Close-in Planets:
From Hot Jupiters to Super-Mercuries

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From exo-Jupiters to exo-Mars

Planets of the KOI-961 system
Distance: 150 light-years from Earth
Star: red dwarf, one-sixth the size of our sun, 70 percent bigger than Jupiter

<table>
<thead>
<tr>
<th>Planet</th>
<th>KOI-961.03</th>
<th>KOI-961.02</th>
<th>KOI-961.01</th>
<th>Kepler-20e</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>4,503 miles (6,792 kilometers)</td>
<td>4,503 miles (7,250 km)</td>
<td>5,767 miles (9,280 km)</td>
<td>6,162 miles (9,917 km)</td>
<td>6,900 miles (11,100 km)</td>
</tr>
<tr>
<td>Year</td>
<td>687 days</td>
<td>less than 2 days</td>
<td>less than 2 days</td>
<td>less than 2 days</td>
<td>6.1 days</td>
</tr>
</tbody>
</table>

The scale of the KOI-01 system is comparable to the orbits of Jupiter's major moons. The size of the planets and star is not shown to scale.
\[ n \equiv \text{number of planets per star} \]
\[ \frac{\partial^2 n}{\partial \ln R \partial \ln P} \propto R^\alpha P^\beta \text{ (say)} \]

\[ n \sim 0.2 \text{ planet per star} \quad (R > 2R_\oplus, P < 50 \text{ days}) \]

Trust detection efficiency down to $1R_\oplus$ and extrapolate to 365 days:

\[ n \sim 2 \text{ planets per star} \quad (R > R_\oplus, P < 365 \text{ days}) \]
Minimum-Mass Kepler-11 system (turns out Toomre Q \sim 2)
In situ formation of rocky planets

Mass accretion rate

$$\dot{M} \sim \rho v R^2 F_{\text{grav}}$$

$$\rho \sim \sigma \frac{h}{\Omega} \sim \frac{v}{\Omega}$$

$$\dot{M} \sim \sigma \Omega R^2 F_{\text{grav}}$$

$$t_{\text{form}} \sim \frac{M}{\dot{M}} \sim \frac{\rho_b R}{\sigma \Omega} \frac{1}{F_{\text{grav}}}$$

$$\sim 10^4 \text{ yr for Kepler-11}$$
In situ formation of hot Jupiters?

Core accretion

\[ M_{\text{atm}}(M_{\text{core}}, \rho, T, \kappa, \dot{M}_{\text{planetesimal}}) \]

if \( M_{\text{atm}} \sim M_{\text{core}} \) \( \rightarrow \) instability
(runaway envelope accretion)
In situ hot Jupiter

\[ R_B = \frac{GM}{c_s^2} \quad (v_{\text{esc}} \sim c_s) \]

\[ \rho, \ c_s \]

\[ M_{\text{atm}} \sim 4\pi \rho R_B^3 \]

\[ \sim M_{\text{core}} \]

\[ \uparrow \text{instability} \]

\[ M_{\text{core,crit}} \sim \frac{c_s^3}{\sqrt{4\pi G^3 \rho}} \]
Formation of hot Jupiters by disk-driven migration

What is the source of disk viscosity?

MRI activity in surface layers only

MRI activity in surface layers only

Lubow et al. 99

FUV

X-ray
MRI accretion rates too low

FUV-ionized layer too thin

X-ray-ionized layer weakened by PAHs and ambipolar diffusion

\[ \dot{M} \sim 2 \times 3\pi \Sigma^* \nu \]
\[ \sim 6\pi \Sigma^* \alpha \frac{kT}{\mu \Omega} \]

Conventional Disk

Observed Rates

FUV

X-ray

Perez-Becker & EC 11ab
Bai & Stone 11, Bai 11
Spin-orbit alignment of hot Jupiters

\[ \lambda = \text{stellar obliquity (sky projected)} \]

~50% are misaligned, including retrograde
Measuring spin-orbit angles by Rossiter-McLaughlin

HAT-P-14
When planet comes close enough to star, strong tides are raised on planet, circularizing its orbit.

