EARLY HYDRODYNAMIC ESCAPE LIMITS ROCKY PLANETS TO ≤1.6 EARTH RADII.

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Introduction: In the past decade thousands of exoplanet candidates and hundreds of confirmed exoplanets have been found [1]. For sub-Neptune-sized planets, those less than ~10 Earth masses, we can separate planets into two broad categories: predominantly rocky planets, and gaseous planets with thick volatile sheaths. Observations and subsequent analysis of these planets show that rocky planets are only found with radii less than ~1.6 Earth radii [1]. No rocky planet has yet been found that violates this limit [2].

We propose that hydrodynamic escape of hydrogen rich protoatmospheres, accreted by forming planets, explains the limit in rocky planet size. Following the hydrodynamic escape model employed by Luger et al. (2015), we modelled the XUV driven escape from young planets (less than ~100 Myr in age) around a Sun-like star [3]. With a simple, first-order model we found that the rocky planet radii limit occurs consistently at ~1.6 Earth radii across a wide range of plausible parameter spaces.

Results and Discussion: Our model shows that hydrodynamic escape can explain the observed cutoff between rocky and gaseous planets. Fig. 1 shows the results of our model for rocky planets between 0.5 and 10 Earth masses that accrete 3 wt. % H_2/He during formation [4]. The simulation was run for 100 Myr, after that time the XUV flux drops off exponentially and hydrodynamic escape drops with it [5]. A cutoff between rocky planets and gaseous ones is clearly seen at ~1.5-1.6 Earth radii.

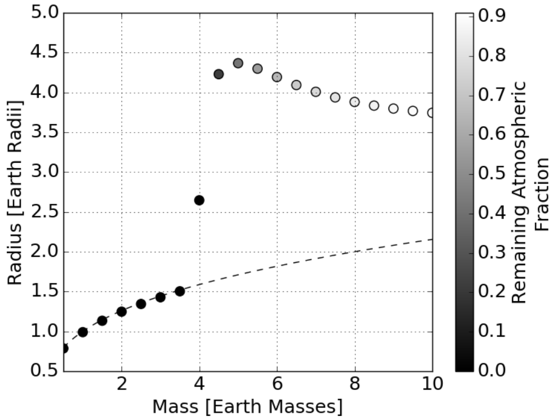

Fig. 1. The atmospheric loss from planets between 0.5 and 10 Earth masses around a Sun-like star.

In Fig. 1, the planets were assumed to have Earth-like density (5.5 g cm^{-3}) and the dashed curve shows the contour of Earth-like density. For each planet, the isothermal atmospheric temperature was set to 2500 K.

We are only interested in the upper size limit for rocky planets. As such, we assumed pure hydrogen atmospheres and the highest possible isothermal atmospheric temperatures, which will produce an upper limit on the hydrodynamic loss rate. Previous work shows that a reasonable approximation for an upper temperature limit in a hydrogen rich protoatmosphere is 2000-3000 K [6], consistent with our assumptions.

From these results, we propose that the observed dichotomy between mini-Neptunes and rocky worlds is simply explained by an early episode of thermally-driven hydrodynamic escape when host stars have saturated XUV fluxes.

References: [1] L.A. Rogers, *The Astrophysical Journal*, 2015, 801, 41. [2] C.D. Dressing *et al.*, *The Astrophysical Journal*, 2015, 800, 135. [3] R. Luger *et al.*, *Astrobiology*, 2015, 15, 57. [4] H. Lammer *et al.*, *Earth, Planets and Space*, 2012, 64, 179. [5]N.V. Erkaev *et al.*, *Monthly Notices of the Royal Astronocal Society*, 2016, 460, 1300. [6] M. Sekiya, K. Nakazawa, C. Hayashi, *Progress of Theoretical Physics*, 1980, 64, 1968.

