tracing them back in time, the satellites would have been at the surface of the planet less than 4.5 X 10^9 years ago" (Goldreich and Soder, 1966). Therefore Goldreich and Soder set Q values for Saturn at 60,000 to 70,000 and for Uranus above 72,000 (Goldreich and Soder, 1966). It is only recently that Lainey and others used measurements from the Cassini spacecraft to calculate a new, much lower Q value (2453) for Saturn (Lainey, 2016). The estimated Q value for Uranus (500) is expected to be substantially refined by future observations (Lainey, 2016).

Tidal Locking

Tidal locking causes the orbital period and rotational period of a body to become equal, thereby locking the same face of a satellite to its planet, as Earth's moon always has the same side facing Earth. This is also called tidal despinning, or tidal braking. Because tidal locking in this portion of the discussion involves tides raised by the larger body's gravity, tidal locking can be considered a *strong* secondary tidal effect. The force for tidal locking is strong enough that it has been used on artificial tethered satellites in a technique known as gravity-gradient stabilization (Fischell, 1964).

Figure 6 illustrates the tidal locking/tidal despinning effect. The planet raises tides on a rotating satellite. Because the satellite is rotating more rapidly than it is orbiting, the highest tides are constantly being rotated a little ahead of a direct line to the planet; the axis of highest tides is not on a straight line to the planet but a little ahead of it. The planet's gravity pulls back on the tidal bulges, slowing down the satellite's rotation. This effect applies to any planet-satellite system in which the satellite rotates faster than it orbits, and to planets with the sun. If a satellite is close enough to a planet so that it orbits faster than it rotates, the effect reverses: the forces work in the opposite direction but still with the end result of locking the satellite to the planet. The effect is analogous to resting a hand on a spinning wheel until it stops spinning.

Because the total angular momentum in the overall planet-satellite system must be preserved, the orbit of the satellite is raised as the satellite despins, until it reaches the point where the satellite is tidally locked to the planet. This increase in the satellite's orbit due to its own tidal locking has not usually been considered in previous treatment of the recession of the moon. For the moon, the increase would be on the order of hundreds (not thousands) of kilometers, marginally strengthening the classic young solar system argument based on lunar recession.

Because the tidal forces are strongest at periapsis and weakest at apoapsis, as the orbit is lifted, the tidal despinning effect tends to increase the eccentricity of the satellite's orbit, though this effect will be very slight.

Tidal locking time can be calculated with this formula (Peale, 1977):

$$t_{lock} = wa^6IQ / 3Gm^2k_2R^5 \qquad (7)$$

where

- w is the initial spin rate expressed in radians per second
- a is the semimajor axis of the motion of the satellite around the planet
- $I = 0.4m_sR^2$ is the moment of inertia of the satellite, where m_s is the mass of the satellite and R is the mean radius of the satellite,
- Q is the dissipation function of the satellite, or tidal quality factor = half the rate at which energy is dissipated through friction.
- G is the gravitational constant, 6.674×10^{-11} N·m^2/kg^2
- m is the mass of the planet

Table 4. Tidal Locking Time Scales of Planets by the Sun.

	Tidal Quality Factor Q[10]	Love Number k_2	Time in Years	Time in Years (Peale, 1977)
Mercury	100	0.451	4.43E+08	2.8E+07
Venus	17	0.295	5.49E+9	2.9E+08
Earth[11]	12	0.302	2.39E+10	1.8E+09
Mars	99.5	0.164	3.25E+12	7.6E+10
Jupiter	35600	0.37	2.59E+17	4.4E+12

[10] Values of Q and k2 are taken from Lainey (2016) and Chen (2013).

[11] The "Time in Years" result for Earth is misleading, since despinning due to the tidal force of the moon will occur five times faster than despinning by the sun.

- k_2 is the tidal Love number of the satellite
- R is the radius of the satellite

All regular satellites[3] in the solar system out through Saturn, except for Saturn's satellite Hyperion, are tidally locked to their planet. Neptune's satellite Triton is tidally locked, and Pluto and Charon are both locked to each other. The satellites of Uranus are presumed to be locked, though this has not been confirmed by observation. No planets are locked to the sun, although Mercury is in a 3:2 spin-synchronous orbit, and Venus rotates very slowly in a retrograde direction. Tables 4 and 5 are illustrative of the time it would take selected planets and satellites to lock to their planet, assuming a theoretical scenario in which the satellites started in their current location and had a rotational period of 12 hours.[4] The times provided in Tables 4 and 5 are dependent on the supplied values of Q and k_2 for the satellites, which are not well known outside the Earth-moon system and may be off by more than an order of magnitude. Also, the initial 12-hour period is only a reasonable guess, and the results are heavily dependent on the distance involved, which may have changed over time. Therefore, the results should be considered illustrative only rather than highly accurate. An alternate set of results (from Peale, 1977) is provided for comparison.

The timescales involved in tidal locking appear problematic all around. Some of the tidal locking timescales, like those for the moon and Saturn's satellite Iapetus, appear to be too long for a young solar system and appear to constrain young solar system models to assume an initial creation with at least some of the regular satellites already in a locked state. The fact that the gas giants spin more quickly than the inner planets could be considered a successful prediction of an old solar system model, since over a long timescale, the sun's tidal locking effect would be significant for the inner planets but negligible from Mars outward. On the other hand, neither Mercury nor Venus is exactly locked to the sun. Since every other body that has locked to its primary is in a 1:1 nearly circular rotation, it is not clear why Mercury would be in an elliptical orbit with a 3:2 spin synchronous rotation nor why Venus should rotate slowly in a retrograde motion. Finally, the fact that Earth spins more quickly than Mars would be unexpected in an old solar system for three reasons: (1) the sun despins Earth more quickly than Mars because Earth is closer, (2) the moon has an even more powerful despinning effect on Earth than the sun does, and (3) Earth has a smaller tidal quality factor "Q" than Mars, which would cause Earth to despin more quickly. The moon's despinning effect would have been stronger in the past when it was closer to Earth and should in fact have slowed Earth's rotation all the way down to a tidally locked state.

Tidal Circularization

Tidal circularization will occur only after tidal locking, since a spinning satellite negates the alignment of the tides described in this section.[5] Because tidal cir-

[3] Regular moons are moons that appear to have their origin connected to the planet they orbit. The solar system also contains irregular moons that appear to not have their origin connected with their planet, but instead appear to have been captured at some later time by the gravity of the planet. Regular moons orbit close to the planet in near-circular orbits near their planet's equator, while irregular moons orbit much farther from their planets, usually with high inclinations and high eccentricity. Neptune's moon Triton stubbornly defies these two obvious categories and would require a treatment all its own.

[4] 12 hours is a rough median for a rotation period of known solar system bodies that are not tidally locked.

[5] The planet Mercury gives an example of a body that is close to but not quite tidally locked to its primary—it has a 3:2 spin-orbit resonance with the sun with a very slow, 58-day rotation period. Despite being nearly locked to the sun, Mercury has the highest eccentricity of any planet, indicating that no significant circularization has occurred.

Table 5. Tidal Locking of Selected Satellites by Planets.

	Tidal Quality Factor Q	Love Number k_2	Time in Years	Time in Years (Peale, 1977)
Moon	37.5	0.02405	2.05E+07	3.2E+06
Phobos	100	0.01	1	880
Deimos	100	0.01	313	9.1E+05
Io	13.6	0.8	26	50
Europa	100	0.25	1180	1200
Ganymede	100	0.6	5210	6600
Callisto	100	0.5	11,750	2.2E+05
Mimas	100	0.1	5.6	140
Titan	100	0.589	1.27E+05	1.9E+05
Hyperion[12]	100	0.1	3.19E+07	9.2E+07
Iapetus	100	0.1	1.13E+10	8.7E+08
Oberon	100	0.1	32993	2.7E+05
Triton	100	0.1	15,100	2000
Charon	100	0.1	21,900	
Pluto (by Charon)	100	0.1	1.77E+06	
Earth (by moon)	12	0.302	5.04E+09	

[12] Hyperion rotates chaotically and is the only regular satellite in the solar system known to be not tidally locked. It is possible that its proximity to and 4:3 resonant orbit with Saturn's large satellite Titan is preventing tidal locking from occurring.

cularization in this discussion involves tides raised by the larger body's gravity, tidal circularization can be considered a *strong* secondary tidal effect.

If a satellite is in an elliptical orbit with its face locked to the planet (like the moon and almost all the regular satellites in the solar system), it must rotate at a uniform rate, but it doesn't orbit around its planet at a uniform rate. Therefore, the tidal bulges move back and forth across the satellite a little. (This flexes the matter in the satellite and can heat the satellite due to friction, as discussed later.)

At periapsis, when the satellite is closest to the planet, the satellite's orbital velocity is at maximum. Here, its rotation begins to lag behind its orbital motion. The near side bulge pulls ahead of the planet, and the far side bulge falls behind. The gravitational pull on the near-side bulge is stronger than the pull on the far-side bulge. Therefore, there is a small backward tug on the near-side bulge, slowing down the satellite's orbital velocity. The rotation catches up with the orbital motion at apoapsis when the satellite is farthest from the planet and then begins to pull ahead. This braking effect at periapsis and acceleration at apoapsis circularizes the orbit. Figure 7 illustrates this effect.

Since none of the planets are tidally locked to the sun, no tidal circularization of the orbits of planets has occurred. Table 6 lists the planets and the eccentricity of their orbits, showing that there is no correlation between their distance from the sun and their orbital eccentricity. In fact, Mercury has the highest eccentricity even though it is closest to the sun. On the other hand, any table of regular satellites in the outer solar system will show lower orbital eccentricities than are present in the planets. As an example, Table 7 shows the eccentricities of the eight interior satellites of Jupiter.

The comparison of the eccentricity of Jupiter's satellites with the sun's planets shows that the satellites as a group have lower eccentricity than the planets (the same pattern is present for satellites of Mars, Jupiter, Saturn, Uranus, and Neptune, though not Earth). Unlike the planets, all these satellites are tidally locked, so tidal circularization may have affected them.

Of all the tidal effects, tidal circularization is the one that is most sensitive to distance. The reason is that in addition to being a secondary effect, a tidally locked satellite has the same rotational period as its orbital period, so if its orbital period is large, its rotation will be slow. The slower a satellite rotates, the weaker the tendency to rotate tides forward becomes. Although the Earth-moon system is undergoing tidal circularization, the one-month rotation period for the moon is so slow that the tidal circularization effect is weaker than the tidal acceleration effect causing the lunar recession, so the moon's orbit is becoming more eccentric rather than circularizing.

