Differential abundances in the HAT-P-4 binary system

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Why is important to study wide binary systems with similar components?

-Under the assumption both components formed in the same environment (from a common molecular cloud)
↳**Ideal laboratories to analyze the effect of planet formation on the stellar composition**

- Wide binary systems with similar components ---> **high-precision relative abundances**

Short list of binary systems (with similar components) hosting planets/disk:

Wide binaries with **planets around both components**:
- WASP-94 (Teske+ 2016)
- XO-2 (Ramírez+2014, Teske+ 2015)
- HD 20782/81 (Mack+ 2014)

Wide binaries with **planets around only one component**:
- HD 80606/7 (Saffe+ 2015)
- 16 Cygni (Ramírez+ 2011; Tucci Maia+ 2014)
- HAT-P-1 (Liu+ 2014)

Wide binaries with **debris-disk around only one component**:
- ζ^2 Ret (Saffe+ 2016)

It is key to study more of these systems!

The HAT-P-4 Binary System

Selected from **Mugrauer+ 2014:**

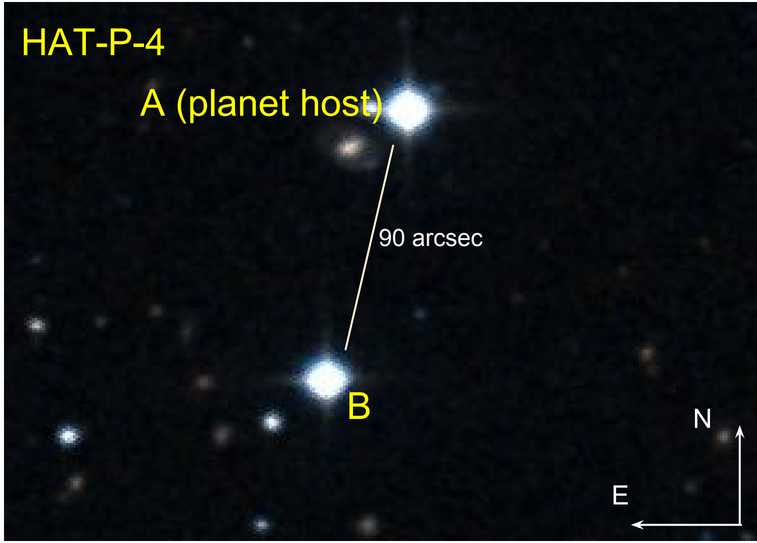
↪ detected seven new wide companions of exoplanet host stars based on proper motions and follow-up spectroscopy

Good candidate to perform a differential abundances analysis based on its characteristics:

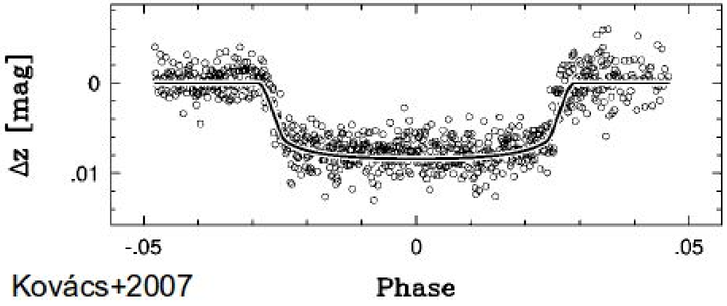
Component	Spectral Type	V mag
Primary (HAT-P-4 A)	G0 V	11.12
Secondary (HAT-P-4 B)	G2 V	11.38

Projected separation of ~28446 AU (Mugrauer+2014)

To date, **<u>no planets detected around HAT-P-4 B</u>**
(Also, monitored by the HATNet survey)



Hosts a giant short-period transiting planet:
(P=3.05 days; M_p=0.68 M_J ;R_p=1.27 R_J)



