I. Introduction

The discovery of an inhabited planet is a primary goal of exoplanetary science. The *Kepler* spacecraft has now found several small candidates in potentially habitable orbits, (e.g. Kepler–62 f; Borucki et al., 2013), and radial velocity surveys are also detecting apparently low–mass planets in habitable zones (HZs), e.g. Gl 667C c (Anglada-Escudé et al., 2012). While the location of an orbit with respect to the HZ is an important first cut on habitability, the composition of the planet is at least as important. Life as we understand it cannot survive on gaseous planets, yet we do not know the mass and/or radius that separates gaseous from terrestrial planets. In particular, the identification of the critical radius between the two, R_{crit}, would provide crucial information for *Kepler*'s primary mission to discover a terrestrial planet in the HZ of a G dwarf.

The primary goal of this proposal is to determine this critical planetary radius between rocky and gaseous bodies using *Kepler* data. We will exploit the expected discrepancy in tidal dissipation of gaseous and rocky bodies to determine the largest orbital periods at which the two classes of bodies circularize. We will use the so–called transit duration deviation, the difference between the observed transit duration and that of a circular orbit, to estimate the minimum eccentricity permitted from the transit data. We will also include the effects of additional planetary companions and atmospheric mass loss, as they also influence the evolution of eccentricity. In order to successfully constrain these theoretical results from *Kepler* data, we require robust characterization of each candidate, and hence we will perform state–of–the–art modeling of all relevant *Kepler* transits. To optimize our sensitivity to these effects, we will examine only those systems with short periods (less than 10 days) and having planetary radii near the anticipated boundary (less than 10 $R_\oplus$). Our proposed research offers the best route to determine which *Kepler* candidates are rocky, independent of mass measurements. In summary:

We propose to use the observed minimum eccentricity and the theory of tidal dynamics to determine the critical radius between rocky and gaseous exoplanets R_{crit}, to constrain their tidal quality factors (Q_r and Q_g, respectively), and to understand the efficiency of hydrogen loss for close–in, small, gaseous exoplanets, using *Kepler* lightcurves.

II. Objectives and Significance

Tidal Theory

Tidal dissipation in celestial bodies in extremely challenging to measure (Goldreich & Soter, 1966; Hut, 1981; Aksnes & Franklin, 2001; Jackson et al., 2008, 2009; Lainey et al., 2012) due to the dearth of known worlds in highly dissipative configurations, the long timescales involved (Gyrs), and the intractability of derivations based on first principles. However, the *Kepler* space telescope has now discovered thousands of exoplanet candidates (Batalha et al., 2013), of which about 1000 orbit FGK stars with orbital periods less than 10 days, and that may experience significant tidal evolution (Rasio et al., 1996; Jackson et al., 2008; Matsumura et al., 2010).

In the equilibrium tide model (Darwin, 1880; MacDonald, 1964; Goldreich & Soter, 1966; Hut, 1981; Ferraz-Mello et al., 2008; Leconte et al., 2010), the figure of a tidally deformed body is a superposition of surface waves with different frequencies. The sum of these waves corresponds to the tidally–deformed figure, and allows for the relatively simple derivation of the time rates of change of orbital and spin properties. While two qualitatively different models have emerged, the constant–phase–lag (CPL) and constant–time–lag (CTL) models (Greenberg, 2009), both rely on this assumption of superposition, and neither has been rejected observationally. Both models make a critical prediction that we will exploit in this proposal: Tidal dissipation in rocky planets is orders of magnitude larger than in gaseous bodies. This disparity implies that rocky planets will evolve much more rapidly than gaseous ones and we expect rocky exoplanets to be tidally circularized on larger orbits. The key is to recognize that gaseous bodies will tidally circularize more slowly than rocky planets, and may still retain non–zero eccentricities after Gyrs. As we show below, the canonical values for Q_g of 10^6 and Q_r of 100 should be measurable, if the transit data and stellar properties can be known to sufficient accuracy. While transit data cannot measure the eccentricity (Barnes, 2007; Burke, 2008; Ford et al., 2008), they *can* provide a lower limit.

The Transit Duration Deviation (TDD)

The transit duration is the time required for a planet to traverse the disk of its parent star, and to first order is:

$$T = \frac{2\sqrt{R_*^2 - b^2}}{v}, \tag{1}$$

where R_* is the radius of the star, b is the minimum impact parameter, and v is the instantaneous velocity of the planet. On a circular orbit, v is constant (v_c) and we expect

$$T_c = \frac{\sqrt{R_*^2 - b^2}}{\pi a} P, \tag{2}$$

where P is the orbital period. However, for an eccentric orbit the orbital velocity as a function of longitude (Kepler's 3rd Law), and is given by

$$v(\theta) = \frac{2\pi a}{P}\sqrt{\frac{1 + 2e\cos(\theta) + e^2}{1 - e^2}}, \tag{3}$$

where e is the eccentricity and θ is the true anomaly, the angle between the longitude of pericenter and the actual position of the planet in its orbit. From transit data alone, the value of θ is unknown, and hence so is e.

However, we can exploit the difference between T and T_c to obtain a minimum value of the eccentricity, e_{min} (Barnes, 2007). The situation is somewhat complicated because T can be larger or smaller than T_c depending on θ. If the planet is close to apoapse, $T > T_c$, while at periapse $T < T_c$. To derive e_{min} we must assume that $\theta = 0$ or π. While the velocity could be larger at some other position in the orbit, we know that the maximum deviation from the circular velocity is at least as large as the measured velocity, and hence e must be at least a certain value. If we define the transit duration deviation, Δ, as

$$\Delta = \left|\frac{T - T_c}{T_c}\right| \tag{4}$$

and for ease of notation, $\Delta' \equiv T/T_c = v_c/v$, then we find that

$$e_{min} = \left| \frac{\Delta'^2 - 1}{\Delta'^2 + 1} \right| \tag{5}$$

is the minimum eccentricity permitted by the transit data. The e_{min} signal is effectively a measure of the actual to circular transit duration, or physically, the circular to actual transverse velocity. Note that in the ratio T/T_c, the minimum impact parameter cancels out (although it is explicitly included in the transit model and will affect other parameters through covariance). This leaves e_{min} a function of 4 parameters: P, a, v, and R_*. We will use the *Kepler* lightcurves to constrain P and R_*/v, meaning that we must determine though other means the semi–major axis and stellar radius. The semi–major axis, and also the reference circular velocity, may be determined through the host star mass, making it critical that we are able to estimate the stellar mass and radius reliably.

As outlined in Ford et al. (2008), transit durations that are *less* than the circular duration may be due to a poorly constrained impact parameter or eccentricity. However, transit durations that are *longer* than circular may only arise due to eccentricity. For long cadence *Kepler* data, the impact parameter is typically the most poorly known of all model parameters, because its primary constraint comes from the ingress/egress durations, which are poorly resolved for small planets at a 30–minute cadence. However, there are now several hundred transits per system to resolve ingress/egress. Our KOI 701.01 analysis below suggests that the dependence of other model parameters on b does not compromise the e_{min} analysis, although we have not fully tested this at large impact parameter ($b \sim 1$).

The transit duration deviation has been used in several studies to constrain the eccentricity distribution. Moorhead et al. (2011) analyzed the first 3 quarters of *Kepler* data and found that the KOIs appeared to be consistent with a mean eccentricity near 0.2. As impact parameters were poorly constrained, they only considered cases in which $T > T_c$. They also found that eccentricities appear to be large regardless of orbital period, and that small planets tend to have larger eccentricities. More recent work has failed to determine if the *Kepler* eccentricity distribution is consistent with the radial velocity planets (Plavchan et al., 2012; Kane et al., 2012). These studies were limited by the number of known candidates, as well as the relatively poor characterization of the transits themselves.

The Boundary Between Rocky and Gaseous Planets

That transit data provide a minimum eccentricity, while tidal theory damps eccentricity to zero, is crucial for our proposed research. If $e_{min} = 0$, *then the orbit is circular.* Of course circular orbits could be primordial, but Jackson et al. (2008) and Matsumura et al. (2010) showed that the observed radial–velocity–detected planets in tight orbits could have formed with eccentricities consistent with the more distant planets and were subsequently tidally damped in both the CPL and CTL framework. If $e_{min} > 0$ then tides have not damped the eccentricity, and, if we know the age of the system, then we can estimate the tidal Q (or in the CTL model, the time lag factor).

