Leveraging host star abundance ratios to constrain directly imaged planet formation and structure

UC San Diego Astronomy and Astrophysics

Lick Observatory

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Direct Imaging and Planet Formation:

- Application of high contrast imaging techniques to exoplanet research revealed a large population of Jovian planets (mass **~2–14 Mjup**) on wide orbits (**~ 9–120 AU**) (Bowler 2016). This is a unique planetary population whose formation is difficult to explain using current models.
- Planet formation and migration through a disk leads to differences in atmospheric metallicities as well as the **atmospheric elemental abundances**.
- A giant planet would be expected to have **stellar or super-stellar C/O ratio** depending on its formation by gravitational instability or core accretion respectively. (e.g., Öberg et al. 2011).
- **Volatile-to-sulfur ratio** can vary depending on formation location as well as the exact accretion mechanism (pebble or planetesimal accretion). Models predict **similar C/O ratio** in both these scenarios (Fig. 1 below)
- Measurements of abundance ratios for **both planets and their host stars** is required to make conclusions about planet formation and subsequent evolution.
- Our survey aims to measure the abundances of 15 elements **(C, O, Na, Mg, Si, S, Ca, Sc, Ti, Cr, Mn, Fe, Ni, Zn, and Y)** as well as several elemental abundance ratios **(C/O, C/S and O/S ratios)** of directly imaged planet host stars using their **visible light spectrum**. Here, we present the results of five stars from our sample.

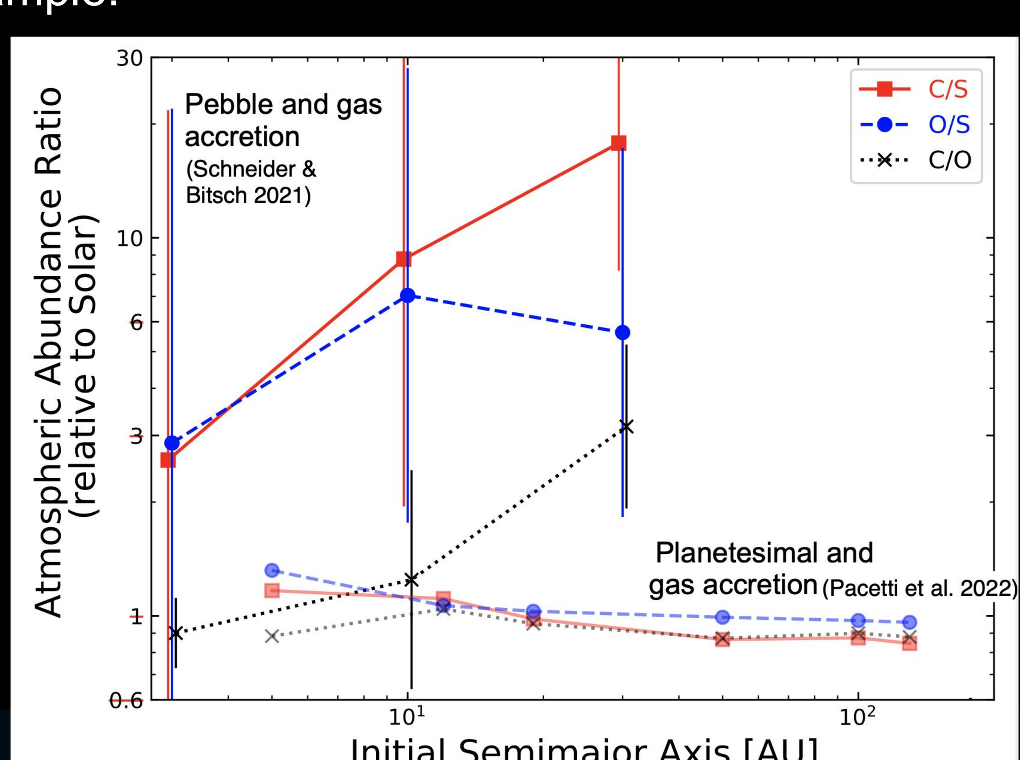


Fig. 1: Figure from JWST GO proposal 5485 (PI Baburaj & Konopacky). Originally adapted from Crossfield (2023).