Meibom and Mathieu (2004) indicate in a study of binary stars that those with an orbital period of 10 days or less tended to be highly circularized, while those with a longer period were not. Figure 8 shows a plot of the eccentricity of solar system satellites against their orbital period, with results similar to those of Meibom and Mathieu (2004). The conclusion is that tidal circularization has a powerful effect close to a planet, but at distances greater than those involving about a ten-day period, the tidal circularization effect is ineffective and/or swamped by other factors.

The equation for tidal circularization timescale given by Rasio et al. (1996) is:

$$t = 4/63Q\,(a^3/GM)^{1/2}\,(m/M)(a/R)^5 \qquad (8)$$

where

- t is the time to circularize an orbit
- Q is the dissipation function of the satellite, or tidal quality factor = half the rate at which energy is dissipated through friction
- a is the semimajor axis
- G is the gravitational constant, 6.674×10^{-11} N·m²/kg²
- m is the mass of the satellite
- M is the mass of the primary
- R is the radius of the satellite

For most satellites in the solar system, equation (8) gives values too high for a young solar system, indicating that if a satellite initially had an eccentric orbit, the time to circularize the orbit would be greater than the life of the solar system. This places a constraint on young solar system creation models that requires satellites to be created in orbits nearly as circular as they are today. It does not mean that tidal circularization has no effect in a young solar system—some satellites close to their planets would circularize even in a short time frame, and almost all satellites would today be in an orbit more circular than the one in which they were created.

For some bodies in the solar system with a circular orbit, equation (8) produces values too great for even an old solar system. The outer satellites of Pluto (Styx, Nix, Kerberos, and Hydra) are all in a nearly circular orbit, though with orbital periods of 20–38 days. Dysnomia, the satellite of the dwarf planet Eris, has a circular orbit with an orbital period of 15 days. These satellites are rotating in any case, so tidal circularization could not have been a factor in their development.

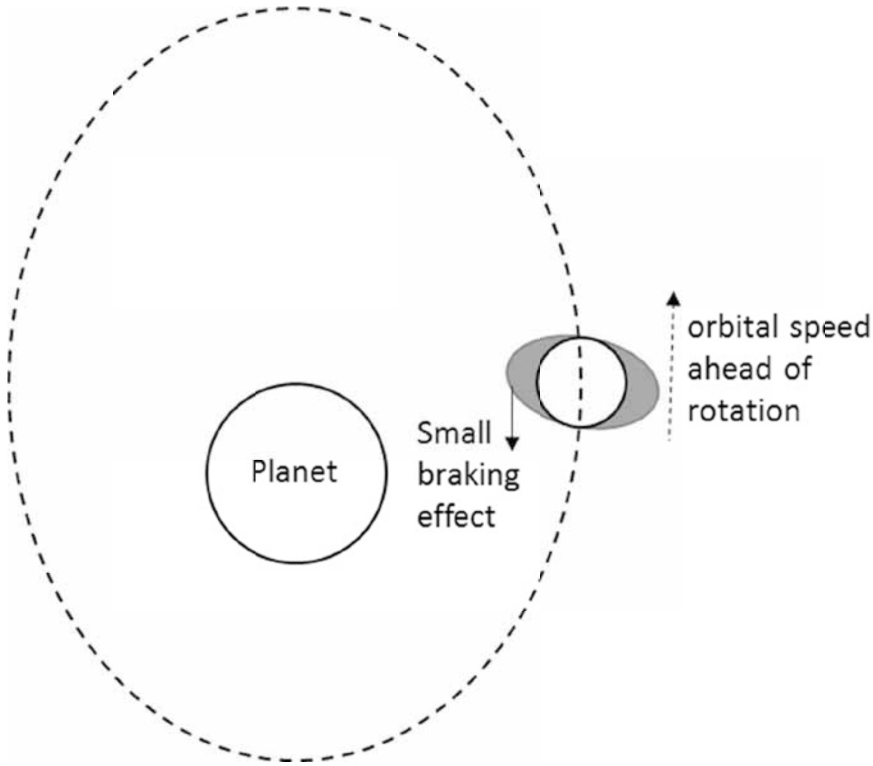

Figure 7. Tidal Circularization applies to a satellite that is already in a spin-synchronous orbit. In an eccentric orbit, the orbital speed varies, but the satellite's rotation is constant. Therefore, the high tides do not always point directly at the planet. When the orbital speed is high and gets ahead of the rotation, the axis of the tides points ahead of the planet. The gravitational force on the near side high tide is greater than the far side high tide, exerting a small braking effect. When the orbital speed is low, the effect is reversed, exerting an accelerating effect, producing a net tendency to circularize the orbit.

Table 6. Orbital Eccentricity of the Planets.

	Distance from the Sun (km)	Eccentricity of Orbit
Mercury	5.79E+7	0.2056
Venus	1.01E+8	0.0068
Earth	1.50E+8	0.0167
Mars	2.28E+8	0.0934
Jupiter	7.78E+9	0.0485
Saturn	1.42E+9	0.0556
Uranus	2.87E+9	0.0464
Neptune	4.50E+9	0.0095

Table 7. Orbital Eccentricity of Jovian Satellites.

	Distance from Jupiter (km)	Eccentricity of Orbit
Metis	1.28E+5	0.0012
Adrastea	1.29 E+5	0.0018
Amalthea	1.81 E+5	0.0032
Thebe	2.22 E+5	0.0176
Io	4.22 E+5	0.0041
Europa	6.71 E+5	0.0094
Ganymede	1.07 E+6	0.0013
Callisto	1.88 E+6	0.0074

The orbits of planets in general are not highly elliptical, though they are not as circular as regular satellites, and tidal circularization could not have been a factor in circularizing the orbits of the planets. Therefore, old solar system models also need to find a reason for circular orbits other than tidal circularization.

Tidal Effects of Multiple Satellites

Multiple satellites orbit the planets Mars, Jupiter, Saturn, Uranus, and Neptune. In addition to the tidal effects between the planets and their satellites, tidal effects between the satellites also exist. These tidal effects are understandably complex and difficult to model mathematically. However, it can be shown that there is a tendency for tidal effects between satellites to decelerate (lower) the lower satellites and accelerate (raise) the higher satellites. "For to the one who has, more will be given, and he will have an abundance, but from the one who has not, even what he has will be taken away" (Matthew 13:12 ESV). The effect is illustrated in Figure 9.

Figure 9 shows a scenario where both satellites are tidally locked to their planet. The inner satellite is orbiting and rotating more rapidly than the outer satellite. Each satellite raises a tidal bulge on the other satellite. As occurs with tides raised on Earth, each satellite rotates its tidal bulge forward, but the inner satellite is rotating more rapidly, so its tidal bulge rotates a little ahead of the tidal bulge on the outer satellite. In the configuration shown in Figure 9, with both satellites on the same side of

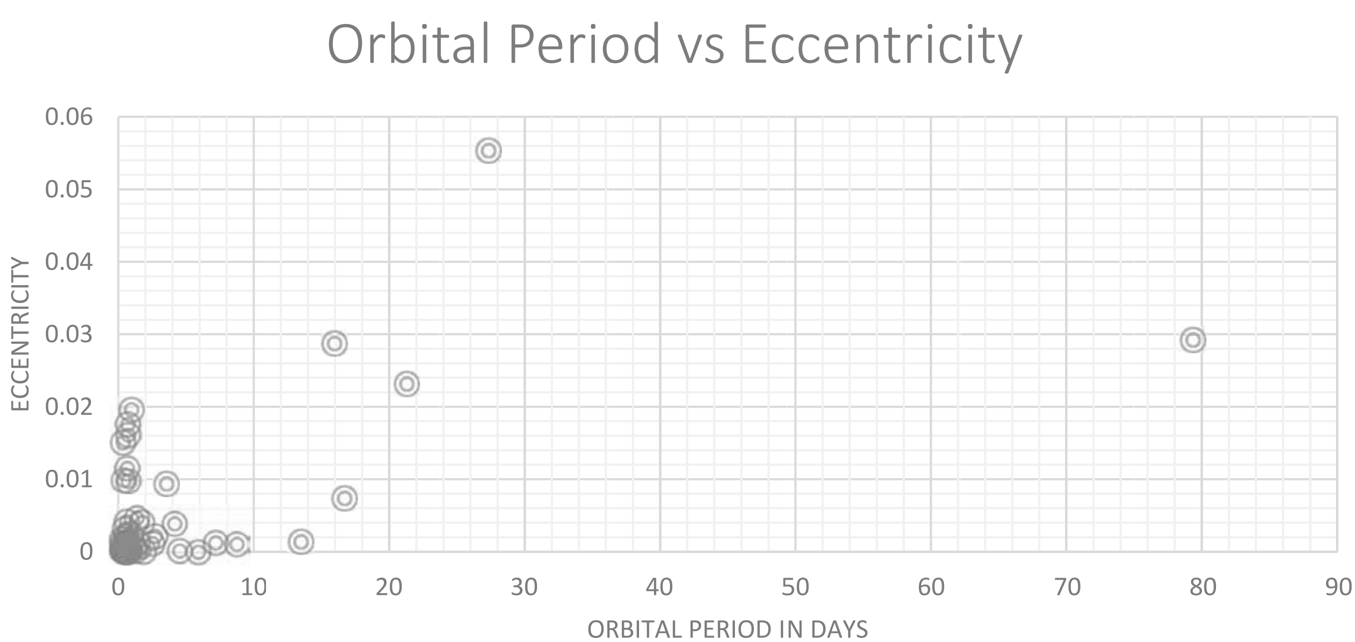

Figure 8. The plot of the eccentricity of 51 regular satellites shows that all satellites with an orbital period of 10 days or less have nearly circular orbits, with eccentricities of 0.02 or less. Satellites with an orbital period greater than 10 days can have more eccentric orbits.