As an example consider the two curves in Fig. 1, produced using the classical tidal theory as described in Barnes et al. (2013). The line shows 10 Gyr of tidal evolution of a 2 $R_\oplus$ planet with a density of 1 g/cm^3 and tidal Q of 10^6 (i.e. a 3.8 $M_\oplus$ "mini-Neptune"), while the

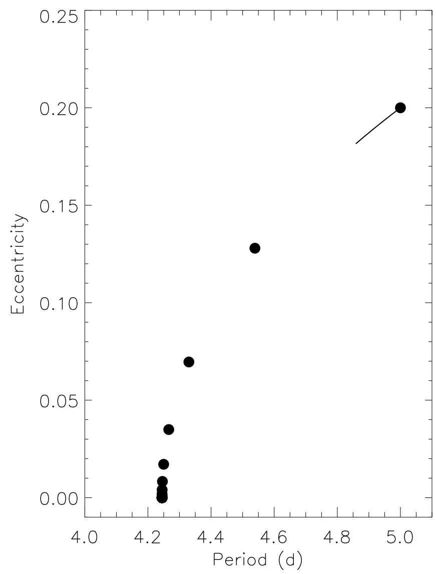

Figure 1: Comparison of the tidal evolution of a 2 $R_\oplus$ mini–Neptune (solid line; for 10 Gyr) and a 2 $R_\oplus$ super–Earth (circles; in 100 Myr intervals). The mini–Neptune experiences little orbital evolution, but the super–Earth circularizes in about 1 Gyr. This discrepancy is due to the 4 orders of magnitude difference in tidal dissipation between gaseous and rocky planets.

filled circles represent the orbit of a 2 $R_\oplus$planet with a mass of 10 $M_\oplus$ and a tidal Q of 100 (i.e. a "super-Earth") every 100 Myr. Both objects start with the same initial orbits. The super–Earth circularizes in about 1 Gyr; the mini–Neptune does not evolve significantly, even after 10 Gyr. This discrepancy is evident despite the fact that equilibrium tidal models predict that evolution scales as mass to the 3/2 power and radius to the 5^{th} power – instead, the large difference between Q_r and Q_g dominates. We therefore hypothesize that the TDD may be able to identify the radius that separates gaseous planets from rocky planets.

To test this possibility, we performed the following test. We created 25,000 synthetic star–planet configurations with initial semi–major axes uniformly in the range [0.01,0.1] AU, radii in the range [0.5,10] $R_\oplus$, stellar masses in the range [0.8,1.2] $M_\odot$, and ages in the range [2,8] Gyr. If the radius is less than 2 $R_\oplus$, we assume Earth-like composition and scale the mass as $(R/R_\oplus)^{3.68}M_\oplus$ (Sotin et al., 2007) and assign a tidal Q in the range [30,300]. If larger than 2 $R_\oplus$, then we assume the density is 1 g/cm^3, and a tidal Q in the range [10^6,10^7]. The initial eccentricity is drawn from the currently observed distribution of distant planets ($a > 0.2$ AU). We then integrate the CPL tidal model forward for the randomly chosen age and assume we observe the system in that final configuration. In Fig. 2, we show the resulting average eccentricities of these planets as a function of planetary radius, R_p, and orbital period, P. The small values of e at low R_p and P shows this effect. Furthermore, we can see the features that correspond directly to three parameters that are currently very poorly constrained: R_{crit} via the rapid rise in $\langle e \rangle$ at 2 $R_\oplus$; Q_g via the rapid rise in $\langle e \rangle$ at 1 day above 2 $R_\oplus$; and Q_r via the rise over 4–8 days and below 2 $R_\oplus$. Thus in this simple model, we see three constraints for three unknowns, yielding the possibility that the right observations may be able to provide values for these elusive quantities.

However, *Kepler* data do not provide eccentricity, but rather the minimum eccentricity. We must therefore transform these simulations into a form that is directly comparable to an observable. In order to calculate e_{min} from these synthetic data, we choose a random value for θ and calculate the velocity according to Eq. 3. We calculate the average minimum

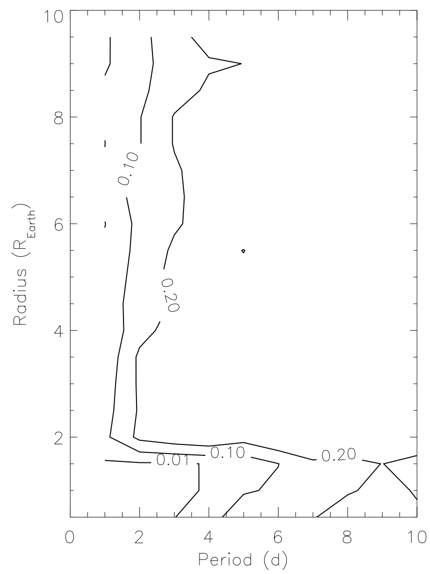

Figure 2: Average final eccentricity of a suite of 25,000 systems of one star and one planet. Planets larger than 2 $R_\oplus$ are gaseous, and those smaller are rocky. The bin-sizes are 0.5 $R_\oplus$ in radius and 0.5 d in period. Gaseous planets retain a residual eccentricity if $P > 1.5$ d, while rocky planets require $P > 4$ d. The transition occurs at 2 $R_\oplus$, which in this case is R_{crit}.

eccentricity $\langle e_{min} \rangle$ for our rocky and gaseous planets in 0.5 day orbital period intervals and plot $\langle e_{min} \rangle$ as a function of orbital period for different radii as solid lines in Fig. 3. For $R < 2$ $R_\oplus$, $\langle e_{min} \rangle \sim 0$ up to about a 4 day period. However, for larger radii, circular orbits are only guaranteed for periods less than about 2 days. *Despite the order of magnitude ranges for each physical planetary property, the disparity in tidal Q's produces a strong signal in* $\langle e_{min} \rangle$ *that distinguishes the rocky and gaseous planets.*

This pilot study is encouraging, but its feasibility rests on the precision of the models of the *Kepler* data. Specifically, impact parameters, stellar and planetary radii, orbital period, and stellar mass must be known and their uncertainties well–modeled. The first four properties are measurable from transit data alone, while the fifth must be estimated by other means. The *Kepler* team has provided these data in various publications and websites. The solid squares show the values of $\langle e_{min} \rangle$ with quantities from the *Kepler* Planet Candidate Data Explorer[1]. Nearly all the observed data are above the predictions. There are two possible explanations for this discrepancy: 1) The theory is wrong, or 2) the reported model parameters are of poor quality. We outline limits of the theory next.

Non–Tidal Effects

First, we note that additional companions can pump eccentricity through mutual gravitational interactions, even if tidal damping is ongoing (Mardling & Lin, 2002; Bolmont et al., 2013). Therefore we must be cautious when interpreting Fig. 3, as additional companions, both seen and unseen, can maintain non–zero eccentricities. However, there are limits: Bolmont et al. (2013) showed that planet–planet interactions cannot maintain the eccentricity of the hot super-Earth 55 Cnc e above 0.1. That system is particularly relevant as there are many close–in planets orbiting a typical G dwarf. Therefore, we conclude that eccentricity pumping can be significant but cannot explain the discrepancy between the observed and simulated systems shown in Fig. 3.

[1]http://planetquest.jpl.nasa.gov/kepler

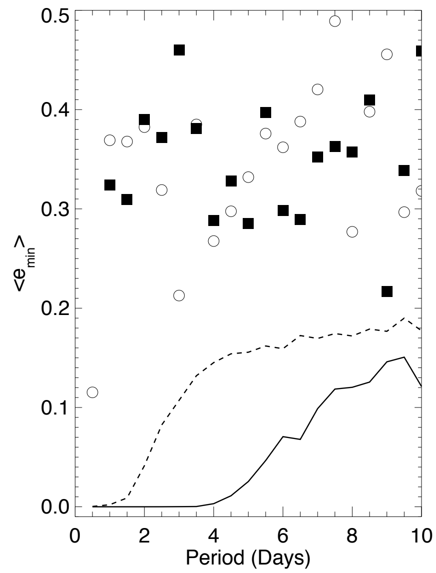

Figure 3: Average minimum eccentricities for transiting exoplanets as a function of period and radius. The solid curve and filled squares represent planets with radii below the selected critical radius of 2 $R_\oplus$, while the dashed curve and open circles are larger planets. The lines are the relationships for the simulated data set, symbols for KOIs. The latter all have values near 0.3–0.4 days regardless of period, whereas model gaseous planets have non–zero eccentricities if the period is larger than 1.5 days, and rocky planets at larger than 4. If tidal dissipation is a function of exoplanet radius, it should be detectable.