Early Hydrodynamic Escape Limits Rocky Planets to ~1.6 Earth Radii

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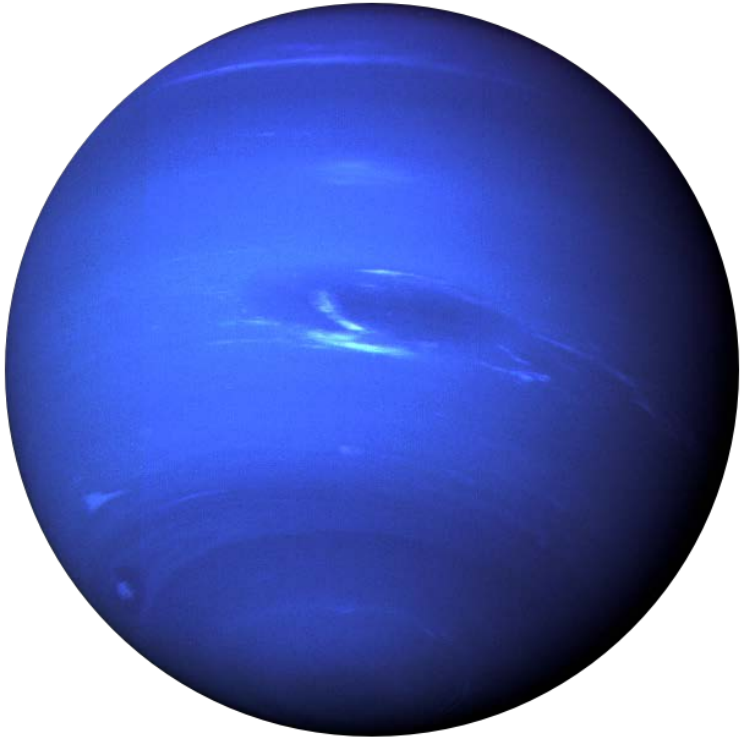
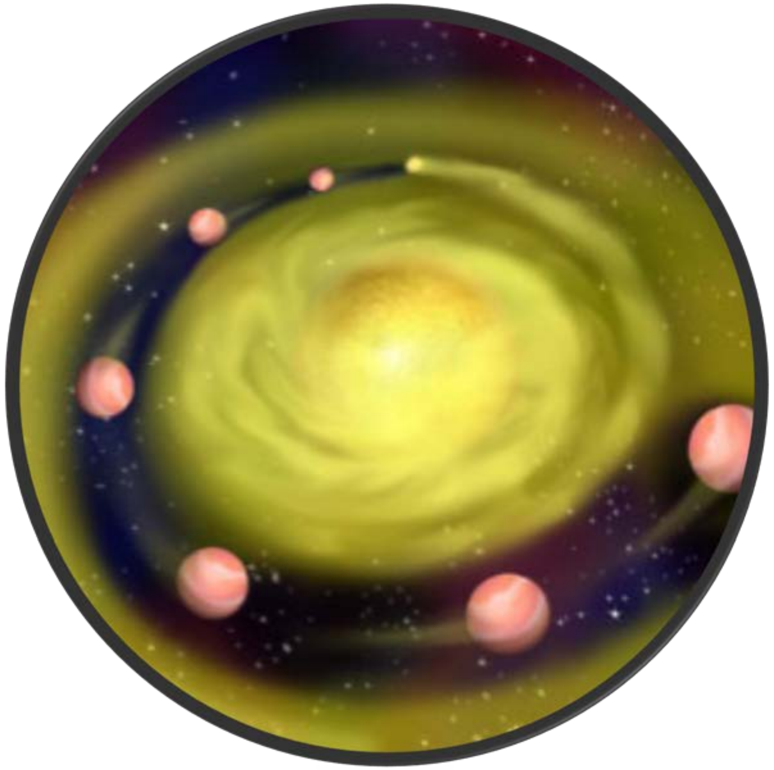


How do planets form atmospheres?

