Heavy meteal rules

The star-planet connection

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SEVENTH FRAMEWORK PROGRAMME

erc

Outline

1. Introduction to exoplanets
   - Diversity of exoplanets
   - Planet formation theories
2. Planet formation and metallicity
   - Giant planets
   - Low-mass planets
   - Planets around evolved stars
3. Planet formation: Importance of other elements
   - Heavy elements in the metal-poor regime
4. Planet architecture and metallicity
   - Period, mass, eccentricity, and [Fe/H]: previous works
   - Period-mass diagram and [Fe/H] with SWEET-Cat
5. Conclusion

1924 confirmed and 4600 planet candidates (*Kepler*)
483 multiple planet systems

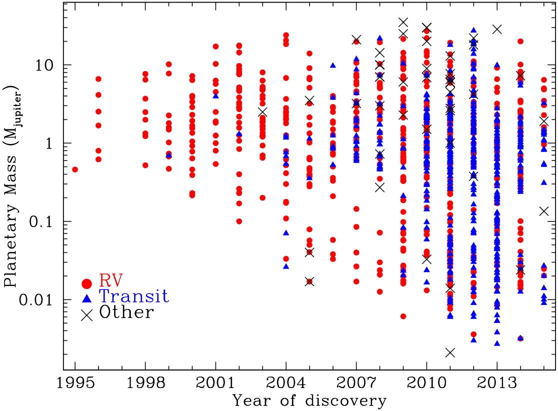


Figure: M_P vs. year of discovery (`www.exoplanets.eu`).

- RV - 602 planets
- Transit - 1206 planets
- Other - 116 planets

The spread in planetary properties

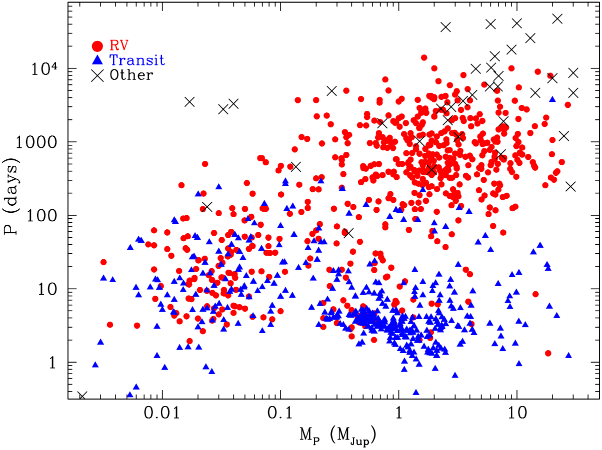
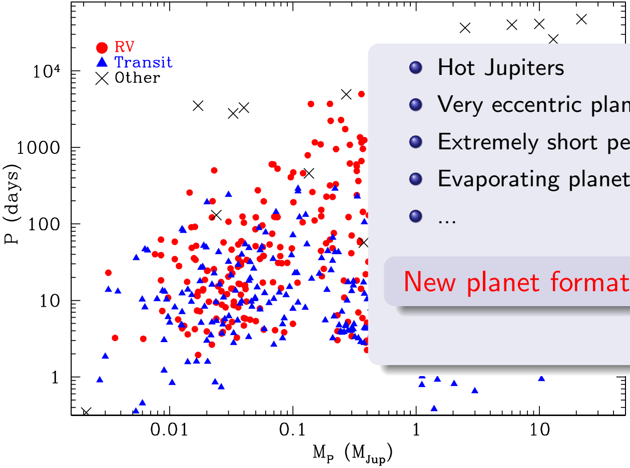


Figure: Period vs. mass (www.exoplanets.eu).

The spread in planetary properties



- Hot Jupiters
- Very eccentric planets (even $e > 0.9$)
- Extremely short period planets ($P < 1$ day)
- Evaporating planets
- ...

New planet formation theories needed

Figure: Period vs. mass (www.exoplanets.eu).

The two main formation theories

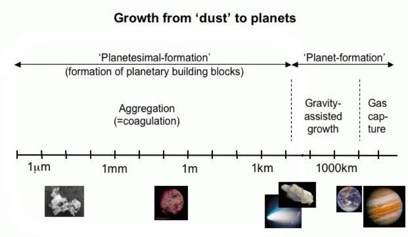
Core-accretion

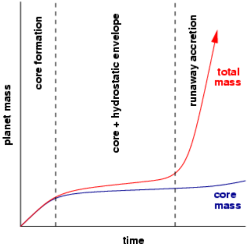
The formation of a giant planet begins with planetesimal coagulation and cor formation (similar to terrestrial planets) which then attract gas, first slowly, and then in a runaway state.
Safronov & Svagina (1969), Pollack et al. (1996)

Gravitational instability

Giant planets form by the gravitational fragmentation in the protoplanetary disk surrounding young stars
Boss (1997)

Core-accretion





Formation in three phases:
I. Accretion of planetesimals within the gravitational reach
II. Slow envelope accretion (formation time is defined by phase II)
III. Runaway (rapid) gas accretion (when $M_{gas} = M_{core} = 5\text{-}20\ M_{\oplus}$)

The model explains formation of giant (*not very massive*) and rocky planets at *not very large* orbits (but see Kikuchi et al. 2014 and at *not very low* metallicities).
See e.g. Ida & Lin 2004; Mordasini 2009,2012; Hasegawa & Pudritz 2014

Gravitational instability

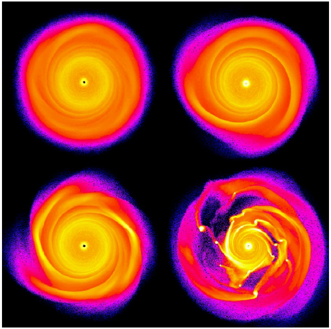


Figure: 3D simulations by Mayer et al. 2002.