- Planet forms far from star
- Eccentricity is excited (somehow)
- When planet comes close enough to star, strong tides are raised on planet, circularizing its orbit
Secular Chaos

● Start with 3 widely spaced, mildly eccentric & inclined planets:

<table>
<thead>
<tr>
<th>$a (AU)$</th>
<th>ecc.</th>
<th>inc. (deg)</th>
<th>mass (Mj)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.066</td>
<td>4.5</td>
<td>0.5</td>
</tr>
<tr>
<td>6</td>
<td>0.188</td>
<td>19.9</td>
<td>1.0</td>
</tr>
<tr>
<td>16</td>
<td>0.334</td>
<td>7.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>

● no close encounters or strong resonances
Secular Chaos and Migration
Hot Jupiters are inflated

Transit radii > Theoretical radii

Burrows et al. 2007
Wind Power and Ohmic Heating

Surface current

\[ j \sim \sigma \frac{v}{c} \times B \]

thermal (Saha) ionization

\~ 0.01 \text{ S/m}

\~ 1 \text{ km/s}

\~ 1 \text{ G}

Ohmic power at RC boundary

\[ P \sim \left( \frac{j^2}{\sigma} \right)_{RC} R^2 z_{RC} \]
Ohmic inflation (or suspension)

only works if hot Jupiter is parked early (cf. secular migration which parks late)
Thermally driven mass loss (Parker winds)

hot Jupiter

\( v_{\text{esc}} \sim 40 \text{ km/s} \)

\( T \geq 10^4 \text{ K} \)

UV heating

PdV work vs. radiative loss (e.g., Ly-\( \alpha \) cooling)

transition from subsonic to supersonic occurs at sonic point

\[ R_s = \frac{GM}{2c_s^2} \]
$T_{\text{eff}} \approx 1300 \text{K}$

1 bar "surface" of planet

Photoionization base ($\tau_{\text{uv}} = 1$)

Sonic point

Roche lobe radius

Pressure balance with stellar wind

Hydrodynamic planetary wind

$R_p \sim 10^{10} \text{ cm}$

$T_{\text{wind}} \approx 3000-10000 \text{ K}$

$T_{\text{eff}} \approx 1300 \text{ K}$

$P \sim 10 \text{ picobar}$

$P \sim \text{nanobar}$
Atmospheric escape from HD 209458b

\[ F_{\text{UV}} = 450 \text{ erg/cm}^2/\text{s} \]

\[ M_p = 0.7 \text{ M}_J \]
\[ R_p = 1.4 \text{ R}_J \]
\[ h\nu_0 = 20 \text{ eV} \]

\[ \rho_{\text{base}} = 4 \times 10^{-13} \text{ g} \]
\[ T_{\text{base}} = 1000 \text{ K} \]
\[ f_{\text{base}} = 10^{-5} \]
\[ \tau_{\text{sp}} = 0.0046 \]
Mass-Loss Rates

At low UV flux, wind is “energy-limited”

\[
\frac{GM \dot{M}}{R} \sim \varepsilon F_{UV} \pi R^2
\]

\[
\Rightarrow \dot{M} \propto F_{UV}
\]

At high UV flux, wind is “recombination-limited”

\[
n_+^2 \alpha_{\text{rec}} \sim \frac{F_{UV}}{h \nu} \sigma_{\text{bf}} n_0
\]

\[
\Rightarrow \dot{M} \propto F_{UV}^{1/2}
\]

Planet loses \(\sim 1\%\) of mass over lifetime

Murray-Clay, EC, & Murray 09
HST Ly-α absorption and charge exchange

-100 km/s  100 km/s

Holmstrom+ 08
Ekstrom+ 10

Vidal-Madjar+ 03

Log density (cm$^{-3}$)

Tremblin & EC, in prep.
Kepler Input Catalog (KIC) 12557548

K-type star

- $M_\star = 0.7$ $M_\odot$
- $R_\star = 0.7$ $R_\odot$
- $T_\star = 4400$ K

Companion

- $P_{\text{orb}} = 15.685$ hr
- $a = 0.013$ AU ($4 R_\star$)
- $T_{\text{eff}} = 2100$ K

eclipse depth varies from orbit to orbit
Fig. 3.— Folded light curves of KIC 12557548 about the 15–685 hour occultation period for the Q2–Q6 data sets— Top panel— unbinned data; bottom panel— folded data averaged into 96 discrete bins— Short illustrative vertical bar on the left is the standard error of the data points within a bin— Note the highly statistically significant depressed flux level following the main occultation— The full width of the occultation with the exception of these small features is the orbital cycle— This corresponds to ∼10 × Kepler periods in duration— If this duration is interpreted simply as indicating the sum of the radii of the occulting “bodies” it corresponds to kR1 + R2 < a.

However, if we take into account approximately the effect of the finite integration time then kR1 + R2 < a.

