The HD 95086 planetary system: from discovery to structure

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Abstract

Before 2013, only three systems had been known where outer planets and debris disks co-exist: β Pic, HR 8799, and possibly also Fomalhaut. Recently, by analyzing direct images in the L′ band, members of our group have discovered a planet around HD 95086, a 17-Myr-old A8-type star belonging to the Lower Centaurus Crux association. HD 95086 b has an estimated mass of ≈5 M_{Jup}, and a projected separation of ≈56 AU. The star also harbors a bright debris disk. We studied the debris disk using the spectral energy distribution and spatially resolved far-infrared images obtained with the Herschel Space Observatory. We found two distinct dust disk components with characteristic temperatures of 187 K and 57 K. The outer component is very extended (r_{out} ≈ 270 AU), while the minimum inner radius of the outer component, estimated from a simple assumption of black-body grains, is r_{in} > 64 AU. The mass in mm-size dust is 0.5 M_{Earth}, making HD 95086 one of the most massive known debris disks. The good agreement between the planet's position and the characteristic radius of the outer dust belt makes HD 95086 the best target to investigate planet-disk interaction. We also present our simulations of the disk's morphology using different planet-disk interaction scenarios.

How do outer planets form?

- Currently, more than a thousand exoplanets are known. Most of them orbit within 5 AU of their host stars, but some of them are far enough to be observable via direct imaging. The in-situ formation of these outer giant planets is difficult to explain within the core accretion model (Marois et al. 2010). Possible alternative scenarios are:
  - In situ formation by gravitational instability (Cameron 1978; Boley 2009; Rafikov 2009)
  - In situ formation by pebble accretion (Lambrechts & Johansen 2012)
  - Core accretion + planet-planet scattering (Veras et al. 2009)
  - Core accretion + planet-disk interaction through outward migration (Papaloiziou et al. 2007; Crida et al. 2009)
- The formation of giant outer planets can be best studied in young systems, which still contain signatures of how the planet formed from the disk, and where the system may not have reached stability yet.

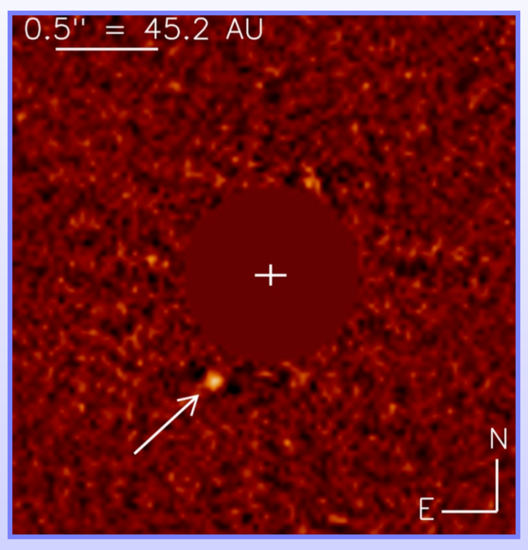
Planet-disk interactions

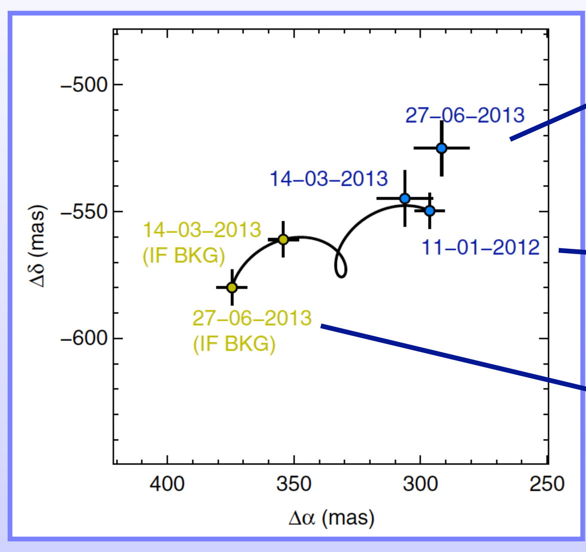
- The planet formation process produced many smaller planetesimals as well. Planets and planetesimals may dynamically interact:
  - Migrating massive planet may trap planetesimals in resonances;
  - Secular perturbations may drive planetesimals onto intersecting orbits, increasing the frequency of collisions;
  - A massive planetesimal population may also influence the orbit of the young planet(s) (Moore & Quillen 2013).
- Planetesimals are invisible, but the debris dust produced in the planetesimals' collisions traces their location.

