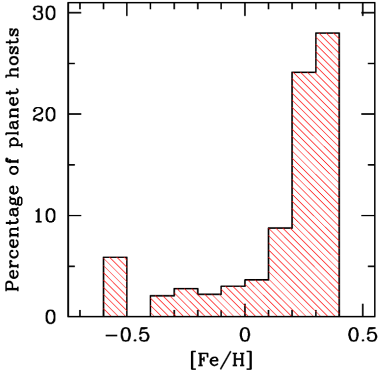
Star-planet connection:
The role of stellar metallicity

Vardan Adibekyan
Centro de Astrofísica da Universidade do Porto
Instituto de Astrofísica e Ciências do Espaço

18 September 2014
Porto, Portugal

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).



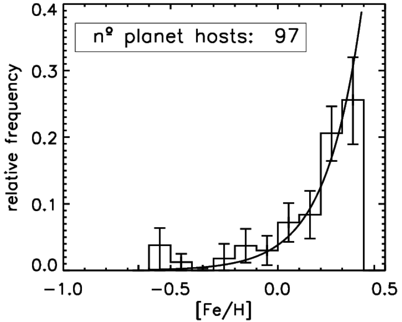
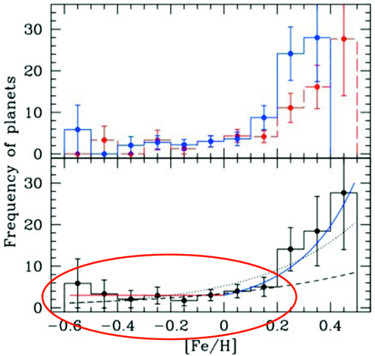


Figure: From Santos et al. 2004 (*left*) and from Sousa et al. 2011 (*right*).

Giant planets - metallicity: the functional form

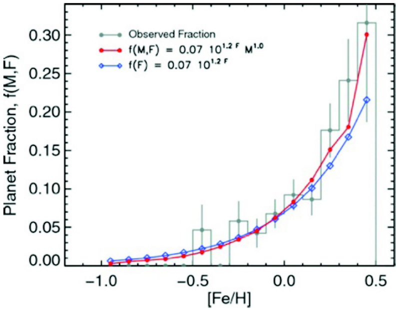
Is the planet formation mechanism the same at low and high metallicities?

A flat tail for low metallicities?



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

A simple power-law?

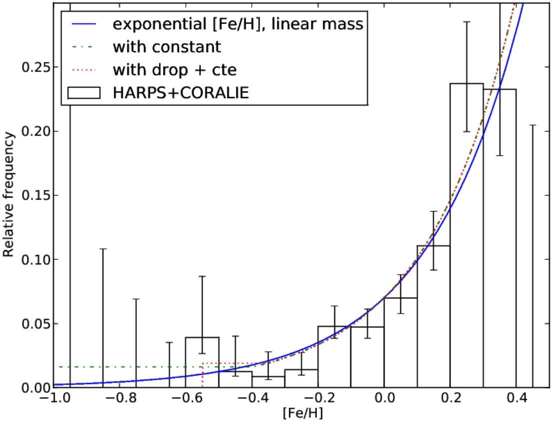


Johnson et al. (2010)

Giant planets - metallicity: the functional form

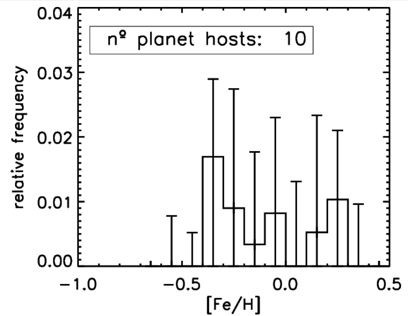
Bayesian analysis with different functional forms

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



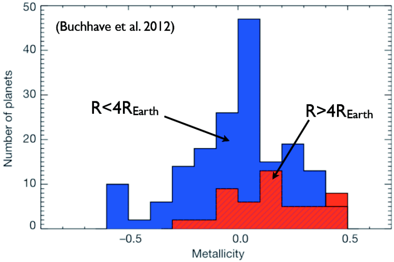


Figure: From Sousa et al. 2011 (*left*) and from Buchhave et al. 2012 (*right*).