Giant planets form extremely rapidly, due to fragmentation of the disk *under specific conditions* (very cool and massive disks etc).

The model explains formation of gas giants (with and without cores) and possibly rocky planets at large distances (but see Nayakshin 2015a,b,c).
See. e.g. Boss 1997, 2011, Mayer et al. 2007; Boley 2009; Vorobyov & Basu 2010

CA vs./and GI

The two processes can be complementary

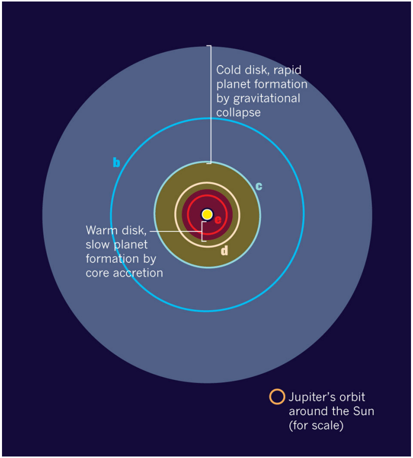


Figure: Courtesy L. Close (2010).

Outline

Different planet formation scenarios offer different observationally testable signatures

However, mixed theories together with some physical processes (e.g. migration, scattering) and specific initial conditions can explain EVERYTHING

Core-accretion

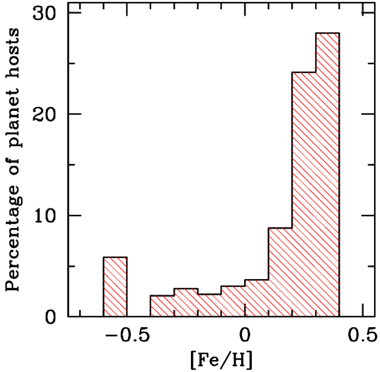
Giant planet - metallicity correlation
Efficiency $\sim$ dust-to-gas ratio $=$ M/H $\simeq$ Fe/H

Gravitational instability

Giant planet - no (apparent) metallicity correlation

Giant planets

Apparent correlation between stellar metallicity and giant planet frequency (e.g. Gonzalez et al. 1998, Santos et al. 2001,2004, Fischer & Valenti 2005, Sousa et al. 2011).



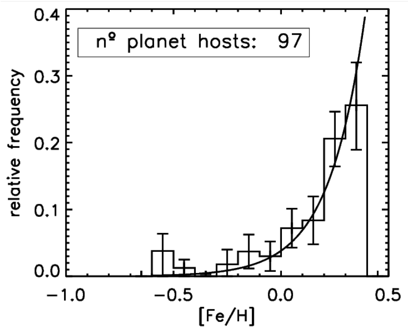
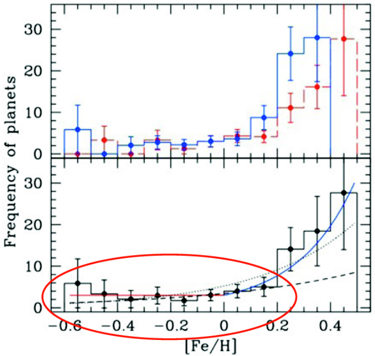


Figure: From Santos et al. 2004 (*left*) and from Sousa et al. 2011 (*right*).

Giant planets - metallicity: the functional form

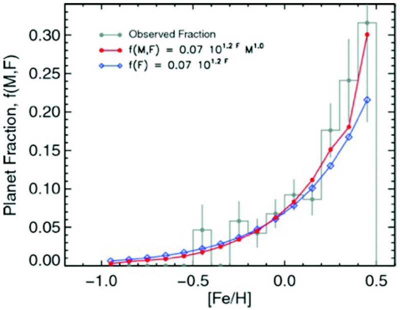
Is the planet formation mechanism the same at low and high metallicities?

A flat tail for low metallicities?



Santos et al. (2004); Udry & Santos (2007)

A simple power-law?

