Probing the Origins of Directly Imaged Planets with Dynamical Masses

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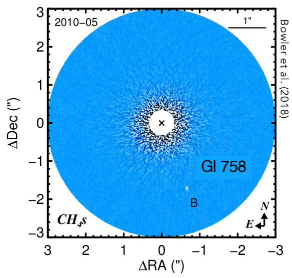
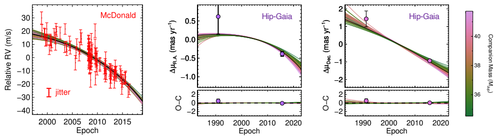
Abstract. Direct imaging is the only exoplanet detection method that gives no model-independent information about planet mass or radius. One of the most exciting developments since the last Protostars and Planets meeting has been the advent of dynamical masses for directly imaged planets derived from ultra-precise astrometry of their host stars. Dynamical masses to date – for the β Pictoris, HR 8799, and 51 Eri systems – are broadly consistent with expectations from "hot-start" evolutionary models. In the case of 51 Eri b, our mass allows us to place the first constraints on its initial entropy.

We have also measured precise orbital parameters and dynamical mass for the host binary in the VHS J1256 system. This enables the first precise age dating of its companion, which implies a mass on the borderline of the deuterium-fusion boundary. The future promises many more dynamical mass measurements for giant planets, both from the increased precision of further Gaia data releases, and also the discovery of new "dynamical beacon" planets like AF Lep b.

Measuring Planet Mass from Host-Star Acceleration

direct imaging → $\rho = r_{AB}\varpi\cos\phi$





$$a_{RV} = \frac{GM_B}{r_{AB}^2}\sin\phi \qquad a_{\alpha\delta} = \frac{GM_B}{r_{AB}^2}\cos\phi$$

Planets exert gravitational accelerations on their host stars. Using RVs needs an assumption for the angle between the star-planet vector and sky plane, ϕ. Astrometry circumvents this by measuring the acceleration in the same plane as the direct imaging separation, ρ.

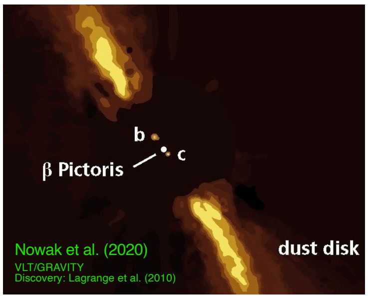
Imaged Planet Masses

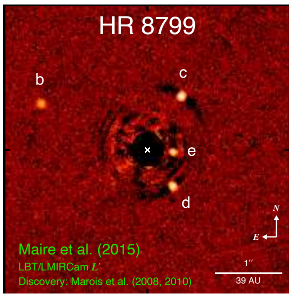
β Pic – in this system, astrometry constrains the mass of the outer planet b (P~24 yr), while RVs measure the mass of the inner planet c (P~3.3 yr). Earlier work (Snellen & Brown 18; Dupuy+19) achieved similar results for b despite being unaware of c because of c's relatively short period.

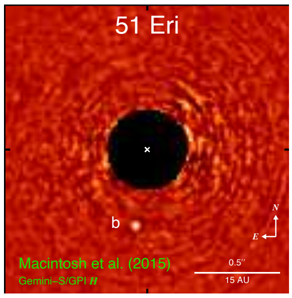
HR 8799 – the acceleration is dominated by the innermost planet e. We showed the derived mass is insensitive to a wide range of assumed mass ratios for e, d, and c.

51 Eri b – is one of the only imaged planets cool enough to be consistent with cold-start models that predict the highest planet masses. Our null detection of acceleration places an upper limit on its mass.

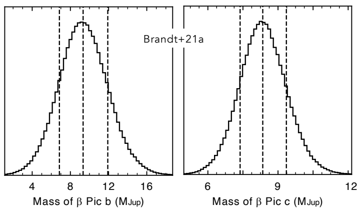
AF Lep b – has recently joined these ranks with the lowest *measured* dynamical mass yet, lying between its β Pic moving group siblings β Pic c and 51 Eri b (see posters ES-03-0021 and ES-03-0037).



