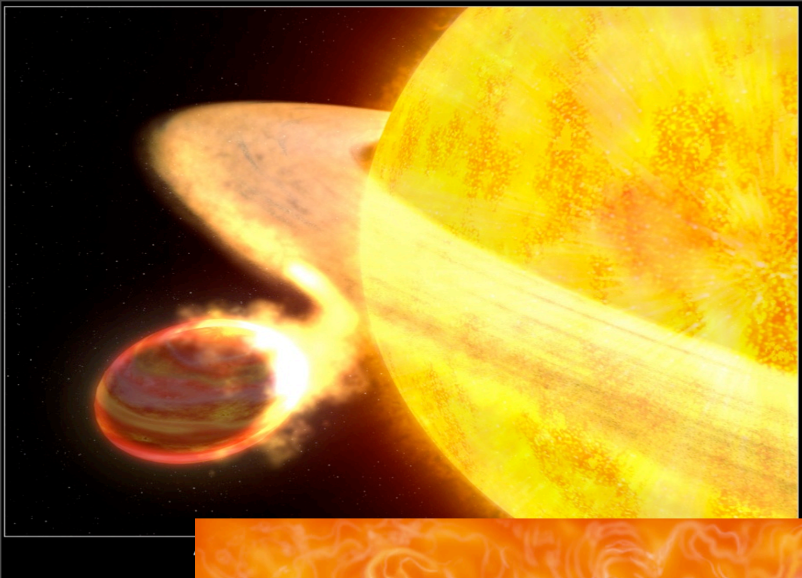
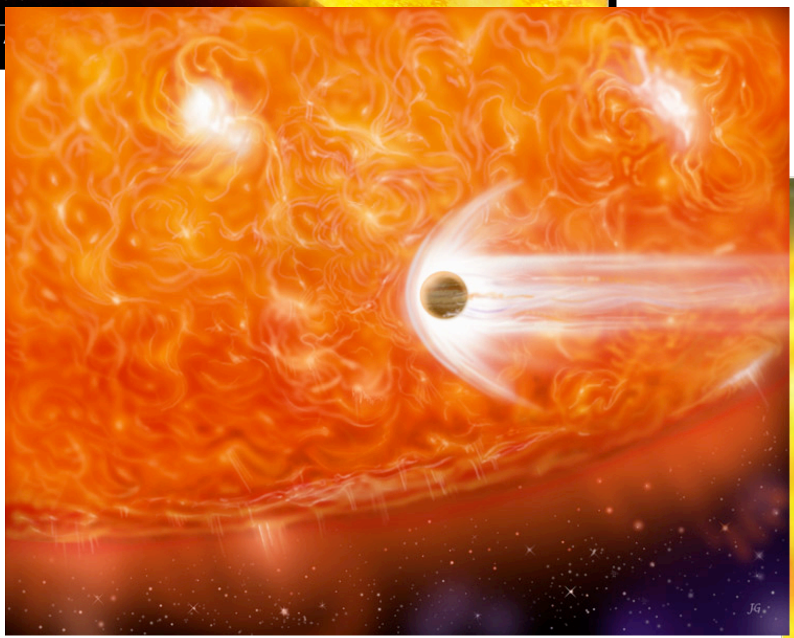
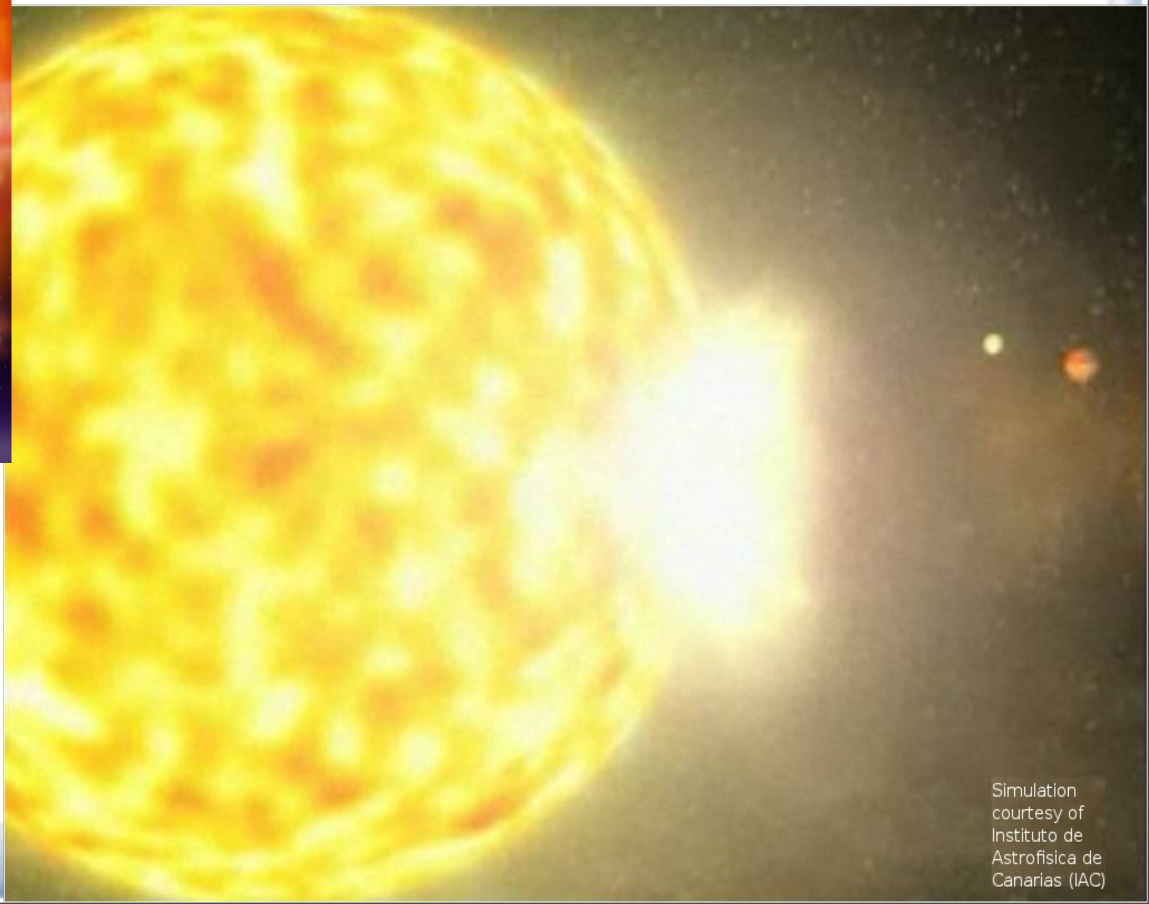


Planets migrating into stars: The shortest period planets, and star-planet correlations





Stuart F. Taylor
Participation Worldscope

2014 April 20-26
Rencontres du Vietnam on Exoplanetary Science
ICISE at Quy Nhon, Vietnam

Planets scattering like bumper cars?

Ongoing planet migration reshapes

"Shortest Period Occurrence Distribution" (SPOD)

…and may pollute stars

Two Debates Over Planets and Their Host stars

Debate 1: Occurrence Distribution

- Why are there more giant than medium planets at such short periods?

Debate 2: Iron Abundance populations

- Why are there correlations between planet parameters and stellar iron abundance?

- Are we seeing only the results of planet formation, or could more recent planet evolution play a role?

Debate 1: Where are the shortest period planets from?

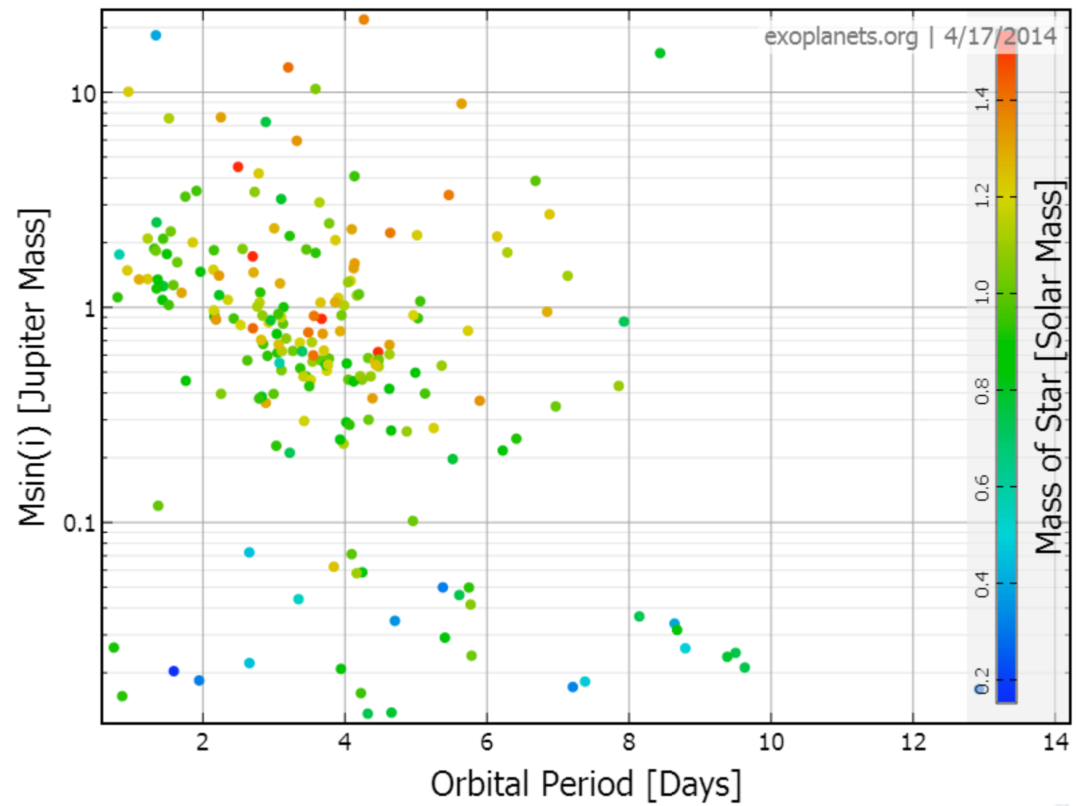
- Is the population of the shortest period planets due only to weak tidal dissipation, or could ongoing planet migration supply a transient population of doomed planets?
- Weak tidal dissipation (1/Q’) versus new planets arriving.
- More giant planets, or fewer medium planets due to evaporation?
- Study planet mass-radius relation with the SPOD.