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

No correlation found ONLY for planets with $R_P < 2R_E$

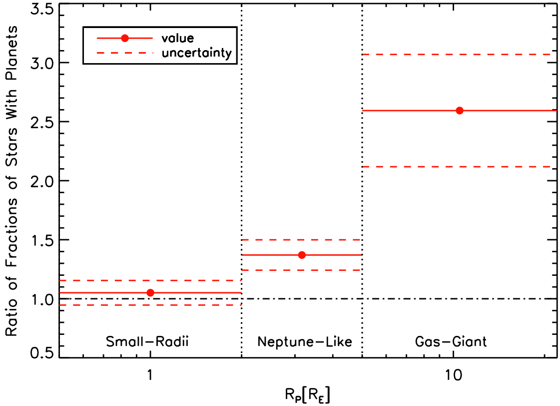


Figure: Wang & Fischer 2013

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

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

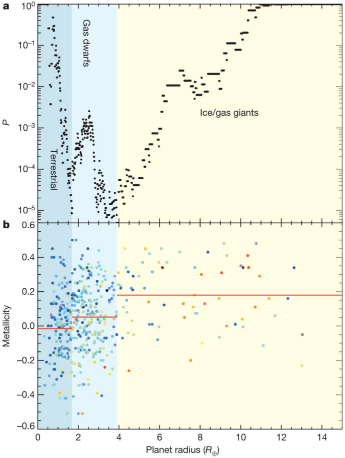


Figure: Buchhave et al. 2014

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

Evolved stars with giant planets

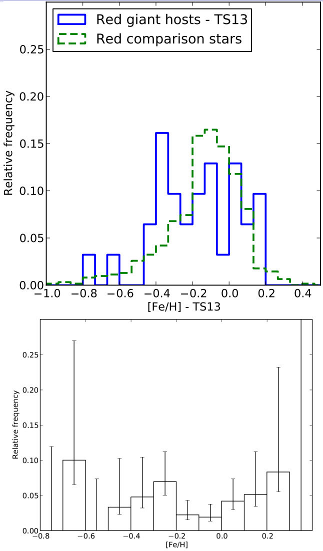


Figure: Mortier et al. 2013b.

No metallicity correlation?

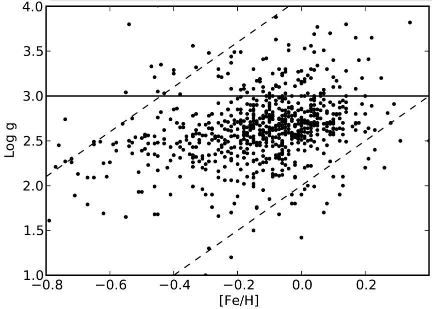
- Evidence for planet engulfment? (Pasquini et al. 2007)
- A mass effect? (Ghezzi et al. 2010)
- A spectroscopic analysis issue? (Hekker & Meléndez 2007; Santos et al. 2009)

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

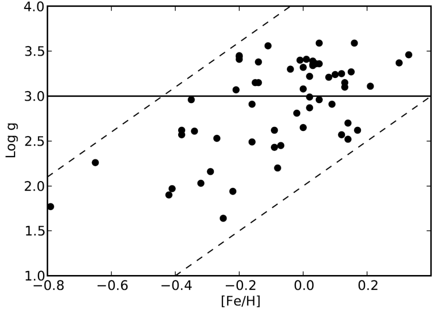
Evolved stars with giant planets

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

Are stars with planets chemically different?

Iron content is usually used as a proxy of overall metalliciy. What about other elements?