Another possibility is that stellar winds and activity can strip an atmosphere, reducing the mass and radius, and potentially changing the planet from a mini–Neptune to a super–Earth (Jackson et al., 2010; Valencia et al., 2010; Leitzinger et al., 2011; Poppenhaeger et al., 2012). Recently, Owen & Wu (2013) argued that the *Kepler* sample is consistent with hydrodyanmic mass loss, and that some low–mass planets could have formed with substantially more mass. Mass loss should decrease the time to circularize the orbit, assuming the radius doesn't become very large, which is unlikely after about 100 Myr (Lopez et al., 2012). Therefore, mass loss could stall circularization for mini–Neptunes, but not for super–Earths. Although few radial velocity measurements exist, planets with radii less than ~ 1.5 $R_\oplus$ have densities consistent with silicate compositions (Batalha et al., 2011). Thus, mass loss seems unlikely to explain the differences seen for the smallest candidates in the *Kepler* field.

Other effects, such as stellar mass loss or the galactic tide will be negligible, but to properly treat the problem, planetary mass loss and planet–planet perturbations must be considered. On the theoretical side, the path forward to determine R_{crit}, Q_r and Q_g is clear: We must first model the full range of plausible values for these three parameters to calculate $\langle e_{min}\rangle(R_p, P)$; include the planet–planet interactions of multiple planet systems over the lifetimes of the systems; and incorporate mass loss, including the possibility that a mini–Neptune can become a super–Earth with its associated change in tidal Q.

In summary, the effects of tidal circularization appear not to be present in publicly available fits to the *Kepler* data, in sharp contradiction with the radial velocity exoplanet sample (Butler et al., 2006). These fits are therefore inadequate to identify R_{crit} and tidal Qs, meaning a state–of–the–art statistical re–analysis of *Kepler* photometry is required to determine these fundamental parameters.

III. Technical Approach and Methodology

We describe below our technical approach to the re–analysis of Kepler data, including simulations to understand how we will be able to constrain system parameters and a validation of this technique using a known exoplanet system, and outline how we will fold these results into tidal theory to understand R_{crit}, Q_r and Q_g.

We will use the quadratic limb–darkened model of Mandel & Agol (2002) to describe the lightcurves. We emphasize that at its core, the Mandel & Agol model is a purely geometric one that describes an opaque planetary disk occulting a limb–darkened stellar disk. Many applications of this technique use planetary orbital parameters such as semi–major axis and inclination as inputs to the model, along with frequent assumptions of zero eccentricity, *but this need not be the case*. Instead we use a purely geometric implementation of Mandel & Agol (2002) whose only assumption is that the planet has constant transverse velocity during transit. This generalization is especially important for our proposal, as we need to compare our measured transit duration with what would be observed in the zero–eccentricity limit.

The main observable in this model is the time it takes the planet to cross the stellar equator, τ (this may also be thought of as a measure of the transverse velocity, $v = R_*/\tau$). This allows us to cast e_{min} in terms of τ, period P, and the (unknown) ratio of the planet's semi–major axis to stellar radius. While the uncertainty in impact parameter will affect our knowledge of the other system parameters through covariance, this uncertainty may be marginalized over by examining posterior distributions, which drives us to use Markov–Chain Monte Carlo (MCMC) modeling in our analysis, described below.

Transit Model

We adopt the quadratic limb–darkened model of Mandel & Agol (2002), which describes transit lightcurves in terms of two (nuisance) limb–darkening coefficients and two (important) system parameters. The first of the system parameters is the planetary radius divided by the stellar radius ($\zeta \equiv Rp/R_*$), which determines the fractional area of the stellar disk that may be occulted by the planet. The second is the impact parameter of the planet ($\beta \equiv b/R_*$). This variable is a function of time, due to the objects' relative motion. This function is dependent on the chord that the planet takes across the stellar disk, itself typically estimated using the orbital parameters semi–major axis ($\alpha \equiv a/R_*$) and inclination.

Instead we use here a purely geometric parameterization. We describe the impact parameter as a function of time using the minimum impact parameter β_0 – when the centers of the sources are maximally aligned at center–of–transit time t_0 – and the location of the planet on the transit chord across the stellar disk. The coordinate of the planet as a function of time is represented as $x(t)/R_* = (t - t_0) * v/R_* = (t - t_0)/\tau$, where v is the (unknown) perpendicular velocity, and τ is the (fitted) amount of time it takes the planet to traverse a distance equal to the stellar radius assuming no acceleration. This allows us to express geometrically the impact parameter as a function of time:

$$\beta(t) = \sqrt{\beta_0^2 + ((t - t_0)/\tau)^2}, \quad (6)$$

which is then used along with ζ to generate a model transit lightcurve. This model yields a 4–parameter fit to each transit: $t_0, \beta_0^2, \tau, \zeta$. The system period P is determined using multiple (N) transits and the ensemble of $t_{0;i=1...N}$. The transit duration T is found from the 2 solutions to $\beta(t) = 1$:

$$T = 2 * \tau\sqrt{1 - \beta_0^2}. \quad (7)$$

Combining Equations 4,5 and 7 we express e_{min} in terms of our model parameters:

$$e_{min} = \left| \frac{P^2 - 4\pi^2\alpha^2\tau^2}{P^2 + 4\pi^2\alpha^2\tau^2} \right| \tag{8}$$

or, more intuitively,

$$e_{min} = \left| \frac{1 - (v_c/v)^2}{1 + (v_c/v)^2} \right|. \tag{9}$$

Equation 8 indicates that e_{min} is purely a function of the fitted parameter τ, the derived period P, and an externally estimated semi–major axis for the planet (in units of the stellar radius) α.

<u>KOI 701.01</u>

We validate our proposed methodology by analyzing *Kepler* data from KOI 701.01 (Kepler 62–b; Borucki et al., 2013). This planet has a period of 5.715 days, $\zeta = 0.018$ ($R_p \sim 1.3$ R_E), and a transit depth of 4×10^{-4} %. We use the limb darkening parameters for the host star from Sing (2010). The *Kepler* data have correlated (red) noise which we must account for before model fitting. To do so, we perform a local detrending by first dividing the data by the proposed model, and fitting a low order spline to the result. The goodness of fit is determined by comparing the product of the spline and the model to the data. We were able to model the first 32 transits before this proposal deadline.

To examine how our knowledge of system parameters evolves as a function of number of transits, we have fit *all* the data up to the time of each transit, for each of $N = 32$ transits. This means that for transit $n \leq N$, we have common model parameters β_0^2, τ, ζ and per–transit parameters $t_{0;i=1..n}$, for a total of $n + 3$ model parameters. This yields an ensemble of N system models, each incorporating one more transit than the previous one.

We used the affine–invariant MCMC sampler `emcee` (Foreman-Mackey et al., 2013) to sample the posterior distribution of the model parameters. This program uses the method of Goodman & Weare (2010) to achieve high sampling performance independent of the aspect ratio of the posterior distribution, meaning covariances between parameters are less important to the efficacy of the MCMC sampling. This provided a set of MCMC chains that we examine to determine our constraints on the fitted parameters. We used the Gelman–Rubin $\hat{\mathrm{R}}$–static (Gelman & Rubin, 1992) to assure that each chain sufficiently samples model space, and required effective chain lengths larger than 10^4 to ensure sufficient mixing in the MCMC sample (e.g. Tegmark et al., 2004). Our trial runs using KOI 701.01 indicated that our chains typically have autocorrelation lengths of ~ 100, requiring a total number of steps per chain of 10^6. We used burn–in times having 10% the requested number of steps, which are then discarded before the final chain commences.