Kovács+2007

Observations

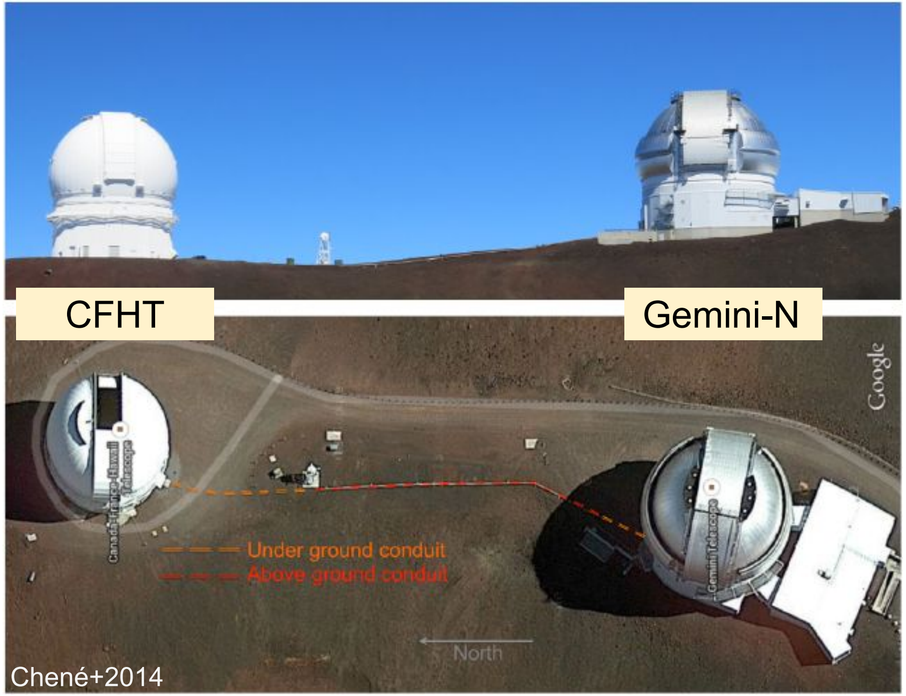
*See Jofré+2015 for more details (first GRACES' science paper)

GRACES (Gemini Remote Access to CFHT ESPaDOnS Spectrograph)*

Gemini North (8.1 m)

270 m fiber optics
(longest astronomical fiber ever made! Chené+2014)

ESPaDOnS (CFHT)



ESPaDOnS spectrograph

Observations

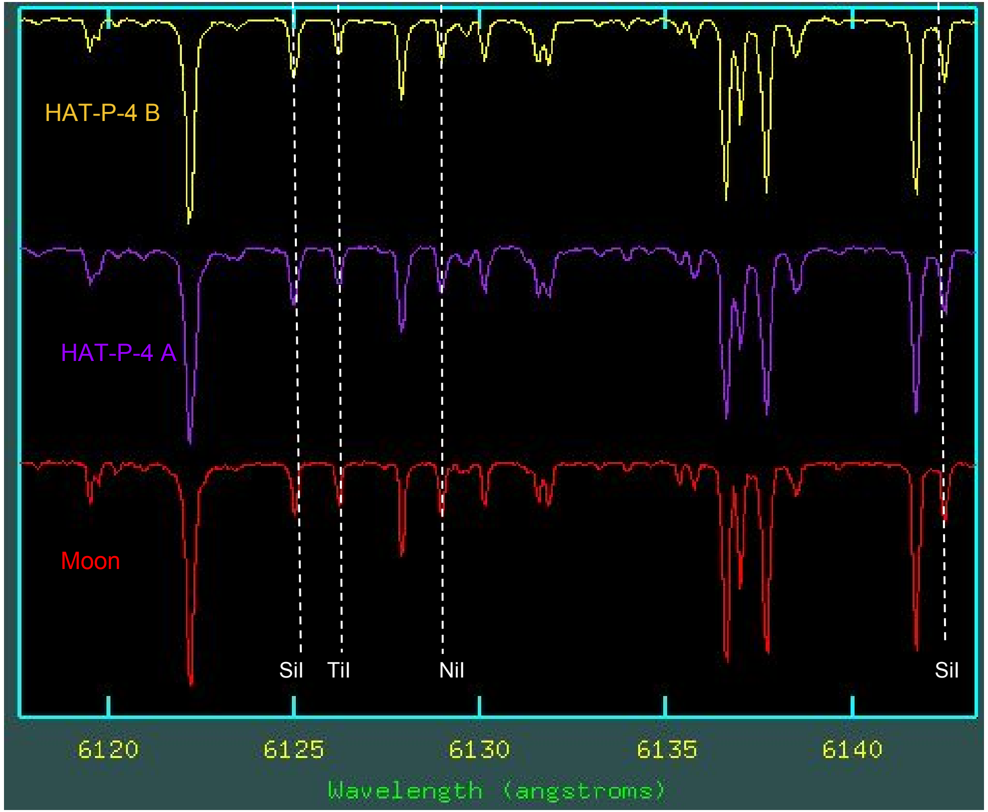
GRACES (Gemini Remote Access to CFHT ESPaDOnS Spectrograph)