What is Q’?: Tidal dissipation strength is expressed as 1/Q’, where Q’ is the fraction of energy dissipated, such that higher Q’ means weaker tidal dissipation.

SPOD reshaped by migration and evaporation

Why more shortest period giant planets than medium planets?

1. Weak tidal dissipation in star?
2. More numerous giant planet migration into star?
3. Evaporation of medium planets? (Mazeh et al. 2005)

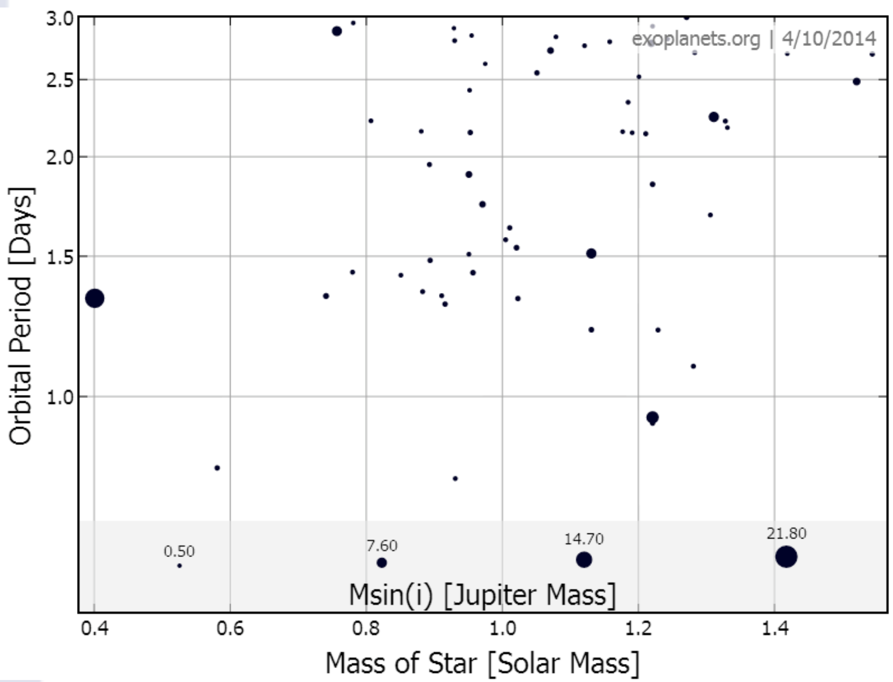


Planet mass versus period

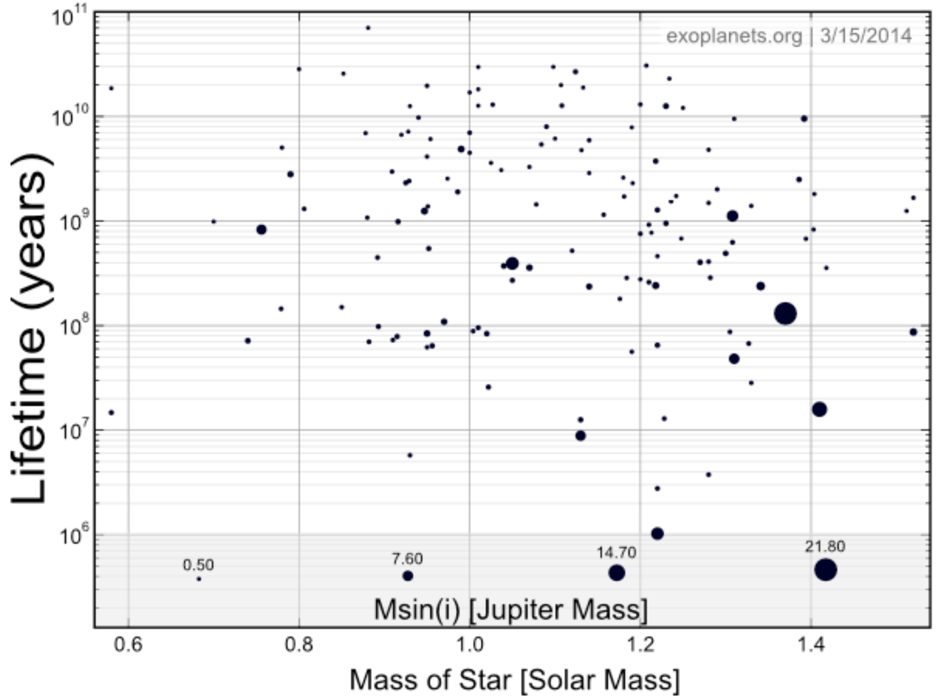
Shows a “Hot-Neptune desert”

Too many giant planets with too short of periods?

Period vs. star mass



Lifetime vs. star mass



Shortest period planets

Shortest lifetimes

Depends on star mass. Lifetime or tidal migration strength effect?

Occurrence Distribution of Kepler Planets Fit to Distributions With Falloff

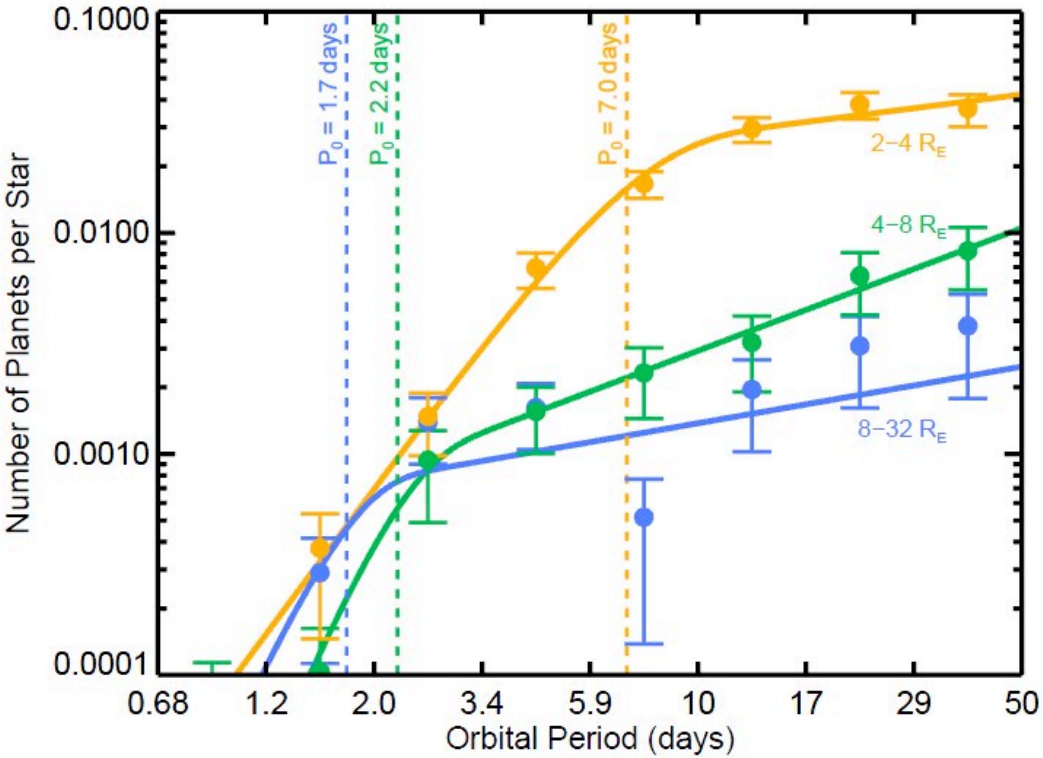
- Two-power indices distribution.

$$\frac{dN(P)}{d\log P} = k_P P^{\beta}\left[1 - e^{-(P/P_c)^{\gamma}}\right]$$

- Inner falloff, initially due to planets not forming near star.
- Inner falloff can also be maintained by migration of planets into star due to the tides they raise on the star (i.e. Jackson+ 2009).
- We use H12's fit to a "power cutoff function", where the slope of the falloff is given by:

$$\alpha = \beta + \gamma$$

- The power index for giant and medium planets is 4.5 +/- 2.5 and 4.8 +/- 1.3 (but ~2.9 +/- 0.4 for small planets)



Howard+ (2012; H12) fit to Kepler statistics for (relatively) large (8-32 R_e), medium (4-8 R_e), and small (2-4 R_e) planets.