For each transit, we marginalized over all other parameters, to examine the per–parameter confidence limits. Figure 4 demonstrates how our marginalized constraints on τ (left panel) and ζ (center panel) evolved as a function of the number of transits used in the fit for 701.01. The solid line provides the maximum of the posterior distribution, and the dashed line indicates its median. The shaded area encloses 68.3% of the distribution. In this manner, we find a maximum likelihood value of $\tau = 0.051^{0.003}_{0.002}$. This may be contrasted to

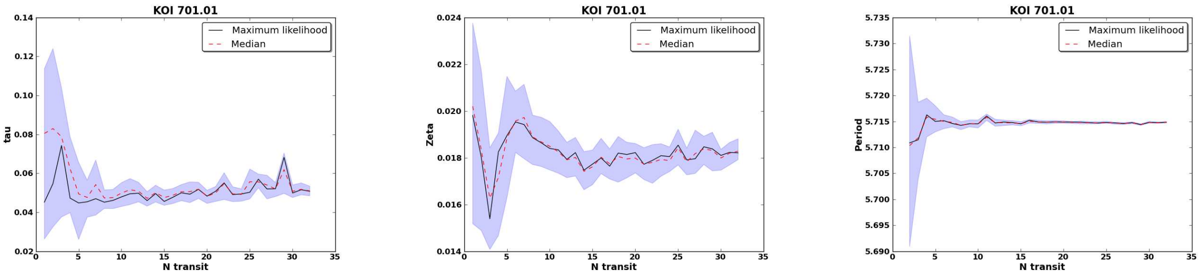

Figure 4: The marginalized distributions of τ (left panel), ζ (center panel), and period P (right panel) as a function of the number of transits being used, for KOI 701.01. For each transit $n \leq 32$ we use *all* data up to and including transit n. The *solid* line represents the maximum of the posterior distribution, while the *dashed* line indicates its median. The shaded area contains 68.3% of the posterior samples.

$\tau = 0.049 \pm 0.003$ derived from reported Borucki et al. (2013) parameters, where they used 171 transits. For completeness, we note our confidence limits on $\zeta = 0.0182^{0.0006}_{0.0003}$ vs the Borucki et al. (2013) result $\zeta = 0.0188 \pm 0.0003$.

To examine our constraints on the system period, we used the $t_{0;1..n}$ posterior distributions from the fits described above. We used `emcee` to sample the posterior space of (nuisance parameter) $t_{0;1}$ and period P. For a given trial $(t_{0;1}, P)$ pair, the likelihood was determined through:

$$\mathcal{L}(t_{0;1}, P) \quad = \quad \prod_{i=1}^{i=n} \kappa_i(t_{0;1} + P * (i-1)) \tag{10}$$

where κ_i is a kernel density estimate of each posterior distribution $t_{0;i}$, which is evaluated at the predicted time of transit $t_0 + P * (i-1)$. By modeling the times of transit separately in the original MCMC analysis, we allow the possibility of using a more complex ephemeris model at this stage of the analysis, such as may be expected from transit timing variations (Agol et al., 2005; Holman & Murray, 2005). The results of this analysis for KOI 701.01 are presented in the right panel of Figure 4.

For the derived period after 32 transits, we find $P = 5.71484^{0.00009}_{0.00015}$. The uncertainty in the period roughly scales as a power law with an e–folding timescale of approximately 15 transits. This may be contrasted to $P = 5.714932 \pm 0.000009$ days reported in Borucki et al. (2013). The differences in e_{min} are more substantial. Using their reported value of $\alpha = 18.7 \pm 0.5$, we derive $e_{min} = 0.043 \pm 0.009$, compared to $e_{min} = 0.021 \pm 0.005$ using the Borucki et al. (2013) results. This difference is almost entirely driven by the (1–sigma) differences in τ, which makes it of utmost importance to model this parameter directly.

To examine our ability to constrain system parameters as a function of transit depth and signal–to–noise (S/N), we generated simulated lightcurves at the *Kepler* cadence. We used a subset of the synthetic systems described in the first section of this proposal. For each, we simulated lightcurves at magnitude 8/10/12/14, adding a random draw from a Gaussian with widths 11.3/29/80/296 ppm (respectively) to each datapoint to simulate white noise. We find that after 10 transits, we are able to recover τ to better than ten percent for all transits deeper than 0.5% down to 14^{th} magnitude; deeper than 0.1% down to 12^{th} mag; deeper than 0.05% down to 10^{th} mag; and deeper than 0.01% down to 8^{th} mag. This analysis is consistent with our results from KOI 701.01, where the host star's magnitude is 13.6, the transit depth is 0.04%, and measured S/N in τ is ~ 7.8 after modeling 10 transits: $0.0479^{0.0073}_{0.0049}$. Note the measured precision in τ increases to a S/N of approximately 20 after 32 transits (Figure 4).

Target Selection and Characterization

We have examined the current KOIs to establish a preliminary target list. We find 890 objects with appropriate values of P and R_p, and with host star mass estimates between 0.7 and 1.4 $M_{\odot}$, i.e. FGK stars. We expect this list to expand somewhat with on–going study of the *Kepler* data; we anticipate running our pipeline on approximately 1000 systems.

As described above, our analysis requires a measure of the orbital separation relative to the stellar radius, $\alpha = a/R_*$, to derive e_{min} (Equation 8). The separation is obtained trivially from Kepler's 3rd Law according to, $a = (M_* P^2)^{2/3}$ where M_* is the mass of the host star. Unfortunately, the mass of an isolated star is not directly observable. Instead, it must be inferred by comparing observed stellar properties to theoretical stellar evolution models and/or empirical calibrations. Thus, to derive the stellar mass, we will interpolate state-of-the-art stellar evolution models from the Dartmouth group (Dotter et al., 2008) in three parameters: effective temperature (T_{eff}), metallicity ([Fe/H]), and gravity ($log\ g$), as we (L. Hebb) have done for many other confirmed transiting planets with radial velocity measurements (e.g. Hebb et al., 2009, 2010).

We plan to primarily use the information available in the literature for T_{eff} and [Fe/H]. Several teams have large, observing programs to obtain spectra of KOIs. Everett et al. (2013) derived stellar parameters for ~ 400 faint KOIs from low resolution data; approximately 1000 targets have been observed with Keck HIRES (J. Johnson et al. in prep) and are currently being analyzed with a new Spectroscopy Made Easy (SME) pipeline (Cargile, Hebb et al. in prep); and the 2.5m Nordic Optical Telescope (NOT) has has an ongoing program to derive stellar parameters of Kepler KOIs (L. Buchave, PI). However, if certain targets lack observed spectra or derived stellar parameters, we will obtain the necessary data with the ARC 3.5m echelle spectrograph through the University of Washington's guaranteed access to the Apache Point Telescopes. We will analyze these data as necessary with our SME pipeline, as we have done for many other targets (i.e. Wisniewski et al., 2012).

We will obtain the $log\ g$ values based on a novel characterization of the high frequency variability in the *Kepler* light curves (Bastien, Stassun et al. 2013, to appear in Nature) which has been shown to reproduce the exquisite astroseismically measured $log\ g$ values (Huber et al., 2013) for dwarf and subgiant stars. The authors present a technique that can be used to derive $log\ g$ values for the majority of Kepler targets with uncertainties of ≤ 0.1 by empirically detecting granulation on the stellar surface. This allows for significantly more accurate and precise gravity measurements than can be derived from typical modeling of broad absorption line wings.

We will interpolate the Dartmouth models considering the uncertainties in the photometrically measured $log\ g$ and in the spectroscopically determined [Fe/H] and T_{eff}. Typical uncertainties of ≤ 0.1 dex in [Fe/H], ≤ 100 K in T_{eff}, and ≤ 0.1 in $log\ g$ result in uncertainties on the resulting stellar mass of $5-8\%$ for well understood F, G and K-dwarf stars. This error budget includes the formal errors from the measured uncertainties on the parameters, and systematic uncertainties arising from variation between different stellar evolution models (2-4%; Southworth, 2009). We expect to generate a catalogue of $\alpha = a/R_*$ values for all the short period KOI transiting planet candidates in our sample with conservative uncertainties of $\leq 10\%$. Finally, our comparison of the stellar parameters to the evolutionary models also allows us to estimate stellar age, which is critical to understanding the tidal quality factors.

Computational Requirements

Using KOI 701.01 as a benchmark, we find a linear relationship in the computation time required to reach 10^6 steps vs. the number of transits: $time_{10^6}(n) = -1105 + 5943 \times n$ seconds. For a 5–day period system having ~ 300 transits over the assumed 17–quarter operational lifetime of *Kepler* , this comes out to ~ 21 CPU–days of analysis. The `emcee` code is natively able to use multiprocessing capabilities, making this trivial to implement on a multi–core system. However, with ~ 1000 systems on our analysis path, this will require ~ 60 CPU–years of computation, requiring the use of NASA's High-End Computing (HEC) facilities. We will also make use of the local `Hyak` compute cluster when it is available.