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

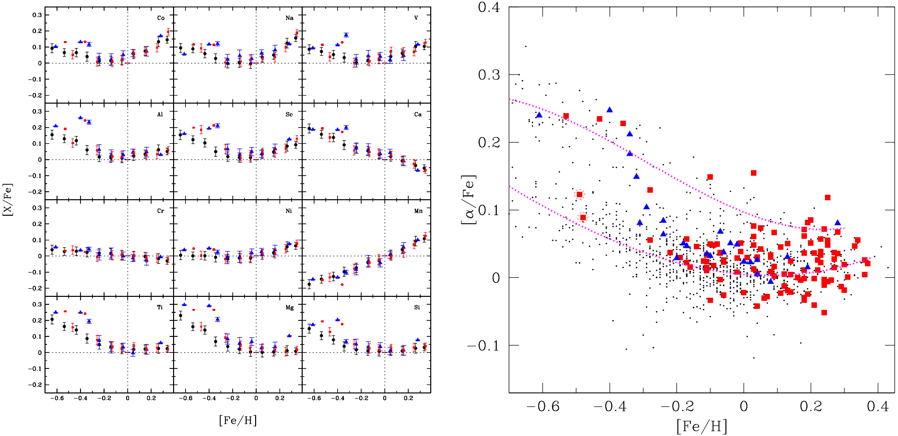


Figure: [X/Fe] vs. [Fe/H] for HARPS sample. Adibekyan et al. 2012a.

Element enhancement of planet hosts

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

α-elements

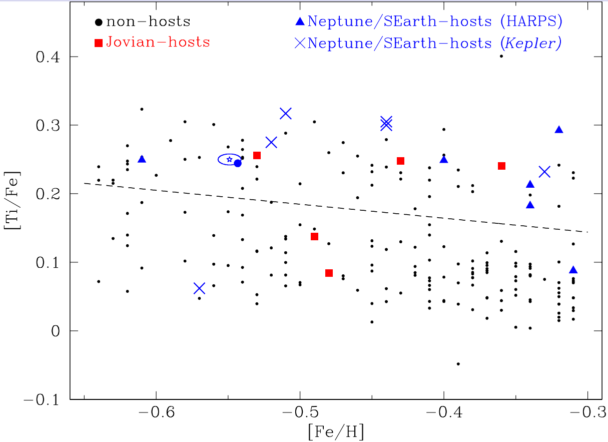


Figure: HARPS + Kepler samples. Adibekyan et al. 2012b.

α-elements

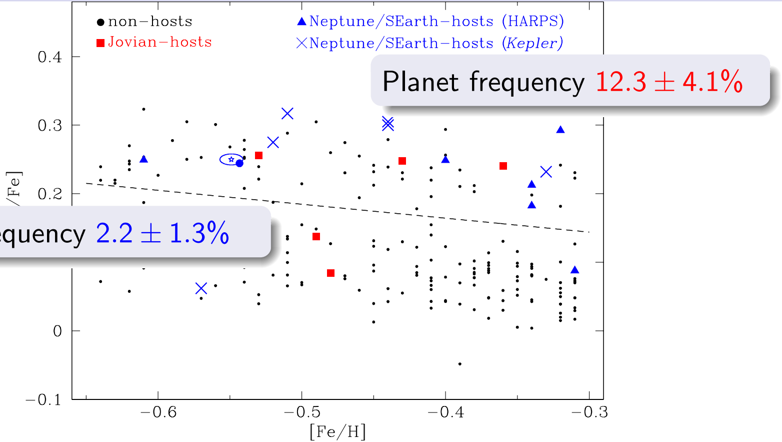


Figure: HARPS + Kepler samples. Adibekyan et al. 2012b.

α-elements

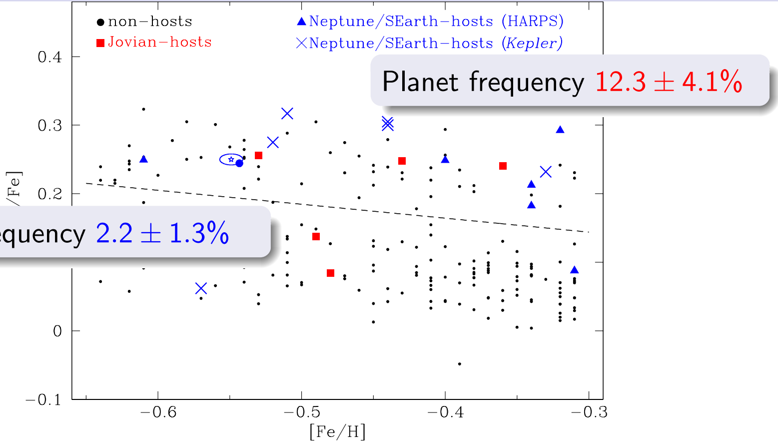


Figure: HARPS + Kepler samples. Adibekyan et al. 2012b.

- In the iron-poor regime other metals are critical for planet formation
- Even (especially?) for low-mass planet formation.