Note that these estimates assume, without justification, equatorial as opposed to grazing occultations.

Finally, we have fitted a constant plus a cosine of twice the orbital frequency to the folded and binned light curve excluding the bins inside the occultation interval.

We find only an upper limit of ∼× 5 for the amplitude of such a feature. This limit will be discussed below in the context of setting a constraint on the mass of any body orbiting the target K star.

2.3. Fourier Search for Modulations

As a check for periodic modulations of the occultation depths for the 8x8 hour period, we carried out an FFT of the data as shown in Fig. but with the portions of the light curve away from the occultation set equal to the mean out-of-eclipse intensity. The purpose of this latter step is to suppress the noise level without sacrificing any significant fraction of the signal. The results are shown in Fig. All higher harmonics of the 8x8 hour period out to the Nyquist limit are clearly visible. In addition, a careful inspection of the amplitudes between the harmonics indicates some evidence for low-amplitude modulation-induced sidebands. However, at least a number of these can be reproduced in an FFT of the window function associated with the occultations. Thus, we find no compelling evidence for periodic modulation of the occultation depth.

2.4. Checks on the Validity of the Data

Because of the unusual exoplanet phenomenon presented in this work, we need to be especially careful to ensure that there are no spurious artifacts in the Kepler data for this object. In this regard, we performed a number of tests on the data. First, as mentioned above, we checked that the occultations are present in all of the quarters of released Kepler public data and that the behavior of the occultations does not change abruptly across quarterly boundaries.

out-of-eclipse variation < 5e-5

⇒ M < 3 M (no ellipsoidal light variation)
A disintegrating super-Mercury

\[ R \sim 0.5 \, R_\oplus \quad M \sim 0.1 \, M_\oplus \]

occulting size \( R_\circ \leq 0.1 \, R_* \quad \leq 15 \, R \)

\[ T_{\text{eff}} \sim 2100 \, \text{K} \]
\[ \Rightarrow c_s \sim 0.7 \, \text{km/s} \]
\[ \Rightarrow v_{\text{esc}} \leq \text{a few km/s (sub-Earth)} \]
Grain and Planet Lifetimes

**Mass loss rate**
\[ \dot{M}_d \sim \rho_d v_o R_o^2 \]

**optical depth**
\[ \tau \sim \rho_d R_o \kappa_d \sim \frac{\rho_d R_o}{\rho_b s^2 / (\rho_b s^3)} \]

**eclipse depth**
\[ f \sim \tau R_o^2 / R_*^2 \]

\[ \Rightarrow \dot{M}_d \sim f s v_o \rho_b R_*^2 / R_o \]
\[ \sim 0.5 \, M_\oplus \text{Gyr}^{-1} \left( \frac{f}{0.01} \right) \left( \frac{s}{0.1 \, \mu\text{m}} \right) \]

**planet lifetime**
\[ \frac{M}{\dot{M}} = \frac{M}{\dot{M}_d + \dot{M}_g} \sim 0.1 \, \text{Gyr} \]

\[ \sim \text{travel time across } R_o \]

pyroxene grain sublimation lifetime \( \sim 10^4 \, \text{s} \)

TBD
Olivine, $T=2100$ K
• Coriolis force + stellar radiation pressure on grains creates trailing tail
• Tail causes prolonged egress
• Scattered light off head of “comet” causes pre-ingress bump
• Predictions: (i) infrared eclipses shallower
  (ii) deeper eclipses in gas absorption lines
• Disk properties / Planet-disk interaction (Herschel, ALMA)
• Highly eccentric hot Jupiters (RV, Kepler)
• Hot Jupiter magnetospheres (LOFAR, SKA)
• Evaporating atmospheres (HST, JWST)
What it is not:

- gas giant (dynamically unstable)
- background blend with RR Lyrae variable star
  (background blends will be further checked with deep imaging)

What it is probably not:

- hierarchical triple containing accretion disk
  (no out-of-eclipse variability)

$P_{\text{orb}} = 15.7 \text{ hr}$
How much extra power and where?

Where: convective interior

Radiative-convective (RC) boundary

How much:

\[
F_{\text{rad}}|_{\text{RC}} \sim \frac{\sigma T_{\text{eq}}^4}{\tau_{\text{RC}}} \\

P \sim \frac{L_*}{4\pi a^2} \pi R^2 \times \tau_{\text{RC}}^{-1}
\]
The Kepler Orrery
credit: D. Fabrycky

$t[BJD] - 2454900 = 65.0$