Falloff distribution reproducible using tidal migration equations on an initial single power SPOD: Power index of falloff of 13/3 (Taylor 2012)

Tidal migration acting on the H12 power law $k_P P^{\beta}$, for periods of

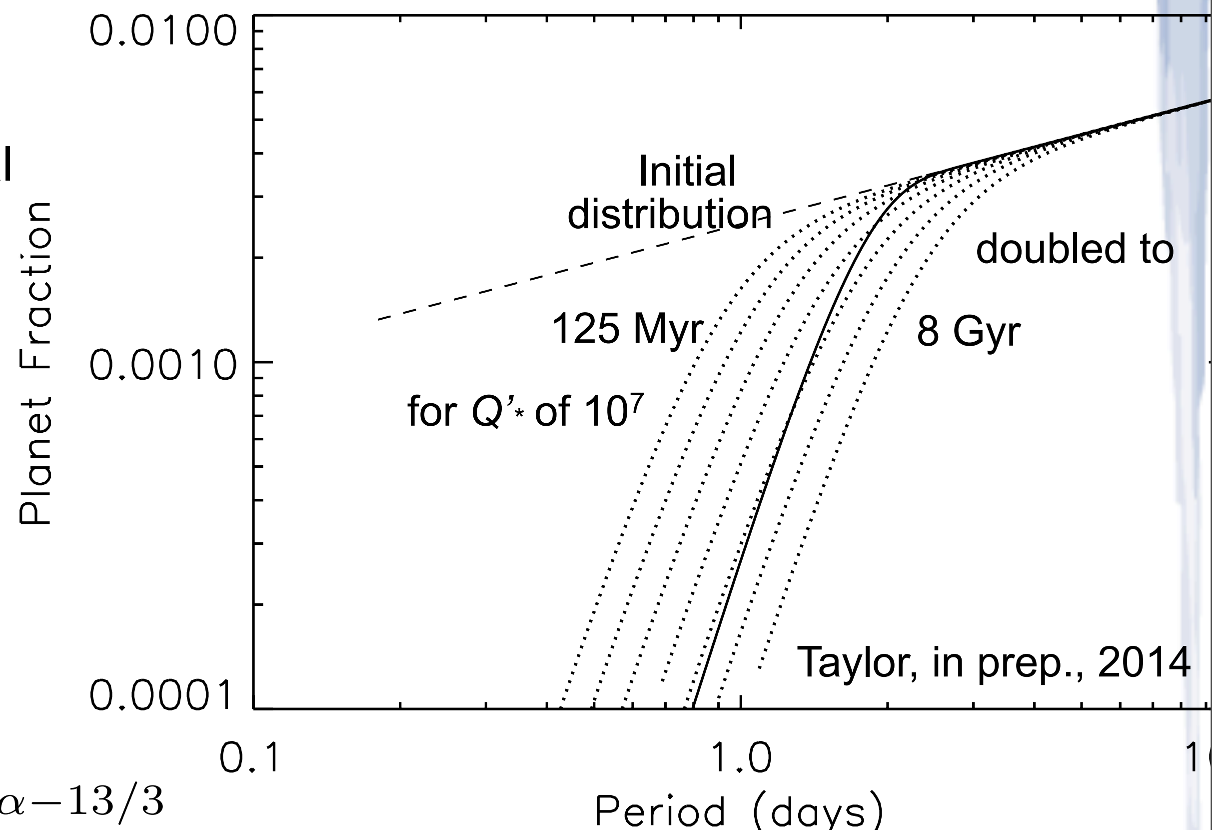
125, 250, 500 ... Myr to 8 Gyr, for Tidal strength Q'_* of 10^7, (Taylor, 2014)

$$\frac{da}{dt} = -\frac{9}{2}\left(\frac{G}{M_*}\right)^{1/2} \frac{R_*^5 M_p}{Q'_*} a^{-11/2}$$

We present that the rate of planets migrating into the star is:

$$\frac{dN}{dt} = \frac{27}{4} \frac{(2\pi)^{13/3} R_*^5 M_p}{G^{5/3} M_*^{8/3} Q'_*} \frac{k_P}{P_c^{\gamma}} P^{\alpha - 13/3}$$

When power index goes to 13/3, the period dependence drops out.

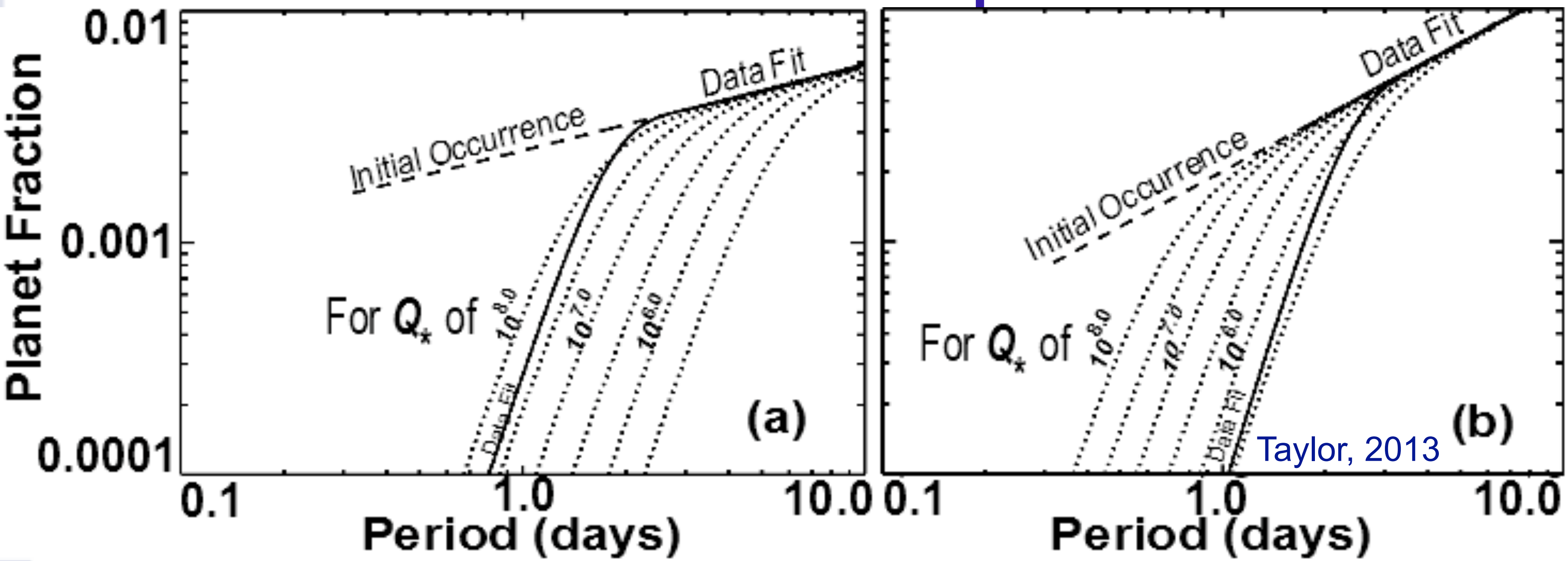


Dashed line: Took the longer period power law all the way into star as distribution