Levy Spectrometer (APF Telescope):

- The Automated Planet Finder (APF) is a 2.4m telescope located at the Lick Observatory in California, USA. It features the **Levy spectrometer**, an optical echelle spectrometer.
- The Levy provides very high spectral resolution (**R~120000**) and spectral coverage in the range **374-900nm**.

Methods:

- Combination of two approaches used to obtain C and O abundances and hence, the C/O ratio:
  - **Spectral fitting**
  - **Equivalent width determination**

HD 206893:

- HD 206893 is a young F5 star hosting two super-Jupiters. The detection of the outer companion **(HD 206893B)** was first reported by Milli et al. (2017). Hinkley et al. (2023) detected the inner companion **(HD 206893c).** The planets have masses of **28Mjup** and **12.7 Mjup** respectively.

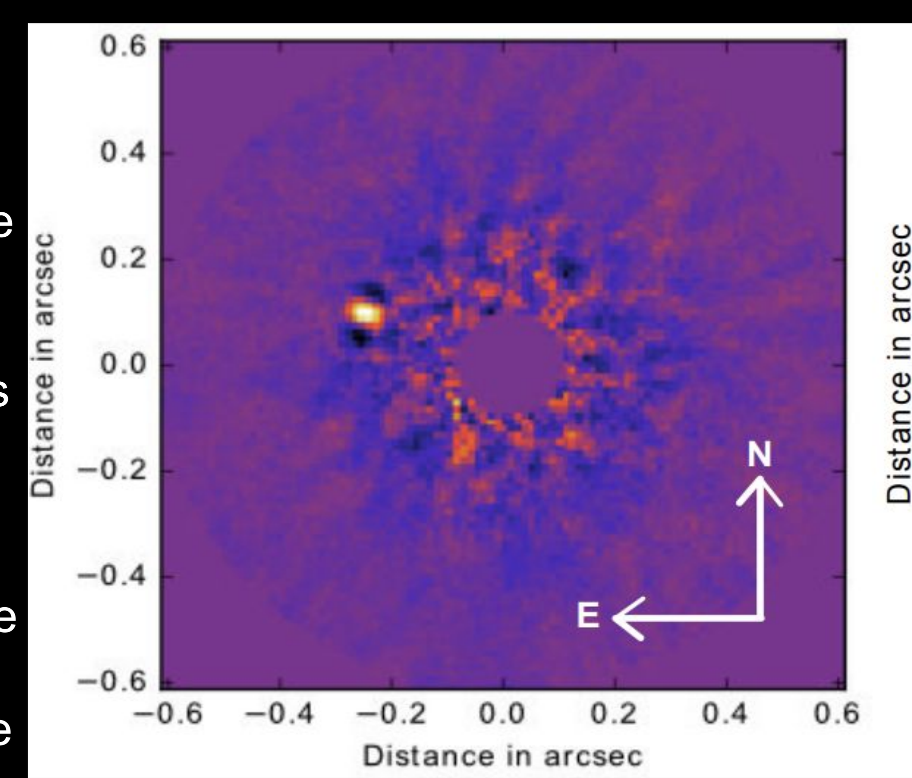
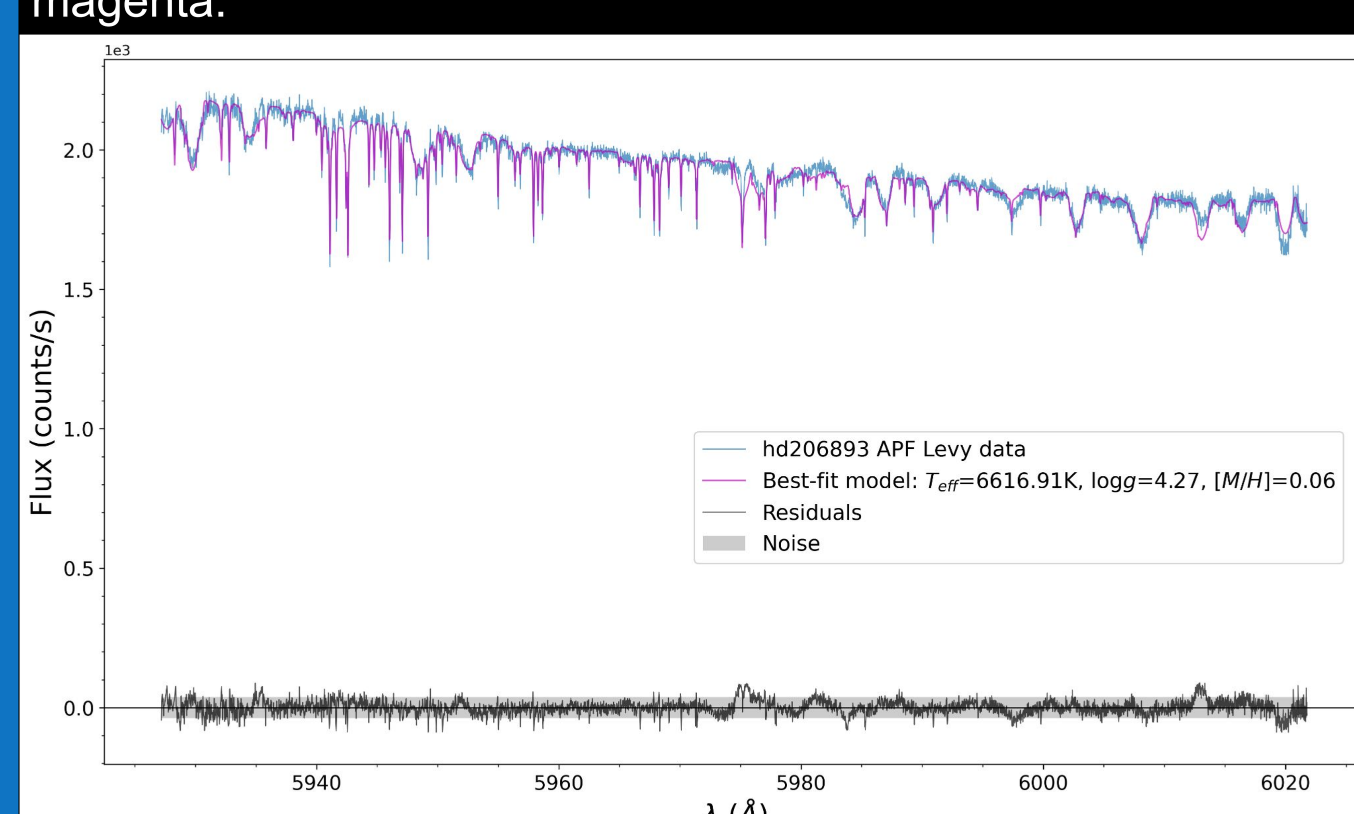


