Searching for signatures of planet formation in stars with circumstellar debris discs

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Outline

1. Introduction
2. Observations and analysis
3. Abundance trends
4. Discussion
5. Summary
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Debris discs: Signatures of planetesimals systems
Continuously produced by collisions of such solid bodies

Frequency around solar-type stars
- *Spitzer*: $\sim 16\%$ (e.g. Trilling et al. 2008)
- *Herschel*: $\sim 20\%$ (DUNES sample)

Planets frequency
- $> 50\%$ planets of any mass, period up to 100 days
- $14\%$ planets with $M_p > 50 \, M_\oplus$, period shorter than 10 years

*Herschel* view of the HD 207129 debris disc
(Marshall et al. 2011)
Debris and planets

Correlated phenomena?

Planetesimals are the “building blocks” of planets ⇒ Do their host stars have similar properties?

| Discs                                                                 |
|----------------------------------------------------------------------|
| Incidence no higher around planet-host stars                        |
| No correlation with stellar properties                              |
| (e.g. Bryden et al. 2009, Kóspál et al. 2009)                       |

| Planets                                                              |
|----------------------------------------------------------------------|
| Trend of ↑ [Fe/H] of stars hosting gas-giant planets                |
| Low-mass planets $M_p < 30 M_⊕$ do not follow this trend            |
| Puzzling results in evolved stars hosting planets (e.g. Maldonado et al. 2013) |

Low-mass planets: a major challenge

- ∼ 55% more SWDPs w.r.t. previous works
- Debris discs and low-mass planets: “Good neighbours?”
  (e.g. Maldonado et al. 2012, Wyatt et al. 2012, Marshall et al. 2014)
- “Fingerprints” of terrestrial planet formation in the stellar photospheric abundances?
  (e.g. Meléndez et al. 2009; Ramírez et al. 2009, 2010, 2014)
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In this study:

Chemical abundances of four samples of solar-like stars

1. Stars with known debris discs (SWDs)
   IRAS, ISO, Spitzer, Herschel data (68 stars)

2. Stars with known debris discs and planets (SWDPs)
   $\sim 55\%$ more SWDPs w.r.t. previous works (31 stars)

3. Stars with known planets (SWPs)
   Stars hosting gas-giant/low-mass planets (32 stars)

4. Comparison sample (SWODs)
   No IR-excess found at Spitzer/Herschel’s $\lambda$s (119)
**Telescopes and instruments**

- **FOCES** 2.20 m  
  Calar Alto  
- **SARG-TNG** 3.56 m  
  La Palma  
- **FIES-NOT** 2.56 m  
  La Palma  
- **HERMES-MERCATOR** 1.2 m  
  (La Palma)  
- **+ Public Archives**  
  S$^4$N  
  ESO-Archive

**IRAF-echelle package**

- overscan, flat-fielding, scattered light, blazeshape removing, order extraction, wavelength calibration

Example of FOCES spectra in the H$_\alpha$ region  
(Maldonado et al. 2010)
Stellar parameters

- Code TGVIT (Takeda et al. 2005)
- Iron ionisation and excitation conditions, match of the curve of growth
- 302 Fe I and 28 Fe II lines
- EWs measurements using ARES (Sousa et al. 2007)
- ATLAS9, plane-parallel, LTE (Kurucz 1993)
- Statistical uncertainties from the converged solution

Elemental abundances

- C, O, Na, Mg, Al, Si, S, Ca, Sc, Ti I, Ti II, V, Cr I, Cr II, Mn, Co, Ni, Cu, Zn
- MOOG program + ATLAS9 model atmospheres
- HFS: V, C, Cu
- Oxygen: nLTE
- Line list mainly from Neves et al. 2009, Ramírez et al. 2014
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Transition towards higher $[\text{Fe/H}]$

**SWODs $\Rightarrow$ SWPs**

**Results**
- SWDs similar to SWODs
- SWDPs behave as SWPs (no matter the planet's mass)
- Hot-giant hosts tend to be more metal-rich than cool-giant hosts