Solid line: Fit to Kepler

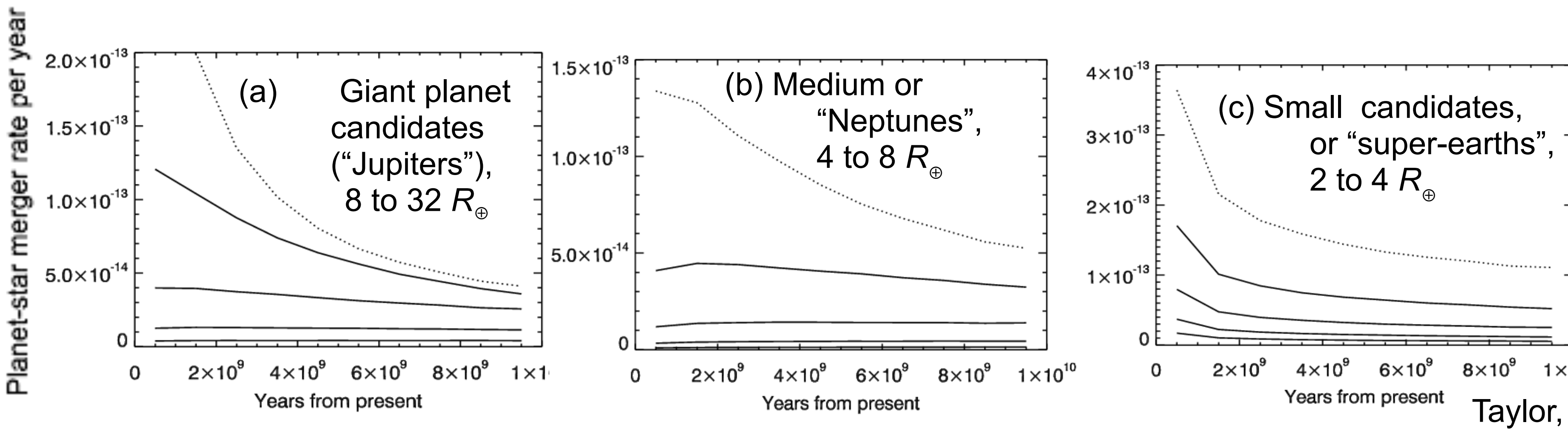
Dotted lines: Migration for 125, 250, 500 Myr, 1,2,4,8 Gyr for Q'_* of 10^7

Occurrence distribution of giant versus medium planets



- Consistent with the power index of 13/3 for tidal fall in for giant and medium planets.
- More giant than medium planets at fall-off, but more medium planets in general.
- Giant planets raise bigger tides on host stars, so undergo faster migration.

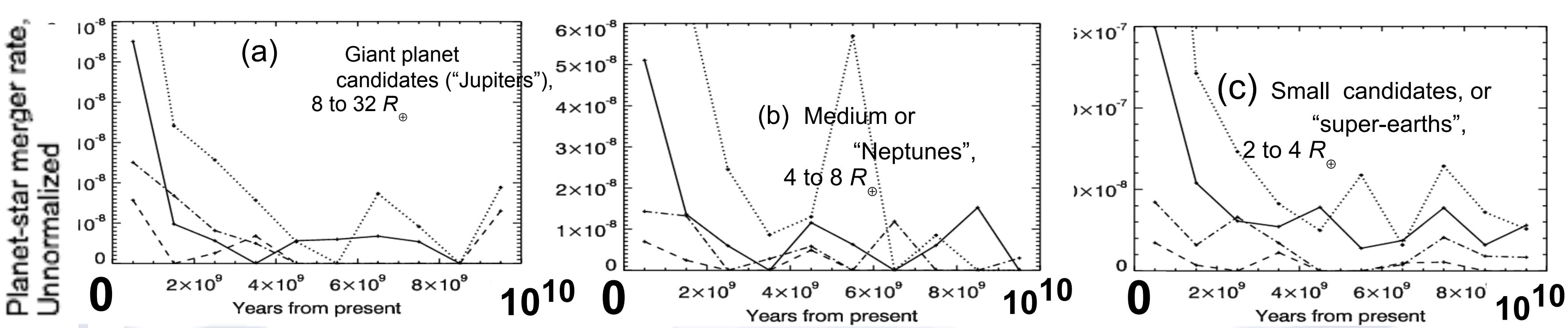
Future infall: Modeling Fit Distribution



Taylor, 2013

Rate of fall into star should be constant

Only a small in-flow should explain why more giant planets without requiring unreasonably weak tidal dissipation



Taylor, 2013

Rate of planet migration into star sustainable with small "flow"

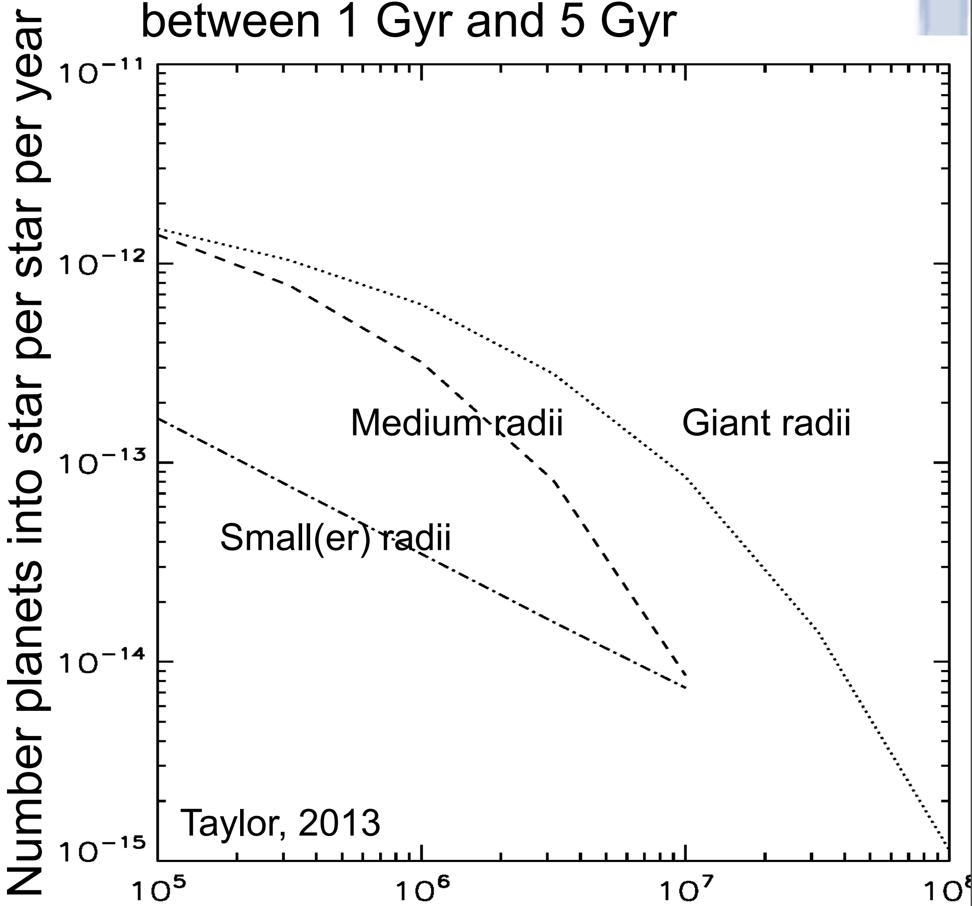
$$\frac{dN}{dt} = \frac{27}{4} \frac{(2\pi)^{13/3} R_*^5 M_p}{G^{5/3} M_*^{8/3} Q'_*} \frac{k_P}{P_c^{\alpha-\beta}} P^{\alpha-13/3}$$

where we use the H12 fitting function, with $\alpha = \beta + \gamma$

$$\frac{dN(P)}{d\log P} = k_P P^\beta \left[1 - e^{-(P/P_c)^\gamma}\right]$$

- Even for tidal dissipation as strong as Q'_* of 10^6, the SPOD can be maintained by less than 1 planet per 10^3 star per gigayear.
- Can be supplied: This rate would only decrease planet occurrence by 1% over 10 Gyr

Difference in the
Rate of planets infalling into star
between 1 Gyr and 5 Gyr



Rate as function of the strength of tides in stars to dissipate orbital energy Q'_*.

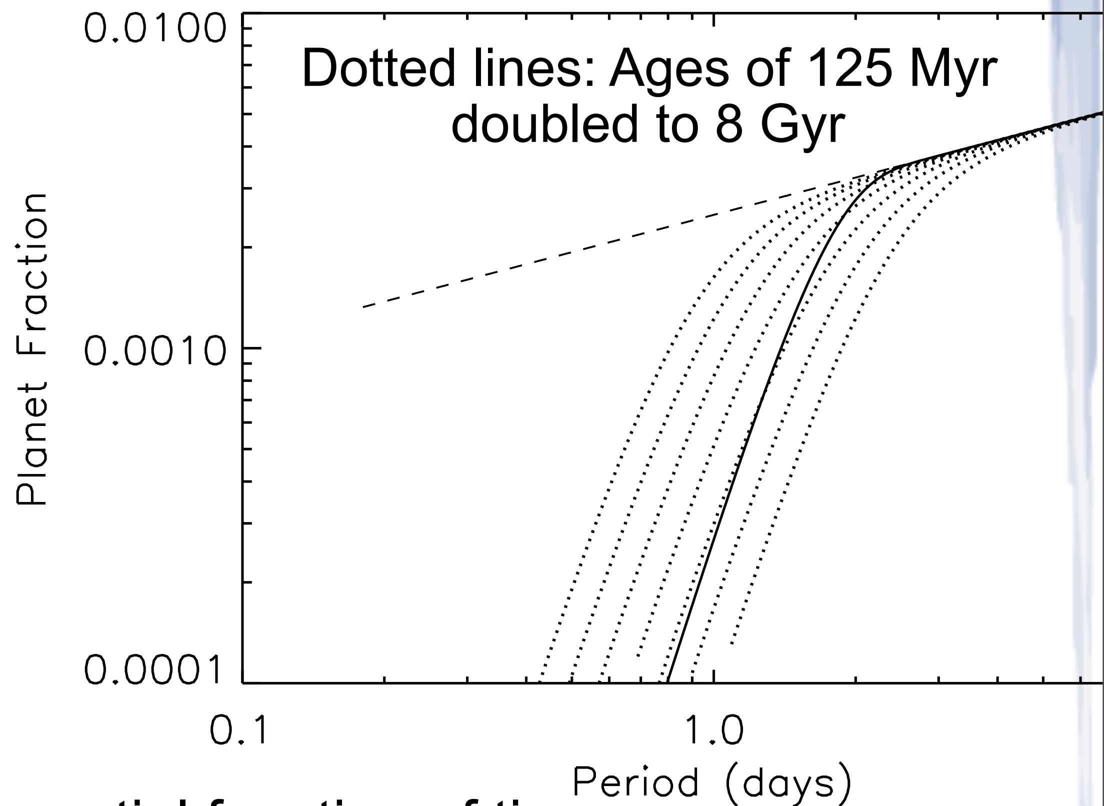
Rate of Falloff Period P_c Evolves With Age