Volatile delivery

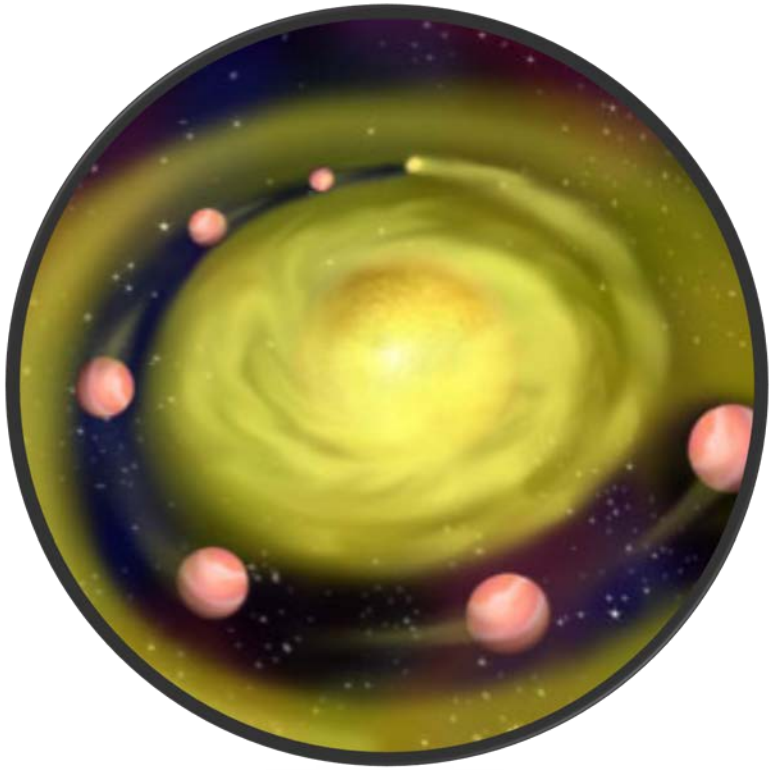
Outgassing



Disk accretion

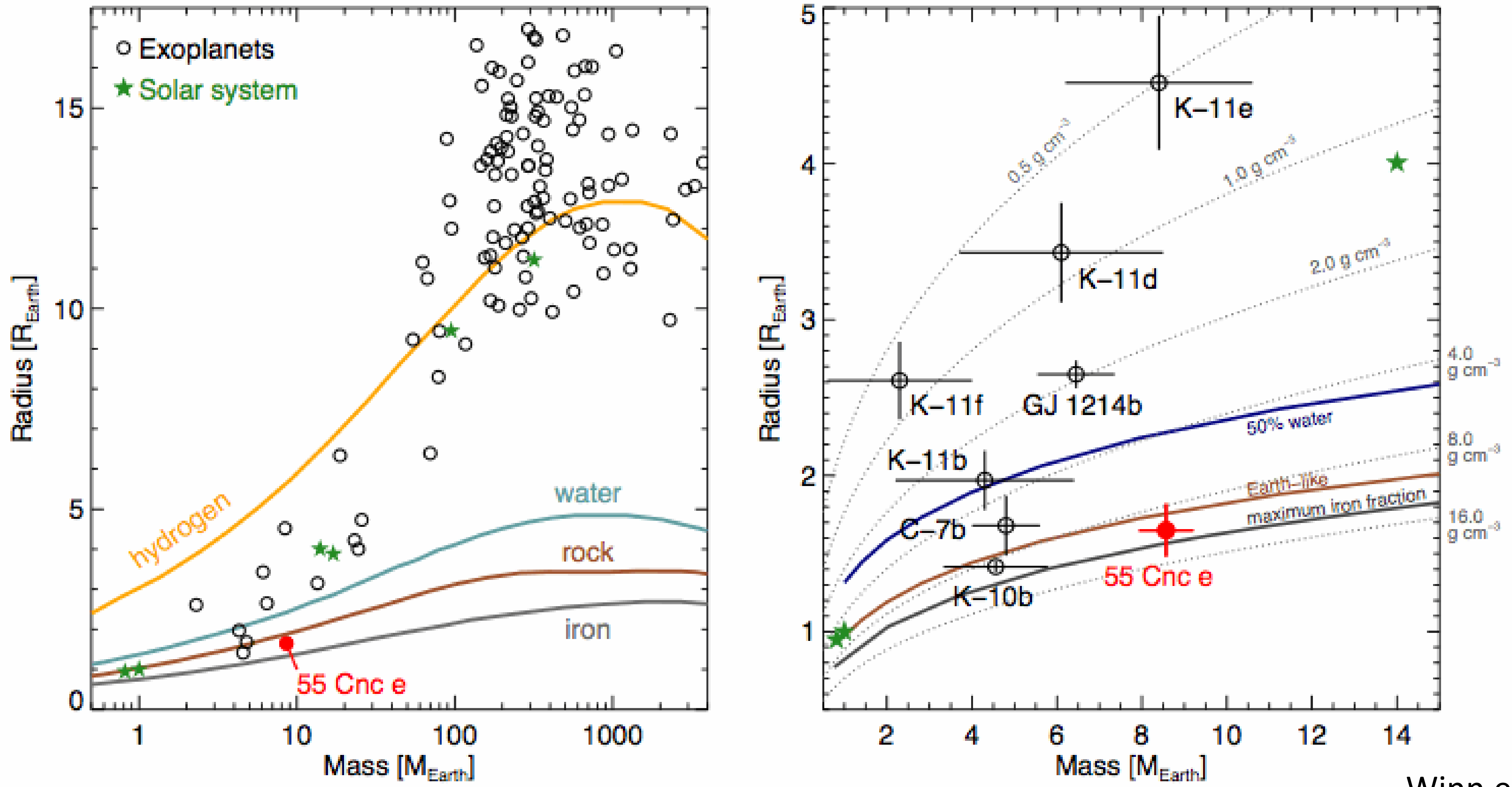
H/He Protoatmospheres

- Can form on planets as small as Mars
- Thousands of bars at the surface
- Very light and puffy
- Not habitable