**31 solar-like SWDPs:**
- 47% multiplanet systems, 6 stars with low-mass planets
- 8 stars host at least one low mass planet
- 2/24 SWDPs hosting only gas giant planets, host “hot”-Jupiters ($a < 0.1$ AU)
No obvious differences SWDs/SWODs

**Kolmogorov-Smirnov probabilities**

| [X/Fe] | p-value | [X/Fe] | p-value |
|--------|---------|--------|---------|
| C      | 0.30    | Ti     | 0.08    |
| O      | 0.96    | V      | 0.88    |
| Na     | 0.82    | Cr     | 0.56    |
| Mg     | 0.10    | Mn     | 0.91    |
| Al     | 0.55    | Co     | 0.83    |
| Si     | 0.63    | Ni     | 0.86    |
| S      | 0.25    | Cu     | <0.01   |
| Ca     | >0.99   | Zn     | 0.04    |
| Sc     | 0.80    |        |         |
Different behaviour $<[\text{X/Fe}]>-T_C$ slope in SWDPs

**All elements**

SWD/ SWODs: $-3.62$

SWD: $-1.89$

SWDPs: $1.14$

$T_c$ (K)
Abundances of volatiles not as reliable as refractories’ ones

Only $T_C > 900$ K

Slope change their signs, but still there is a difference in SWDPs wrt SWDs/SWODs
Comparison with planet hots (all elements)

- SWDPs behave as stars with planets
- Differences between stars with cool and low-mass planets
Comparison with planet hots (only refractories)

SWDPs behave as stars with planets
Differences between stars with cool and low-mass planets

Cool: $-0.75$
Debris+Cool: $-3.87$
Low-mass: $6.87$
Debris+Low: $4.17$
Hot: $14.36$
Debris+Hot: $-24.79$
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Previous analysis:

- **Meléndez et al. 2009**: Deficit of refractory in the Sun wrt other solar twins. Related to the formation of low-mass planets.

- **González Hernández et al. 2012, 2013; Adibekyan et al. 2014**: Galactic chemical evolution effects age/Galactic birth place explanation.
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In this work:

1. Similar behaviour SWDs/SWODs
2. Similar behaviour SWDPs/SWPs
3. No differences in stars with low-mass planets (wrt SWODs/SWDs)
4. Different behaviour in stars with cool-Jupiters
5. Positive slopes in stars with hot-Jupiters
**Previous analysis:**

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**Key questions:**

1. Might the $<[X/Fe]>-T_C$ trends be influenced by GCE effects?
2. Do the $<[X/Fe]>-T_C$ trends fit in the ME09 hypothesis?
Might the $<[X/Fe]>-T_C$ trends be influenced by GCE effects?

**Abundance patterns may be affected by GCE effects**

$T_C$ slope vs. $[\text{Fe/H}]$, age, and $R_{\text{mean}}$

![Graph showing $[X/Fe]$ vs $T_C$ slope vs $[\text{Fe/H}]$ and $T_C$ slope vs $[\text{Fe/H}]$ with correlation coefficients and significances.](image-url)
Might the $\langle X/Fe \rangle$-$T_C$ trends be influenced by GCE effects?

Abundance patterns may be affected by GCE effects

$T_C$ slope vs. $[\text{Fe/H}]$, age, and $R_{\text{mean}}$

| Factor   | Correlation |
|----------|-------------|
| $[\text{Fe/H}]$ | Moderate, significant |
| Age      | Weak, but significant |
| $R_{\text{mean}}$ | Not clear correlation |

GCE corrections

$[\text{X/H}]$ vs. $[\text{Fe/H}]$ linear fits
- Still correlations with the chromospheric age and the stellar radius remain
- Might this correction “delete” possible chemical depletions?
Do the $<[X/Fe]>-T_C$ trends fit in the ME09 hypothesis?

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Do the \([X/Fe]-T_C\) trends fit in the ME09 hypothesis?