[Fe/H] $\neq$ [M/H] at low-iron regime: Galactic chemical evolution

Planet frequency and [Ref] index

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

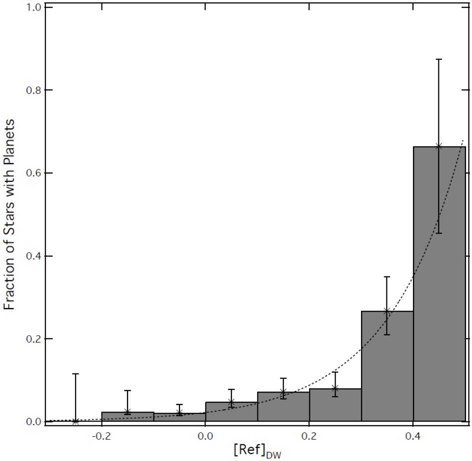
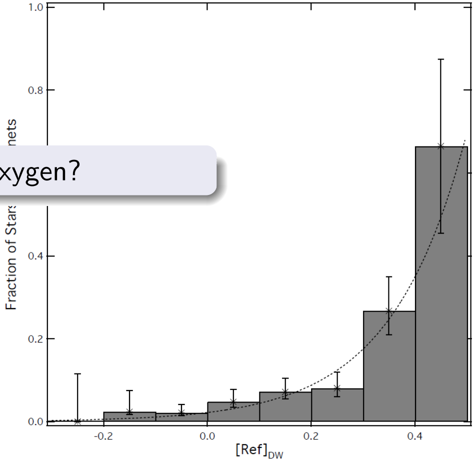


Figure: Gonzalez 2014.

Planet frequency and [Ref] index

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



What about oxygen?

Figure: Gonzalez 2014.

Are all the chemical peculiarities observed in planet host stars related to planet formation?

Lithium: star-planet connection is bidirectional

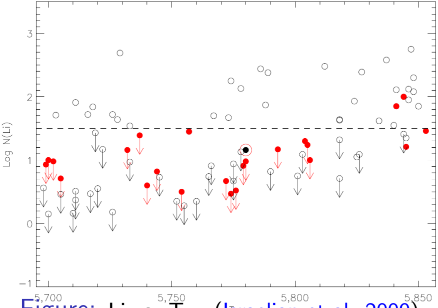


Figure: Li vs. T_{eff} (Israelian et al. 2009).

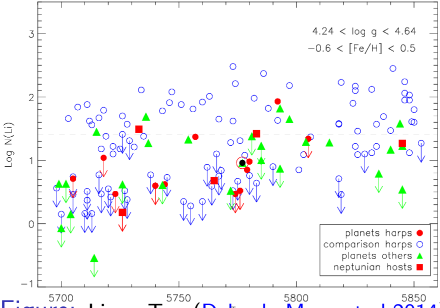


Figure: Li vs. T_{eff} (Delgado Mena et al 2014).

Stars that host planets are mostly Li-depleted

- The presence of a planet (planetary disc) may produce extra mixing
- An extra Li depletion through violent accretion-burst episodes of planetary material

Lithium: star-planet connection is bidirectional

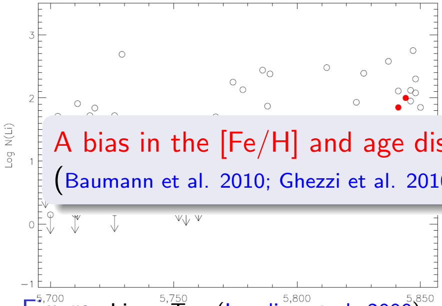


Figure: Li vs. T_{eff} (Israelian et al. 2009).

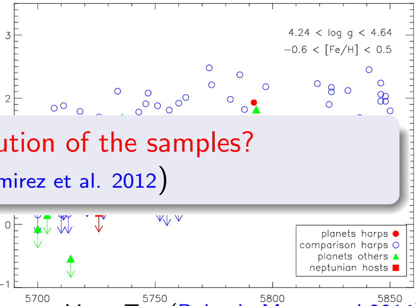


Figure: Li vs. T_{eff} (Delgado Mena et al 2014).

A bias in the [Fe/H] and age distribution of the samples?
(Baumann et al. 2010; Ghezzi et al. 2010; Ramirez et al. 2012)

Stars that host planets are mostly Li-depleted

- The presence of a planet (planetary disc) may produce extra mixing
- An extra Li depletion through violent accretion-burst episodes of planetary material

Lithium: star-planet connection is bidirectional

Figure: Li vs. T_{eff} (Israelian et al. 2009).