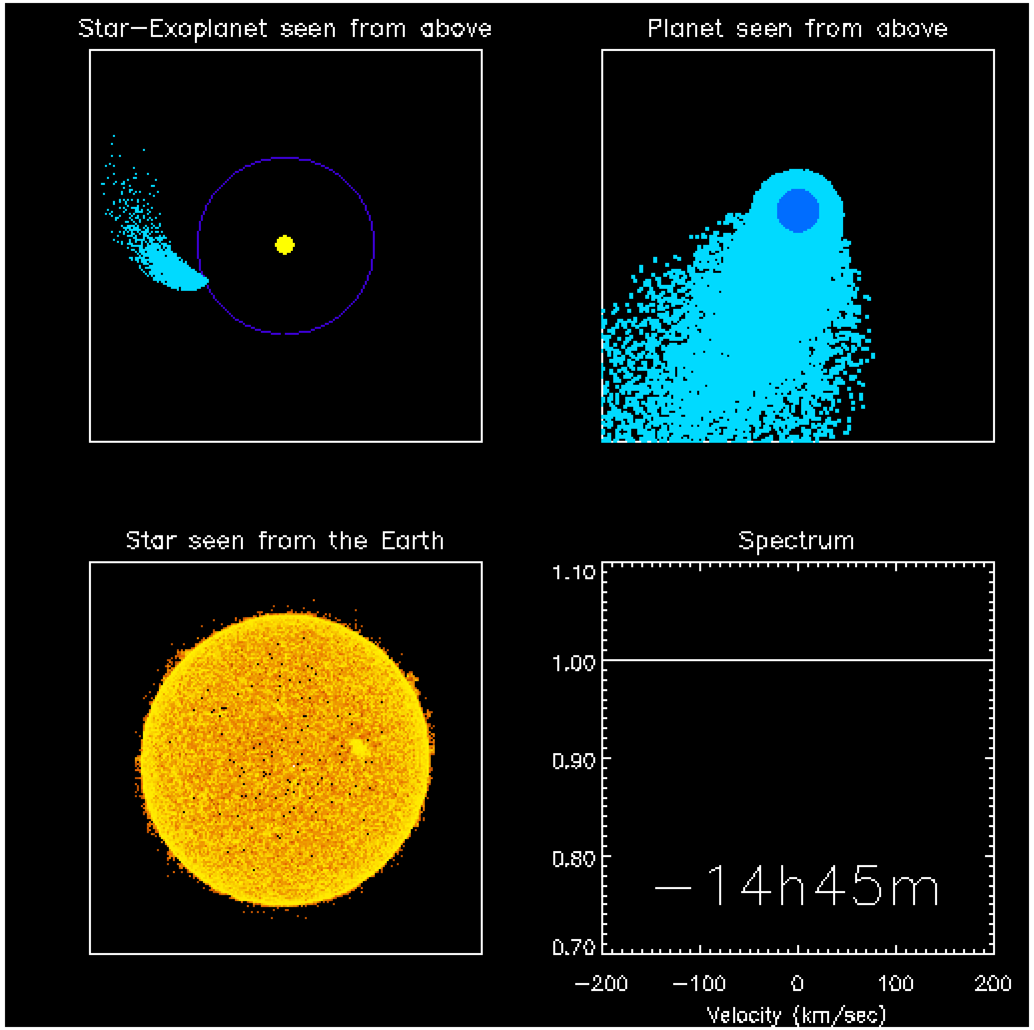
Disk accretion

Observed exoplanet masses and radii



Winn et al., 2011

Hydrodynamic escape



http://vega.lpl.arizona.edu/~gilda/extrass.html