Fast Turnaround observing mode (GN-2016A-FT-25, Argentinian time) on June 3, 2016
1-fiber (object only)
---> R~68000
---> wavelength coverage: 400 -- 1000 nm

Object	exptime	S/N (6000 Å) combined spectra
HAT-P-4 A	2 x 16 min	~400
HAT-P-4 B	2 x 18 min	~400
Moon	3 x 10 sec	~450

-Reduction
→ OPERA (Open-source Pipeline for ESPaDOnS Reduction and Analysis; Martioli +2012)* (See ESPECTRO webpage http://wiki/espectro)

-Doppler correction, spectra combination, normalization
→ IRAF



GRACES spectra spanning the wavelength range from ~6118 to 6145 A

Stellar parameters and chemical abundances analysis

Methodology:

1- Measurements of EWs of Fe I and Fe II lines and other chemical species ----> SPLOT (IRAF)

(Line list and laboratory data: Liu+2014; Meléndez+2014, and Bedell+2014)

2- Atmospheric parameters (T_{eff}, log g, [Fe/H], ξ) of HAT-P-4 A & B ---> excitation and ionization balance of Fe I and Fe II lines based on a **<u>line-by-line differential analysis</u>**:

I) A and B relative to the Sun (Teff = 5777 K, log g=4.44 dex, [Fe/H]=0, and vt = 1.00 km/s)

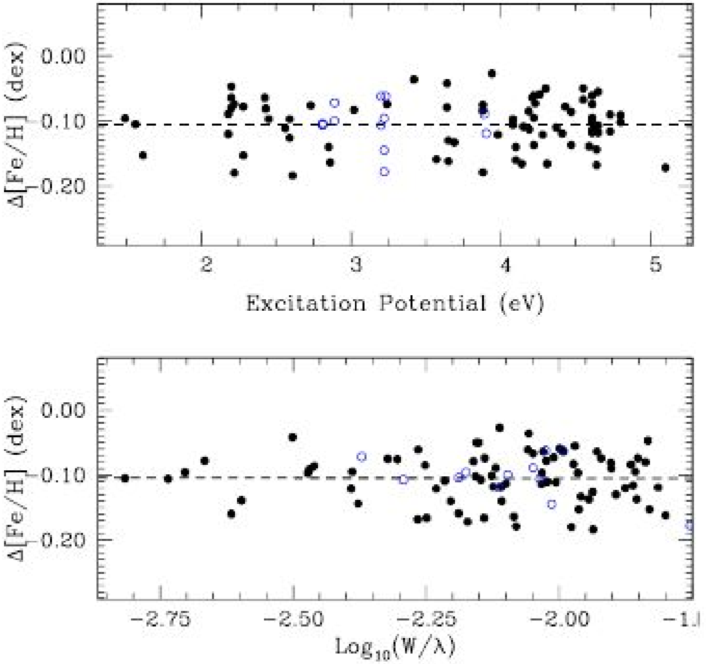
II) HAT-P-4 B relative to HAT-P-4 A

↳**FUNDPAR code** (differential version, Saffe+2015)