1. Similar behaviour SWDs/SWODs
2. Similar behaviour SWDPs/SWPs
3. No differences in stars with low-mass planets (wrt SWODs/SWDS)

- Planet: key factor in revealing the chemical behaviour of the star
  - Consistent with core-accretion model of planet formation.

- Correlation between dust and low-mass planets?
  - Significant fraction of low-mass hosts among the SWDPs.
  - In agreement with recent results (e.g. Wyatt et al. 2012, Marshall et al. 2014)
Do the $<\text{[X/Fe]}>-T_C$ trends fit in the ME09 hypothesis?

- No differences in stars with low-mass planets (wrt SWODs/SWDs)
- Different behaviour in stars with cool-Jupiters
**3. No differences in stars with low-mass planets (wrt SWODs/SWDS)**

**4. Different behaviour in stars with cool-Jupiters**

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**Not in agreement with ME09**

**Low-mass planet hosts:** only \(<\) slopes for all elements, but similar to SWDs/SWODs

**Cool-Jupiter hosts:** differences in \(T^\text{all}_C\) and \(T^\text{ref}_C\); \(<\) slopes in \(T^\text{ref}_C\) analysis
Do the $<[X/Fe]>-T_C$ trends fit in the ME09 hypothesis?

3. No differences in stars with low-mass planets (wrt SWODs/SWDs)

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Not in agreement with ME09

Low-mass planet hosts: only $<$ slopes for all elements, but similar to SWDs/SWODs

Cool-Jupiter hosts: differences in $T_C^{all}$ and $T_C^{ref}$; $<$ slopes in $T_C^{ref}$ analysis

5. Positive slopes in stars with hot-Jupiters
Do the $\langle\text{X}/\text{Fe}\rangle$-$T_C$ trends fit in the ME09 hypothesis?

3. No differences in stars with low-mass planets (wrt SWODs/SWDs)

4. Different behaviour in stars with cool-Jupiters

- **Not in agreement with ME09**
  - **Low-mass planet hosts:** only $\text{<}$ slopes for all elements, but similar to SWDs/SWODs
  - **Cool-Jupiter hosts:** differences in $T_C^{\text{all}}$ and $T_C^{\text{ref}}$; $\text{<}$ slopes in $T_C^{\text{ref}}$ analysis

5. Positive slopes in stars with hot-Jupiters

- **Caution, small sample size!**
  - Also SWDs/SWODs show $\text{>}$ slopes in $T_C^{\text{ref}}$
  - Indication of non low-mass planets?
Signatures of pollution

[X/Fe]-T_C slope correlation: natural prediction of self-enrichment hypothesis

- **R_⋆**: proxy of the convective envelope size
  - **Early-type:** ↑ R_⋆, ↓ CZ
  - **Late-type:** ↓ R_⋆, ↑ CZ

- K-stars show larger negative slopes
  - But, only in T^all_C analysis
  - Against the pollution hypothesis
No apparent trends between disc/planet properties with $[X/Fe]$-$T_C$ slope

\[ \rho = -0.11 \]
\[ \text{prob.} = 0.23 \]
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Summary

Detailed chemical analysis of SWDs and SWDPs

- No differences SWDs/SWODs
- SWDPs driven by the type of planet
  - In agreement with core-accretion models
  - Correlation debris disc/low-mass planets?
  - Lack correlation debris discs/giant planets?
- Tentative $[X/\text{Fe}]-T_C$ trends in SWPs
  - Different behaviour in stars with cool-planets
  - Similar behaviour low-mass planets hosts / non-planets samples
  - Stars with hot Jupiters: higher $[\text{Fe}/\text{H}]$, positive slopes?
- Chemical depletions/Planet formation?
  - Low statistical significances
  - Correlation $T_C-[\text{Fe}/\text{H}]$
  - After GCE corrections: still correlations with age, radius
| Introduction | Observations and analysis | Abundance trends | Discussion | Summary |
|-------------|--------------------------|------------------|------------|---------|
|             |                          |                  |            |         |

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