Data Interpretation

In the following sections, we describe the theoretical component of our research plan in more detail. In Task A, we consider systems consisting of one star and one planet. In Task B, we include multiple planet systems. In Task C, we incorporate mass loss. For each task, our final step will be a comparison between simulated data and the ensemble of well–characterized *Kepler* targets. This will be done by comparing the measured distributions of e_{min} to those simulated using R_{crit}, Q_r, and Q_g (and possibly factoring in multiplicity, metallicity, and mass loss).

Task A: Tides in Star–Planet Systems

We begin with the simplest treatment, a single planet orbiting a single star in an orbit that can be modified by tides. We will mostly follow the procedure described for our pilot study, but will expand the analysis to a broader range of initial conditions as well as include alternative tidal models. The pilot study (25,000 simulations of ~ 5 Gyr each) requires about 4 hours on a modern workstation, and therefore many such trials are easily tractable. The free parameters are the mass–radius relationship for both rocky and gaseous bodies, the value of R_{crit}, the Qs of rocky and gaseous bodies, the initial eccentricity distribution, and the age distribution of *Kepler* stars.

The choices in the pilot study were necessarily limited, and we will explore many more options during this investigation. While we assumed that rocky bodies were Earth–like in their composition, other scaling laws are possible (e.g. Seager et al., 2007; Fortney et al., 2007; Lissauer et al., 2011). We will use these other scalings for the masses of the rocky planets, as well as mixing the models to allow for a range of compositions. For the gaseous planets, we will assume different densities in the range 0.5 – 3 g/cm^3. The value of R_{crit} is the parameter we are most interested in; we will grid from 1 to 2.5 $R_\oplus$in 0.1 $R_\oplus$intervals. We will consider two different models for $Q(R)$, the tidal Q as a function of planetary radius. First we will use the same differences as in the pilot study, but we will also consider a three–tiered model, in which intermediate mass planets have intermediate Qs. Neptune, and possible even Saturn, have a Q value of 10^4 (Zhang & Hamilton, 2008; Lainey et al., 2012), and hence we must consider this possibility. This also introduces a new radius cut–off, R_{mid}, which we will allow to move from 2 to 5 $R_\oplus$. The Q range for these systems will have values between 3000 and 30,000. We will randomly choose a stellar mass in the range 0.7–1.4 $M_\odot$as we are interested in FGK stars. Finally, we will keep the initial eccentricity distribution consistent with that of more distant exoplanets. Ultimately we expect to run several hundred suites of systems, easily do–able on a modern multi–core workstation.

The examples in Figs. 1–3 used one tidal model, in which the lag angle between the tidal bulge and the perturber is constant regardless of frequency (e.g. Goldreich & Soter, 1966; Jackson et al., 2008). Another popular model assumes that the lag angle is instead a function of frequency (e.g. Hut, 1981; Matsumura et al., 2010). We will also employ this model with the same ranges as described above, and relating Q to the time lag τ as $Q = 1/n\tau$, where n is the mean motion (e.g. Correia et al., 2012). In reality there is no general conversion between the two, but this relation is in common use. Thus, our work may also shed light on the frustrating ambiguity in determining the most appropriate equilibrium tidal model.

Task B: Multi–planet Systems

Mutual gravitational interactions between planets can maintain an eccentricity, even in the presence of strong tidal damping (Mardling & Lin, 2002; Greenberg & Van Laerhoven, 2011; Correia et al., 2012). To assess this effect, we will perform simulations of multiplanet systems undergoing tidal damping. The Gyr timescales for damping are too long for accurate N-body modeling, so will use classical secular theory to model the planet-planet interactions. The second order theory is insufficient for many of the cases we consider, which will have eccentricities up to 0.9. Therefore, we will use higher order theories, which have been previously developed (e.g. Ford et al., 2000; Veras & Armitage, 2004; Libert & Henrard, 2005). To maximize accuracy, and take advantage of the high degree of coplanarity of close–in *Kepler* systems Fabrycky et al. (2012), we will use the coplanar 12th order theory of Libert & Henrard (2005) to evaluate the evolution.

More challenging is the choice of initial conditions. While many *Kepler* systems are multiple, we do not yet know the underlying distribution of orbital architectures. A full exploration of parameter space with arbitrary multiplicity and orbital elements would be intractable, and would be very challenging to interpret. We therefore will limit our study to suites of 25,000 systems with multiplicity that follows from the observations. To better match the *Kepler* systems, we will limit the size of our planetary systems to < 0.5 AU. The physical properties of the planets will be in the same ranges as above. We will perform numerical tests of stability of initial conditions, and will throw out systems that divergently cross strong mean motion resonances – such 2:1, 3:1, and 3:2 – that lead to system break–up (e.g. Gomes et al., 2005).

Additionally, it may be that many of the close–in systems cannot have initial eccentricities comparable to the non–tidally–evolved planets because they would be unstable. In those cases, the orbits are probably close to their primordial morphologies and migrated during the protoplanetary disk phase. Recently Dawson & Murray-Clay (2013) showed compelling evidence that high metallicity stars are more likely to host eccentric planets. Therefore, we will make two comparisons with the *Kepler* sample: the full set and the high metallicity set.

TASK C: ATMOSPHERIC MASS LOSS

We will employ the classic mass loss of model of Watson et al. (1981) in which XUV photons liberate hydrogen atoms in the upper atmosphere. Mass loss can be a very complicated process (Yelle, 2004; Lammer et al., 2007; Khodachenko et al., 2007; Leitzinger et al., 2011; Lammer et al., 2013), and with so many unknowns for any given planet, this simple model is most appropriate. The key parameter in this formulation is the efficiency of transforming incident XUV radiation into escaping atoms, ϵ. Most studies of hot Jupiter place ϵ in the range 0.1 – 0.4. We will therefore explore a range of 0.05 – 0.5 in increment of 0.05 and apply these to the configurations of Task A and Task B. For the XUV flux, we will use the empirical relationship derived in Ribas et al. (2005) for G dwarfs. While this formulation is not strictly valid for F and K dwarfs, analogous studies do not exist for those spectral types, and the Ribas model is probably a close approximation. The Watson and Ribas models are already in `eqtide` (Barnes et al., 2013), and hence minimal code improvements are required for this step. This final theoretical task requires about 2–3 times more computational resources than the other two combined, but is still dwarfed by the *Kepler* lightcurve analysis, and can easily be completed within a few months on a workstation, or on UW's local supercomputer.

Unfortunately the inclusion of mass loss leads to a degeneracy in our model. The three parameters R_{crit}, Q_r and Q_g, are all related to features in Figure 3. Mass loss complicates the picture by blurring these boundaries. On the other hand, it is entirely possible that we will fail to reproduce the observed $\langle e_{min} \rangle$ distribution without it. At the conclusion of Task C, we will have about 2000 suites of simulations with different physical parameters to compare to the *Kepler* planet candidates. If we succeed in identifying R_{crit}, then planets found in the HZ of *Kepler* targets can be characterized as gaseous or rocky (and potentially habitable), independent of knowledge of their masses. This is the ultimate goal of this proposal.

IV. Team Qualifications and Previous NASA Support

PI Becker is PI on NASA OSS grant NNX09AB32G, "3.5m Transit Timing Observations at 100% Duty Cycle", which observed multiple transiting exoplanet systems for evidence of transit timing variations (Kundurthy et al., 2011, 2013b; Becker et al., 2013; Kundurthy et al., 2013a). Much of the software developed for that project has been modified to operate with the *Kepler* data, and used in the analyses presented here. He has considerable expertise in using modern software packages implemented on distributed computing infrastructures to model multi–dimensional systems.

Co–I Barnes was a Co–I on NASA OSS grant 811073.02.07.01.15 "Simulating the Initial Planetesimal Disk" which produced the first N-body simulation of 1 km planetesimal accretion (Barnes et al., 2009). As part of this effort, Barnes used several hundred thousand hours of CPU time at NASA HPC facilities, such as the Columbia and Plaiedes supercomputers. He has published ~ 40 papers on tidal theory and orbital dynamics, including secular modeling (Barnes & Greenberg, 2006), tidal effects (**?**Barnes et al., 2013), and coupling with atmospheric mass loss (Jackson et al., 2010; Barnes et al., 2013).