Our target: HD 95086

- Belongs to the Lower Centaurus Crux (LCC) association (de Zeeuw et al. 1999)
- Distance: 90.4 ± 3.4 pc (van Leeuwen 2007)
- Age: 17 ± 4 Myr (Meshkat et al. 2013)
- Spectral type: A8
- Prominent infrared and mm excess, indicating a massive dusty disk (Rhee et al. 2007, Chen et al. 2012, Rizzuto et al. 2012)

The planetary companion





Where the object was actually detected in 2013

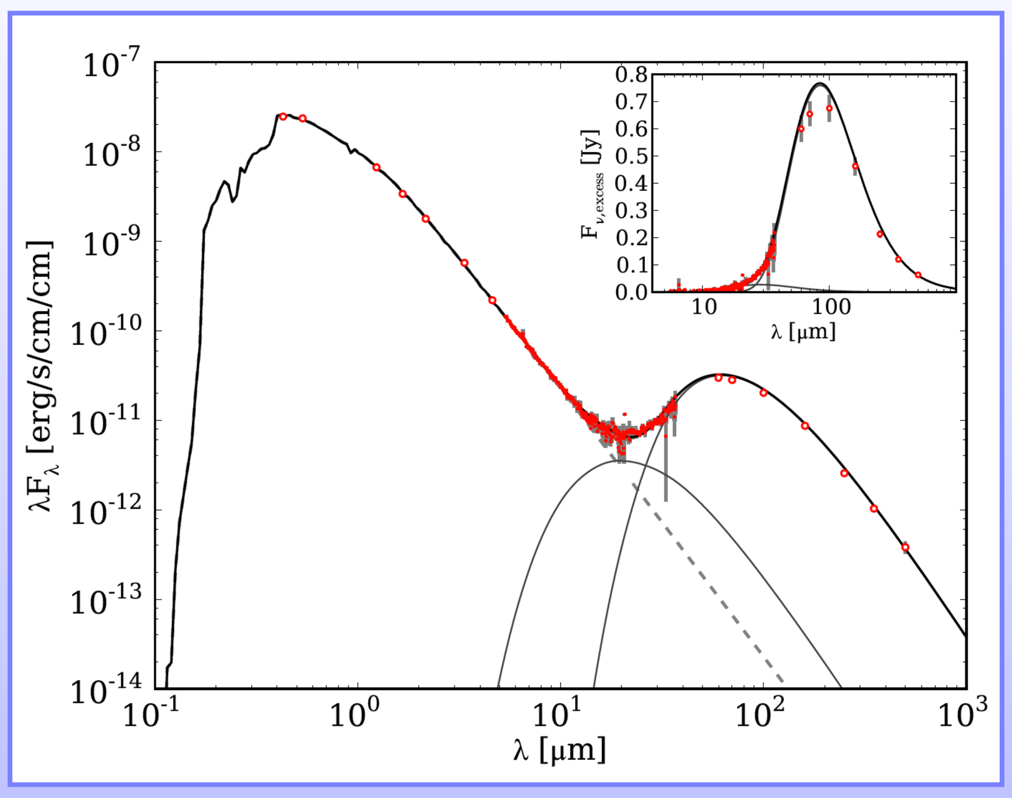
First detection in 2012

Where the object would have been in 2013 if it was a background star

- Discovery and confirmation were based on three VLT/NaCo datasets spanning 18 months (January 2012, March 2013, and June 2013), on L′-band images (3.8 μm).
- Method: angular differential imaging (ADI): exploits the fact that the field and the pupil rotate with respect to each other during the observation, thus enabling the subtraction of the speckle halo around the target star.
- 5 independent reductions pipelines and 3 different flavors of ADI algorithms were used.
- Proper motion analysis shows that the discovered object is co-moving with the star. The hypothesis that it is a background object has a probability of only 10^{-16}.