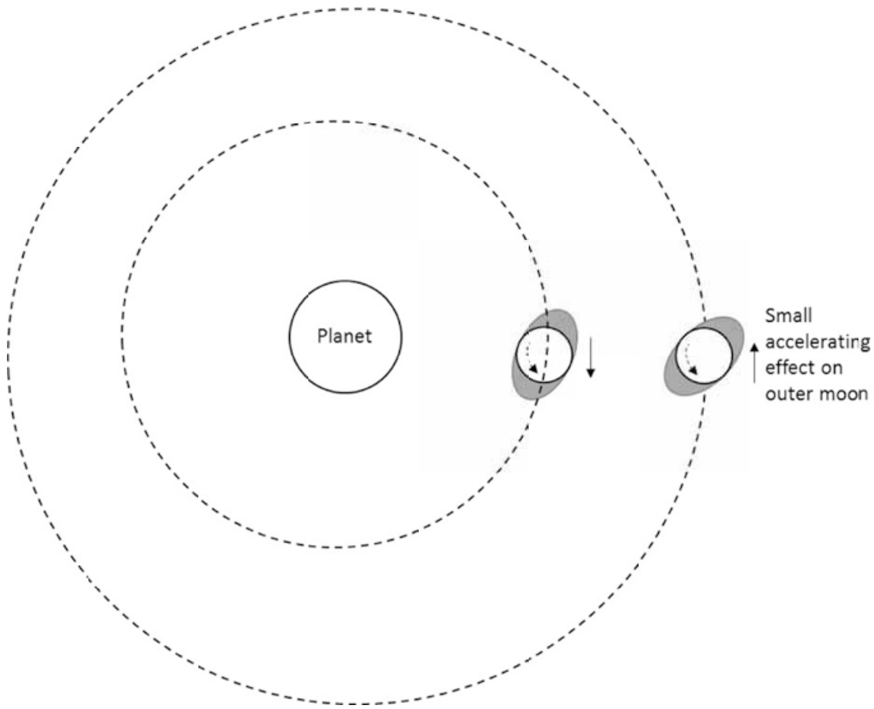

Figure 9. Tides on two Satellites. Both satellites raise tides on each other, and both rotate their tides forward. The inner satellite rotates more rapidly. When the satellites are in conjunction on the same side of the planet, the inner satellite's near side high tide will point ahead of the outer satellite, and the outer satellite's near side high tide will point behind the inner satellite. The gravitational pull of these tides will accelerate the outer satellite and decelerate the inner satellite.

the planet, the outer satellite's gravity pulls back on the tidal bulge of the inner satellite, decelerating the inner satellite and at the same time accelerating the outer satellite. The inner satellite pulls the tidal bulge of the outer satellite forward, with the same effect that the outer satellite is accelerated while the inner satellite decelerates. This effect is present regardless of whether the satellites are in a resonant orbit with each other, as some of the outer solar system satellites are. When the two satellites are on opposite sides of the planet, the tidal bulges get aligned in the opposite direction, so that the inner satellite is accelerated and the outer satellite is decelerated. However, when the satellites are on opposite sides of the planet, the distance between them is greater and the force involved is less, sometimes by more than an order of magnitude. Therefore, the tendency to decelerate the inner satellite and accelerate the outer satellite predominates.

This author is not aware of an accepted mathematical formula quantifying the tidal effects of a multiple satellite system, but it can be shown by analogy that this effect is weak. Io and Europa are the two closest large satellites in the solar system. At their nearest point, using equation (6), Io only accelerates Europa at a rate of 3 centimeters per century. Therefore, while all inner satellites accelerate all outer satellites and all outer satellites decelerate inner satellites, the conclusion should be clear that the tidal interaction between satellites is sufficiently weak that it has not played a significant role in the development of the solar system.

In a study based on analysis of historical eclipses in the Jupiter system, Lainey asserts that from 1893 to 2009, a period of 116 years, Io's semimajor axis has contracted by 55 km (kilometers, not meters), while Europa's increased by 125 km and Ganymede's increased by 365 km (Lainey, 2009). In other words, Io moved closer to Jupiter while Europa and Ganymede moved farther away. Since these satellites are moving away from each other, they should eventually escape their current 1:2:4 resonance. Whether this phenomenon is consistent or not with an old solar system could be the subject of further research. However, this analysis indicates that tidal forces between satellites are not the mechanism driving these changes.

Tidally Induced Heating

If a satellite were tidally locked and in a perfectly circular orbit, there would be no tidally induced heating on the satellite. When a satellite has an eccentric orbit, the tidal acceleration changes over the course of the orbit; it is greatest at periapsis, when the satellite is close to its planet, and least when the satellite is at apoapsis, farthest from the planet. The change in tidal force from periapsis to apoapsis creates a stretch/release process that can create friction and internal heat within the satellite. Also, a satellite in an elliptical orbit must rotate at a uniform rate, but it doesn't orbit around its planet at a uniform rate. Its tidal bulges move back and forth across the satellite a little and add to the tidally induced heating. Because tidally induced heating in this discussion deals with tidal forces created from the gravity of the larger body (the planet), this can be described as a strong effect. Tidally induced heating does not rely on a back reaction; it is a direct tidal effect rather than a secondary effect.

Tidally induced heating can be compared to squeezing (or stretching) a

Table 8. Tidal Force and "Stretch Factor" for Major Satellites.

Primary	Satellite	Mean Tidal Force	Eccentricity	Apoapsis/Periapsis Delta	Stretch Factor
Earth	Moon	2.44E-05	0.0554	8.19E-06	3.00E-07
Jupiter	Io	6.15E-03	0.0041	1.51E-04	8.55E-05
Jupiter	Europa	1.31E-03	0.0094	7.38E-05	2.07E-05
Jupiter	Ganymede	5.44E-04	0.0013	4.24E-06	5.93E-07
Jupiter	Callisto	9.15E-05	0.0074	4.06E-06	2.45E-07
Saturn	Titan	1.07E-04	0.0288	1.86E-05	1.16E-06
Neptune	Triton	4.14E-04	0.000016	3.98E-08	6.77E-09

Figure 10. Jupiter's satellite Io on November 17, 1997. Color mosaic photo from NASA's Galileo spacecraft, showing volcanic plumes. Photo courtesy of NASA/JPL-Caltech.

rubber ball. If the ball is squeezed with a constant level of force that never changes or flexes, there will be no heating due to friction. This is analogous to a satellite that is tidally locked and in a perfectly circular orbit. On the other hand, if the squeezing force increases and decreases periodically, the ball will flex and heat due to friction. This is analogous to a tidally locked satellite with an eccentric orbit, like almost all regular satellites in the solar system. The greater the difference in the maximum and minimum squeezing force, the greater the heating due to friction. Therefore, as the eccentricity of a satellite increases, the greater the differential tidal force and the greater the heating. Finally, if the ball is made to spin as it is being squeezed, the heating will increase further because the axis on which the ball is flexed will be constantly changing. Unlike the spinning ball, most regular satellites do not rotate now, but it is possible to postulate that if they did rotate in the past, their tidal heating would be greater than it is today.

Table 8 shows the tidal force acting on the seven largest satellites in the solar system and calculates a "stretch factor" based on each satellite's eccentricity, its rotational/orbital period, and the tidal force exerted by its planet. The stretch factor is a number without units, but it can give a comparative idea of the heating potential of the tidal forces on each body. This stretch factor is calculated by multiplying a satellite's orbital period by the difference in its tidal force at periapsis and apoapsis. The stretch factor is a measure of stress. Each satellite's ability to dissipate that stress will vary based on its composition and density.

The takeaway from Table 8, based on the far-right column, is that Jupiter's satellite Io has a far larger stretch factor due to tidal forces than any other large satellite in the solar system. Io's stretch factor is more than 250 times as great as what is experienced on the moon. Europa is in second place with four times less stretch factor than Io. Titan is a very distant third, followed in order by Ganymede, the moon, Callisto, and Triton. Correspondingly, Io is by far the most active tectonic body in the solar system, with constant volcanic activity, as shown in the Figure 10 photograph. Europa is tectonically active enough to have a smooth surface with few craters and possibly enough warmth for underground liquid oceans. Triton has shown geyser-like eruptions of nitrogen gas and dust. None of the other large satellites are thought to be very tectonically active.

Smaller icy satellites will dissipate heat more rapidly than the larger rocky satellites. Still, tidal stress on these satellites may cause tectonic activity. Since these are smaller satellites, their gravitational pull and corresponding escape velocity is weaker, and any tectonic activity, if it occurred, could cause matter from the satellites to be lost. Saturn's satellite Enceladus has a stretch factor of 5.26E-

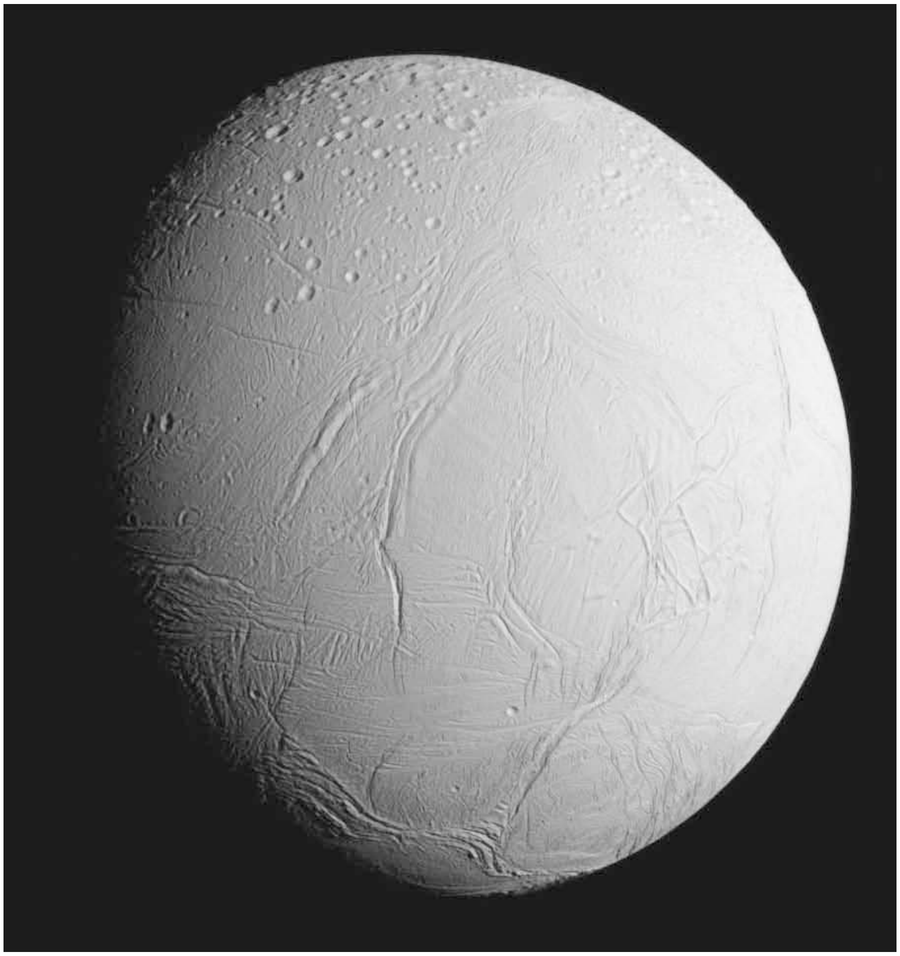

Figure 11. Saturn's Satellite Enceladus on October 28, 2015. Photo by the Cassini Spacecraft. Parts of Enceladus are cratered, but other parts have apparently been resurfaced by tectonic activity. Photo courtesy of NASA/JPL-Caltech.