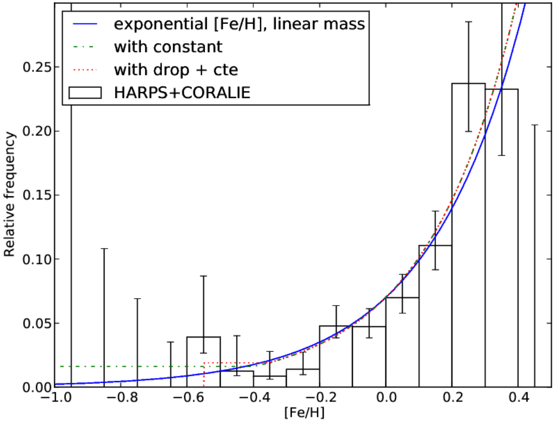


Johnson et al. (2010)

Giant planets - metallicity: the functional form

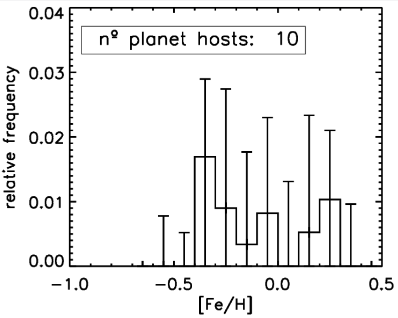
Bayesian analysis with different functional forms

Flat or exponential - no statistical difference. Mortier et al. 2013a



Low-mass planets

No correlation found for Super-Earth/Neptune-like planets ?
e.g. Sousa et al. 2011, Mayor et al. 2011, Buchhave et al. 2012



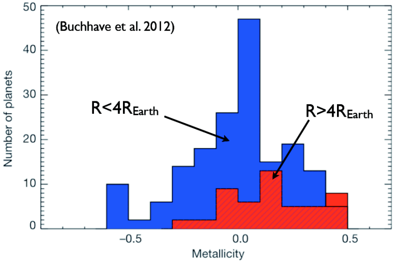


Figure: From Sousa et al. 2011 (*left*) and from Buchhave et al. 2012 (*right*).

Small-size planets: Boundary at $\sim 2R_\oplus$?

The sample – Kepler multi-planet candidates
Parameters – KIC

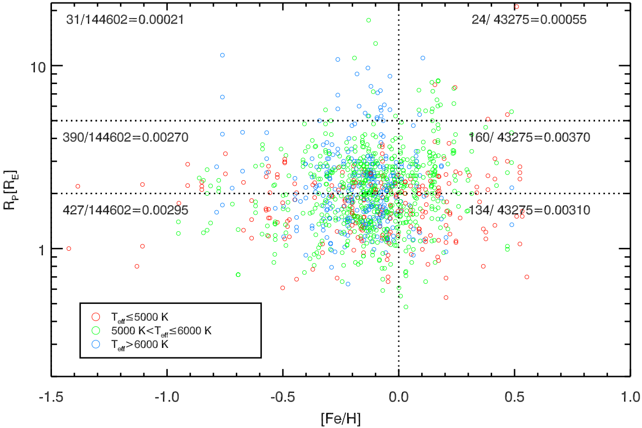


Figure: Wang & Fischer 2013, submitted

Small-size planets: Boundary at $\sim 2R_\oplus$?

Planet-metallicity correlation for all but planets with $R_P < 2R_\oplus$

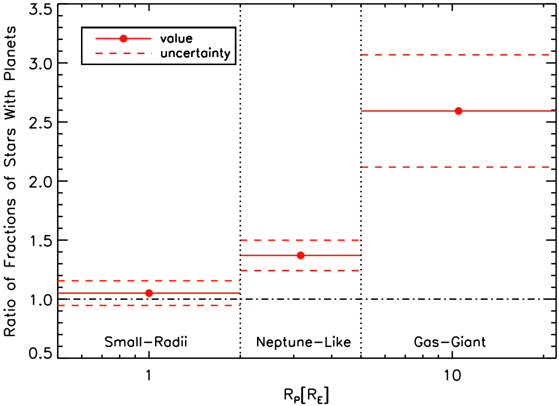
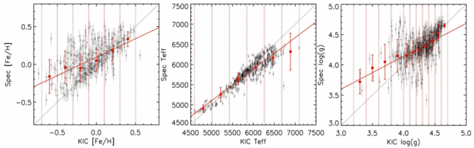
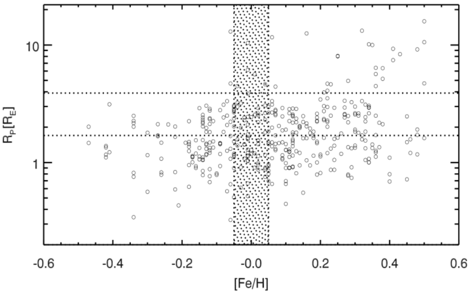


Figure: Wang & Fischer 2013, submitted

Small-size planets: Boundary at $\sim 2R_{\oplus}$?

The sample – Planet candidates from Buchhave et al. 2014 - B14
Parameters – B14 and KIC corrected according B14





Small-size planets: Boundary at $\sim 2R_\oplus$?