Theoretical framework being done in Taylor, in preparation (2014):

Rate that cutoff period P_c moves outwards:

$$\frac{dP_c}{dt} = \frac{27}{4} \frac{(2\pi)^{13/3} R_*^5 M_p}{G^{5/3} M_*^{8/3} Q'_*} P_c^{1-\alpha+\beta}$$

Movement of falloff curve with time: Fall off curve for $Q'_* = 10^7$



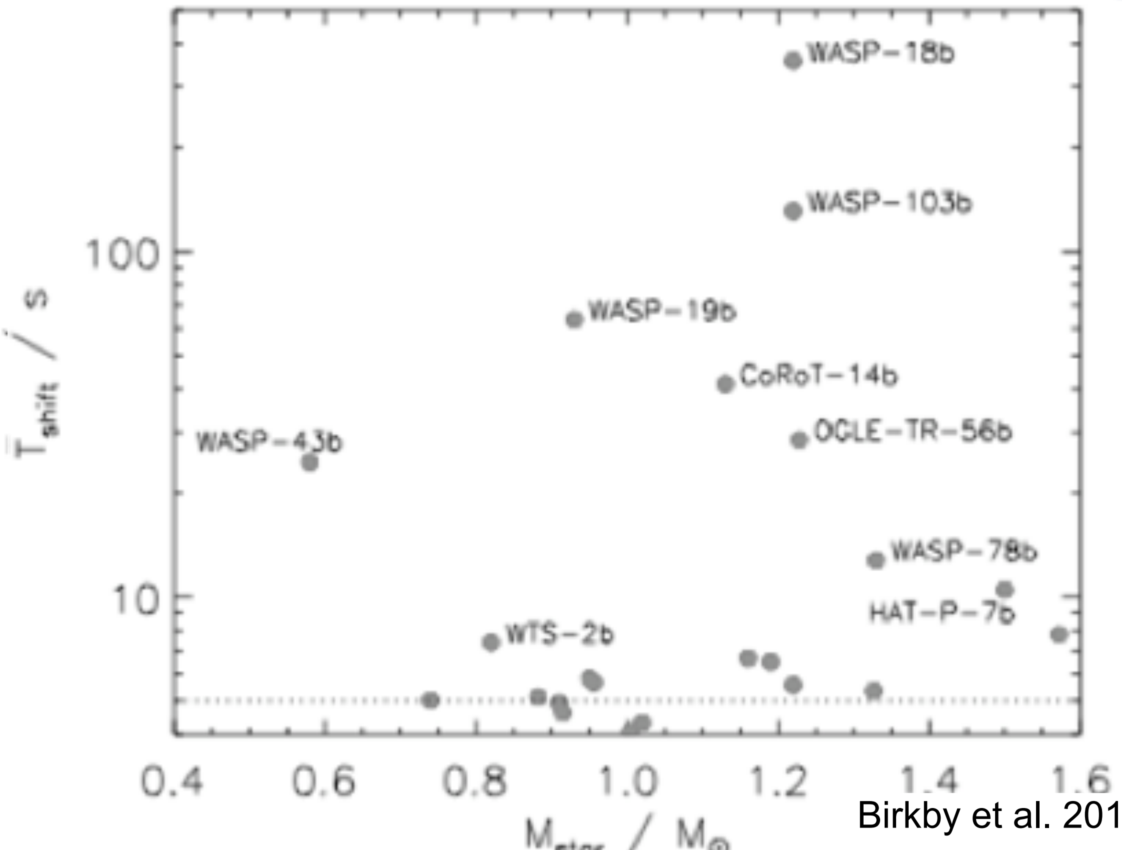
Evolution of cutoff period is an exponential function of time:

$$P_c = \left[\frac{27(\alpha - \beta)}{4} \frac{(2\pi)^{13/3} R_*^5 M_p}{G^{5/3} M_*^{8/3} Q'_*} t \right]^{1/(\alpha-\beta)}$$

Watch this: Time shifts will constrain or show Q

Within 10 years we will be able to constrain Q'_* for a range of stellar masses -- or will measure a time shift that will determine Q'_*.

(Birkby et al. 2014)



Birkby et al. 2014

Transit time shifts after 10 years for known transiting hot Jupiters for Q'_* of 10^6.

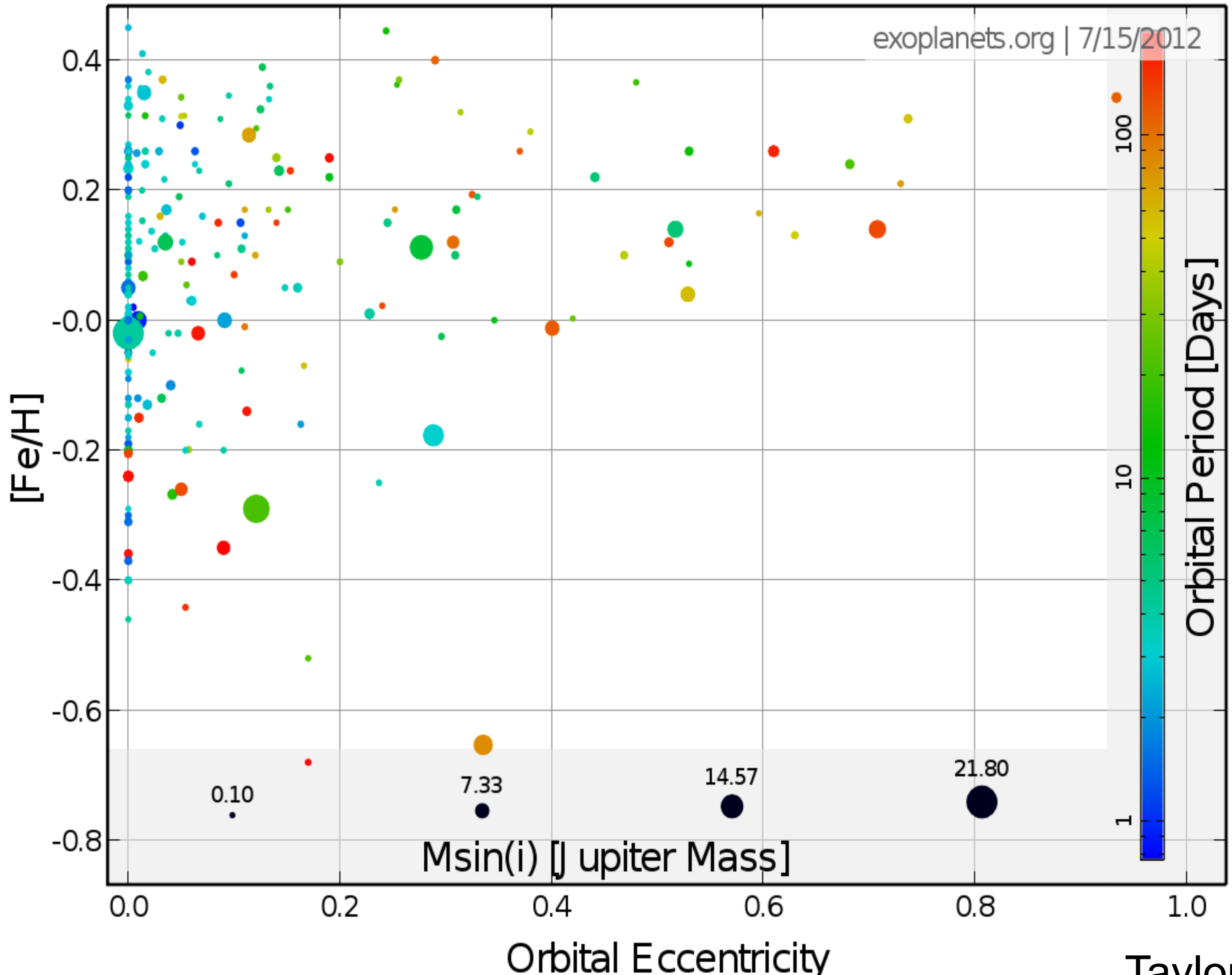
Shift proportional to Q'_*.