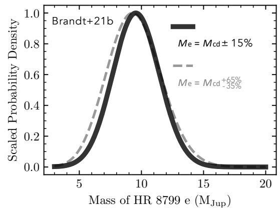




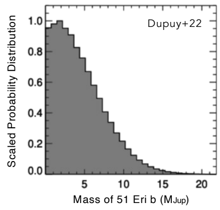
$M_b = 9.3 \pm 2.6\ M_{Jup}$ $M_c = 8.3 \pm 1.0\ M_{Jup}$



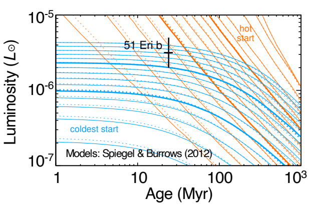
$M_e = 9.6 \pm 1.9\ M_{Jup}$



$M_b < 11\ M_{Jup}$ (2σ)

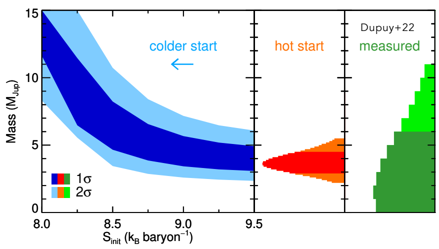


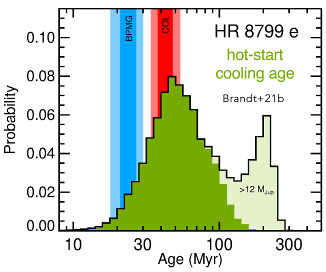
Testing Initial Entropy & Evolutionary Models



Planets with sufficiently low luminosities can either be high-mass with low initial entropies (cold start) or low-mass with high initial entropies (hot start). Planets like β Pic b,c and HR 8799 b,c,d,e are all much more luminous than this ($>10^{-5}\ L_\odot$), while 51 Eri b is ideal for such a test given its young age and low luminosity.

Our upper limit on the mass of 51 Eri b (right) agrees with the hot-start mass (middle) and rules out the coldest-start models (left). We constrain the initial entropy to be > 8 k_B (Boltzmann's constant) per baryon at 97% confidence. Thus, warm-start models are still possible.



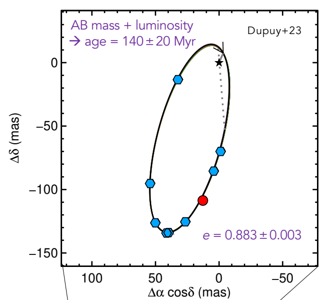


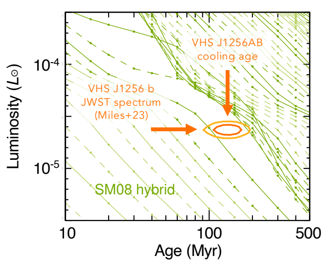
With a measured mass and luminosity for HR 8799 e, we computed a substellar cooling age from evolutionary models. We found that its cooling age matches the Columba association (42 Myr), of which HR 8799 has been posited to be a member. This validates hot-start models of planet evolution at even older ages than the β Pic moving group. (The top 10% of the mass posterior is $>12\ M_{Jup}$, which is dynamically unstable.)

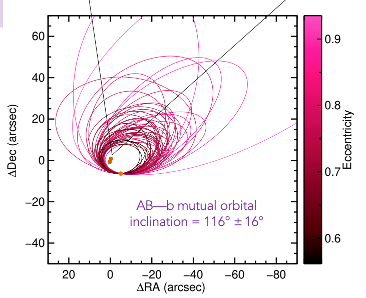
Masses & Orbits in the VHS J1256-1257 System

Using Keck astrometry, we measured the full orbit of the host binary VHS J1256AB and an orbital arc for VHS J1256 b. The host's masses are near the substellar boundary, allowing us to compute a rather young cooling age of 140±20 Myr. This age places the companion right on the D-fusing boundary, resulting in a bimodal inferred mass distribution: $11.8 \pm 0.2\ M_{Jup}$ or $16 \pm 1\ M_{Jup}$.

The high mutual inclination we find, and large eccentricities, are consistent with VHS J1256 b dynamically scattering to its current orbit and then pumping the host binary's eccentricity via Kozai-Lidov.







References. Bowler 2016, PASP, 128, 2001 • Bowler et al. 2018, AJ, 155, 159 • Brandt et al. 2021a, AJ, 161, 179 • Brandt et al. 2021b, ApJL, 915, 16 • Dupuy et al. 2019, ApJ, 871, 4 • Dupuy et al. 2022, MNRAS, 509, 4411 • Dupuy et al. 2023, MNRAS, 519, 1688 • Miles et al. 2023, ApJ, 946, 6 • Saumon & Marley 2008, ApJ, 689, 1327 • Snellen & Brown 2018, NatAs, 2, 883 • Spiegel & Burrows 2012, ApJ, 745, 174

Image credits. β Pic graphic – Axel Quetz / MPIA Graphics Dept; HR 8799 and 51 Eri – Bowler 16