Co–I Agol has originated several important ideas in the field of extrasolar planets, including analytic light curve modeling (Mandel & Agol, 2002), transit timing variations (Agol et al., 2005), and discovery of the smallest diameter planet in the habitable zone of another star (Borucki et al., 2013). He is currently a *Kepler* collaborator.

Co–I Hebb is an expert in the field of characterizing exoplanet host stars using state-of-the-art stellar evolution models (e.g. Hebb et al., 2009, 2010; Bouchy et al., 2010; Gómez Maqueo Chew et al., 2013).

V. Relevance to NASA Programs

This project addresses directly multiple objectives that are in–scope for the Origins of Solar Systems call for proposals, including:

- **Observations and theoretical investigations related to the formation and evolution of planetary systems**: This proposal will explore the current minimum eccentricity distribution as a function of orbital period and planetary radius. These data will be combined with extensive and novel theoretical analyses to constrain the initial conditions and evolution of these systems. Critically, this proposal will measure for the first time tidal circularization model parameters R_{crit}, Q_r and Q_g.
- **Characterization of extra-solar planets to explain observations of extra-solar planets**: This proposal will help to draw the critical boundary between gaseous and rocky planets, helping to interpret the observations of exoplanet systems having longer orbital periods (and potentially in their host star habitable zones).

VI. Project Development Plan

PI Becker will be technical lead the project for the first 1.5 years, which will constitute the data analysis (MCMC) portion of the project. Co–I Barnes will serve as technical lead for the project for the second 1.5 years, as the project transitions from analysis of the data to interpretation and constraints on tidal evolution theory. Co–I Agol has significant experience with *Kepler* data, and will advise as–needed throughout the project. Co–I Hebb has extensive experience inferring the stellar properties of exoplanet host stars, and will serve as the lead for determining the host stars' mass and radius. PI Becker will serve as the project lead throughout. We will have weekly meetings at the University of Washington to manage progress, and yearly meetings including Hebb to focus on host star characterization.

We regard the professional development of students as an important responsibility of *any* research project. In this regard, the graduate students funded by this proposal will have the opportunity to attend at least one relevant conference each year, and encouraged to give oral presentations on our work. This will become a requirement as the project progresses. We expect the graduate student to become an expert in both areas of this project, both the computational/modeling side and the theoretical side, and will work full–time with both Becker and Barnes throughout. This is a powerful combination and one not seen often enough in the field. We consider this dual–aspect training a strong component of this project.

Year 1 (2014): This first year of the project will start with PI Becker bringing the student up to speed in modeling transit lightcurves, in leaning Bayesian techniques, and in implementing a robust application of the `emcee` package (or other affine–invariant sampler, if needed). This includes making the software robust to detrending errors, missing data, and initial conditions. Discovering and understanding the failure modes will be a main focus of this computationally–intensive first year. Becker will lead this effort, and transition the student into lead during the year. The generation of the MCMC chains is expected to take ~ 60 CPU–years, requiring the use of high–end computing facilities. The validation of these chains is expected to take a comparable amount of time, as some chains are expected to have to be re–run or extended. The goal of this first year is to have finalized the MCMC chains on $t_0, \beta_0^2, \tau, \zeta$ for all transits of all KOIs. We will make the chains and modeling software publicly available through a `github` site specifically designed for this project.

Year 2 (2015): The second year will begin with the MCMC analyses of the periods, include a strong focus on characterizing the host star mass and radius, and transition to theoretical interpretation of the systems. During this year, Barnes will begin working with the graduate student on the theoretical components. They will design and simulate the models described in Task A and publish preliminary estimates of R_{crit}, Q_g, and Q_r. During this year we will also begin running simulations of multiplanet systems with tidal damping.

Year 3 (2016): During the final year, we will finish all theoretical modeling, including the incorporation of mass loss. We will publish a paper on the role of multiplicity in the e_{min} distribution. The graduate student will perform a final analysis of all available *Kepler* data and will compare this final data set to the synthetic data produced by the tides+multiplicity+evaporation model. A final paper will summarize the results of the investigation, including final values, with error estimates, for R_{crit}, Q_r, Q_g, and ϵ.

VII. Data Sharing Plan

All investigators are committed to the sharing of data and software. PI Becker has been behind real–time public alert systems for many time–domain astronomical surveys. This includes the MACHO survey, the Deep Lens Survey, the SuperMACHO and ESSENCE surveys, and the SDSS–II Supernova Survey, all of which have released their events to the public in near–real time through web pages, Astronomer's Telegrams, IAU circulars, and VOEvents. He is currently working part–time on the Large Synoptic Survey Telescope (LSST), which is both open–source and open–data.

We will version release all software developed for this project on the publicly available open–source collaboration website http://github.com (`github` hereafter). The website has become a leading collaboration platform; it enables distributed users to download code and contribute back to the project. All code we develop for this project will be made available under the terms of the open source BSD license[2] whenever possible. We will make a new `github` account for this project that we will use to stage code and data releases, as described in the project development plan. Analysis packages used in our publications will be released as `iPython`[3] notebooks to help establish reproducible research standards in the field. `iPython` allows the exchange of portable environments (notebooks) that enable the user to follow the analysis path leading to a given scientific result, and also to interact with it at the code level to understand (and verify) the methodology.

[2] http://www.opensource.org/licenses/bsd-license.php

[3] http://ipython.org

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Selected Publications[1]

[1] **Becker, A. C.**, J. J. Bochanski, S. L. Hawley, Ž. Ivezić, A. F. Kowalski, B. Sesar, and A. A. West. Periodic Variability of Low-mass Stars in Sloan Digital Sky Survey Stripe 82. *ApJ*, 731:17, April 2011.

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Postdoctoral advisor : J. Anthony Tyson, University of California, Davis

Previously on doctoral committees of : Ricardo Covarrubius, Branimir Sesar, Eric Hilton, Praveen Kundurthy, Sarah Schmidt, and Jacob Vanderplas

[1]Aggregate citations to previous publications are in the top 1% in the field of Space Science, Thompson Reuters; http://sciencewatch.com/inter/aut/2010/10-may/10mayBeck/

Dr. Rory Kevin Barnes

Address	Astronomy Dept. University of Washington Box 351580 Seattle, WA, USA	**Phone** **FAX** **E-mail** **Citizenship**	(206)543-8979 (206)685-0403 rory@astro.washington.edu USA

EMPLOYMENT

2011 – Research Staff, Astronomy Dept. & Astrobiology Program, U. of Washington
2009 – 2011 VPL/IGERT Postdoctoral Research Associate to Victoria Meadows, Astronomy Dept., U. of Washington
2004 – 2008 Postdoctoral Research Associate to Richard Greenberg, Lunar and Planetary Laboratory, U. of Arizona.

EDUCATION

Ph.D. Astronomy, University of Washington, 2004
Dissertation: Dynamics of the Initial Planetesimal Disk (Adviser: Thomas Quinn)
M.S. Astronomy, University of Washington, 1999
B.S. Astronomy, University of Arizona, 1998
B.S. Physics, University of Arizona, 1998

HONORS AND AWARDS

2002-2004 NASA GSRP Fellowship
2009 NASA Group Achievement Award (for my contribution to the SIM Double Blind study)

SELECTED RELEVANT PUBLICATIONS

A. Book

Formation and Evolution of Exoplanets. 2010. **R. Barnes** (Ed.), Wiley-VCH. Berlin

B. Refereed Publications

Barnes, R. *et al.* 2013. Tidal Venuses: Triggering a Climate Catastrophe via Tidal Heating. *Astrobiology*, 13, 279–291.

Kundurthy, P., **Barnes, R.** *et al.* 2013. APOSTLE: Longterm Transit Monitoring and Stability Analysis of XO-2b. *Astrophys. J.*, submitted.

Barnes, R. *et al.* 2011. Origin and Dynamics of the Mutually Inclined Orbits of υ Andromedae c and d. *Astrophys. J.*, 726, 71.

Jackson, B., Miller, N., **Barnes, R.**, *et al.* 2010. The Roles of Tidal Evolution and Evaporative Mass Loss in the Origin of CoRoT-7 b. *Mon. Not. Roy. Astron. Soc.*, 407, 910-922.

Barnes, R. *et al.* 2008. Tides and the Evolution of Planetary Habitability. *Astrobiology*, 8, 557-568.

Barnes, R., & Greenberg, R., 2006. Behavior of Apsidal Motion in Planetary Systems. *Astrophys. J.*, 652, 53-56.