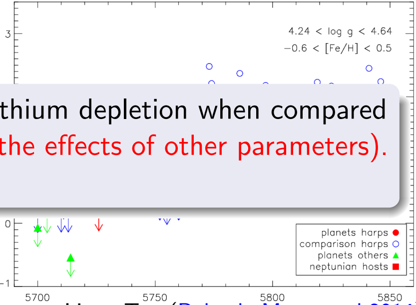


Figure: Li vs. T_{eff} (Delgado Mena et al 2014).

Planet-host stars exhibit enhanced lithium depletion when compared with non-host stars (after removing the effects of other parameters). (Figueira et al. 2014)

Stars that host planets are mostly Li-depleted

- The presence of a planet (planetary disc) may produce extra mixing
- An extra Li depletion through violent accretion-burst episodes of planetary material

Condensation temperature trends and planets

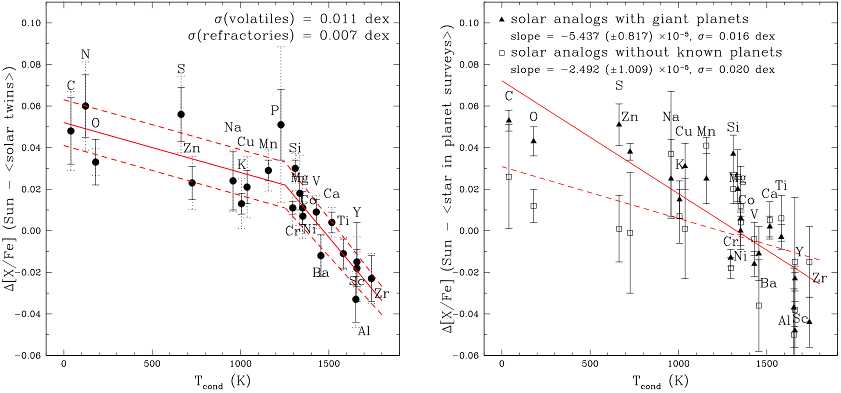


Figure: From Melendéz et al. 2009.

Anomalous volatile-to-refractory ratio of the Sun compared to solar twins.

Refractories remained in rocky planets (Ramirez et al. 2009,2010).

Condensation temperature trends and planets

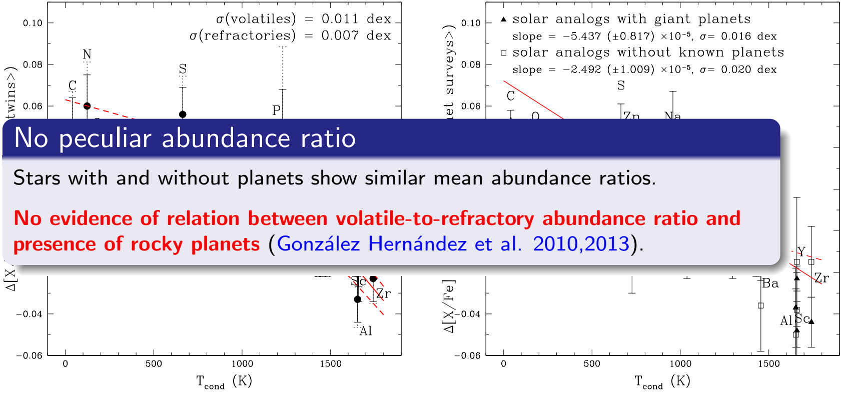


Figure: From Meleńdez et al. 2009.

No peculiar abundance ratio

Stars with and without planets show similar mean abundance ratios.

No evidence of relation between volatile-to-refractory abundance ratio and presence of rocky planets (González Hernández et al. 2010,2013).

Anomalous volatile-to-refractory ratio of the Sun compared to solar twins.

Refractories remained in rocky planets (Ramirez et al. 2009,2010).

