Astro2020 Science White Paper

Establishing an Empirical Substellar Sequence to Planetary Masses

Thematic Areas:
☐ Planetary Systems ☐ Star and Planet Formation ☐ Stars and Stellar Evolution

Principal Author:
Name: Trent J. Dupuy
Institution: Gemini Observatory, Northern Operations
Email: tdupuy@gemini.edu
Phone: +1 808 974 2568

Co-authors:
Kraus, A. L. (UT Austin)
Theissen, C. A. (UC San Diego)
Bardalez Gagliuffi, D. (AMNH)
Burgasser, A. J. (UC San Diego)
Girard, J. (STScI)
Gizis, J. (University of Delaware)

Abstract (optional): Mass is the most fundamental parameter governing the life-history of all gaseous objects from stars to brown dwarfs and giant planets. Extending measurements of mass to the regime of directly imaged gas-giants, and spectroscopically characterizing this mass sample, will require the leap in angular resolution and sensitivity offered by the ELTs.

1 Science Context

It is a maxim of astrophysics that, after the end of assembly, the properties and life cycle of a star, brown dwarf, or planet are largely set by its mass. Masses are also the fundamental component encoded in the broadest testable feature of star formation models, the IMF. The vast majority of objects in our universe are not amenable to direct mass measurements, so their masses must be inferred by comparing observable properties (such as luminosity or temperature) to the predictions of (sub)stellar evolutionary models. It is therefore important to calibrate the mass predictions of theoretical models by observing stars where the mass can be directly measured, usually from binary system orbits. This need will only become more acute over the next decade. Wide-field surveys with *Gaia*, *HST*, and *JWST* will offer unprecedented demographic censuses of young stellar populations spanning five orders of magnitude (from $> 100\,M_\odot$ to $< 1\,M_{\rm Jup}$), and theoretical models will impose systematic uncertainties that completely dominate over Poisson statistics.

The characterization of old, main-sequence field stars is now entering the regime of precision stellar astrophysics, such that models can match observations to within a few percent (e.g., Boyajian et al. 2014; Mann et al. 2015, 2019) and are probing the impact of second-order properties like rotation and metallicity. The latest observational campaigns are even enabling the first substantive tests of pre-main sequence stars (e.g., Rizzuto et al. 2015) and old brown dwarfs (Dupuy & Liu 2017; Figure 1). However, these analyses are running up against the ultimate limits of aperture size ($=D = 60$ mas for AO imaging on 8-m-class telescopes) and Kepler's Law, along with a severe trend that typical binary orbits are dramatically tighter at low masses. Nearly all of the young brown dwarf binaries in the nearest star-forming regions (D 150 pc; $M_{\rm tot}$ $0{:}1\,M_\odot$) and

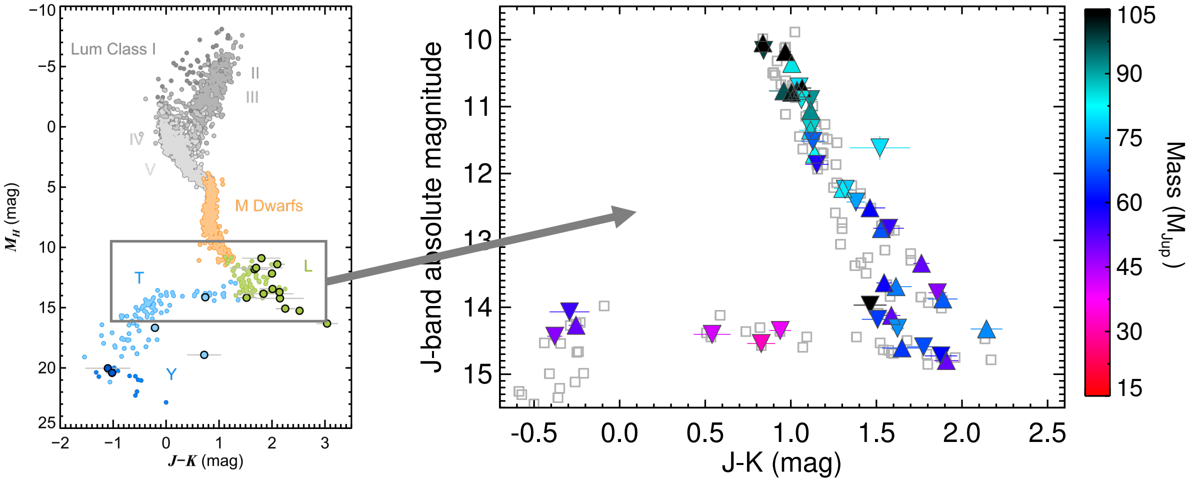

Figure 1: Model-independent dynamical masses are crucial to connect our empirical sequence of stellar and substellar objects to theory. On the left is a near-infrared color–magnitude diagram that extends from supergiant stars to the coldest brown dwarfs. On the right are dynamical mass measurements (colored triangles) for objects at the bottom from the main sequence to methane-bearing T dwarfs. While this field has seen substantial growth in recent years, we still lack masses for the coldest (< 1000 K) and lowest-mass ($< 30\,M_{\rm Jup}$) substellar objects.

planetary-mass brown dwarf binaries in the field (D 20 pc; $M_{\rm tot}$ 15 $M_{\rm Jup}$) that are resolvable with current telescopes have orbital periods of many decades. Only a handful of unique measurements are available from eclipsing systems (e.g., Stassun et al. 2006) and one or two fortuitous planetary-mass binaries among our closest neighbors (e.g., Best et al. 2017).