06, more than all the satellites except Io and Europa. Enceladus has active geysers, and 200 Kg of material escapes the planet's gravity each day to form the E ring of Saturn (Czechowski, 2014). Unlike the more prominent inner rings, the E ring is outside Saturn's Roche limit. Figure 11 shows Enceladus, with evidence of portions of the satellite having been resurfaced by tectonic activity.

Most of the regular satellites in the solar system are tidally locked to their planet. However, in a theoretical scenario or early solar system scenario in which they were rotating with a 12-hour period, the cumulative stretch factor would increase, since in addition to being stretched once per orbit, they would also be stretched twice per 24-hour day. If their eccentricity were increased, that would also lead to increased heating, since the length of the stretch would increase. Table 9 shows how the stretch factor would change in two theoretical scenarios: (1) if instead of being tidally locked, all satellites were rotating with a 12-hour period, and (2) if instead of having nearly circular orbits, all satellites had the same eccentricity (0.0554) as Earth's moon.

The conclusion from Table 9, based on the two right-hand columns, is that

Table 9. Tidal Force and "Stretch Factor" of Theoretical Rotating Satellites.

Primary	Satellite	Mean Tidal Force on Satellite Surface	Real Stretch Factor	Stretch Factor if 12 Hour Rotation	Stretch Factor if 0.0549 Eccentricity
Earth	Moon	2.44E-05	3.00E-07	1.67E-05	3.00E-07
Jupiter	Io	6.15E-03	8.55E-05	3.88E-04	1.16E-03
Jupiter	Europa	1.31E-03	2.07E-05	1.68E-04	1.24E-04
Jupiter	Ganymede	5.44E-04	5.93E-07	9.07E-06	2.55E-05
Jupiter	Callisto	9.15E-05	2.45E-07	8.37E-06	1.84E-06
Saturn	Titan	1.07E-04	1.16E-06	3.83E-05	2.25E-06
Neptune	Triton	4.14E-04	6.77E-09	8.63E-08	2.37E-05

friction and heating in these theoretical satellites responds aggressively to greater rotation and eccentricity. The theoretical Europa's stretch factor becomes greater than the real Io, and most of the other theoretical satellites surpass the real Europa. This might then imply intense tectonic activity on all these satellites. The radical response of these theoretical satellites to such high levels of rotation or increased eccentricity can be a subject of further study and may constrain theories of the origin of the solar system. One example may be on Neptune's large satellite Triton, which has an orbit too circular to generate much tidal heating today. Triton shows evidence of tectonic activity, which may be due to its having a more elliptical orbit in the past. Since Triton is close to the planet Neptune, it could have circularized its orbit quickly, but not yet cooled sufficiently to dissipate all its tidally generated heat.

Conclusions

A young solar system creation model will need to assume that most regular satellites were created in an already tidally locked configuration, because the tidal locking effect takes too much time to start with rotating satellites. A young solar system will also need to assume that most regular satellites were created with orbits nearly as circular as they are today, because in most cases, not enough time has elapsed for tidal circularization to take place.

Tidal forces present several problems for an old solar system model. These include (1) The recession of the moon, which has been understood for years and is marginally increased when the moon's despinning is factored in; (2) the recession of at least four of Saturn's satellites and two of Uranus's satellites at rates similar to or greater than Earth's moon; (3) Earth should not be rotating faster than Mars and should probably already be tidally locked to the moon; and (4) tidal circularization does not provide an adequate reason for the nearly circular orbit of some bodies, like the planets in general or the outer satellites of Pluto.

The destructive capacity of tidal forces when a body enters its Roche limit could be factored into a young solar system analysis of comets. Since so many satellites are already within their Roche limit, future observations of changes in their orbits could indicate whether this fact has any bearing on the age of the solar system.

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The Challenges of Extrasolar Planets

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Abstract

Much has been learned about extrasolar planets in the past 20 years. An overview of the status of the research is presented, addressing exoplanet detection, planet formation and orbit migration, and issues that challenge current theories. Though the observational evidence of extrasolar planets is good in many cases, there are some difficulties in the analysis of the data and limitations of the methods. Extrasolar planetary systems often are very different from our own planetary system. Many known exoplanets are located closer to their stars than Mercury is to the sun. This has prompted development of theories for the migration of planet orbits. Migration theories have challenges in explaining why so many exoplanets have not spiraled into their star and have difficulty explaining exoplanets with orbits that are inclined compared to the equators of their stars. Recent reports from some researchers have expressed concerns that a surprising percentage of transit detections of exoplanets could be due to eclipsing binary stars or brown dwarf stars rather than exoplanets. Another challenge is the large radii of many so-called "hot Jupiters." Known mechanisms may not be adequate to explain the sizes of these planets. Though there is much interest in finding evidence of habitable extrasolar planets, there is still no clear evidence that any exist. The meaning of "habitable zone" is discussed in relation to extrasolar planet research. Extrasolar planets can be understood as being created on the fourth day of the creation week rather than forming from protoplanetary disks.

Introduction

For many years astronomers attempted unsuccessfully to detect evidence of planets orbiting other stars. Then in 1992, an extrasolar planet was found orbiting the pulsar PSR 1257+12 by the use of what is now known as the radial velocity (RV) technique. After some controversy over this discovery, soon there was confirmation of at least two planets orbiting PSR 1257+12 (Wolszczan, 1994), with reason to believe there were more. Since 1992, the technology and methods for detection of extrasolar planets (also known as exoplanets) have improved significantly.

In December 2015, the International Astronomical Union (http://nameexoworlds.iau.org) established

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official names for certain extrasolar planets, including the three planets orbiting PSR 1257+12. The discovery of planets orbiting a pulsar was a major surprise to astronomers. The question of the origin of such a system is still debated today.

There are now significant resources in terms of manpower and equipment that are dedicated to the search for exoplanets. In 2009, the Kepler spacecraft was placed into space in an Earth-trailing orbit. The Kepler spacecraft has dramatically increased the number of possible extrasolar planets known, as well as improved the data available on the objects it observes. Today the NASA exoplanet archive lists 3,373 confirmed exoplanets (NASA, 2016). "Confirmed" indicates that the detection has been confirmed by at least one research team, in addition to the discoverers. Most of these cases are likely to be extrasolar planets, but some are occasionally recategorized as observational errors, brown dwarfs, or other kinds of false positives.

The search for extrasolar planets is strongly motivated by evolutionary ideas and naturalistic assumptions regarding planet formation and the belief that life could evolve on other planets outside our solar system. It is thought that if life evolved on planet Earth, then it could evolve on other planets orbiting other stars, if the exoplanets are habitable. Thus, there is a great interest in finding Earth-like habitable planets orbiting other stars. (In extrasolar planet research, the term "Earth-like" primarily means similar in mass and size.) Statistical estimates based on various observations have been used to gauge the number of exoplanets there could be in in our galaxy. The number of exoplanets in our galaxy (the Milky Way) may be comparable to the number of stars in the galaxy, which implies approximately 100 billion (Clavin, 2012). This is a conservative estimate. The number of exoplanets in our galaxy easily could be double this due to the number of systems with multiple planets. However, this does not mean that life could exist on all these exoplanets.

Prior to the discovery of extrasolar planets 25 years ago, astronomers generally assumed that models of the formation of our own solar system could be used to explain planetary systems that might exist around other stars. But certain key differences were found between our own solar system and the extrasolar planetary systems. First, in many extrasolar systems the planets are so near their stars that the equilibrium temperatures would be too hot for gases to condense onto the planets' cores. Second, exoplanets are not always in "regular" or stable orbits. The orbits of the planets in our system have low eccentricities and low inclinations with respect to one another. Mercury has the most peculiar orbit, with an eccentricity of 0.21, and is tilted seven degrees with respect to the ecliptic, the plane of the earth's orbit. The low eccentricities and inclinations of planets in the solar system make their planet orbits quite stable. But in many exoplanet systems, the orbits are more elliptical than in our system. This makes gravitational interactions possible between planets (if there are multiple planets), and this could lead to the planets altering each other's orbits. Third, many exoplanets orbit so closely to their stars that their spin rates probably are tidally locked, just as our moon is in a tidal lock with Earth. The correct term for this is *synchronous rotation*, which means that the rotation period matches the orbital period. Consequently, this results in one side of an exoplanet always facing the star and the opposite side of an exoplanet always facing away from the star. Fourth, the stars that exoplanets orbit often are not so constant and stable in their energy output as the sun. These characteristics of extrasolar planetary systems have led to changes in planet origins theories. Some of the challenges to planetary science raised by exoplanets have been addressed in new theories, and some challenges are still largely unresolved.

Exoplanet Detection

The detection technique which is applicable to the largest variety of stars is the RV technique (Anderson, 2008; Knutson et al., 2014, Konacki, 2005). This is a spectrographic measurement of the Doppler motion of a star a planet may be orbiting. Due to Newton's third law of motion, the orbit of a planet around a star causes a periodic change in the velocity of the star. This is detected as a component of the star's velocity along Earth's line of sight. If more than one planet is present, there can be more than one superimposed periodic change in the star's radial velocity. As the star's redshift varies, observations over several orbits can sort out these multiple periodicities. It is necessary to rule out other types of variations in the star's light interfering with the measurement.

The RV technique is more effective when the exoplanet is nearer to the star, the exoplanet's mass is greater, or the star's mass is less. The exoplanet's orbit can be determined, assuming there is good data on the star and no complicating observational issues. Thus, the RV technique has a bias toward smaller stars and larger planets. In some systems where the star is more massive and the planet could be small, such a small planet may be more difficult to detect. Finally, if the star is far from Earth, the spectral signal may be weak, and this can limit the method. The RV technique is generally used for relatively nearby stars in our galaxy. Until 2014, there were more discoveries of exoplanets by the RV technique than by any other technique. The RV technique reveals an exoplanet's mass, but not its size (radius).

Since the Kepler telescope spacecraft was deployed in space in 2009, more exoplanets by far have been discovered using the transit photometry technique than any other technique

(Borucki et al., 2009; Steffen et al., 2010). Kepler is not the only instrument that does transit measurements, but it has been the most productive. The Kepler spacecraft has an array of cameras that simultaneously record the brightness of thousands of stars in a large patch of the sky. Sampling star brightness every twenty minutes, Kepler has discovered many variable stars. However, its intended purpose is to detect planets as they pass in front of their stars once each orbit. The transit technique works only if we lie very close to the orbital plane of an exoplanet. Therefore, most extrasolar planets would escape detection by this method. The fact that Kepler has found many exoplanets indicates how common extrasolar planets are.