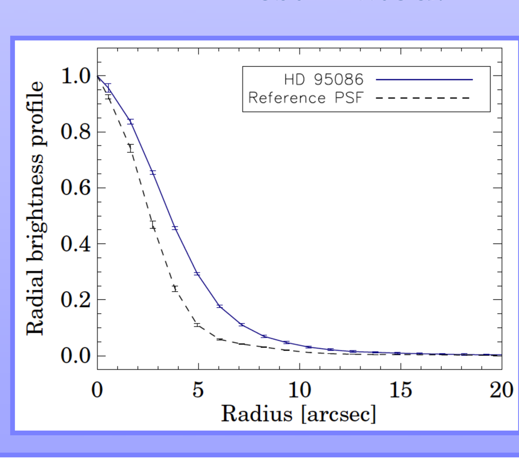
Planet properties	Value
Projected distance	55.7 ± 2.5 AU
Absolute L′ magnitude	11.5 ± 1.1 mag
Mass	5 ± 2 M_{Jup}
Effective temperature	1000 ± 200 K
Surface gravity	3.85 ± 0.5 dex

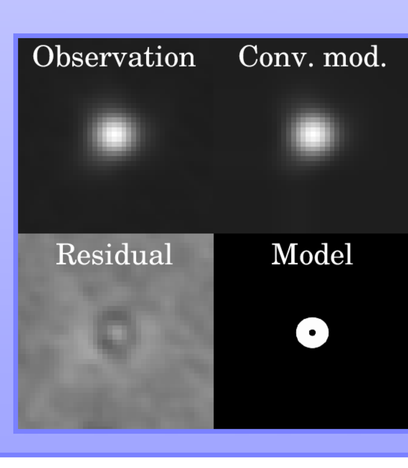
The debris disk



- Young debris disk with a very high fractional luminosity: 1.5 x 10^{-3}.
- Does not contain CO gas (our APEX observations give an upper limit for the CO mass of 1.5 x 10^{-4} M_{Earth}).
- SED modeling assuming blackbody grains: the disk contains two dust belts: a warm inner belt at about 5-6 AU and a cold outer belt starting at >64 AU.
- Our Herschel/PACS images spatially resolve the outer disk, so size and inclination could be estimated.