A universal planet-metallicity correlation for all planets

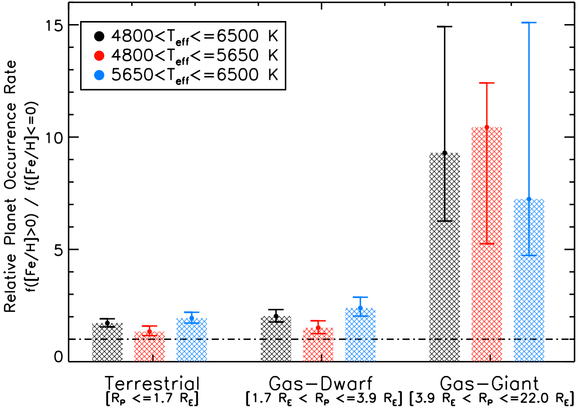


Figure: Wang & Fischer 2015, accepted

Small-size planets: Boundary at $\sim 2R_\oplus$?

Three size regimes of exoplanets: Boundaries at $1.7R_\oplus$ and $3.9R_\oplus$
Metallicity controls the structure of planetary systems.

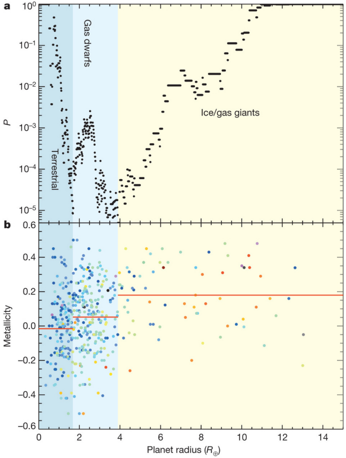


Figure: Buchhave et al. 2014

Three distinct populations of planets with different metallicities.

$R_P < 1.7R_E$ - terrestrial-like planets

$1.7R_E < R_P < 3.9R_E$ - gas dwarf planets with rocky cores

$R_P > 3.9R_E$ - ice or gas giant planets

Small-size planets: Boundary at $\sim 2R_\oplus$?

No evidence for the proposed radius boundary at 1.7 $R_\oplus$

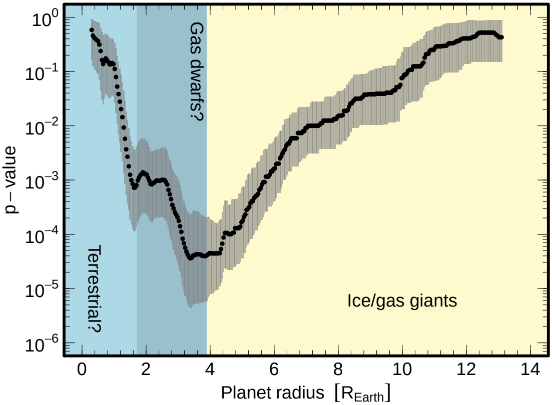


Figure: Schlaufman 2015

Small-size planets: Important but difficult

Planet frequency vs. metallicity is very important to constrain the formation theories, but it is difficult from the observational point of view. Difficult to create a "comparison" sample (especially in the transit surveys).

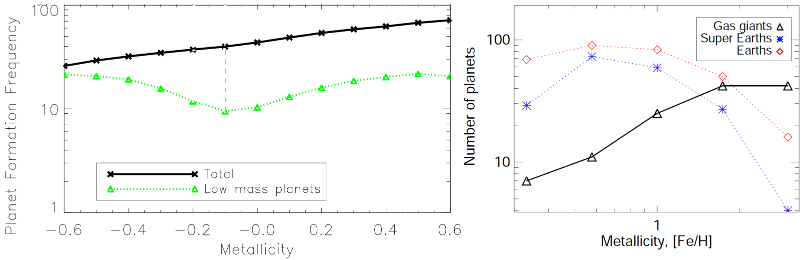


Figure: Hasegawa & Pudritz 2014 (left) and Nayakshin 2015 (right)

Evolved stars with giant planets

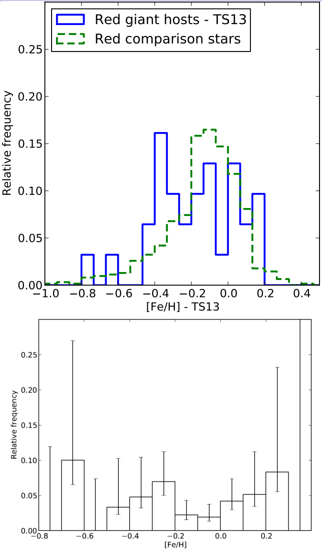


Figure: Mortier et al. 2013b.

No metallicity correlation?

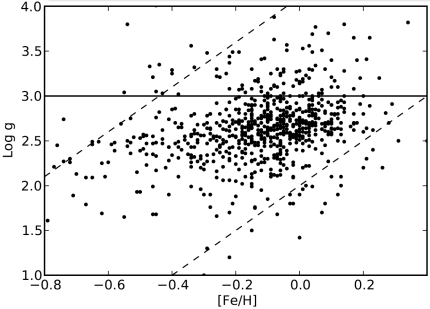
- Evidence for planet engulfment? (Pasquini et al. 2007)
- A mass effect? (Ghezzi et al. 2010)
- A spectroscopic analysis issue? (Hekker & Meléndez 2007; Santos et al. 2009)

There is a correlation after all? (Quirrenbach et al. 2011; Reffert et al. 2015)

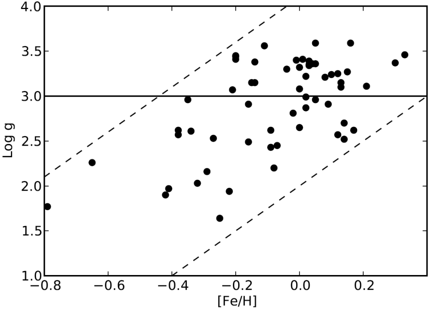
Evolved stars with giant planets

A selection bias? (Mortier et al. 2013b).