Meanwhile, the field of direct imaging is being transformed by the ultra-high-precision astrometry now possible with *Gaia* that has for the first time allowed mass measurements for faint companions, including brown dwarfs, giant planets, and stellar remnants. Traditionally, the Achilles heel of direct imaging of exoplanets has been the lack of fundamental physical properties, unlike radial velocities and microlensing events that provide masses and transits that provide radii. By combining *Gaia* DR2 and *Hipparcos* data from 25 years earlier, the first model-independent mass has been measured for Pictoris b (13 3 $M_{\rm Jup}$; Dupuy et al. 2019). The future of direct imaging will be to use such astrometric reflex motions of host stars as signposts to conduct targeted searches for companions that are too faint or close to their host star to have been previously detected. These signposts will grow in number greatly with the release of the 5-year *Gaia* catalog in several years. Combining these astrometric accelerations with moderate-precision radial velocities, newly discovered companions will render their masses immediately with a single epoch of imaging.

2 Binaries Near & Far

The dramatically sharper resolution of diffraction-limited imaging with the ELTs will unlock entire samples of these objects. From Kepler's Law, a factor of 3 increase in resolution will open up systems with orbital periods that are 5 times shorter. After considering inclination effects, an 8-m telescope observing a pair of 5 $M_{\rm Jup}$ brown dwarfs at 15 parsecs could only measure orbits with a 2 AU and $P > 25$ years, and few (or no) such systems even exist. In contrast, a telescope 3 larger in diameter could resolve a 0.6 AU binary that completes its orbit in only 5 years. Such observations will be straightforward with adaptive optics and a near-infrared camera such as the guiders for GMTIFS or GMTNIRS on the GMT. Even in the more distant young star-forming regions, dynamical masses will become accessible down to a few tens of Jupiter masses, enabling direct calibration of the luminosity–mass relation that underlies every IMF measurement. The ELTs will revolutionize the characterization of substellar and planetary properties, unlocking the full impact of the vast number of IMF studies over the coming decades.

Brown dwarf binaries with dynamical masses have some of the best constrained *physical* properties of any substellar objects. However, their surface properties (spectral type, etc.) are among the most poorly known because their light is blended in seeing-limited observations. Thus, spectroscopic characterization of brown dwarfs with dynamical masses will be a major effort in the coming years. The coldest brown dwarf binaries (late-T and Y spectral types) will remain inaccessible to current or planned facilities even in the *JWST* era. They are too faint for ground-based spectroscopy on 8-m-class telescopes, and they are too tight for *HST* and *JWST* spectroscopy ($< 0:1$ arcsec). Only the ELTs will be able to obtain spectra for the faintest, lowest mass brown dwarfs in binaries ($< 15\ M_{\rm Jup}$).

In the 2020s, LSST will begin to transform the way brown dwarf binary mass measurements are obtained. By obtaining a decade's worth of astrometry out to 1 m, LSST will reveal all the tightest substellar binaries in the solar neighborhood. With astrometric orbits in hand, a single snapshot of imaging is all that is needed for a dynamical mass measurement. These binaries with periods of 10 years or less are not resolvable with current facilities except for a handful of very nearby systems. To study intrinsically rare populations (very young objects, high- and low-metallicity), a wide net must be cast, meaning more distant binaries and higher angular resolution. The ELTs will also open the door to dynamical masses for binaries in the nearest young associations (e.g., the Scorpius-Centaurus complex and the Pleiades). The resulting empirical sequence with measured mass *and* age *and* metallicity (calibrated off much better tested stellar models) is the holy grail of this field.

3 Directly Imaged Companions

Gaia is now enabling the measurement of dynamical masses for directly imaged companions, not by Kepler's Law ($M_{\rm tot} = a^3=P^2$) but rather by $F = ma$. As shown in Brandt, Dupuy & Bowler (2018), a projected separation and two accelerations for the host star (one in the plane of the sky, the other orthogonal to that) measured contemporaneously yield the companion mass without needing detailed orbit determination. Figure 2 shows the amplitude of the astrometric acceleration in terms of an apparent change in proper motion between the epochs of *Hipparcos* and *Gaia* DR2, as a function of companion separation. With the angular resolution afforded by 8-m-class telescopes, we can only reach the widest companions, corresponding to higher masses. The only planetary-mass object accessible to this method currently is Pictoris b because it has one of the smallest physical separations of any directly imaged planet.