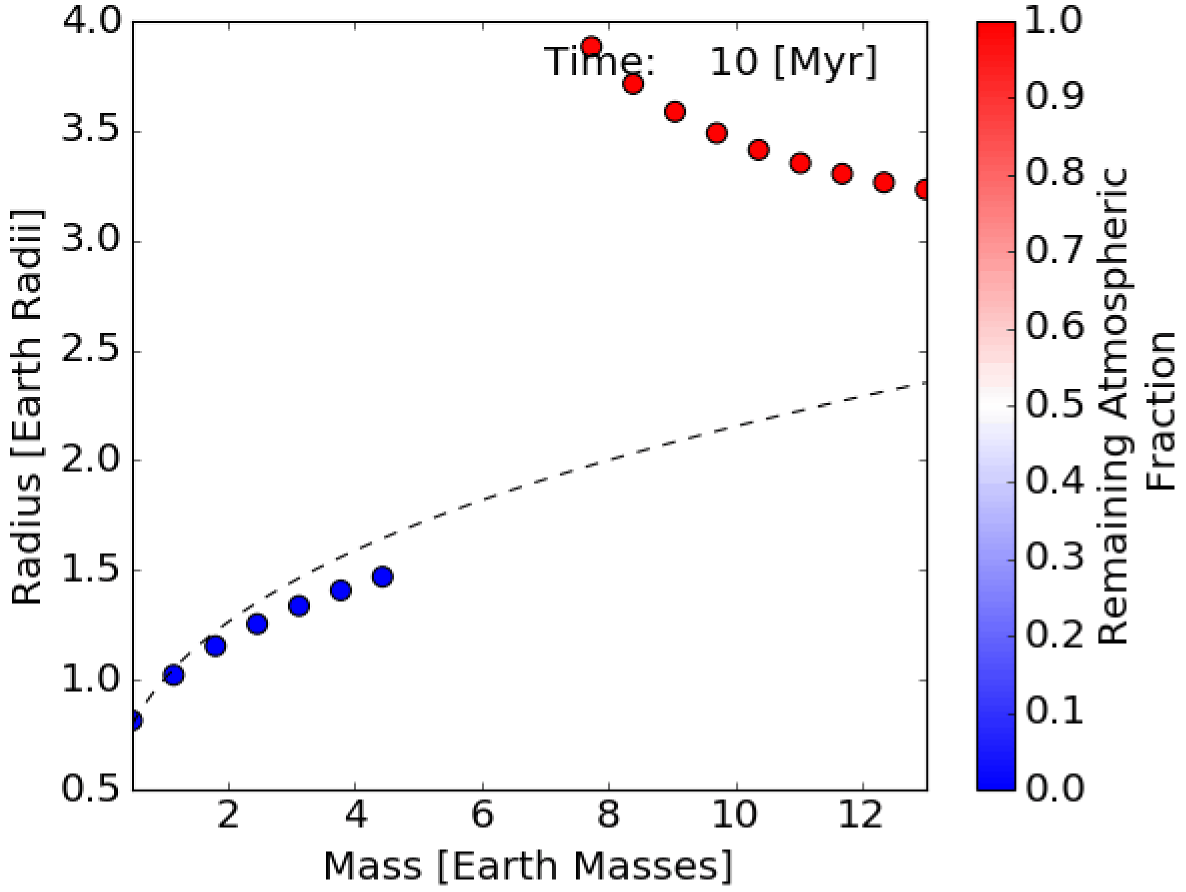
- Atmosphere expands when heated by XUV
- Similar to comets entering the inner Solar System
- Can rapidly remove entire atmosphere of small planets in under ~100 Myr