Missing metal-rich stars in the giant star sample from (giant) planet search programs due to B-V cuts.



Takeda et al. 2008 + da Silva et al. 2006 + Zielinski et al. 2012



Giant planet hosts

Planet - metallicity

A lot has been done in this field but there are still many open questions and conflicting observations and theories.

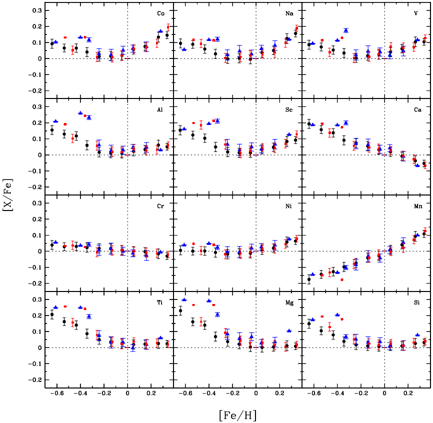
Outline

Are stars with planets chemically different?

Previous studies yielded contradictory results

- Most studies found no systematic difference in abundances (Takeda 2007; Bond et al. 2008; Neves et al. 2009; Delgado Mena et al. 2010)
- Possible enrichment in some species (Bodaghee et al. 2003; Robinson et al. 2006; Brugamyer et al. 2011; Kang et al. 2011)

Refractory elements



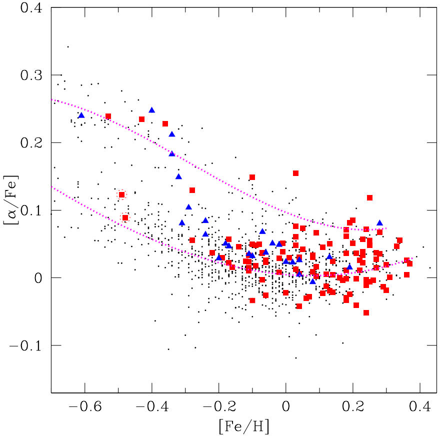


Figure: [X/Fe] vs. [Fe/H] for HARPS sample. Adibekyan et al. 2012a.

Element enhancement of planet hosts

Mg,Ti, Si, Sc, and Al at [Fe/H] $\lesssim$ -0.2 dex

α-elements

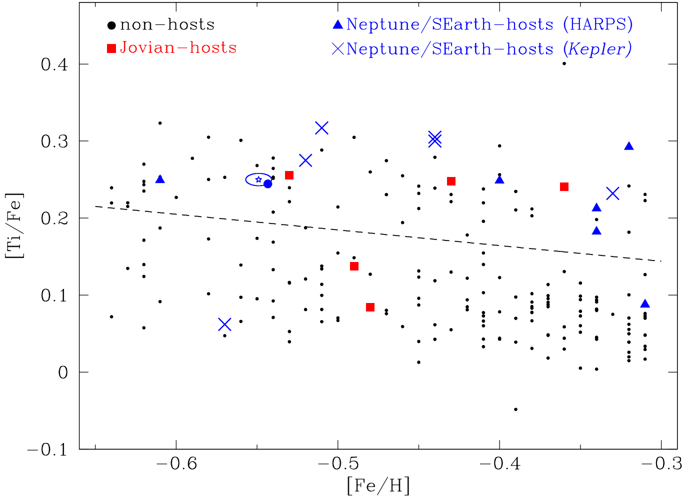


Figure: HARPS + Kepler samples. Adibekyan et al. 2012b.

α-elements

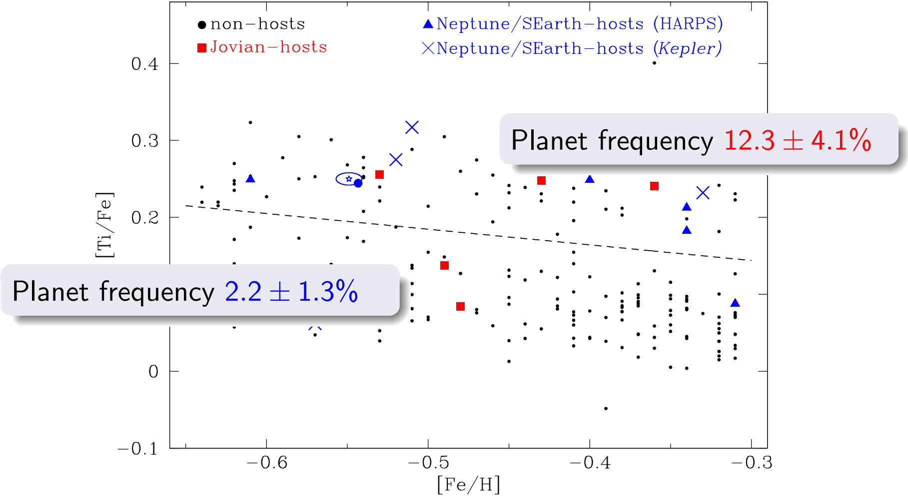


Figure: HARPS + Kepler samples. Adibekyan et al. 2012b.