The transit method reveals an exoplanet's size, but not its mass. However, if we can combine data from a transit measurement and the RV technique, we know both the mass and radius, and the exoplanet's density follows. There have been attempts to probe the atmospheres of exoplanets as they transit. As this technique improves, it may be possible to learn much more about exoplanets than was ever possible with the RV technique. In 2013, there was a failure of part of the pointing mechanism in the Kepler spacecraft. An innovative solution was found that allowed putting Kepler back into use but with certain limitations. The spacecraft must be aligned in a certain orientation in its orbit, and this limits the regions of the sky it can observe. The modification to the spacecraft to allow it to return to service has been called the K2 mission.

Another method, which is a variation on the transit technique, is transit timing variations (TTV). This method carefully determines whether transits start in a strictly periodic manner (Steffen et al., 2010; Xie, 2013; Barros et al., 2014). In some systems, this method can be used to verify other techniques. For example, if a system has more than one transiting planet (which is rare), it can cause variation in the transit timings. Or if an exoplanet orbits a binary star, there may be variations in the transit timing because the stars are moving. Note that in most cases even if a star has multiple planets, it may be that only one of the exoplanets has the proper orbit alignment and distance from the star to allow a transit measurement from Earth.

Direct imaging is becoming a more commonly used technique for detecting exoplanets. Direct imaging most often is attempted in the infrared part of the spectrum, because the difference in brightness between planets and their stars is least in the infrared. Furthermore, an occulting disk normally is employed to block the light of the star (Marois et al., 2008). If the light of the star can be sufficiently well characterized, it can be cancelled out, leaving the infrared glow of nearby planets in the image. This method allows direct observation of the motion of the exoplanets. The NASA exoplanet archive shows 42 cases of confirmed exoplanets detected with this method as of September 2, 2016.

Another method is gravitational microlensing. This uses an effect from general relativity in which a foreground star is used as a lens to image a much more distant star. The foreground star would be the star hosting the exoplanet. This technique can be used to detect exoplanets for stars much more distant, but it requires such precise alignment of the two stars that it is unlikely to ever happen again. The mass of the exoplanet can be roughly estimated, but determination of the orbit is very uncertain. There are some confirmed exoplanets using this technique.

Other methods used occasionally are eclipse timings of eclipsing binary stars, orbital-brightness modulation, pulsar timing, and pulsation timing from non-pulsar stars. In orbital-brightness modulation, light reflecting off the exoplanets causes variations in the star's light. There are a few pulsars with exoplanets. Pulsar pulse timings are a very good means of detecting planets orbiting them, because pulsars have extremely regular periods, so any motion of the pulsars due to orbiting planets shows up easily. Some variable stars have periods regular enough that this technique can be used to detect orbiting planets using the same method. Table 1 shows the number of confirmed extrasolar planets from various techniques as of September 2, 2016 (NASA, 2016).

Planet Formation and Migration

Planet formation theories start with a flattened disk of gas and dust around a newly formed star. This protoplanetary disk is supposed to be material that failed to amalgamate into the star. Presumably, the disk and star have the same composition, except that the disk may have a lower proportion of hydrogen and helium than the star has. Small particles of dust can collide and stick together. It is known from experiments that small particles (up to about 1 mm) can stick together due to static charge and other effects, but there has never been an adequate explanation of how solid rocky objects could grow to become sizable objects, such as 1 km in size. This is important, because computer simulations often start with model objects of 1 km diameter because simulations cannot effectively simulate objects growing to this size. The process of solid objects growing is often referred to as "accretion." But the dynamics of particles of different sizes and compositions colliding in a material medium is a complex mix of processes. If one assumes the planetesimal objects start at approximately 1 km diameter, then gravity may pull them together if they do not have too much velocity. But it is well known that even objects smaller than this 1 km size tend to break each other apart in collisions. The following extended quote from Halliday, 2003 (p. 516) explains the problems with small objects combining to make larger objects:

Table 1. Confirmed Exoplanets by Detection Method.

Detection Method	Number Confirmed
Transit Photometry	2664
Radial Velocity	593
Direct Imaging	42
Microlensing	39
Transit Timing	14
Eclipse Timing (Binary stars)	8
Orbital Brightness Modulation	6
Pulsar Timing	5
Pulsation Timing (non-Pulsars)	2
TOTAL	**3,373**

Table 1. Number of extrasolar planets listed in the NASA Exoplanet Archive (http://exoplanetarchive.ipac.caltech.edu/index.html) as of Sept. 2, 2016. Of the 2,664 transit detections above, 2,427 of these were with the Kepler telescope.

> Laboratory experiments on sticking of dust have been reviewed by Blum (2000), who concluded that sticking microscopic grains together with static and Van der Waals forces to build millimeter-sized compact objects was entirely feasible. However, building larger objects (fist- to football pitch-sized) is vastly more problematic. Yet it is only when the objects are roughly kilometer-sized that gravity plays a major role. Benz (2000) has reviewed the dynamics of accretion of the larger of such intermediate-sized objects. The accretion of smaller objects is unresolved.

The process of accretion is something all planetary origin theories depend on, and yet there is no explanation for the physics of it, except for the formation of small dust particles millimeters to centimeters in size. Another group of authors examine the issue and give the following comments while discussing the early stages of the formation of our solar system (Montmerle et al., 2006, pp. 75–76):

> The growth from dust grains to kilometer-size planetesimals is still unexplained. … The simulations assume rocky objects, but it is still unclear how a puffy pile of dust becomes a solid rock.

In the early stages of the growth of planet cores, the key process is random collisions. This is usually referred to as “oligarchic growth.” Once a planet core grows to a certain critical mass, estimated as about 10 Earth masses, then gravity is expected to be able to capture and add other material to the planet core in a rapid fashion. This is known as the “runaway” growth stage because it is believed both gases and solid material can rapidly accumulate on a planet’s core in this period (Montmerle et al., 2006). A planet the size of Jupiter or Saturn must accumulate most of its mass in less than about 5 million years according to this scenario. If it does not accumulate its mass in this runaway stage, it never will, because the protoplanetary disk will dissipate. The original disk of gas and dust is essentially replaced with many planetesimals. The planetesimals have formed by the same accretion process assumed to form the larger planet cores. Planetesimals are solid objects made up of a variety of minerals, ice, and some organics believed to be very much like today’s asteroids.

Smaller planets are thought to require longer times to form than larger planets. The size of planets is understood to be related to the density, thickness, and other properties of the disk. Rocky planets such as Earth or Mars are thought to form from random collisions of objects, often referred to as “planetary embryos.” Planetary embryos are objects larger than planetesimals, possibly as large as Earth’s moon, which could be made up of rock or ice. In several million years, a disk of dust would dissipate, leaving planetesimals and planet embryos.

The formation of planets is understood to be very dependent on the properties of the protoplanetary disk and other planets (or stars) present in the system. The properties of the star greatly affect the process as well. Near the star, the equilibrium temperature may be too high for gases to condense. Near some stars, even some metals may boil away from planets. Planet orbit migration has come to be an accepted process in planetary science. Orbit migration was first considered as a means of allowing planets to form at a greater distance from the star than where they are observed today. This allowed more material to be available to accumulate on them in the early stages. For example, a planet could form at perhaps 4 or 6 A.U. from its star and then migrate inward. When the disk was depleted in some systems, planetary migration would stop. However, today there are believed to be multiple types of planet migration scenarios possible. Planet migration has been related to spiral density wave theory and planet-planet orbit interactions so that migration either can be inward toward the star or outward. Orbit migration has not really been observed except in the sense of cases where we can see that a planet has a decaying orbit, or perhaps a resonant relationship exists with another planet that could affect it in a predictable manner over a few years of observations. But orbit migration theory often involves planets moving very significant distances, perhaps as much as 5 or 10 A.U. in some cases. This kind of large-scale orbit change has not been observed.

Though the theories of planet orbit migration have received much attention in the scientific literature, such theories still have serious limitations and problems. The most serious problem may be that if a planet begins migrating inward, it tends to fall into the star. Scientists want to show how a planet migrating inward could migrate over a timescale that is longer than the time for the disk to dissipate. This would allow the planet to migrate inward until the disk dissipates. However, in scenarios planets migrate too rapidly and fall into the star before the disk dissipates (Hasegawa and Ida, 2013). A timescale on the order of 10^5 years is often estimated for the migrating planet to spiral into the star, but this depends on the system. This problem has been referred to as the "death spiral."

Migration theories are thus lacking in clarifying mechanisms that would stop the planet from spiraling into the star. There are two main types of migration that have received attention in the research, known as Type I and Type II (Plavchan and Bilinski, 2013; Hasegawa and Ida, 2013). In Type I migration, the disk is very massive compared to the mass of the planet, so that the planet's migration does not have a great effect on the disk. In Type II migration, the mass of the planet is greater, and the disk material is significantly affected by it. In Type II migration, a gap usually is opened in the disk due to absorption of gas and dust by the migrating planet. Both Type I and Type II migration scenarios involve the formation of density waves that can exist around the planet. The density wave can theoretically push the planet forward in the right conditions, making it spiral outward, or slow its motion, causing it to spiral inward. Spiraling inward is considered more common and is focused on more in the research to try to explain the many so-called "hot Jupiters" that exist close to their star.

As an example of a typical "hot Jupiter" type exoplanet, we can consider object Kepler-74. This exoplanet was referred to as KOI-200b, when it was first detected from a Kepler spacecraft transit measurement in 2012 (Hebrard et al., 2013). (The letters "KOI" refer to "Kepler Object of Interest.") The Kepler-74 designation was used after it was confirmed. It was confirmed by radial velocity measurements from two high-precision spectrographs, SOPHIE (in France) and HARPS-N (in Spain) (Hebrard et al., 2013). Kepler-74 orbits an F8V-class star with a mass estimated at 1.40 + 0.14, -0.11 solar masses and an estimated radius of 1.51 ± 0.14 solar radii. Kepler-74 is estimated to have a mass of 0.68 ± 0.09 times the mass of Jupiter (M_{Jup}) and a radius of 1.32 ± 0.14 compared to Jupiter (R_{Jup}). The star is estimated to have an effective temperature of 6,050 ± 110 Kelvin. The planet's orbital period is 7.34 days, and the eccentricity of its orbit is estimated to be 0.287 ± 0.062 (Hebrard et al., 2013). For comparison, Mercury in our solar system has an orbital period of 87.97 days and an eccentricity of 0.206. Kepler-74 is similar to many other cases of exoplanets.

An ongoing debate among exoplanet researchers continues over the question of how so many planets can migrate from some distance inward until they are very close to the star and then stop migrating. Several mechanisms for stopping migration have been considered (Plavchan and Bilinski, 2013; Nagasawa and Ida, 2011). The mechanism with the most promise is sometimes referred to as dynamical tides. The dynamical tide is the tidal force created by the star on the planet as a function of distance. If a planet has an orbit that is significantly eccentric (preferably more than Kepler-74), when it is at its point of closest approach to the star (periastron), tidal forces are greater than when it is at its farthest point (apastron). This tidal force tends to circularize planetary orbits as planets migrate closer toward their stars. Migration ought to cease once an orbit is sufficiently circular. Exoplanets close to their stars usually do not have significant eccentricities. Compared to other hot Jupiters, the eccentricity of Kepler-74 is somewhat high for a planet so near its star.