Our model

- Simple, energy-limited hydrodynamic escape model
- Rocky cores surrounded by thick protoatmospheres
- Young, Sun-like star with planets at 0.1 AU

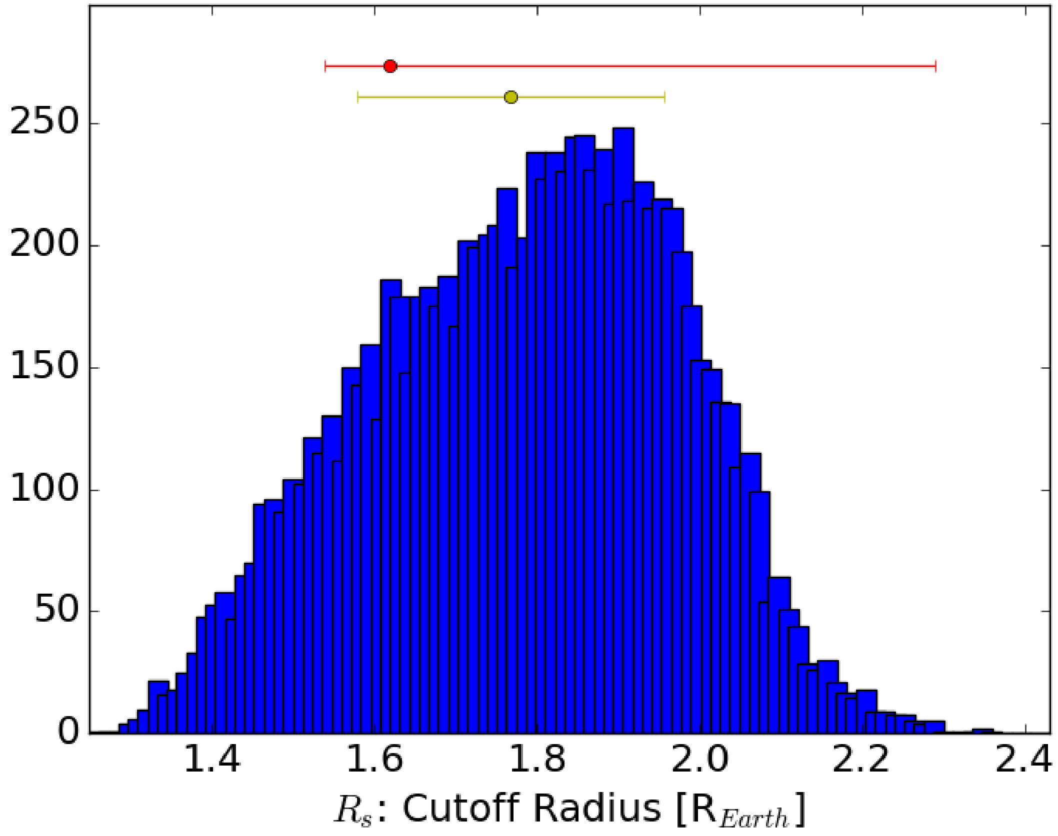
Parameter	Range	Units
Isothermal atmospheric temperature	$500 \le T \le 3000$	K
XUV Flux	$43 \le F_{XUV} \le 172$	W m^{-2}
Initial atmospheric mass fraction	$0.01 \le \alpha \le 0.1$	Dimensionless
Escape efficiency	$0.1 \le \eta \le 0.6$	Dimensionless
Pressure at base of thermosphere	$0.1 \le p_{XUV} \le 10$	Pa
Specific gas constant	$3600 \le R_g \le 4157$	J kg^{-1} K^{-1}
XUV saturation time	$80 \le \tau \le 120$	Myr