$[Fe/H] \neq [M/H]$ at low metallicities

Planet frequency and [Ref] index

[Ref] - the mass abundances of Mg, Si and Fe relative to the Sun

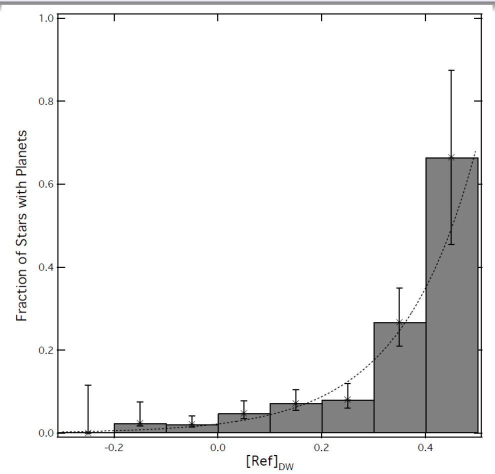


Figure: Gonzalez 2014.

Planet frequency and [Ref] index

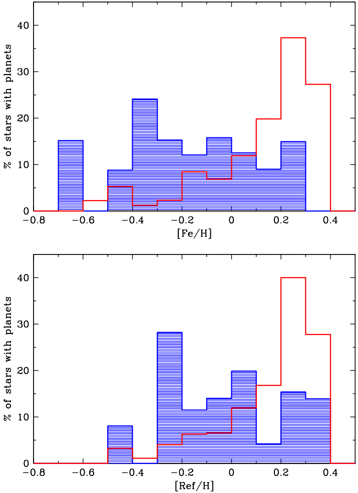


Figure: Adibekyan et al. 2012. Super-Earths (blue), giants (red)

Interior structure of planets and chemical elements

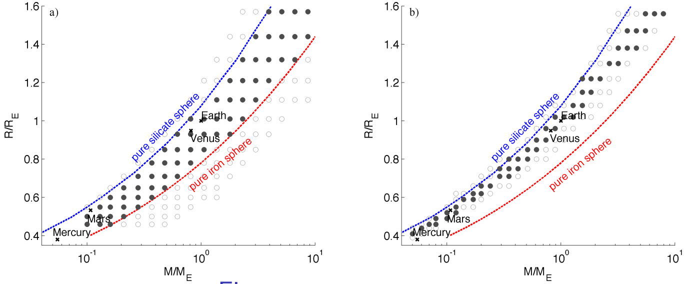
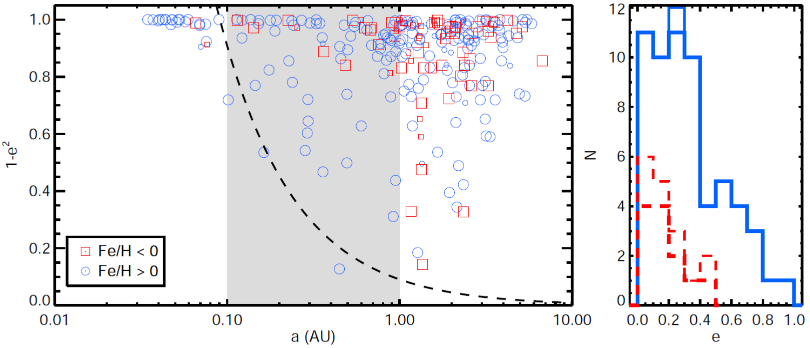


Figure: Dorn et al. 2015.

- Observations of mass and radius are sufficient to constrain core size
- Stellar elemental abundances (Fe, Si, Mg) are principal constraints to reduce degeneracy in interior structure models and to constrain mantle composition