Fig. 2: Image from Milli et al. (2017).

Spectroscopic Data:

Spectral data of HD 206893 was taken using the Levy spectrometer on four separate nights in 2023 (7 August, 9 August, 25 August and 26 August). Initial forward modeling results for the basic atmospheric parameters are shown below (Fig. 3) for one of the spectral orders of HD 206893 (blue). The best-fit stellar + telluric model based on these results is in magenta.



Fitting a custom PHOENIX grid with solar overall metallicity ([M/H] = 0), and varying carbon and oxygen gives **C = 8.57 ± 0.03, O = 8.66 ± 0.07; C/O = 0.81 ± 0.14.** Spectral fitting thus gives a **super-solar C/O** upto 2σ.

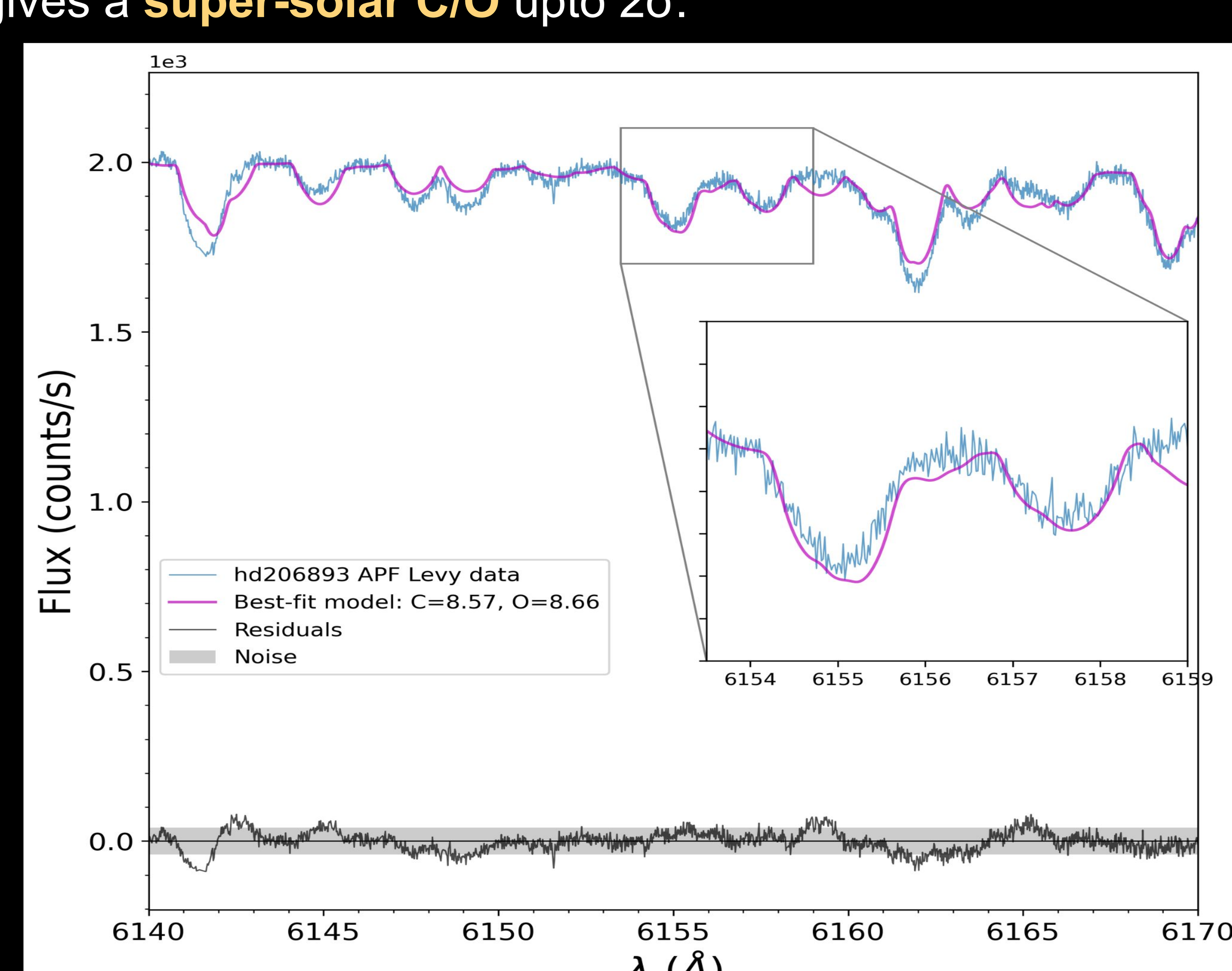


Fig. 4: APF Levy data (blue) for HD 206893 spectral order with OI triplet line at 6155—58Å overplotted with best-fit C, O model (magenta). Noise is shown in gray and residuals in black.

Meanwhile, the equivalent width approach gives **C = 8.55 ± 0.10, O = 8.71 ± 0.15; C/O = 0.69 ± 0.29.** Equivalent width C/O agrees with solar (~0.55). We also obtain **S = 7.14 ± 0.05** from the equivalent width method. This gives **C/S = 25.70 ± 6.62; O/S = 37.15 ± 13.53.** These ratios are solar to within 1σ (Solar C/S = 20.42, O/S = 37.15).

Other targets:

- The other four targets in this sample: 51 Eridani, HR 8799, HD 984, and GJ 504 all have a **solar C/O ratio (~0.55)** within 1σ.
- 51 Eri, HD 984, and GJ 504 also have **solar C/S and O/S ratios**. HR 8799 has **super-solar C/S and O/S** as it is a λ Bootis star with sub-solar sulfur abundance.