However, dynamical tides consider only half of the tidal physics. Some researchers may believe dynamical tides solve the migration problem in many cases. But even if an exoplanet's orbital eccentricity is close to zero, it can still spiral into the star. This is due to the tidal bulge raised by the planet on the star. When a planet is very close to the star, in many cases the planet may revolve more rapidly than the star rotates. The tidal bulge on the star induced by the planet may cause the planet to lose orbital energy and spiral inward. In addition, planets near their stars sometimes lose significant mass from the star pulling gases off the planet. The rotation rate of the star and the size of the planet are significant factors in how the tidal forces affect the planet. The exoplanet can either spiral inward and be absorbed by the star or spiral outward to a more stable orbit in some cases. However, some researchers have argued that rather than looking for a mechanism for "saving planets" from spiraling into their star, perhaps they do not stop (Jackson et al., 2009). Perhaps tidal destruction is more common than halted migration. I find this line of argument to be more realistic, but more observations of these exoplanets over time and analysis of their dynamics are required to be more certain. Even if many of the hot Jupiters do spiral into their stars, it may require millions to billions of years. However, some exoplanets would spiral into their stars in only several hundred thousand years. These are only estimates arrived at from computer simulations.

Challenges to Current Theories

There are several ongoing challenges to current theories of extrasolar planetary systems listed below. All these issues are topics of great interest today in extrasolar planet research. They also give hints of possible advantages of a young-age creation view over an old-age naturalistic perspective. A creationist view can allow for supernatural formation of exoplanets in the creation week. Also in a creation approach, our own solar system becomes special in being a stable system that allows for life on Earth.

- Retrograde or high inclination exoplanet orbits
- False positives in transit measurements
- Gas planets whose radii are too large for their mass and distance from the star
- Problems with the habitability of exoplanets

High Inclinations of Exoplanet Orbits

In April 2010, the Royal Astronomical Society and the European Southern Observatory put out a press release announcing that six exoplanets were orbiting their stars in a retrograde direction, opposite the direction their stars spin (RAS/ESO, 2010). This was determined from transit observations. (These six cases have designations of WASP-2b, WASP-5b, WASP-8b, WASP-15b, WASP-17b, and WASP-33b.) One of the scientists involved, Andrew Cameron, professor from the University of St. Andrews in Scotland, made the statement, "The new results really challenge the conventional wisdom that planets should always orbit in the same direction as their star's spin" (RAS/ESO, 2010).

The evidence for high inclinations and some retrograde orbits among exoplanets comes from an observational technique known as the Rossiter-McLaughlin (RM) measurement (Bouchy et al., 2008; Fabrycky and Winn, 2009; Lund et al., 2014). The RM measurement examines an effect at the edges of the disk of the star as it is observed. On one side, the redshift will be greater because the surface of the star is moving away from the observer. On the other side of the star, the red shift will be less because the surface of the star moves toward the observer. This produces a predictable distortion in the redshift that allows estimating an angle that can be related to the spin axis of the star. An observer sees only a projection of the actual angle the star makes with the planet's orbit, not the actual angle. This projected angle is referred to as λ (lambda). The projected angle λ is what is measured in an RM determination. It is a projection of the actual angle between the star's spin axis and a line normal to the planet's orbit.

The actual angle between the star axis and the planet orbit is known as the stellar obliquity, and it is designated by ψ. The two angles λ and ψ are in two different planes (Fabrycky and Winn, 2009; Lund et al., 2014). Determination of ψ requires developing a detailed model of the star, such as from the changes due to stellar spots or from a technique known as asteroseismology. In asteroseismology, stellar oscillations are analyzed in terms of a sum of oscillation harmonics over time. An asteroseismology model can be compared to similar models of other stars and then applied to the star in question. The result is a model of the spectrum of the star as a function of its rotation. This allows determination of the star's obliquity.

RM measurements have been done only for a limited number of exoplanet systems. Data in Figure 1 come from a catalog of exoplanet transit data from Keele University, UK (Southworth, 2016). In this catalog, there were 166 exoplanets listed for RM measurements. Those which included both the λ and ψ angles were just 20 out of 166 as of September 2, 2016. Of these 20, four data points were of exoplanet HAT-P-07, and two were of HAT-P-11 (Table 2). The other 14 data points were each of different exoplanets (see Table 2). The chart shows the estimated actual obliquity angle on the vertical axis and the projected angle along the horizontal axis. The numeric values above each point show the angle ψ. In Figure 1, the points labeled 106 and 97 are the two HAT-P-11 measurements. This shows HAT-P-11 as being in a near polar orbit around the star, moving in a slightly retrograde manner. The data points labeled with 101 and 87 are two of the HAT-P-07 measurements. HAT-P-07b is also in a near polar orbit. The two HAT-P-07 data points on the graph had an error in ψ too small for the error bars to display. Some data points have a large amount of uncertainty, and the reported error varies significantly from one exoplanet to another. Four data points show a ψ value comparable to or less than the obliquity of our sun in our own solar system. The other 16 data points show a

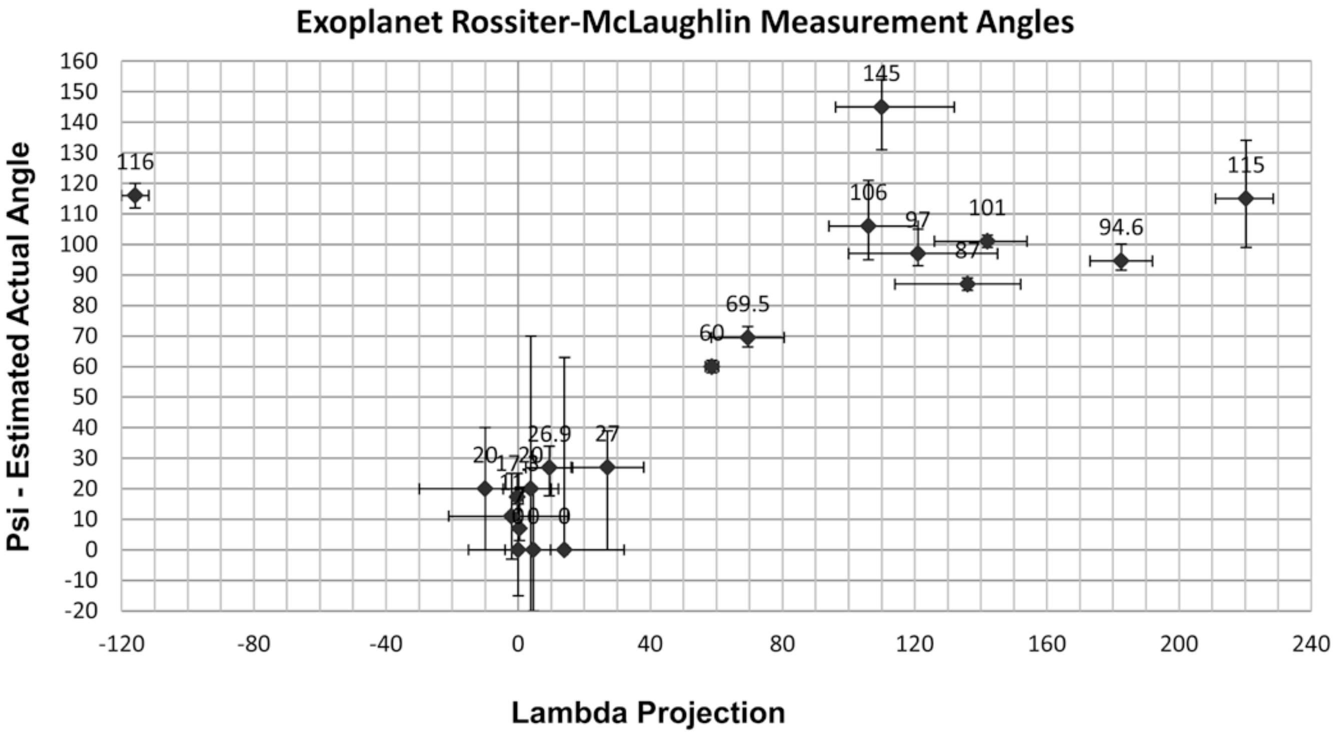

Figure 1. Chart showing exoplanet data from 20 RM measurements of 16 stars using data presented in Table 2. The estimated actual stellar obliquity angle ψ is plotted versus the projected angle λ. Numbers above the data points are the angle ψ in degrees.

higher ψ value than in our system. There appear to be two clusters of data points, one cluster at the lower angles and one at the higher angles. This trend has been noticed by exoplanet researchers, and it is often attributed to two different migration mechanisms. Though there is need for more RM measurements and perhaps more asteroseismology analysis for the exoplanet stars, the implied inclinations of the exoplanet orbits have been a challenge for planetary scientists. High inclinations of the exoplanet orbit compared to the star's axis are not explicable as due to the "traditional" process of planets forming from a protoplanetary disk.

The inclination of exoplanet orbits compared to the spin axes of their host stars is generating significant research today. In our own solar system, the orbits of all the planets are measured by the ecliptic plane, which is defined by Earth's orbit. Our sun's spin axis is tilted slightly over 7° compared to the ecliptic. This has been a challenge for models of the formation of our own solar system. In the traditional nebular hypothesis for the formation of our solar system, the spin energy of the star and the orbital motion of the planets must initially come from the spinning protoplanetary disk. This would make the orbits of the planets initially lined up with the equator of the star, and their orbital motion would be in the same sense as the spin of the star. This is accepted for extrasolar planetary systems as well, except that orbit migration is thought to explain how planets might exist today in different orbits than those that they initially formed in. Today, because planet orbit migration is considered to be common, it is thought that many systems may have had some planets spiral into their star and some other planets that may have been ejected out of their systems.

Type I and Type II migration described above are two forms of disk migration. In these models, the mass of the disk is primarily responsible for the migration of planets. Disk migration does not provide a mechanism to make planet orbits significantly tilted compared to the spin axis of the star.

Other theories for planet orbit migration have been proposed that are often referred to as planet-planet scattering. Planet-planet scattering is thought to explain highly inclined or retrograde exoplanet orbits. If a planet orbit changes in disk migration, it must happen early, in the first several million years of the

Table 2. Exoplanet data plotted in Figure 1.