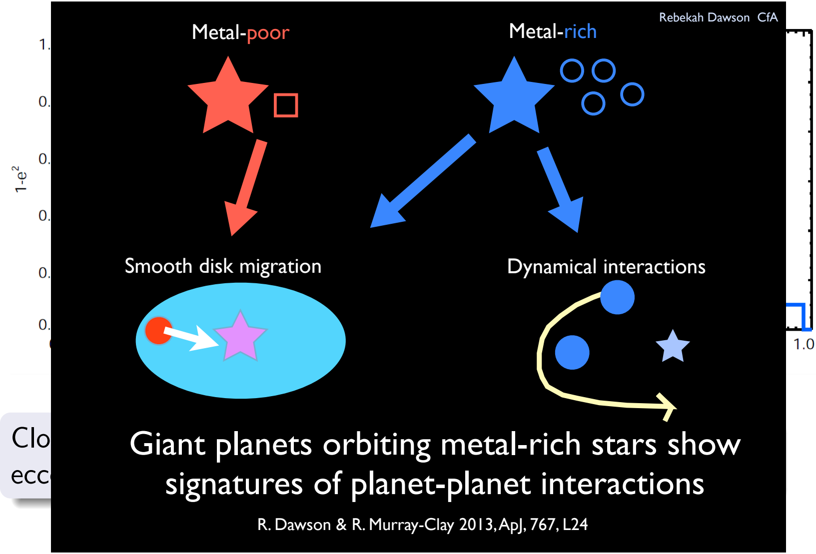
Outline

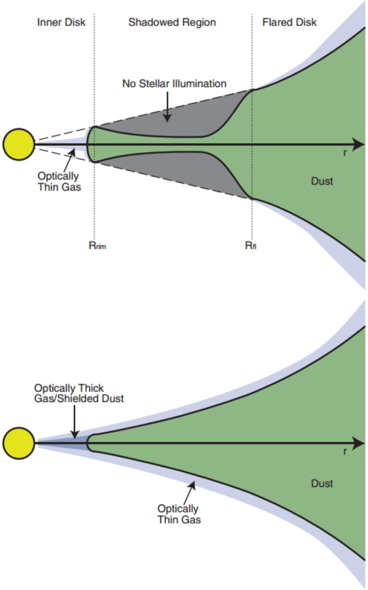
Dawson & Murray-Clay (2013)



Close-in giant planets orbiting metal-poor stars have lower eccentricities than those orbiting metal-rich stars.

Dawson & Murray-Clay (2013)



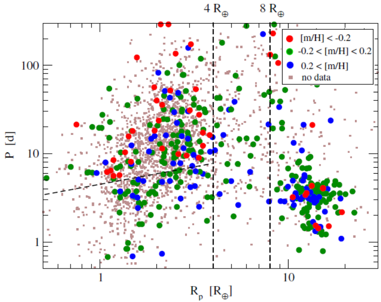


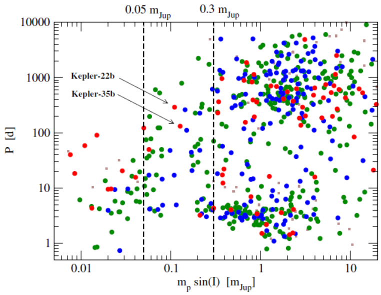
Tsang, Turner, & Cumming 2014

In the shadowed region (0.1 - 1 AU), lack of gap insolation allows disk interactions to damp eccentricity.

Outside such shadowed regions stellar illumination can heat the planetary gaps and drive eccentricity growth for giant planets.

Beaugé & Nesvorniý (2013)





- A lack of R $\lesssim 4R_\oplus$ planets with periods P $<$ 5 days around metal-poor stars
- A paucity of sub-Jovian planets around metal-poor stars with P $<$ 100 days

Small planets around metal-poor stars do not migrate far
Disk migration?

SWEET-Cat: a catalog of stellar parameters for stars with planets

SWEET-Cat: a catalog of stellar parameters for stars with planets

SWEET-Cat is a catalogue of stellar parameters for stars with planets listed in the Extrasolar Planets Encyclopaedia. It compiles sets of atmospheric parameters previously published in the literature (including Teff, logg, and [Fe/H]) and, whenever possible, derived using the same uniform methodology (see e.g. Santos et al. 2004; Sousa et al. 2008).

The catalog is described in Santos et al. 2013. However, it is continuously being updated as new planets are announced and new stellar parameters derived. If major changes occur concerning the structure of the catalog they will be described here or in a subsequent paper.

SWEET-Cat is built from literature data, either published or to be published soon. Although we do not encourage, we understand that for simplicity the user may wish to cite only the catalog presentation paper if using it in a statistical way. However, we strongly encourage the user to give the propper credit to the original source of stellar parameters.

(click on any specific header to sort, a detailed description of each field can be found here)

Download Data

Name	HD number	RA	Dec	Vmag	σ(Vmag)	π	σ(π)	Source of π	Teff	σ(Teff)	logg	σ(logg)	LC logg	σ(LC logg)	Vt	σ(Vt)	[Fe/H]	σ([Fe/H])	Mass	σ(Mass)	Reference	Homogeneity flag	Last Update	Comments
11 Com	107383	12 20 43.02	+17 47 34.33	4.74	0.02	11.25	0.22	Simbad	4830	79	2.61	0.13	-	-	1.70	0.10	-0.34	0.06	2.00	0.29	Mortier et al. 2013b	1	2013-08-01	-
11 UMi	136726	15 17 05.88	+71 49 26.04	5.02	-	8.19	0.19	Simbad	4340	70	1.60	0.15	-	-	1.60	0.80	0.04	0.04	1.80	0.25	Dollinger et al. 2009	0	2013-02-26	-
42 Dra	170693	18 25 59.13	+65 33 48.52	4.83	-	10.36	0.20	Simbad	4513	100	2.24	0.10	-	-	1.59	0.30	-0.39	0.12	1.74	-	Luck & Heiter 2007	0	2013-02-26	-
47 Uma	95128	10 59 27.97	+40 25 48.92	5.04	0.05	71.11	0.25	Simbad	5954	25	4.44	0.10	-	-	1.30	0.04	0.06	0.03	1.04	0.08	Santos et al. 2004	1	2013-02-26	-
51 Peg	217014	22 57 27.98	+20 46 07.79	5.46	0.05	64.07	0.38	Simbad	5804	36	4.42	0.07	-	-	1.20	0.05	0.20	0.05	1.04	0.08	Santos et al. 2004	1	2013-02-26	-
55 Cnc	75732	08 52 35.81	+28 19 50.95	5.95	0.05	81.03	0.75	Simbad	5279	62	4.37	0.18	-	-	0.98	0.07	0.33	0.07	0.93	0.09	Santos et al. 2004	1	2013-02-26	-
6 Lyn	45410	06 30 47.10	+58 09 45.48	5.88	-	17.92	0.47	Simbad	4978	18	3.16	0.05	-	-	1.10	0.07	-0.13	0.02	1.70	0.20	Sato et al. 2008	0	2013-02-26	-
61 Vir	115617	13 18 24.31	-18 18 40.30	4.74	0.01	99.99	0.22	Simbad	5577	33	4.34	0.11	-	-	1.07	0.04	0.01	0.05	0.94	0.08	Santos et al. 2005	1	2013-02-26	-