Barnes, R., & Greenberg, R. 2006. Extrasolar Planetary Systems Near a Secular Separatrix. *Astrophys. J.* 638, 478 – 487.

Eric Agol

Associate Professor, University of Washington

Astronomy Department	Phone: (206) 543-7106
University of Washington Box 351580	Email: agol@astro.washington.edu
Seattle, WA 98195-1580	Web: http://www.astro.washington.edu/agol/

Education: 1997 - PhD., Physics, University of California, Santa Barbara
1992 - B.A., Physics and Mathematics, University of California, Berkeley

Employment: 2009 to present - Associate Professor, University of Washington
2003 to 2009- Assistant Professor, University of Washington
2000 to 2003 - Chandra Fellow, California Institute of Technology
1997 to 2000 - Postdoctoral fellow, Johns Hopkins University

Prior scientific performance: I have co-authored 100+ refereed papers, including more than 40 related to extrasolar planets, with over 4000 citations. Some of my discoveries include: 1) an analytic formulation of transiting planet light curves (Mandel & Agol 2002); 2) transit-timing variations (Agol et al. 2005); 3) the first phase functions of hot Jupiters and longitudinal map (Knutson et al. 2007); 4) the white dwarf 'habitable' zone (Agol 2011); 5) the first secondary eclipse of an exoplanet (Majeau et al. 2012); 6) the smallest diameter planet in the habitable zone of another star, Kepler-62f (Borucki, Agol et al. 2013); 7) the closest two orbiting planets, Kepler-36 (Carter, Agol et al. 2012).

Selected Publications:

Borucki, W., Agol, E., et al., Kepler-62: A five-planet system with planets of 1.4 and 1.6 Earth radii in the Habitable Zone, *Science* **340**, 587–590 (2013).

Carter, J. & Agol, E., The Quasiperiodic Automated Transit Search Algorithm, *ApJ* **765**, 132 (2013).

Eastman, J., Gaudi, B.S. & Agol, E., 2013, EXOFAST: A Fast Exoplanetary Fitting Suite in IDL, *PASP* **125**, 83–112 (2013).

Carter, J., Agol, E., et al., Kepler-36: A Pair of Planets with Neighboring Orbits and Dissimilar Densities, *Science* **337**, 556–559 (2012).

Majeau, C., Agol, E. & Cowan, N.B., A Two-dimensional Infrared Map of the Extrasolar Planet HD 189733b, *ApJL* **747**, 20 (2012).

Agol, E., Transit Surveys for Earths in the Habitable Zones of White Dwarfs. *ApJL* **731**, 31 (2011).

Knutson, H. A., et al., A map of the day-night contrast of the extrasolar planet HD 189733b. *Nature* **447**, 183–186 (2007).

Agol, E., J. Steffen, R. Sari, & W. Clarkson, On detecting terrestrial planets with timing of giant planet transits. *MNRAS* **359**, 567–579 (2005).

Mandel, K. & Agol, E., Analytic Light Curves for Planetary Transit Searches, *ApJL* **580**, 171–175 (2002).

Leslie Hebb

Professional Preparation

University of Denver, B.S. in Electrical Engineering, 1996, Outstanding Senior Woman
The Johns Hopkins University, Ph.D. in Physics & Astronomy, 2006
University of St Andrews , Postdoctoral Research Associate, 2006-2009
Vanderbilt University, Research Associate 2009-2011, Assistant Research Faculty 2011-2012
University of Washington,Visiting Faculty, Host: Suzanne Hawley, Eric Agol, Aug 2012 - Present
Hobart and William Smith Colleges, Assistant Professor, Sep 2012 - Present

Synergistic Activities

- Co-Instructor for Minority Graduate Student Course in "The Art of Being a Graduate Student"
- "Astronomy Expert" at the Edinburgh Science Festival, St Andrews Science Fair, Museum of St Andrews, & James Gregory Telescope Public Open Nights 2006-09
- Women in Physics Group Organizer, Physics & Astronomy, Johns Hopkins University, 1999-2003
- "Space Expert" for the Lanacane Itching to Know Science Contest (answered 2000 question about space sent in by school children), 2002
- Coordinator, Inst. for Electrical & Electronic Engineers Student Awareness Conference, 1994-95

Publications Most Closely Related to this Project

Hebb, L., Collier-Cameron, A., Loeillet, B., Pollacco, D., Hebrard, G., Street, R.A., Bouchy, F., and the SuperWASP Collaboration 2009, "*WASP-12b: The hottest transiting planet yet discovered*", Astrophysical Journal, 693, 1920

Hebb, L., Collier-Cameron, A., Triaud, A.H.M.J., Lister, T.A., Smalley, B., Maxted, P.F.L, Hellier, C., and the SuperWASP collaboration, 2010, "*WASP-19b: The shortest transiting extra-solar planet yet discovered*", Astrophysical Journal, 708, 224

Hellier, C., Anderson, D.R., Collier-Cameron, A., Gillon, M., Hebb, L., Maxted, P.F.L., and the SuperWASP Collaboration 2009 "*An orbital period of 0.94 days for the hot-Jupiter planet WASP-18b*", Nature, 460, 1098

Hebb, L., Petro, L., Ford, H.C., Ardilla, D.R., Ignacio, T., Minniti, D., Golimowski, D.A., and Clampin, M., 2007, "*A search for planets transiting the M-dwarf debris disc host, AU Microscopii*", Monthly Notices of the Royal Astronomical Society, 379, 63

Enoch, B., Collier Cameron, A., Parley, N. R. and Hebb, L., 2010, "*An improved method for estimating the masses of stars with transiting planets*", Monthly Notices of the Royal Astronomical Society, 516, 33

Students and Postdocs Advised or Co-Advised

Master's Thesis Students: Colin Simpson (2008-09), John Ilee (2008-09), Victoria Davidson (2007-08), Amy Cowen (2006-07)

Undergraduate Students: Woody Austin (2011-13), Rebecca Rattray (2010-11), Alex Richert (2010), Heather Cegla (2009), Emily Ramsden (2008), John Rostron (2007)Rebekah Price (2012), Taruj Haj-Khalil (2012)

Collaborators Within Past 48 Months

S. Aigrain (Oxford), J. Bouvier (Grenoble), A. Collier-Cameron (St Andrews), H.C. Ford (Johns Hopkins), J. Irwin (CfA), P. Maxted (Keele), D. Pollacco (Warwick), E. Shkolnik (Lowell), B. Smalley (Keele), K.G. Stassun (Vanderbilt), E. Stempels (Uppsala), J. Pepper (Vanderbilt), P. Cargile (Vanderbilt), K. vonBraun (Caltech), Y. Gomez Maqueo Chew (Warwick), F. Faedi (Warwick), S. Fleming (Penn State), E. Moraux (Grenoble), G. Hussain (ESO), J. Morin (Gottingen), J.F. Donati (Toulouse), L. Ghezzi (Brazil), A. Triaud (Geneva), R. Street (LCOGT)

CURRENT & PENDING SUPPORT
DR. ANDREW BECKER

PENDING GRANT SUPPORT:

Project Title:	Exploring the Critical Radius Between mini-Neptunes and super-Earths with Kepler
Source of Support:	NASA OSS 2013
Total Requested:	$476,301
P.I.:	Dr. Becker (University of Washington)
Total Award Period:	01/01/14 – 12/31/16
Location of Project:	University of Washington
Person-Months per Year:	Cal: 6.0 Acad: 0.0 Sumr: 0.0

Project Title:	Mapping the Milky Way's Disk with Asymptotic Giant Branch stars from Wide-field Infrared Survey Explorer
Source of Support:	NASA ADAP 2013
Total Requested:	$225,925
P.I. :	Dr. Zeljko Ivezic (University of Washington)
Co-I.:	Dr. Becker (University of Washington)
Total Award Period:	11/18/13 – 11/17/15
Location of Project:	University of Washington
Person-Months per Year:	Cal: 1.0 Acad: 0.0 Sumr: 0.0

CURRENT GRANT SUPPORT:

Project Title:	Detection and precision masses of super-Earth transiting planets in the Kepler data
Source of Support:	NASA OSS 2012
Total Requested:	$268,007
P.I. :	Dr. Eric Agol (University of Washington)
Co-I.:	Dr. Becker (University of Washington)
Total Award Period:	01/01/13 – 12/31/15
Location of Project:	University of Washington
Person-Months per Year:	Cal: 0.0 Acad: 0.0 Sumr: 0.0