Time shift increases with time baseline squared.

Debate 2:

- Did the giant planet-metallicity correlation come from formation or from pollution, and if pollution, was the pollution from the primordial disk or from planets migrating into the star?
- Ever since the giant planet-metallicity correlation was found (Gonzales 1997), there has been a debate whether it was due to formation or accretion from the disk. Whole planet pollution was not considered as strongly as pollution from the disk due to the large mass required to pollute the star.
- Several works do not find the higher presence of refractory than volatile elements expected from pollution from the disk.
- Mayor & Chaboyer (2002, MC02) showed that perhaps as little as 6 M_{earth} would be needed to pollute the convective zone (CZ), or given that more massive stars no longer have a CZ, what they call the surface mixing layer (SML). The CZ mass decreases with increasing stellar mass.
- MC02 find increased Fe versus decreasing SML mass.

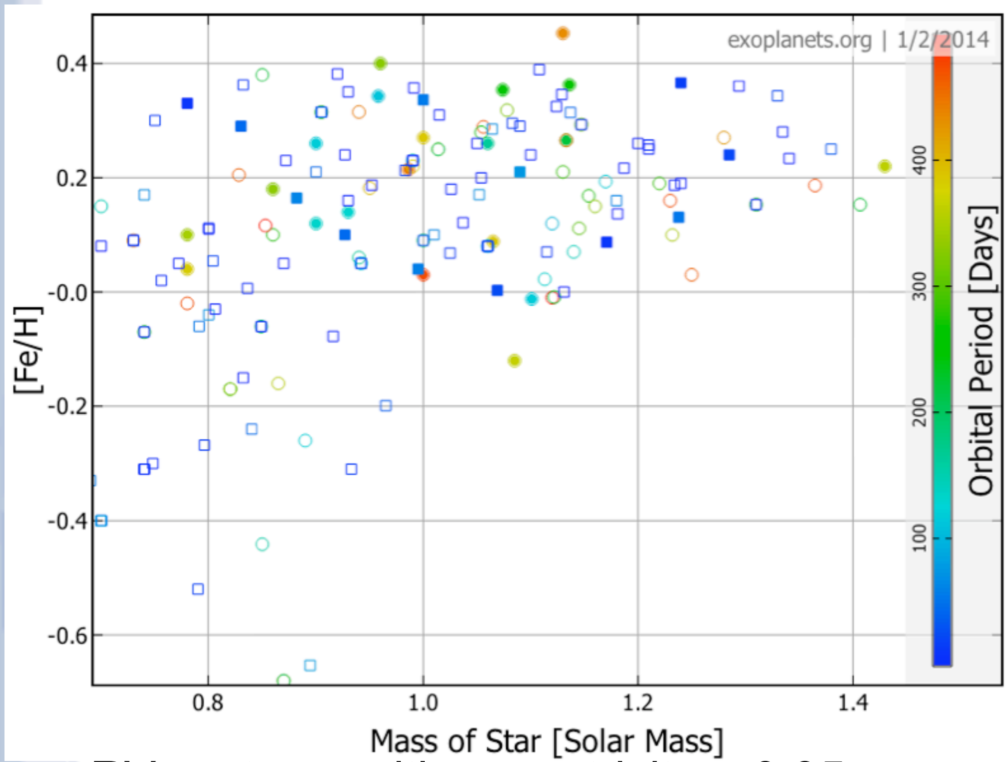
Pollution:
Correlation of [Fe/H] with eccentricity



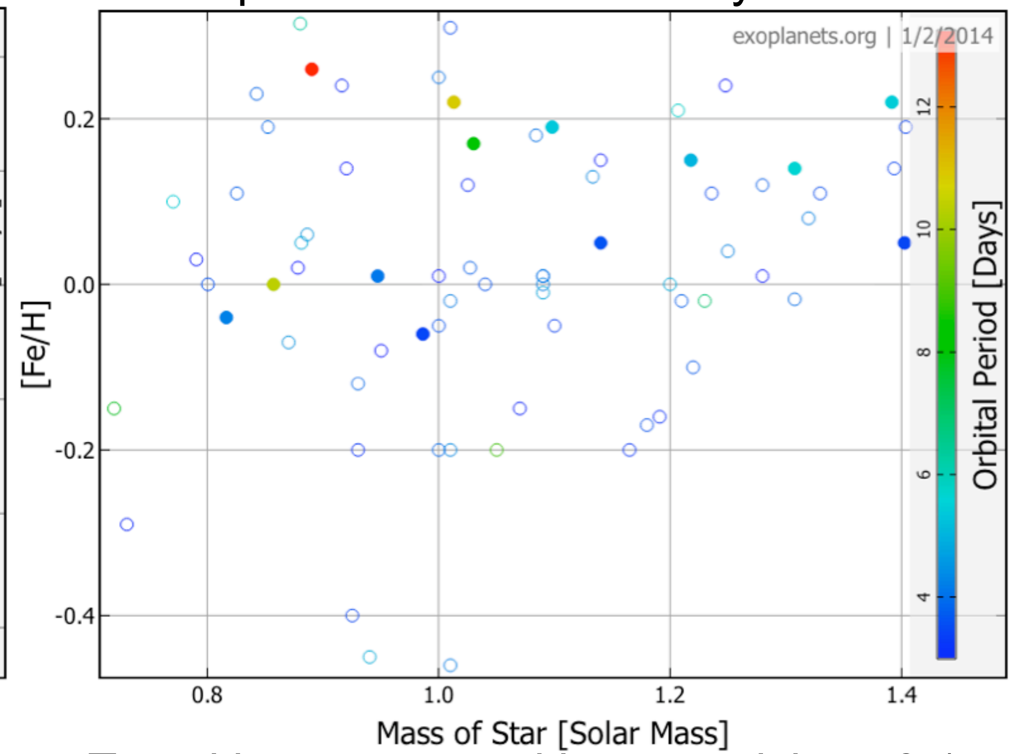
Taylor 2012, 2013

Fe vs M_{star} correlation

RV systems with periods < 500 d



Ground-based Transiting systems with periods from 3 to 50 days



RV systems with eccentricity > 0.35 shown with filled symbols.
Circles show systems with periods 100 to 500 days,
Squares for systems less than 100 days.

Transiting systems with eccentricity > 0.1 shown with filled symbols.

Showing systems with temperature from 4500 to 6500 K, log g >4, radius of star not greater than twice the mass relative to the sun.

High and low eccentricity systems small probability same population

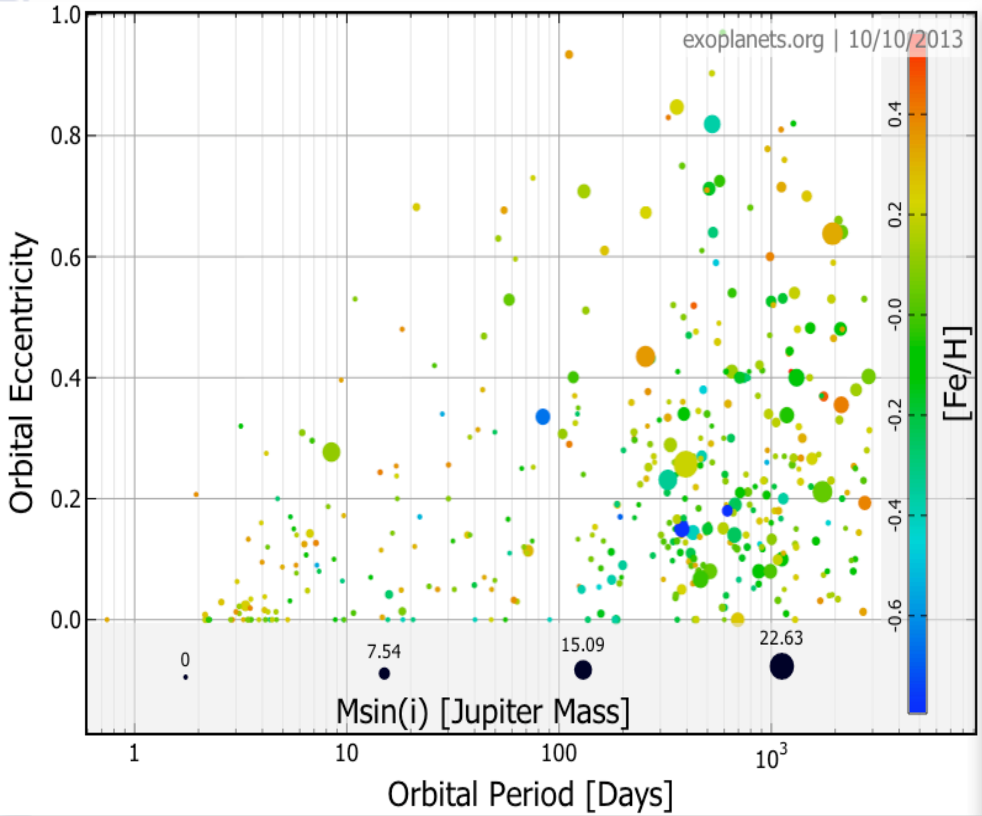
Table 1. Stellar [Fe/H] for regions separated in period and eccentricity, with the T-means probability of the systems below and above the given values of eccentricity being the same population.

