Star-planet connection: 
The role of stellar metallicity

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1. Planet formation and metallicity
   - Giant planets
   - Low-mass planets
   - Planets around evolved stars

2. Planet formation: Importance of other elements
   - Heavy elements in the metal-poor regime
   - Chemical peculiarities and planets

3. Planet architecture and metallicity
   - Metallicity in the mass-period diagram
   - Orbital eccentricity and metallicity

4. Conclusion
**Giant planets**


![Figure](http://example.com/figure.png)

**Figure:** From Santos et al. 2004 (left) and from Sousa et al. 2011 (right).
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
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 1.7\( R_E \) and 3.9\( R_E \)

Metallicity controls the structure of planetary systems.

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<th>Small-size planets: Boundary at ( \sim 2R_E )?</th>
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<td>Three distinct populations of planets with different metallicities.</td>
<td>( R_P &lt; 1.7R_E ) - terrestrial-like planets</td>
<td>( 1.7R_E &lt; R_P &lt; 3.9R_E ) - gas dwarf planets with rocky cores</td>
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<tr>
<td>( R_P &gt; 3.9R_E ) - ice or gas giant planets</td>
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*Figure: Buchhave et al. 2014*
Evolved stars with giant planets

No metallicity correlation?

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

There is a correlation after all? \((\text{Quirrenbach et al. 2011})\)

Figure: Mortier et al. 2013b.
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.


Giant planet hosts
Are stars with planets chemically different?

Iron content is usually used as a proxy of overall metallicity. 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
Planet formation and metallicity

Other elements

P-M and [Fe/H]

Conclusion

$\alpha$-elements

Figure: HARPS + Kepler samples. Adibekyan et al. 2012b.
Planet formation and metallicity

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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] ≠ [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. $T_{\text{eff}}$ (Israelian et al. 2009).

Figure: Li vs. $T_{\text{eff}}$ (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

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

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

The presence of a planet (planetary disc) may produce extra mixing

An extra Li depletion through violent accretion-burst episodes of planetary material

Stars that host planets are mostly Li-depleted
Anomalous volatile-to-refractory ratio of the Sun compared to solar twins. **Refractories remained in rocky planets** (Ramirez et al. 2009, 2010).
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).

Figure: From Melendez et al. 2009.
**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?
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Figure: Tc slope vs. stellar age. Adibekyan et al. 2014.

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Planet formation and metallicity

Other elements

P-M and [Fe/H]

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Planet architecture and metallicity...
Metallicity in the mass-period diagram

**Figure**: Beaugé & Nesvorníy (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$_{\text{P}}$ diagram and [Fe/H] with SWEET-Cat**

**Planets around metal-poor stars**

Have longer periods than planets around metal-rich stars ($\approx10M_\oplus < M_P < \approx4M_{\text{Jup}}$).

- 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

**Figure:** P-M$_{\text{P}}$ from Adibekyan et al. 2013.
Close-in giant planets orbiting metal-poor stars have lower eccentricities than those orbiting metal-rich stars.
Close-in giant planets orbiting metal-poor stars have lower eccentricities than those orbiting metal-rich stars.

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

Figure: Dawson & Murray-Clay (2013)
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
How to Build a Planet: Heavy Metals Are Key Ingredients

Nola Taylor Redd, SPACE.com Contributor  |  August 23, 2012 07:24pm ET

Heavy metal rules

See? I've been trying to tell my mom since I was a teenager that "heavy metal rules."

There was a previous study that showed low mass earth sized planets can develope easily around stars
Questions?

Thank you!