Single model run

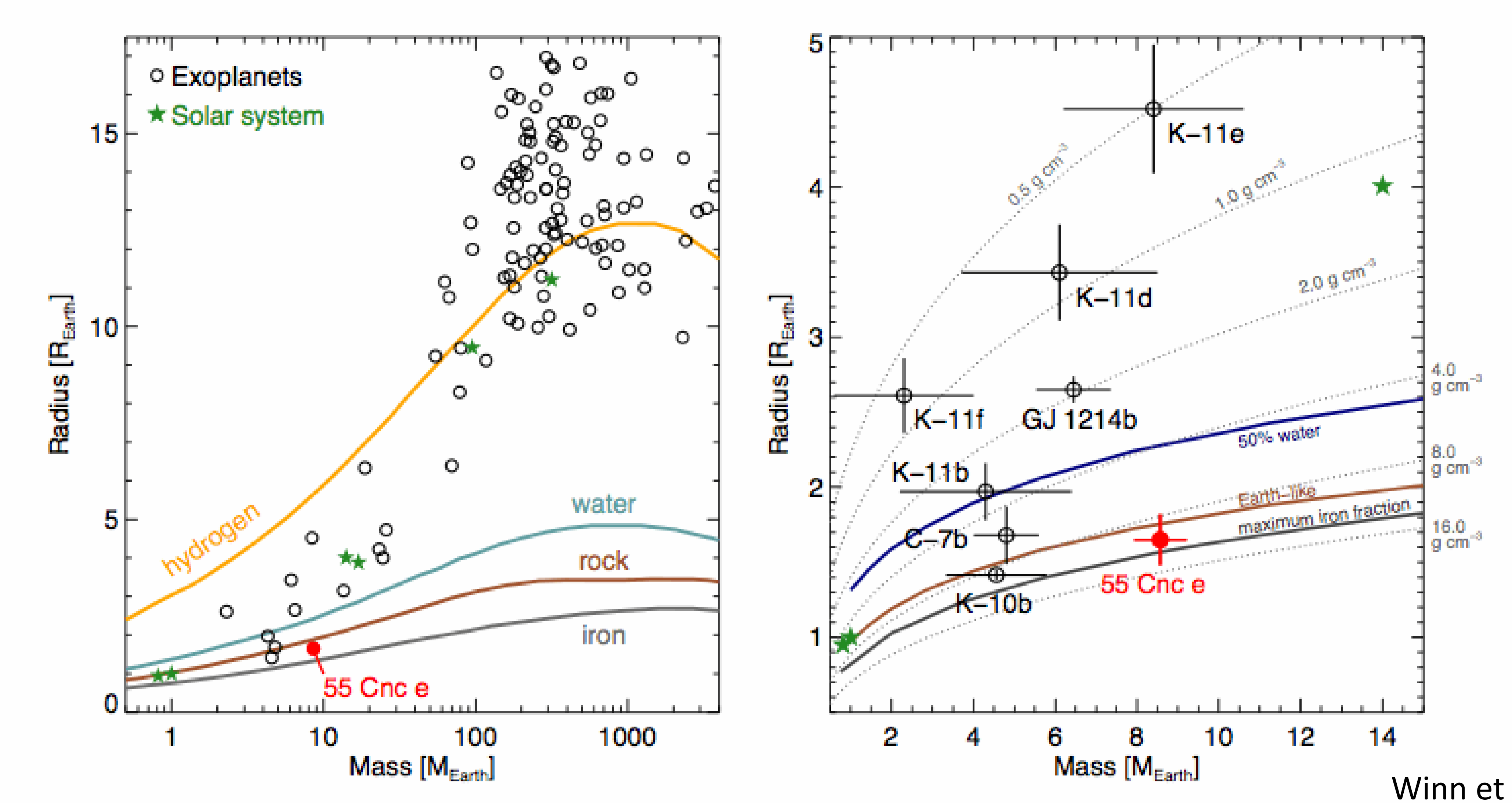


Model Results

- 10,000 parameter combinations, the cutoff radius histogram is shown in blue
- The red dot and error bar (95% confidence interval) is the observed cutoff radius from Rogers et al., (2015)
- The yellow dot and error bar show the mean and 1σ confidence interval

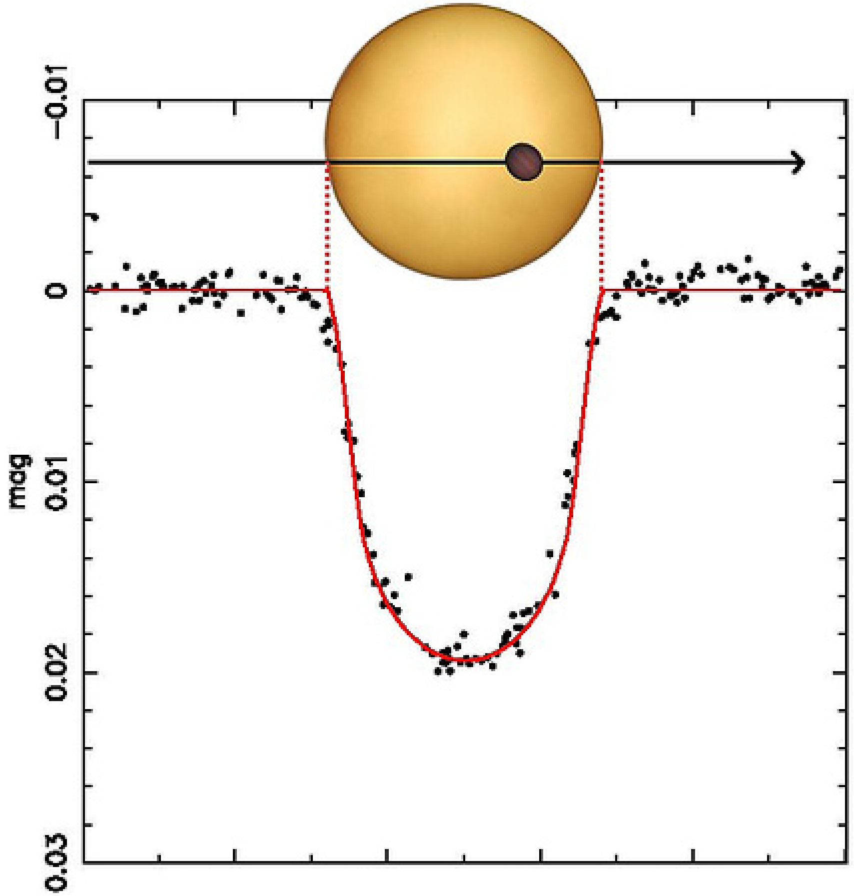


Observed exoplanet masses and radii



Winn et al., 2011

Why is the rocky planet limit important?



Jason Rowe via scienceblogs.com

- Rocky planets have the potential to be habitable
- Planetary radius is easily measured during transit. The rocky planet radius limit can help determine which exoplanets deserve additional study.

Summary

- There is a transition from rocky to gas-enveloped planets at roughly 1.6 Earth radii
- We modeled the hydrodynamic escape of protoatmospheres from a range of planet masses
- We found that rocky planets with radii less than 1.7 Earth radii typically lose their envelopes during the XUV saturation time
- The model shows hydrodynamic escape can explain the observed cutoff radius across a wide range of sampled parameter space