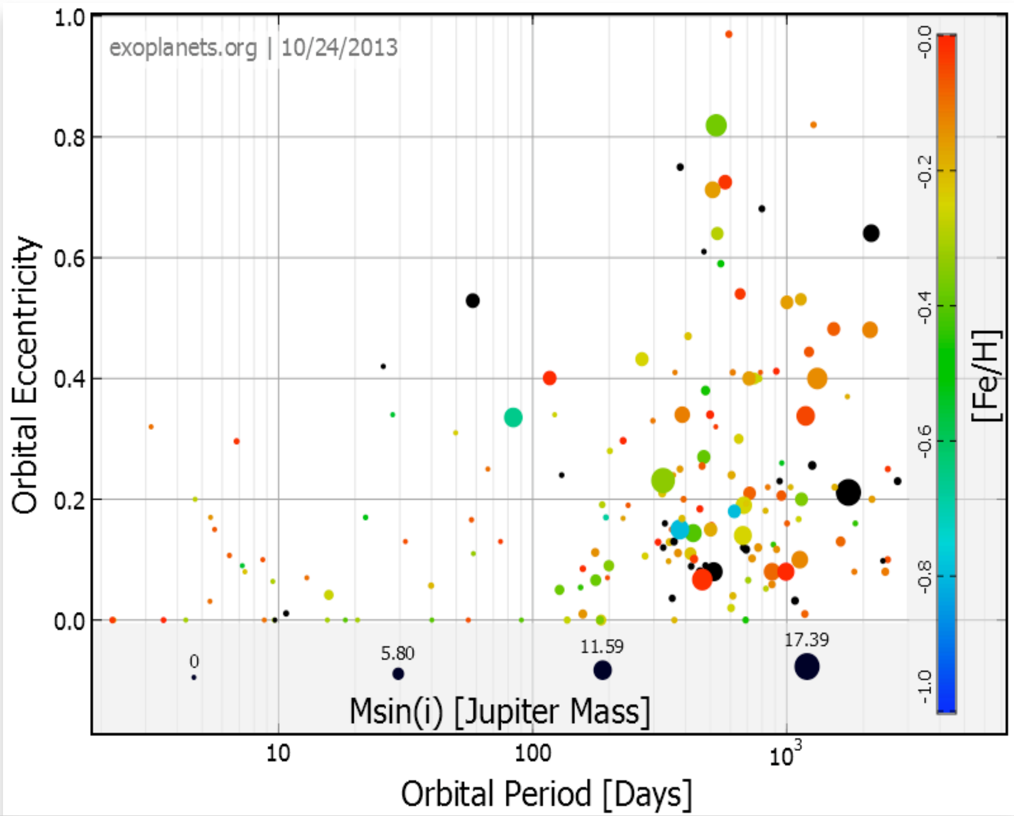
Period Region, days	Probability same population	Number of systems	Mean stellar [Fe/H]	var-iance	Number of systems	Mean stellar [Fe/H]	var-iance
		eccentricity < 0.35			eccentricity > 0.35		
< 500 d	7.6×10^{-2}	116	0.071	0.05	29	0.19	0.02
> 600 d	0.40	33	0.12	0.04	60	0.12	0.04
		eccentricity < 0.55			eccentricity > 0.55		
< 500 d	0.014	135	0.088	0.05	10	0.20	0.014
> 600 d	0.035	84	0.080	0.05	9	0.24	0.03

Systems restricted to those with stellar log $g > 4.0$, and 4500K < T_{eff} < 6500, following Dawson and Murray-Clay (2013, DM13).

Iron-rich and iron-poor systems are different populations

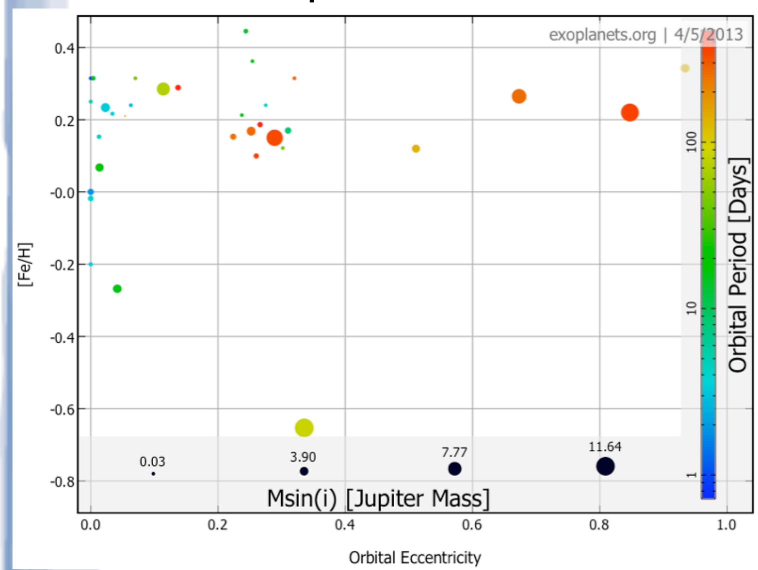
- Iron-rich systems have higher eccentricity over most periods
- Iron-poor systems have a narrow range in period of high eccentricity between 500 to 600 d.



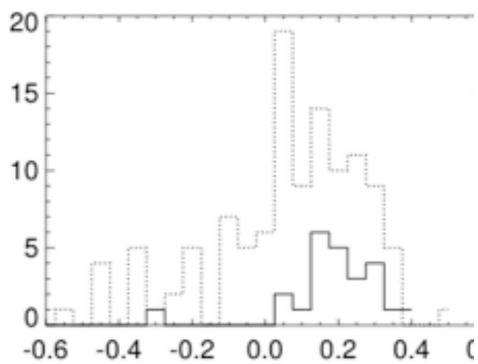


Presence of stellar companions correlated with higher iron abundance

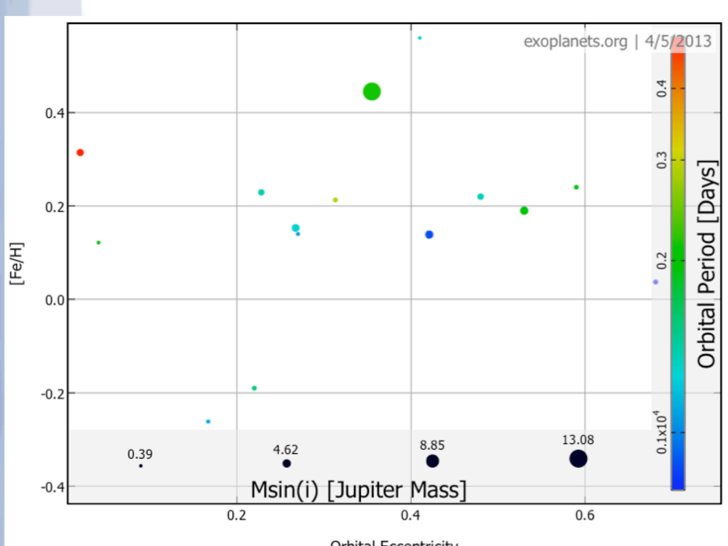
BSWPs with periods < 500 d



Comparison of BSWPs (solid line) with SSWPs (dashed line) for systems with periods < 500 d



BSWPs with periods > 600 d



Stars with planets (SWPs) with stellar companions (Binary SWPs, BSWPs) have [Fe/H] generally above zero at most eccentricities.