There are many advantages to working with companions of nearby stars. Extremely precise distances are available from *Gaia*, the metallicity of the system can be measured from the host star, and in many cases the host star also provides age information. The main disadvantage of working with these objects is that it can be very challenging to obtain spectroscopy of them. Even objects with measured spectra typically only have very low spectral resolution data (R 100) over a narrow wavelength range. Higher spectral resolution (R few thousand) is essential for abundance studies that provide the chemical fingerprint of the planet formation process. A moderate spectral resolution IFU behind a high-contrast AO system (e.g., GMTIFS on GMT) will enable the sample of directly imaged companions with dynamical masses to live up to their true potential. While some planets have been detected spectrally in integrated-light data (e.g., Brogi et al. 2012; Birkby et al. 2013), that method is only feasible for the hottest and brightest planets.

While *JWST* will be the only facility sensitive to truly cold Jupiters that are bright only at 4-micron, the ELTs working in the near-IR will be ideal for studying hot, young giant planets that are in the process of forming in regions like Taurus and Upper Scorpius. Angular resolution has been the main limiting factor in this potentially quite messy area, as young planets embedded in the disk from which they are accreting gas are not likely to be clean point sources. To find younger analogs of planets like HR 8799b in even the nearest star-forming regions like Taurus requires the angular resolution of the ELTs.

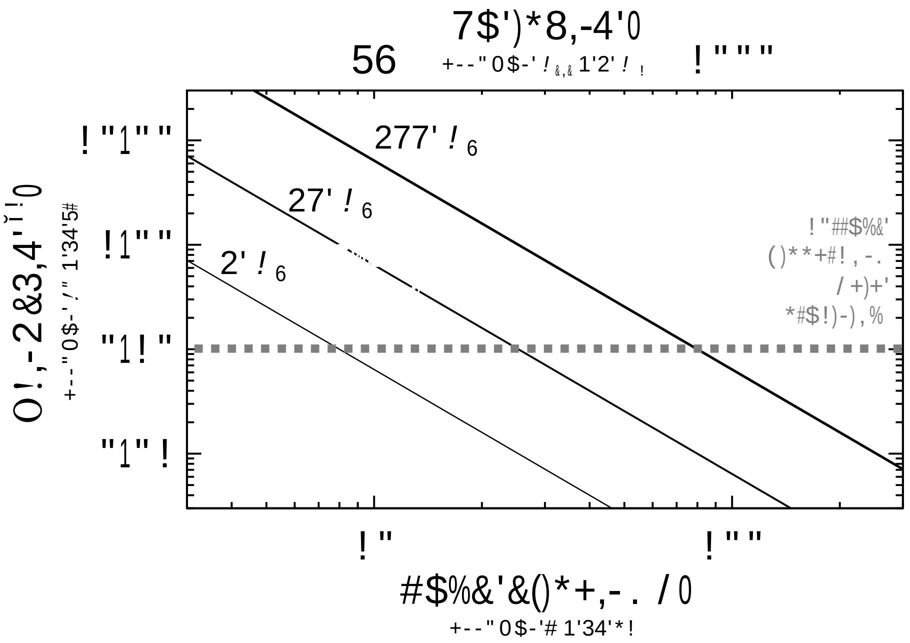

Figure 2: The acceleration induced on the host star by wide, directly imaged companions as a function of their separation, over the 25-year time baseline between *Hipparcos* and *Gaia*. For the widest separations, corresponding to the angular resolution limits of current direct imaging facilities, only relatively massive objects (brown dwarfs and low-mass stars) are accessible to dynamical mass measurements from *Gaia* astrometry. The angular resolution of the ELTs is required to reach either smaller separations or younger analogs of wide planets like HR 8799b in star-forming regions that are a few times more distant than the directly imaged planet hosts in the solar neighborhood. *JWST* will not have the angular resolution to study such planets at their formation epoch, but it will be excellent for studying the coldest Jupiters around the very nearest stars.

References

[1] Boyajian, T. S., van Belle, G., & von Braun, K. 2014, *AJ*, 147, 47

[2] Mann, A. W., Feiden, G. A., Gaidos, E., Boyajian, T., & von Braun, K. 2015, *ApJ*, 804, 64

[3] Mann, A. W., Dupuy, T., Kraus, A. L., et al. 2019, *ApJ*, 871, 63

[4] Rizzuto, A. C., Ireland, M. J., & Kraus, A. L. 2015, *MNRAS*, 448, 2737

[5] Dupuy, T. J., & Liu, M. C. 2017, *ApJS*, 231, 15

[6] Stassun, K. G., Mathieu, R. D., & Valenti, J. A. 2006, *Nature*, 440, 311

[7] Best, W. M. J., Liu, M. C., Dupuy, T. J., & Magnier, E. A. 2017, *ApJL*, 843, L4

[8] Dupuy, T. J., Brandt, T. D., Kratter, K. M., & Bowler, B. P. 2019, *ApJL*, 871, L4

[9] Brandt, T. D., Dupuy, T. J., & Bowler, B. P. 2018, arXiv:1811.07285

[10] Brogi, M., Snellen, I. A. G., de Kok, R. J., et al. 2012, *Nature*, 486, 502

[11] Birkby, J. L., de Kok, R. J., Brogi, M., et al. 2013, *MNRAS*, 436, L35