Star Name	Effective Star Temperature (Kelvin)	Lambda (X) in degrees	Lambda Error	Psi (Y) in degrees	Psi Error
CoRoT-18	5440	-10	± 20	20	± 20
HAT-P-07	6310	182.5	± 9.4	94.6	+5.5, -3
HAT-P-07	6310	220.3	+8.2, -9.3	115	+19, -16
HAT-P-07	6310	142	+12, -16	101	± 2
HAT-P-07	6310	136	+16, -22	87	± 2
HAT-P-11	4780	106	+15, -12	106	+15, -11
HAT-P-11	4780	121	+24, -21	97	+8, -4
HAT-P-36	5620	14	± 18	0	+63, -0
HD_189733	5050	0.4	± 0.2	7	+12, -4
KELT-17	7474	-115.9	± 4.1	116	± 4
Kepler-13	7650	58.6	± 2	60	± 2
Kepler-17	5781	0	± 15	0	± 15
Kepler-25 c	6270	9.4	± 7.1	26.9	+7, -9.2
Kepler-63	5576	110	+22, -14	145	+9, -14
WASP-19	5460	4.6	± 5.2	0	± 20
WASP-32	6100	-2	+17, -19	11	± 14
WASP-52	5000	3.8	± 8.4	20	± 50
WASP-84	5280	-0.3	± 1.7	17.3	± 7.7
WASP-117	6040	69.5	± 11	69.5	+3.6, -3.1
XO-2	5332	27	± 11	27	+12, -27

Extrasolar planet data for cases plotted in Figure 1. Data obtained from http://www.astro.keele.ac.uk/jkt/tepcat/rossiter.html on Sept. 2, 2016.

formation of the system before the disk of gas and dust dissipates.

One form of migration is where planetesimals cause the migration of the planet. Migration via planetesimals happens after the protoplanetary disk is dissipated but while the planets are still accreting material from colliding planetesimals. This type of migration depends on the existence of a disk (or ring) of planetesimals that is massive enough to affect the planets' orbits. Migration by planetesimals also would not be expected to cause planet orbits to be tilted by large angles. Often planetary scientists seem to simply assume that the 7-degree angle in our own system somehow arose from random collisions in the planetesimal-accretion stage.

Another model for planet migration is where multiple planets form and their mutual gravity pulls them into resonance, so that their orbital periods are close to being whole number ratios of each other. If a system has multiple planets that can cause changes in each other's orbits, this process is considered something that can theoretically continue for long periods of time until something stops the process. If two planets come into a resonance, it is also dynamically possible that they could migrate together. Today a mixture of all these concepts has been applied to our own solar system in the Nice model (Tsiganis et al., 2005) and the Grand

Tack model (Walsh et al., 2011; Walsh et al., 2012). These concepts have been worked out from years of research on extrasolar planetary systems. Thus, scientists have attempted to develop theories that explain both other planetary systems and our own solar system.

One scenario for planet-planet scattering is known as Kozai cycles or Kozai oscillations (Fabrycky and Tremaine, 2007; Plavchan and Bilinski, 2013). The Kozai mechanism was originally developed as an explanation for how binary- and triple-star systems could come to have a near binary pair orbiting each other with a more distant companion star. If there is a star at a greater orbital distance than the binary pair, the distant companion can alter the inclination of the binary pair. The process could apply in some planetary systems where there are either multiple stars or multiple planets or both. It could apply if the system has a star (or a binary pair) that is orbited by a planet and there is another object, more distant and in an eccentric, highly inclined orbit. The distant object could theoretically be either a planet or a star. The distant object being in an inclined eccentric orbit can cause precession and oscillations of the inner planet orbit in this configuration. Over time the inner planet orbit in this scenario would become more eccentric for a time, but then as the planet orbit becomes closer to the inner star, the tidal forces from the inner star would round the orbit of the planet. So early in the Kozai cycles process the outer inclined object would affect the planet more, but later in the process the planet orbit has shrunk and then the tidal forces of the inner binary become more important. Computer simulations have been done of the mechanics of the Kozai cycles process.

The Kozai mechanism would not be applicable in a system with only one planet, but there could be some exoplanet systems where it could apply. There must be at least two objects orbiting a star not too far apart but in different planes if they are to influence each other gravitationally. In computer simulations, the Kozai process can produce planet orbits close to a star (or binary pair) that are highly inclined. Because the Kozai cycle mechanism is a slow process, it would require long periods of time, on the order of 1 or 2 billion years in simulations (Fabrycky and Tremaine, 2007). It is also possible that if a system has multiple planets in similar orbital planes that the planets can prevent the Kozai orbit oscillations. Multiple planets in similar orbital planes tend to stabilize the system, not increase orbital inclinations.

In extrasolar planet research, appeal often is made to the Kozai mechanism as a possibility, but it would not be applicable to many exoplanet systems. However, there are exoplanets in binary- and trinary-star systems. In some extrasolar planet systems, if there is evidence for a high inclination in a planet orbit, researchers sometimes merely assume that there was a distant companion object in an inclined orbit, whether there is observational evidence for such an object or not. If one is not observed, it can be argued that the distant object was ejected during the orbit oscillations of the Kozai process. A more distant exoplanet can be hard to detect, however, and exoplanets in distant orbits rarely undergo a transit. Showing that exoplanet orbits are undergoing a long-term change that is due to the Kozai mechanism would be difficult because we cannot observe the history of the exoplanetary system. The Kozai mechanism may require a distant companion planet that cannot be observed. Thus, the Kozai cycles scenario has limited applicability, even though it is a physically valid mechanism.

The Kozai cycles process generally ends with the exoplanet near its star (or binary pair) in a near circular but inclined orbit. But like other cases of hot Jupiter planets, it could still spiral into the star. The Kozai process attempts to explain how a distant object in a tilted orbit can cause another orbit to tilt. But it raises the unanswered question of how the distant object came to be in a tilted orbit. The Kozai mechanism gives some insight into how a system of multiple planets and multiple stars can change over time. In a creation view, it may be that planet-planet scattering and Kozai cycles do not have time to alter orbits greatly. In a naturalistic or uniformitarian approach to planetary systems, planet orbits must migrate by possibly several astronomical units over millions or billions of years. On the other hand, a creation alternative would be to view the exoplanets as being formed on the fourth day of the creation week at the time the star was formed. Then some limited migration could be possible over a young-age timescale.

Some exoplanet researchers have argued that high orbital inclinations could be related to various complicating observational effects and thus are not valid. One of the effects suggested is differential rotation in the star (Hirano et al., 2012). Stars may have latitude bands that rotate at different speeds, as does our own sun. Though differential rotation is probably common in stars, it is not clear how much it would interfere with transits or determinations of ψ. Another model was proposed suggesting that the outer layers of a star could "decouple" from the interior of the star, causing the star to have two rotation axes (Rogers et al., 2012). The star core and interior would have a different spin axis than the star's outer layers. It is not clear whether known exoplanets provide support for this model.

As more analysis is done of the data, these processes are likely to be either ruled out or better understood and better accounted for in models. The growing list of examples of exoplanets with possible high inclinations are not likely to all be explained away as observational issues. The highly inclined and retrograde exoplanet orbit issue seems to not go away, though better data and analysis is needed to clarify it. Even if no exoplanets were found to have orbit inclinations more than 7°, that would only confirm that exoplanets have the same unexplained problem that has been found in our own system.

False Positives in Transit Measurements

In 2012 and 2013, scientists analyzing Kepler transit data realized that false positive detections with the Kepler spacecraft were much more common than had been expected (Santerne et al., 2012; Santerne et al., 2016). There are systems with eclipsing binary stars that can be almost indistinguishable from a planet transiting the star. One such case could be a brown dwarf that transits the star. Another case could be a blended binary, where a bright star is orbited by a binary pair that is less bright. Another case is known as a grazing binary system in which a dim star just barely overlaps the field of view of the other star. The grazing binary is thought to be the most common of these cases. The problem stems from apparently underestimating the number of eclipsing binary systems that could appear like planet transits.

The Kepler spacecraft was designed to be sensitive enough to detect the transit of an Earth-sized exoplanet, but this new issue of false positives will raise questions about reliably detecting such planets. There has been great interest in the scientific community in doing transit studies of exoplanets smaller than Jupiter or Saturn. Some have been found that are approximately double Earth's mass. These exoplanets are often referred to as "super-Earths." In some cases, the eclipsing binary possibility can be tested, given the proper analysis. But there are many transiting exoplanets that cannot be verified by the radial velocity technique. The radial velocity technique measures the change in the motion of the star due to the planet. For some transiting exoplanets, the velocity change in the star is too small to reliably detect with any instruments available today. This limits the ability of researchers to clearly show that the decrease in the star's light from Kepler is due to a planet and not an eclipsing star. In some cases, it will become a statistical argument rather than a physical argument to claim that it was an exoplanet that transited the star and not another star transiting the star. Virtually all Earth-sized or super-Earth exoplanets would be in this category. Thus, the problem of false positives from eclipsing binaries is a serious one, and in my opinion, it makes the detection of Earth-sized exoplanets very uncertain.

The false positives problem varies with the planet size and distance from its star. In 2012, Santerne et al. reported that for giant exoplanets with orbital periods of less than 25 days, the percent of likely false positives is 34.8 ± 6.5%. This was after studying a sample of 46 well-chosen transit cases. In 2015, Santerne et al. published updated results saying that as many as 54.6 ± 6.5 % of gas giant planets with orbital periods of 400 days or less could be false positives! This recent effort used a larger sample of Kepler Objects of Interest (KOI). Known false positives were first removed from the KOI list, and then the list was further parred down to those stars bright enough to be verified by the SOPHIE spectrograph (in France), leaving 2,481 KOI objects. Undoubtedly techniques will be refined to address this issue, but creationists should be cautious about accepting all claims of detection of exoplanets, especially for exoplanets orbiting very closely to their stars.

The Size of Gas Exoplanets

Another issue has become a significant ongoing mystery in extrasolar planet research: the sizes of many gas exoplanets near their stars. In recent years, scientists have noticed that many exoplanets near their stars have radii larger than expected in models (Baraffe et al., 2003; Anderson, 2010; Leconte, 2011; Southworth et al., 2014). There are several known effects that can cause a gaseous planet to expand near its star. But the magnitude of the radii for some exoplanets may defy all known mechanisms. The equilibrium temperature of the planet naturally increases as its distance from the star decreases. There is also a heating effect from tidal forces that can heat a planet near its star, known as *tidal dissipation*. Some would argue that tidal effects would heat these planets sufficiently to explain their large radii. But this has not really been shown clearly in tidal dissipation calculations. A recent paper (Martin, Spruit, and Tata, 2011) shows that this seems to require unrealistic values of the quality factor (Q), which is an important parameter in tidal dissipation calculations. The Q value has been estimated for Jupiter and various moons and planets in our own solar system. Estimates of Q frequently use a lower value for the star than for the exoplanet, and they use a value for the planet that is at least a magnitude higher than estimates for Jupiter in our own system. This is questionable because this tends to make the tidal force on the planet by the tidal bulge of the star less. I find it more likely the star would have a higher Q than the exoplanet.