Tc slope and stellar age

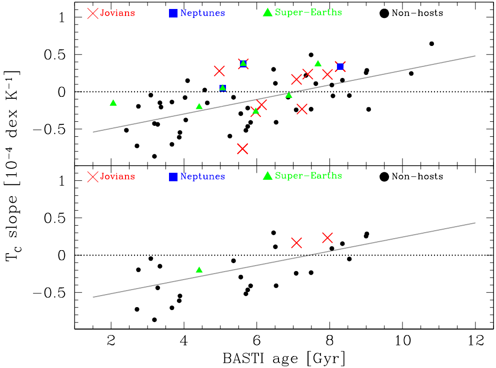


Figure: Tc slope vs. stellar age. Adibekyan et al. 2014.

Tc slope strongly correlates with the stellar age: Older stars show lower refractory-to-volatile ratio.
Most planet hosts are “old“

Same trend is seen with galactic birth radius: Stars with smaller Rmean show larger Tc slopes.
Most planet hosts have “smaller“ Rmean

Tc slope and stellar age

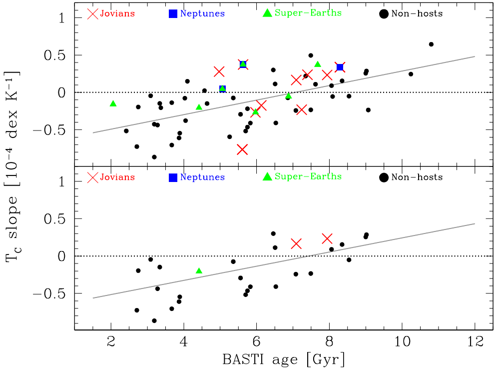


Figure: Tc slope vs. stellar age. Adibekyan et al. 2014.

Tc slope strongly correlates with the stellar age: Older stars show lower refractory-to-volatile ratio.
Most planet hosts are "old"

Same trend is seen with galactic birth radius: Stars with smaller Rmean show larger Tc slopes.
Most planet hosts have "smaller" Rmean

Galactic birth place and age are determinant to establish Tc slopes.
Tc slope trends: no direct relation with presence of planets?

Planet architecture and metallicity...

Metallicity in the mass-period diagram

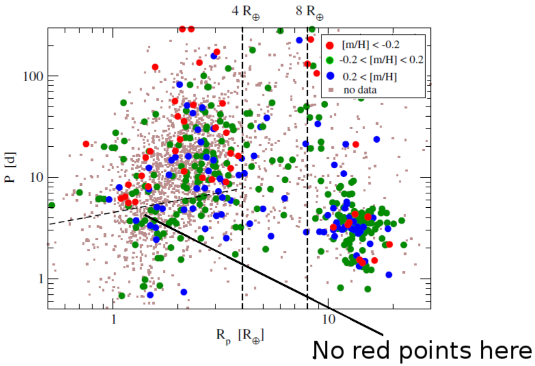


Figure: Beaugé & Nesvorniý (2013)

Kepler data:
A lack of R $\lesssim 4R_\oplus$ planets with periods P $<$ 5 days around metal-poor stars

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

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

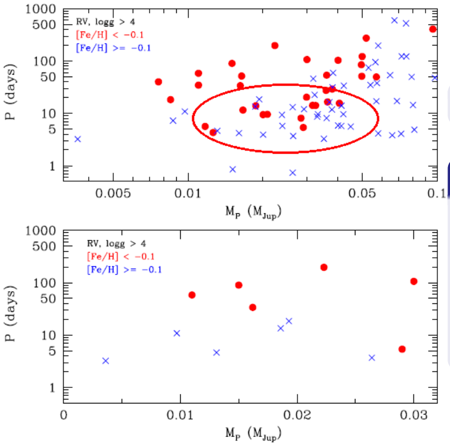


Figure: P-M_P from Adibekyan et al. 2013.

RV and Transit: Contradiction

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?)

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

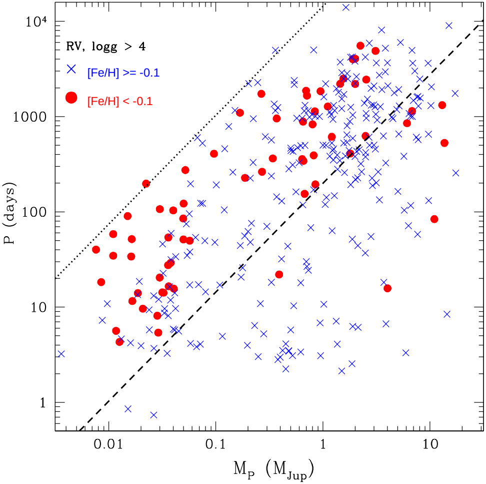


Figure: P-M_P from Adibekyan et al. 2013.