Project Title:	Mapping the Milky Way: Data-miners, Modelers, Observers, Unite!
Source of Support:	NSF AAG
Total Requested:	$379,447
P.I.:	Dr. Zeljko Ivezic (University of Washington)
Co-I.:	Dr. Becker (University of Washington)
Total Award Period:	10/01/10 – 09/30/12
Location of Project:	University of Washington
Person-Months per Year:	Cal: 0.0 Acad: 0.0 Sumr: 0.0

Project Title:	LSST Data Management
Source of Support:	LSST Corporation
Total Requested:	$315,000
P.I.:	Dr. Andrew Connolly (University of Washington)
Total Award Period:	01/09/10 – 8/31/11 (renewing yearly)
Location of Project:	University of Washington
Person-Months per Year:	Cal: 6.0 Acad: 0.0 Sumr: 0.0

Project Title:	Time Domain Studies of the 2MASS Calibration Point Source Working Database
Source of Support:	NASA ADP
Total Requested:	$312,828
P.I.:	Dr. Becker (University of Washington)
Total Award Period:	07/01/09 – 06/30/12 (extended to 06/30/13)
Location of Project:	University of Washington
Person-Months per Year:	Cal: 3.0 Acad: 0.0 Sumr: 0.0

Project Title:	3.5m Transit Timing Observations at 100% Duty Cycle
Source of Support:	NASA SSO
Total Requested:	$424,815
P.I.:	Dr. Becker (University of Washington)
Total Award Period:	01/01/09 – 12/31/12 (extended to 12/31/13)
Location of Project:	University of Washington
Person-Months per Year:	Cal: 3.0 Acad: 0.0 Sumr: 0.0

Current & Pending – Rory Barnes

Current Support

Title: The Dynamical Origin of Planetary System Architecture
Principle Investigator: Rory Barnes
Sponsoring Agency: National Science Foundation
Total Award: $328,000
Award Period: 07/01/2011 – 06/30/2014
Commitment: 8 mo/yr
Program Officer: Maria Womack (mwomack@nsf.gov)

Title: The Virtual Planetary Lab
Principle Investigator: Victoria Meadows
Sponsoring Agency: NASA
Total Award: $9,560,00
Award Period: 1/01/13 – 12/31/17
Commitment: 4–6 mo/yr
Program Officer: Mary Voytek (mary.voytek@nasa.gov)

Eric Agol: Current and Pending grants

Pending: n/a

Current:

Title: Detection and precision masses of super-Earth transiting planets in the Kepler data
PI: Eric Agol
Program: NASA Origins of Solar Systems, Larry Petro, (202) 358-4424 larry.d.petro@nasa.gov
Performance period: 1/1/2013-12/31/2015
Total budget: $268k
Time commitment: Eric Agol, 1 month/yr

Title: Long Term Dynamics of Kepler Multiple Planet Systems
PI: Matt Holman
Program: NASA Origins of Solar Systems, Larry Petro, (202) 358-4424 larry.d.petro@nasa.gov
Performance period: 1/1/2013-12/31/2015
Total budget: $94k (subaward to Eric Agol at University of Washington)
Time commitment: Eric Agol, 1 month/yr

Title: Searching for circumprimary and circumbinary Planets in Kepler data
PI: Nader Haghighipour
Program: NASA Astrophysics Data Analysis Program, Douglas M. Hudgins, (202) 358-0988 Douglas.M.Hudgins@nasa.gov
Performance period: 1/1/2013-12/31/2015
Total budget: $103k (subaward to Eric Agol at University of Washington)
Time commitment: Eric Agol, 1 month/yr

Title: CAREER: Prospecting for Planets
PI: Eric Agol
Program: National Science Foundation CAREER grant, Robert 'Scott' Fisher, 703-292-8225, rfisher@nsf.gov
Performance period: 03/15/07 - 02/28/14
Total budget: $790,720
Time commitment: Eric Agol, 2 month/yr

Title: Collaborative Research: Diagnosing the SEEDS of Planet Formation
Science PI: John Wisniewski; Administrative PI: Eric Agol
Program: National Science Foundation AAG, Maria Womack, 703-292-2301, mwomack@nsf.gov;
Performance period: 09/01/10 - 08/31/14
Total budget: $557,312

Current and Pending Support
for Leslie Hebb

Investigator: PI
Support Level: Current
Project Title: Bringing eclipsing binaries to the next level of benchmark precision: Critical testing of stellar evolution and fundamental understanding of young and low mass stars
Period of Performance: 09/01/2010 - 08/31/2013
Source of Support: NSF AST-1009810
Total Award Amount: $350,823
Location of Project: Vanderbilt University
Person-months per year committed to project: 6.0

Investigator: Co-PI (PI P. Cargile)
Support Level: Current
Project Title: Collaborative Research: Triangulating on the Ages of Stars: Using Open Clusters to Calibrate Stellar Chronometers from Myr to Gyr Ages
Period of Performance: 08/01/2011 - 07/31/2014
Source of Support: NSF AST-1109612
Total Award Amount: $363,022
Location of Project: Vanderbilt University
Person-months per year committed to project: 0.1

Investigator: PI
Support Level: Pending
Project Title: Collaborative Research: Mapping small and large scale magnetic fields on low mass stars
Period of Performance: 09/01/2013 - 08/31/2016
Source of Support: NSF
Total Award Amount: $233,348
Location of Project: Hobart and William Smith Colleges
Person-months per year committed to project: 2.0

Investigator: PI
Support Level: Pending
Project Title: Mapping small-scale starspots on low mass stars
Period of Performance: 06/01/2014 - 05/31/2015
Source of Support: NASA - Kepler GO 5
Total Award Amount: $59,828
Location of Project: Hobart and William Smith Colleges
Person-months per year committed to project: 0.9

Budget Justification

PI Salaries:

We include 6 months salary in the first year for PI Becker, and 3 months in the second year. Becker is on the Research Faculty at UW, meaning his salary must be obtained through grants such as this one. Benefits are calculated at the rate of 26.9%. We budget for a 2% annual increase in these salaries.

We include 3 months salary in the second year for Co–I Barnes, and 4 months in the third year. Barnes is on the Research Staff at UW, meaning his salary must be obtained through grants such as this one. Benefits are calculated at the rate of 34.0%. We budget for a 2% annual increase in these salaries.

Other Salaries:

One graduate student will be funded for 3 academic quarters per year at 60% time, and 2 summer quarters at 100% time. Benefits are calculated at the rate of 14.2%. We budget for a 2% annual increase in these salaries.

Tuition Costs:

We include tuition fees for one graduate student at the rate of $4,689 per quarter (first year), for 3 academic quarters per year. We budget for a projected 10% annnual increase in these fees after the first year, and 12% subsequently.

Equipment:

None

Travel:

We budget for 2 domestic trips per year for collaboration and conferences, at the rate of 1,500 per trip (to cover travel to and 4 days lodging to the East Coast). This will be shared by the investigators and graduate student. We budget for one additional trip per year specifically for Co–I Hebb to visit the University of Washington.

Publication Charges:

Publication costs are budgeted at the electronic publishing charge of $110/page, for 20 pages/year.

Computing Fees:

Computer support fees are budgeted at the nominal rate of $67 per person per month by the Physics and Astronomy Computing Services group (PACS) at UW.

Indirect Costs:

Indirect costs are based on the MTDC rate of 54.5% per the negotiated agreement with DHHS dated 3/5/2013.

Personnel and Work Effort:

PI Becker will work on this project at 50% effort for the first year of the project, and 25% for the second. His focus will be on implementing a robust MCMC analysis of all the Kepler data, in debugging failure modes, and in training the graduate student in the art of Bayesian analysis.

Co–I Barnes will work on this project at 25% effort in the second year of the project, and 33% in the third.

Co–I Hebb will lead the host star characterization effort.

Co–I Agol will assist as–needed.

The graduate student will work on this project at 60% FTE for 3 academic quarters, and 100% FTE for 2 summer quarters, for all 3 years of the project. Their role will be to become an expert in the analysis of the data, and in the interpretation of the results and how it relates to tidal dissipation in the population of planets studied.

Facilities and Equipment:

As this is a compute–heavy proposal, we will be making use of the local University of Washington `Hyak` compute cluster, as well as applying for time on NASA's High-End Computing (HEC) facilities. The University provides office equipment for all investigators.