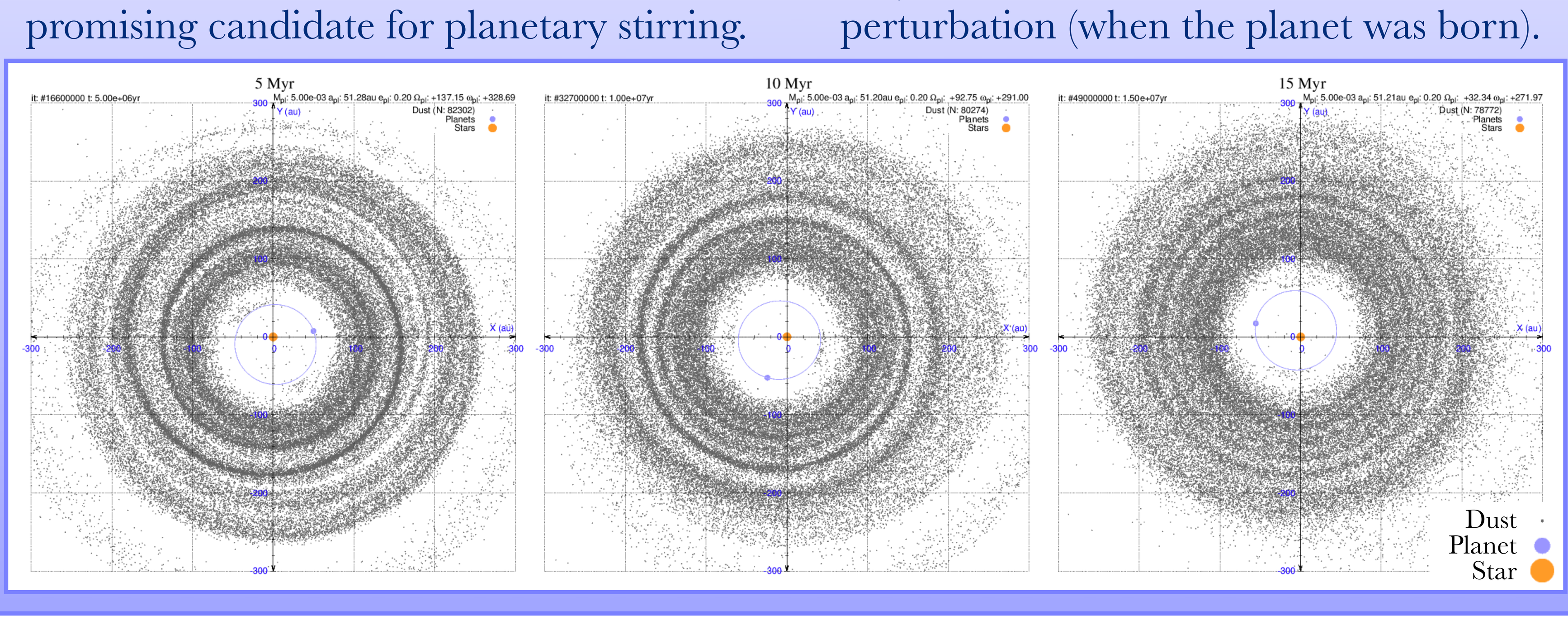
Disk properties	Value
Major and minor axes	530 x 490 AU
Inclination	23 ± 5 deg
Mass	0.5 ± 0.1 M_{Earth}
Temperature	187 and 57 K
Blackbody radius	6 and >64 AU





Planet-disk interactions in HD 95086

- Using the disk's inclination, the planet's deprojected distance (62 AU) and the minimum inner radius of the outer dust belt (64 AU) agrees very well.
- Planet may be orbiting just inside the cold outer dust belt.
- HD 95086 is young, and the debris dust belt is extended → self-stirring is not plausible → promising candidate for planetary stirring.
- Planet may sculpt the inner edge of the outer dust belt through secular perturbations and induce spiral-like azimuthal asymmetries if its orbit is eccentric (see below our N-body simulations assuming e=0.2).
- The time-evolution of the spiral structure may be used to infer the onset of secular perturbation (when the planet was born).



References

Boley 2009, ApJL 695, L53 • Cameron 1978, M&P 18, 5 • Chen et al. 2012, ApJ 756, 133 • Crida et al. 2009, ApJL 705, L148 • de Zeeuw et al. 1999, AJ 117, 354 • Lambrechts & Johansen 2012, A&A 544, A32 • Marois et al. 2010, Nature 468, 1080 • Meshkat et al. 2013, ApJL 775, L40 • Moore & Quillen 2013, MNRAS 430, 320 • Papaloizou et al. 2007, Protostars & Planets V • Rafikov 2009, ApJ 704, 281 • Rhee et al. 2007, ApJ 660, 1556 • Rizzuto et al. 2012, MNRAS 421, L97 • van Leeuwen 2007, Astrophysics and Space Science Library, Vol. 350 • Veras et al. 2009, ApJ 696, 1600

Our HD 95086 papers

- Rameau et al.: *Discovery of a Probable 4-5 Jupiter-mass Exoplanet to HD 95086 by Direct Imaging* (2013), **ApJL 772**, L15
- Meshkat et al.: *Further evidence of the Planetary Nature of HD 95086 b from Gemini/NICI H-band data* (2013), **ApJL 775**, L40
- Moór et al.: *A resolved Debris Disk around the Candidate Planet-hosting Star HD 95086* (2013), **ApJL 775**, L51
- Rameau et al.: *Confirmation of the Planet around HD 95086 by Direct Imaging* (2013), **ApJL 779**, L26

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