Homogeneous stellar parameters. Santos et al. 2013

- Over 65% of all planet host stars known
- More than 90% of all stars with RV-detected planets

P-M_P diagram and [Fe/H] with SWEET-Cat

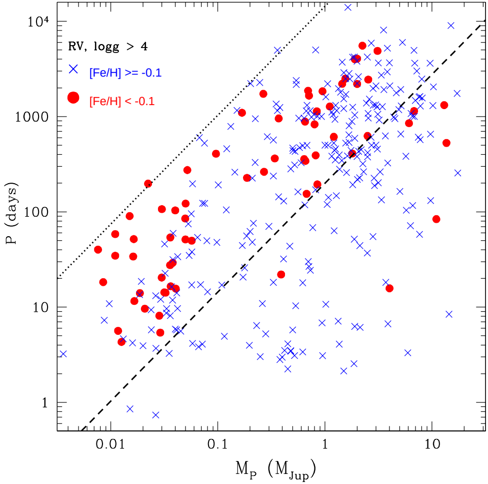


Figure: P-M_P from Adibekyan et al. 2013.

Planets around metal-poor stars

Have longer periods than planets around metal-rich stars ($\approx 10 M_\oplus < M_P < \approx 4 M_{Jup}$).

- Form farther out
- Form later and do not have time to migrate far

Giant planets show long periods (>100 days)

- Migration is less rapid than assumed

P-M_P diagram and [Fe/H] with SWEET-Cat: Earth-like planets

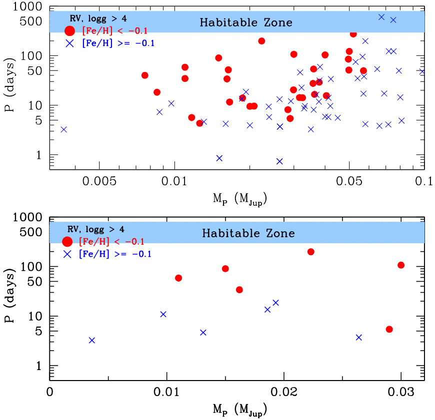


Figure: P-M_P from Adibekyan et al. 2013, modified.

No metal-rich planet with long period

Detection bias?

If not, then

- Metal-rich systems ordinarily migrate
- Always form close to their parent stars (Is there enough material?)

Habitable planets should be more common around metal-poor stars?

Different Formation Mechanisms for Hot versus Warm Super-Earths?

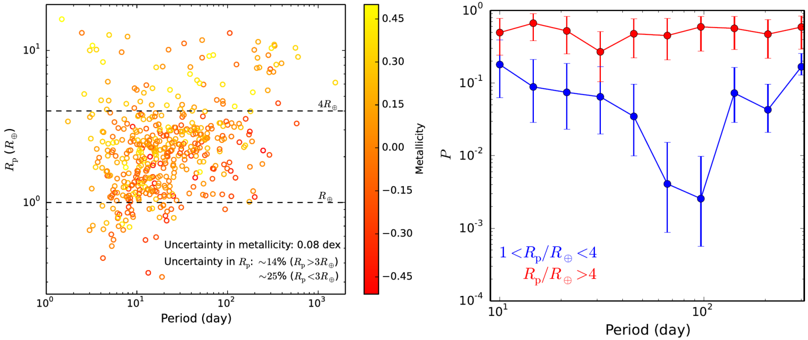


Figure: Zhu 2015.

Short- and long-period super-Earths show different dependence on the host metallicity: transition at 70-100 days.

Outline

Conclusion

Metallicity and planet formation and evolution

Metallicity is an important factor for planet formation and evolution

- Elements other than iron are also important for planet formation
  Are all the elements equally important?
- Even low-mass/small-size planets need metals to form
  Which metals do they need?
- Orbital parameters may depend on the metallicity (directly or indirectly)
  Imposes new constraints in the models


ありがとう