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

Orbital eccentricity and metallicity

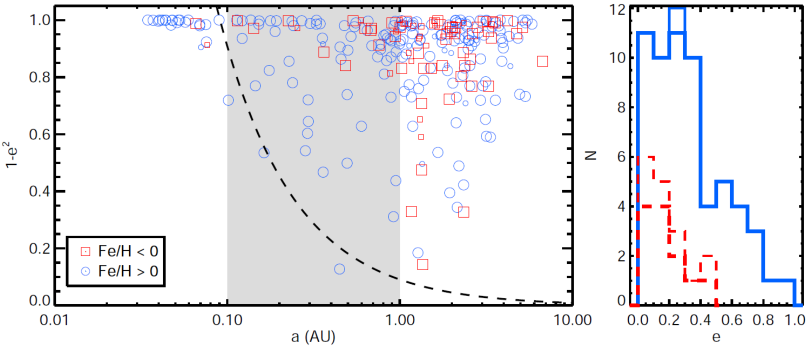


Figure: Dawson & Murray-Clay (2013)

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

Orbital eccentricity and metallicity

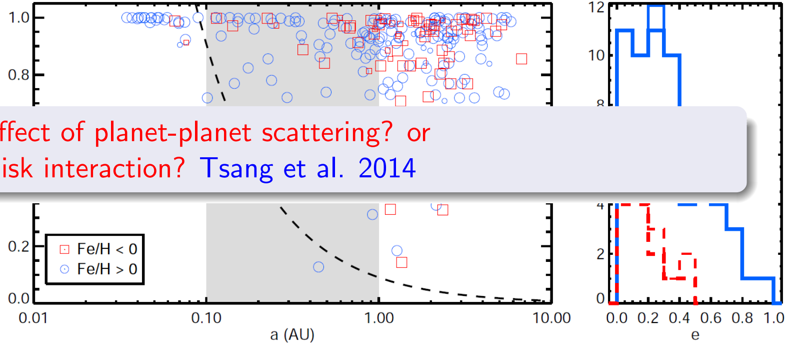


Figure: Dawson & Murray-Clay (2013)

Effect of planet-planet scattering? or
Disk interaction? Tsang et al. 2014

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

Conclusion

Metallicity and planet formation

Metallicity is an important factor for planet formation

- 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?

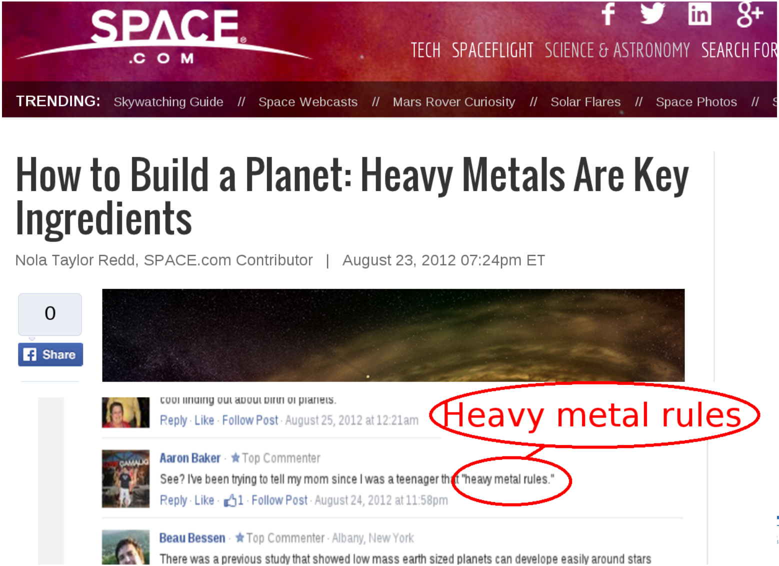
Metallicity and planet evolution

- Metallicity also influences planet architecture
  Imposes new constraints in the models

Centro de Astrofísica da Universidade do Porto

FCT Fundação para a Ciência e a Tecnologia

Summarized conclusion



Questions?

Thank you!