-MOOG (Sneden 1973)

-ATLAS9 model atmospheres (Kurucz 1993)

Example of balancing plot



Stellar parameters and chemical abundances analysis

Final atmospheric parameters

HAT-P-4 A Reference	T_{eff} (K)	log *g* (cgs)	[Fe/H]	ξ(km/s)
HAT-P-4 A	6036 ± 46	4.33 ± 0.10	0.277 ± 0.007	1.29 ± 0.07
HAT-P-4 B	6035 ± 36	4.39 ± 0.10	0.172 ± 0.006	1.22 ± 0.07
Δ(B-A)	1 ± 59	0.06 ± 0.19	**-0.105** ± 0.009	-0.07 ± 0.09

Parameters (T_{eff}, log g, ξ) of both components are very similar---> “twin stars”

HAT-P-4 A is more metal-rich than HAT-P-4 B by ~0.10 dex

Stellar parameters and chemical abundances analysis

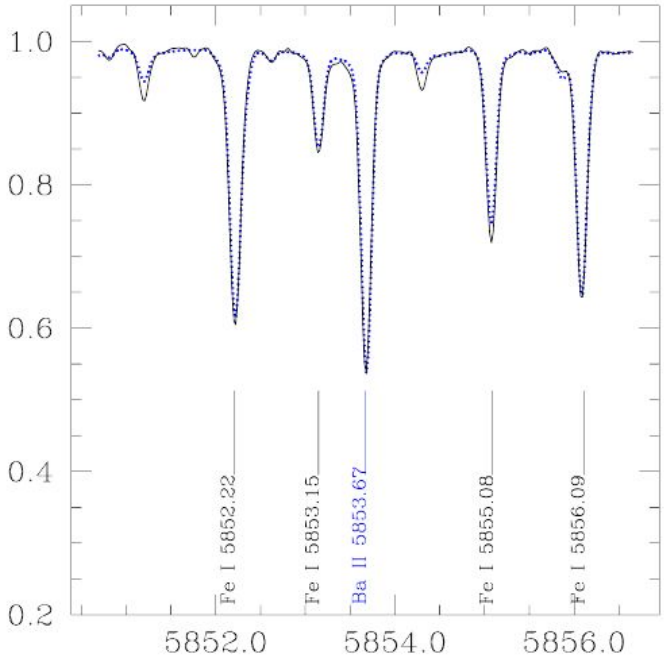
Elemental abundances for 20 elements:

- C, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, Cr, Ni, Sr, Y, Ce

↳Curve-of-growth analysis within MOOG from EWs

- V, Mn, Co, Cu, Ba, Li

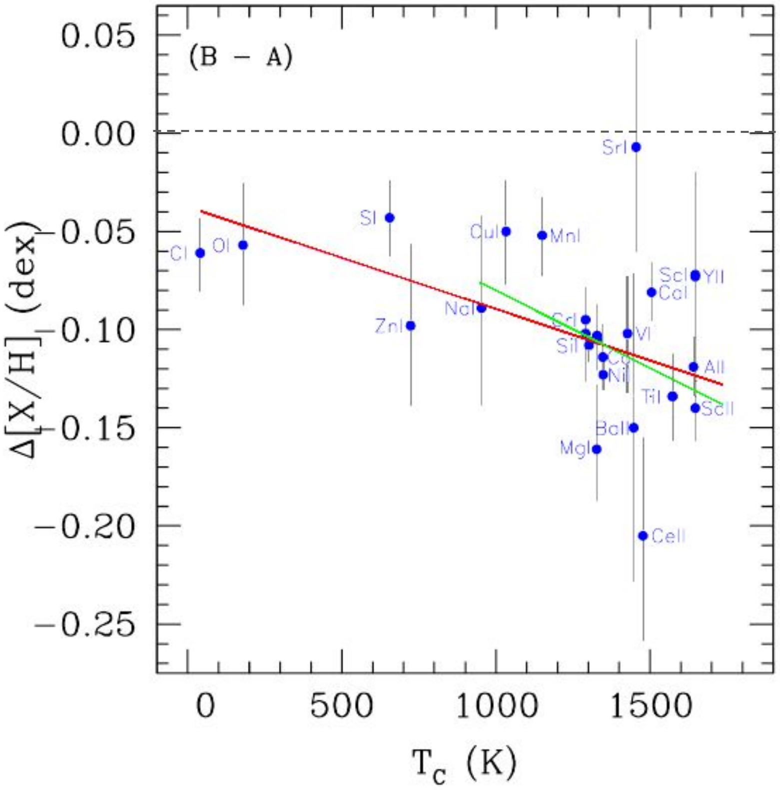
↳spectrum synthesis



The abundances were computed on a strictly **differential line-by-line basis** using both the Sun and the A star as reference

Results

Differential elemental abundances of HAT-P-4 B − HAT-P-4 A as function of dust condensation temperature (T_c)

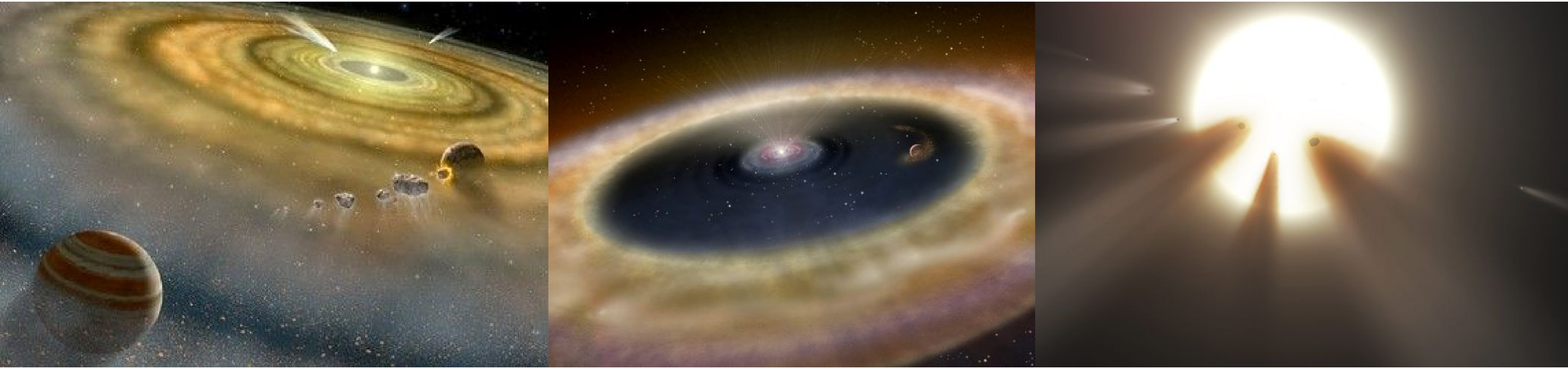


#Slopes:
-all elements: $(-5.18 \pm 1.15) \times 10^{-5}$ dex K^{-1}
-refractories: $(-7.81 \pm 2.61) \times 10^{-5}$ dex K^{-1}

Average differential (B−A) abundances:
$<\Delta[X/H]>_{refractories} = -0.105 \pm 0.007$ dex
$<\Delta[X/H]>_{volatiles} = -0.065 \pm 0.015$ dex

The primary star (planet host) is enhanced in refractory elements relative to volatiles when compared with the secondary (without planets)