The large radius of exoplanets also presents a time problem, because these planets are believed to form at some distance and migrate inward to near the star, then stop migration and remain stable for many years. As a planet migrates inward close to the star, it comes into synchronous rotation (tidal lock) with the star. At that point, one side of the planet cools very efficiently, because it is always facing away from the star. Though a gaseous planet in this configuration could have very high winds, and it might lose gases to the star, it would cool over long periods of time. But indications are that many of the "hot Jupiters" are hotter than expected from gas models and planet interior models.

However, this problem does not apply to all the exoplanets near their stars. For example, it would not apply to a planet with a high abundance of metals or a planet that is likely to have a large, dense core. An example case was discussed by Baraffe, et. al. in 2003. The following quote eloquently explains the nature of the issue (Baraffe et al., 2003, p. 712):

> In summary, we do not expect irradiation effects alone to explain the large observed radius of HD 209458b. In the same vein, tidal interactions will affect only the early stages of evolution of the planet but will probably be dissipated too rapidly to affect the long-term contraction of the object. Other sources of energy, representing about 100 times the intrinsic luminosity of the planet, seem to be required to explain the observed radius.

Exoplanet HD 209458b, mentioned above, has a mass of approximately 69% the mass of Jupiter, and yet its radius is roughly 30% more than Jupiter. A much more recent paper from Spiegel et al. (2014, p. 12623) made this statement summarizing the problem: "Despite the lack of a consensus mechanism, it is clear that objects must either be quite young or very highly irradiated to have significantly inflated radii." The expression "quite young" is not intended to mean several thousand years as in a young-age timescale. Planetary scientists have recently proposed a solution to the large radius problem by suggesting a collision event could have occurred in these systems (Martin, Spruit, and Tata, 2011). The collision proposed is referred to as a binary merger, and the authors suggest it could have taken place 100 million years ago or less. On the other hand, it would be a very plausible solution to propose that these "puffy" exoplanets have primordial heat that remains from their formation. But this does not fit planet formation models because the heat should have dissipated in billions of years. Thus, a catastrophic event has been proposed that generated a large ring that such an exoplanet could form from. Models of the gas dynamics of exoplanets very close to their stars require more research to clarify the problem. But this issue may be an indication of the young age of these exoplanets. Planetary scientists tend to look for an age in the millions of years to allow the dust ring to dissipate, the planet to form, and then allow the young planet to migrate inward. On the other hand, if these exoplanets were created supernaturally only several thousand years ago, they could still be hot and "inflated" from their formation. This is a tentative interpretation, but it does seem consistent with other evidence from our solar system (Spencer, 2003, 2015a).

The Habitability of Exoplanets

The driving motivation for much of the research on extrasolar planets is to find evidence of habitable planets like Earth. In recent years the technology applied to exoplanet research has improved, and this is driven by a desire to find smaller exoplanets, since it is believed this makes finding a habitable planet more likely. The concept of the "habitable zone" (HZ) has itself undergone refinements over the years. The HZ primarily is defined as the region around a star in which a planet having the proper atmosphere could have liquid water on its surface. How do planetary scientists set about the process of searching for habitable planets? Most of the time, they focus on low-mass dwarf stars. These stars usually have a lower mass than our sun, making it easier to detect even small planets by the RV method. Furthermore, the HZs of such stars are very close to the stars, yielding short orbital periods, making it more likely to observe transits. If both RV and transit measurements are made, we directly can determine the density of a planet. Scientists do not expect life to exist in gas giant planets, thus determining the density is important.

Transits may allow the determination of the major composition of planetary atmospheres (assuming the planets have atmospheres). The general requirements scientists look for on such a rocky exoplanet is that the temperature and pressure conditions on the surface allow for liquid water and that there be carbon dioxide (CO_2) in the atmosphere. Oxygen is not considered essential for life per se, but an atmosphere made up of mostly N_2, H_2O, and CO_2 is considered ideal for plant life to start. Thus, scientists generally look for a reducing atmosphere similar to what they believe Earth's early atmosphere was between about 3 billion and 2.3 billion years ago. Scientists believe it was because of photosynthetic bacteria that Earth's atmosphere switched from a reducing to an oxidizing nature approximately 2.3 billion years ago. Some scientists would consider an atmosphere more like the Earth's or Saturn's moon Titan to be more likely, where the major constituent is N_2 but there is a mixture of many organic gases, with some CO_2.

How common are rocky exoplanets? As of October 1, 2016, the NASA Exoplanet Archive listed 344 cases of confirmed exoplanets that showed both the semimajor axis and the density to be determined. Of these, 49 cases had densities 3.0 g/cm^3 or greater. Note that these 49 would be approximately 1.5% of the total of confirmed exoplanets in Table 1. (For comparison, Earth's moon has a density of 3.34 g/cm^3.) Of these 49, 5 show a density of 14 or more, with the highest as 28 g/cm^3. These high densities are probably suspect, so further research is needed on these cases. Error is not always reported in the density data and when it is, it is highly variable from one determination to another. Also, even if a very small error is reported, there are observational issues or data interpretation issues that could cause large errors, especially in light of the false positives problem discussed above.

How is the HZ defined? One of the best determinations of the HZ is published in Kopparapu et. al., 2013. For our solar system, the HZ is listed by Kopparapu as from 0.99 to 1.70 A.U. This distance range would start just inside Earth's orbit and range out to slightly past the orbit of Mars. There is thought to be some unknown error in this kind of estimate from the effects of clouds in climate models. This range of distances for the HZ is defined based mainly on the greenhouse effect as a function of distance from the star. It is thought that cloud cover tends to expand this range of distances. At the inner boundary of the HZ, water cannot be retained on the surface due to the high temperatures. At the outer boundary, the greenhouse effect is not significant enough to prevent water from freezing. Note that determining the range of distances from a star that would correspond to the HZ depends on making assumptions about the planet having an atmosphere. Often the assumption made for determining the HZ distance range is that the exoplanet has an atmosphere similar to Earth's in density. It has been estimated that if Earth's atmosphere disappeared, the surface would freeze. This shows how critical the nature of a planet's atmosphere is for habitability.

Even if a planet is in the HZ distance range, various effects can render it uninhabitable. First, most of the extrasolar planets studied with transit measurements probably are in tidal lock with their stars. If a planet is in tidal lock, the atmosphere could migrate to the cold side and then freeze out onto the surface. However, it is thought that if the atmosphere is dense enough, it would have a sufficient greenhouse effect and wind circulations to prevent this. A very challenging question would be, how could life find a safe place to live on a tidally locked planet? Such a planet would have extreme conditions on it that would not be very hospitable.

Second, many of the exoplanets are exposed to strong flares from their star, or bursts of ultraviolet or X-rays in some cases. This problem is likely to affect Proxima Centauri b for example, which was detected in August 2016 (Anglada-Escudé, 2016; Clery, 2016; Davenport et al., 2016). The star system Alpha Centuari has two stars referred to as A and B, and Proxima Centauri is thought to be a third star that is more distant but part of the same system. Proxima Centauri is a dwarf star, and it has an exoplanet that has been detected using the RV technique and has been confirmed. Proxima Centauri b orbits its star in 11.2 days, and the mass calculated for it is about 30% more than Earth. Orbital models of the Proxima Centauri system with its planet have been done, but since the RV measurement is the only data available, we cannot be sure of the mass since the RV technique gives only a minimum mass for the planet. Even if we knew its mass, we do not know its size, so the density of Proxima Centuari b is completely unknown. So, it could be more like Uranus or Neptune than Earth. Also, nothing is known of the composition of its atmosphere, or even if it has an atmosphere.

Stellar flares and radiation bursts are often far more intense for many other stars than what we experience from our sun. Our sun is exceptionally stable as a star. Another problem is that the planet could migrate inward to a position near the star early in that system's history, but then the star could boil off the water before life could get started (Spencer, 2015a).

For many of the exoplanets that are thought to be in the HZ for their stars, we know very little about them, because we do not know if they are rocky or gaseous. Large gaseous planets have their own reasons why life would be unlikely. They would have a high gravity and no solid surface, possibly limited water, little availability of light for bacteria, and they may possess ionizing radiation and magnetic phenomena that could destroy bacteria. The study of extrasolar planets shows how special our own planet and our own solar system are in being well suited to life and to our needs as humans.

Conclusions

Extrasolar planets are a very active topic of research in astronomy today. After many refinements of techniques and even special spacecraft being put into space for the observations, there remain many challenges to naturalistic theories on the origin of exoplanets. Experimental evidence for the existence of extrasolar planets is good in many cases, yet the limits of detection methods and the analysis of the data have many inherent challenges. Scientists want to find evidence of Earth-like extrasolar planets, but the primary discovery has been that extrasolar planetary systems are different from our own solar system. In many cases little is known about the exoplanets themselves. Though the Kepler spacecraft has done transit measurements for many exoplanets, there is a significant outstanding problem in that a large percentage of these detections could be false positives due to dwarf stars or eclipsing binary stars.

The existence of extrasolar planets is not in conflict with a biblical worldview, but naturalistic origins theories are. Extrasolar planets are often found to be very close to their star despite an apparent tendency for them to spiral in and be absorbed by the star. This may suggest these planets have not existed long enough to be absorbed by the star. Extrasolar planetary systems are not as safe or stable an environment as our own solar system is from our privileged place on Earth. Planet origins models have been adapted to incorporate the concept that planets can form in one orbit and then migrate to another, very different orbit. In these models, planets can form and fall into their star or be ejected into space. Exoplanets are sometimes found in orbits that are inclined at angles very different from the equators of their stars. This has led to application of models in which multiple planets (or stars) that orbit in different planes can scatter or alter each other's orbits over time. This planet-planet scattering concept presumes a history for these systems that cannot be verified.

Planet origins models assume processes that often cannot be verified by observations. Some exoplanets have also been found with a radius that seems so large that it challenges existing theories. These large "puffy" exoplanets may be explained better as being young objects. Though some exoplanets are within the HZs of their respective stars, usually very little actually is known about these planets. Also, the possibility of liquid water on the surface of an exoplanet does not explain how life could evolve there from nonliving matter. The planet's atmosphere and stellar flares are critical factors that rule out life on many exoplanets. Extrasolar planets are best understood as examples of the variety created by God to demonstrate design in our own solar system. Extrasolar planets could have been created in the creation week on the fourth day only thousands of years ago. Exoplanets could have been created in various orbital configurations in the beginning, rather than forming from a spinning disk of dust and gas.

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