Analysis of C/O Ratios:

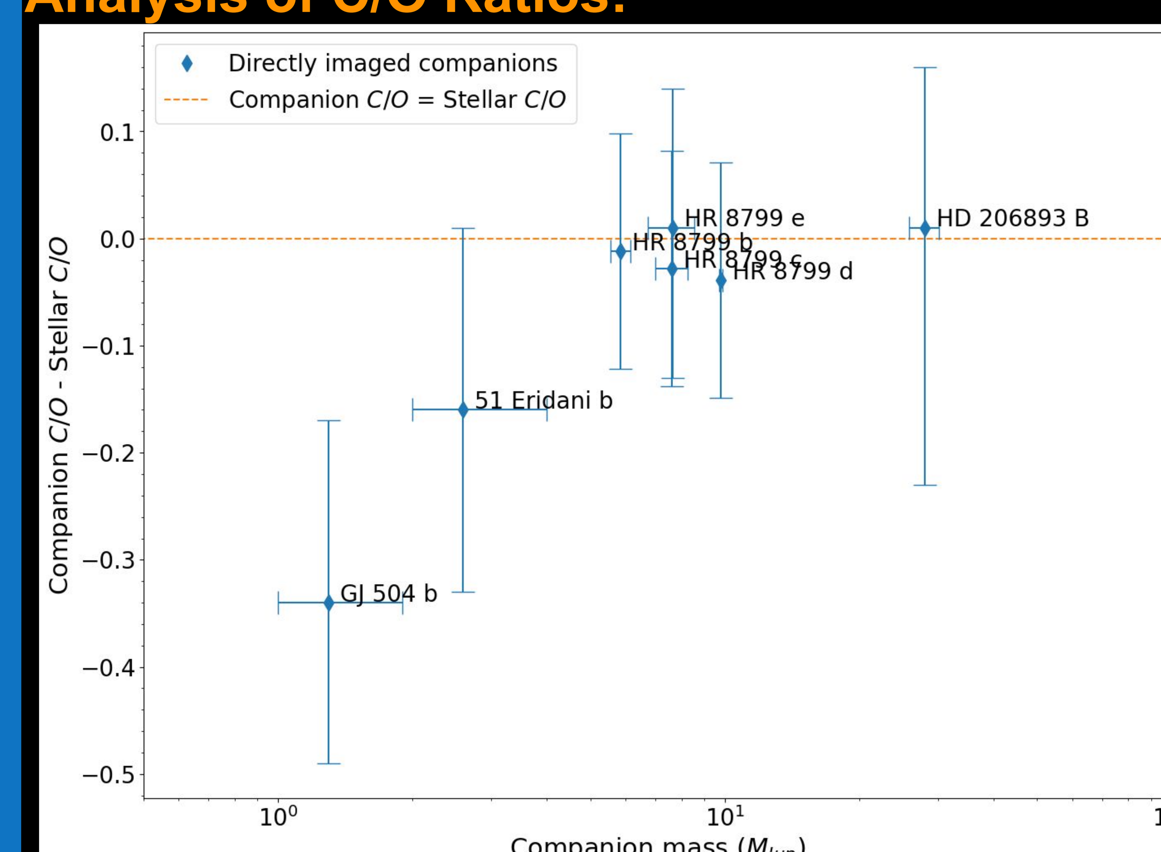


Fig. 6: Difference between the planet and stellar C/O values plotted against the companion mass for all host star - companion pairs with available C/O measurements. The orange line denotes where the planet C/O equals the stellar value.

- All the HR 8799 planets, 51 Eridani b, and HD 206893B have a **stellar C/O** ratio to within 1σ.
- GJ 504 b has a **sub-stellar C/O** ratio at a 1σ level.
- C/O ratios for the companions are not solely dependent on formation and can be altered significantly by processes like **migration** through the disk. Other elemental abundance ratios might help resolve some of these degeneracies.
- Sulfur abundance has **not been measured** for any of the companions so far. However, certain **SO_2** and **H_2S** features might be accessible using **JWST** (e.g., Crossfield 2023). JWST programs aimed at detailed atmospheric characterization have been approved for **HR 8799 b, c, d, e** (GTO 1188; PI Hodapp), **GJ 504 b** (GTO 2778; PI Perrin), **51 Eridani b** (GO 3522; PI Ruffio), and **HD 206893B** (GO 5485; PI Baburaj & Konopacky)
- **Mg/Si** ratios for the host star could tell us about the mineral composition of the (potentially) rocky/icy cores of these gaseous companions. Mg/Si ratio has been proposed to govern the silicate distribution within the protoplanetary disk and the distribution of silicon among different minerals depending on the Mg/Si ratio in the disk (Thiabaud et al. 2015).

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