SWPs with stellar companions different population that single SWPs

Comparison of binary SWPs (BSWPs) and SSWPs for systems with periods less than 500 days

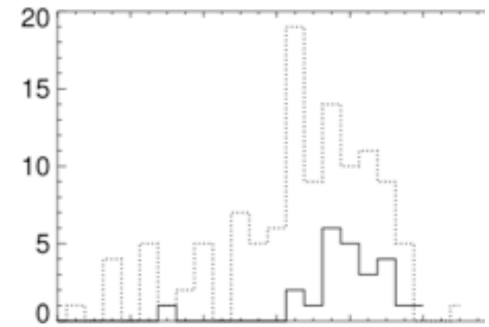


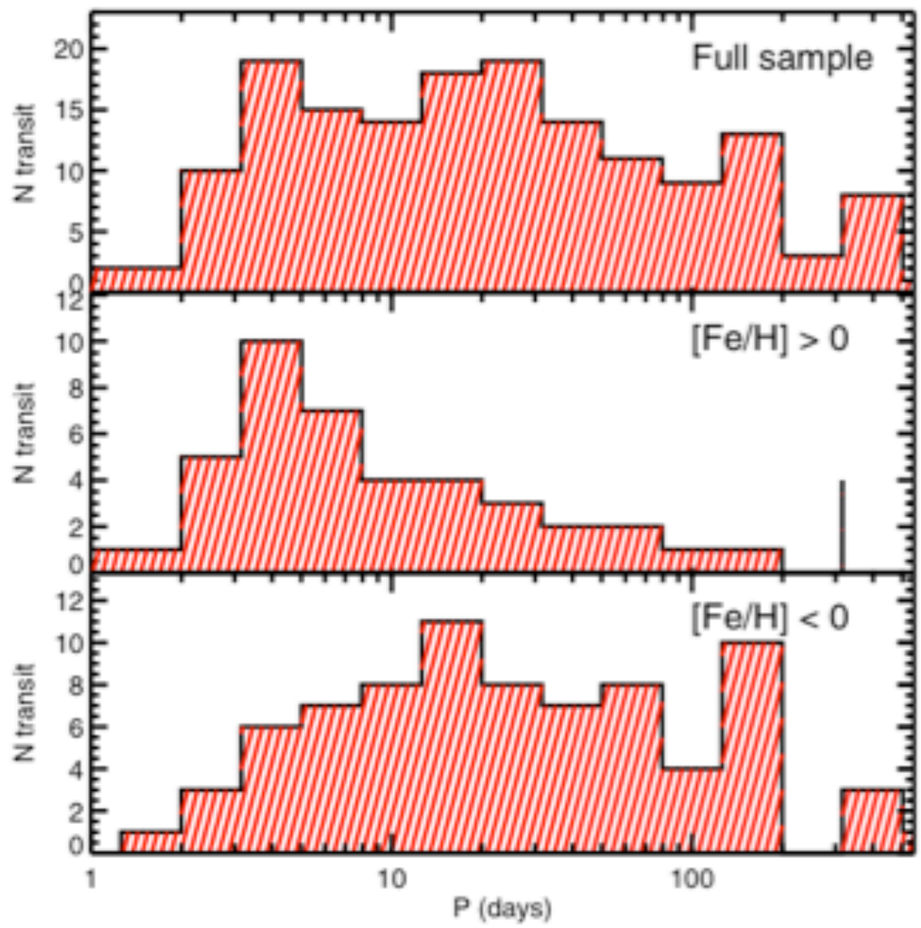
Table 2. Planet hosting star (SWP) [Fe/H] for regions separated in planet period and eccentricity. with the T-means probability of BSWP and SSWP systems in the given range being the same population.

Period Region, days	Eccentricity Region	Probability same population	Binary Stars with Planets			Single Stars with Planets		
			Number of systems	Mean stellar [Fe/H]	var-iance	Number of systems	Mean stellar [Fe/H]	var-iance
< 500 d	< 0.35	0.040	25	0.18	0.05	116	0.071	0.05
	> 0.35	0.55	4	0.24	0.009	33	0.19	0.02
> 600 d	< 0.35	0.91	8	0.090	0.04	60	0.081	0.05
	> 0.35	0.10	7	0.26	0.03	33	0.12	0.04

Systems restricted to those with stellar log $g > 4.0$, and $4500K < T_{eff} < 6500$, following Dawson and Murray-Clay (2013, DM13).

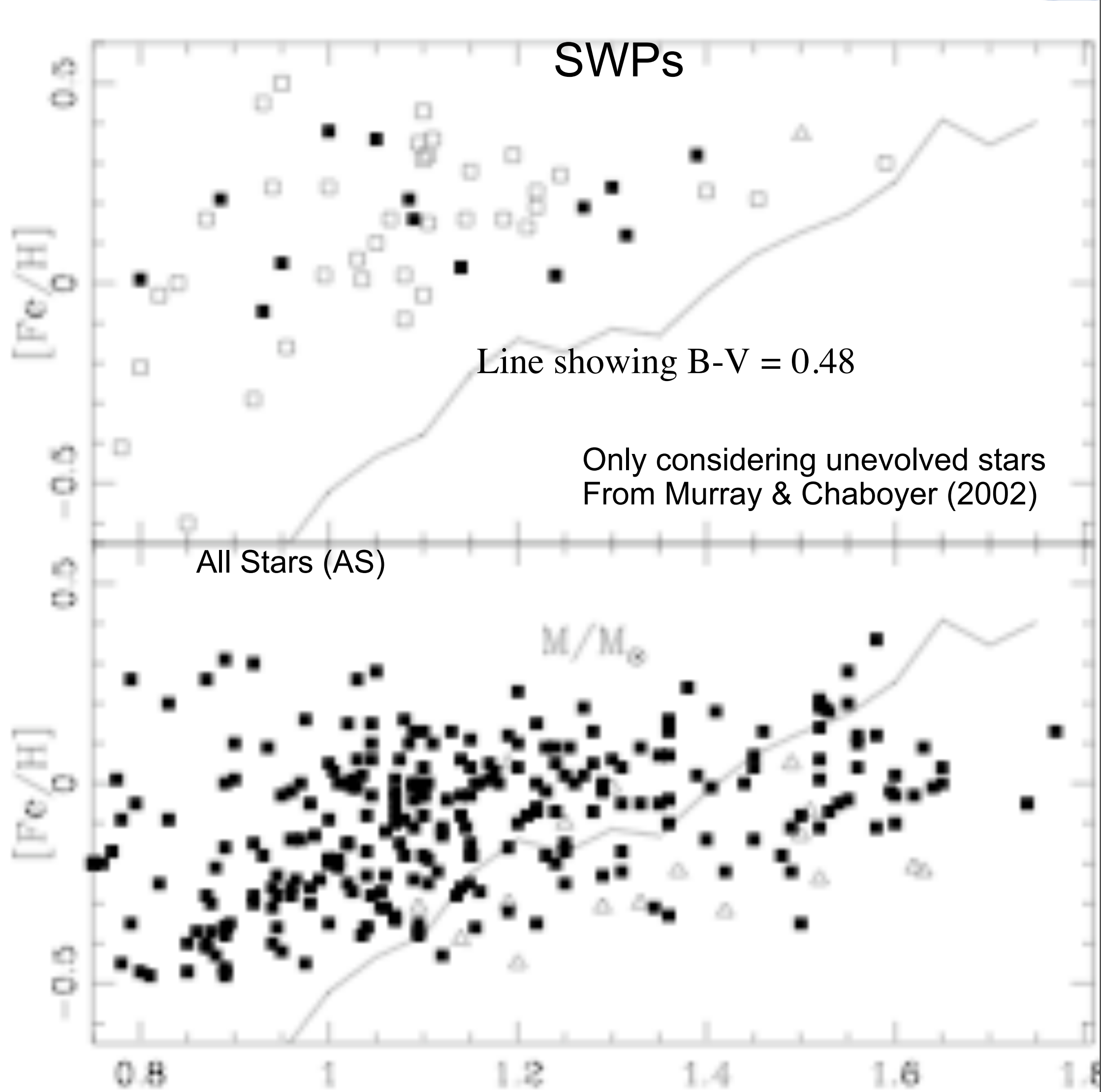
Three-day pileup of giant planets a feature of high Fe abundance

- Pile-up of giant planets much weaker in Kepler field than in solar neighborhood
- Dawson & Murray-Clay (2013) found several differences between high and low Fe abundance stars with planets (SWPs)
- Recovered much of though not all of pileup in the Kepler sample.



[Fe/H] increases with smaller surface mixing layer (SML) for stars

- Increase in [Fe/H] with SML found associated with presence of planets by Murray & Chaboyer (2002)
- Surface Mixing Layer (SML) is roughly the convective zone (CZ) in solar mass stars. CZ decreases in mass with increase in mass of stars, until very small mass SML.






These results made possible from years of contributing to planet statistics.
The work that goes into us confirming enough
planets to be able to planet distributions.

Conclusions

- Rate of inward planet migration not too high when compared with total number of planets. Perhaps not too high to be supplied by the pileup.
- Excess of shortest period giant planets would require a different tidal dissipation strength than medium planets if no new planet supply.
- High and low iron abundance systems have different distribution of planet orbit parameters.
- Correlation of stellar [Fe/H] with planet eccentricity.
- Competing explanations: Pollution vs Formation, or both? If more crowded formation leads to scattering that raises eccentricity, then this scattering could lead to more whole planet pollution.
- Quantify what migration leads to what distribution and what pollution.

Future work:

- Watch for period decreases
- Model whether medium eccentricity could create pileup, and extreme eccentricity could send planets right through pileup
- Model pollution in stars, first to estimate time of convection to mix away from stellar surface.