Possible scenario: engulfment of rocky material in HAT-P-4 A

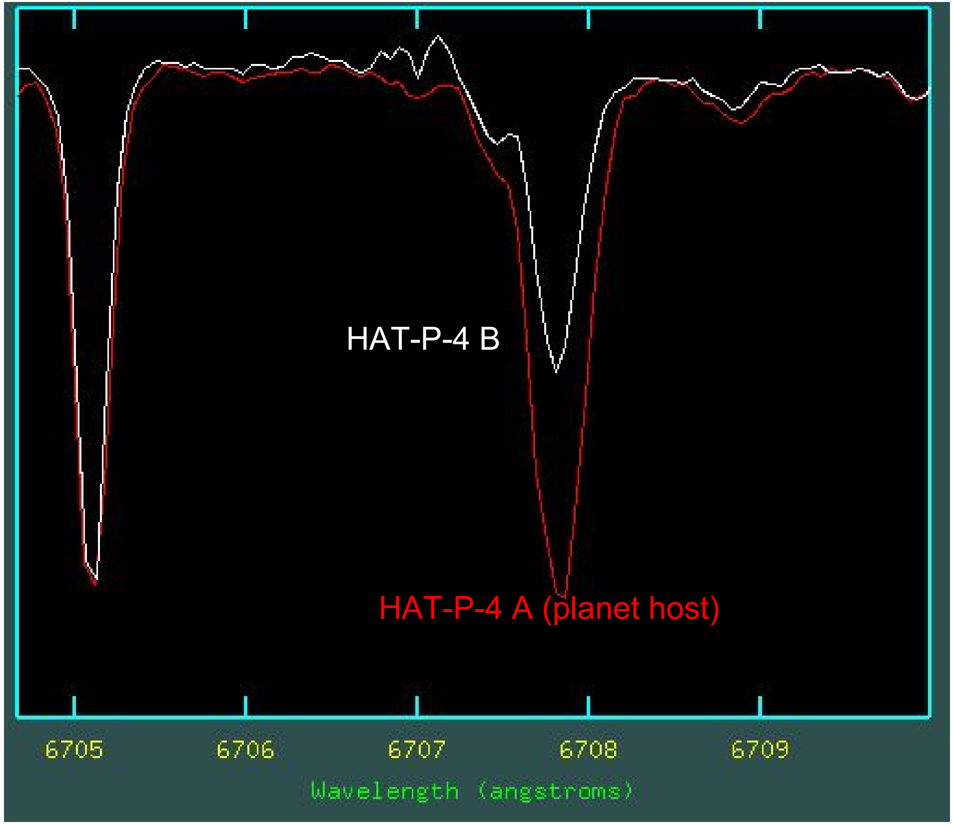


1- At the time of planet formation, the primary star locked refractory material in planetesimals and/or rocky planets, and also formed the gas giant in the external disk.

2- The migration of the giant planet from the external disk towards its current location could have triggered dynamical instabilities in the orbits of the rocky planets and/or planetesimals causing their ingestion into the convective zone of HAT-P-4 A and increasing the abundance of refractories.

A very similar scenario was recently proposed for the solar-twin star HIP 68468 (Meléndez+2017)

Lithium Abundances



The accretion scenario could be supported by the lithium abundances:

$A(Li)_{\text{HAT-P-4 A}} = 1.47 \pm 0.04$
$A(Li)_{\text{HAT-P-4 B}} = 1.17 \pm 0.06$

Lithium is clearly enhanced in HAT-P-4 A compared with the HAT-P-4 B by ~0.3 dex

However, the **slight difference in the stellar mass** between both components,
$M_A = 1.24 \pm 0.06\ M_\odot$ vs. $M_B = 1.17 \pm 0.04\ M_\odot$,
could also explain the difference in lithium

Summary

First high-precision differential abundances analysis of the **HAT-P-4 (A_{planet}+ $B_{no\text{-}planet}$) binary system** based on high-quality GRACES spectra

The planet host star (A) is more metal-rich than the B component by ~0.1 dex

HAT-P-4 A is enhanced in refractory relative to volatiles when compared to B
↳scenario: ingestion of rocky material during the migration of the detected transiting planet

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