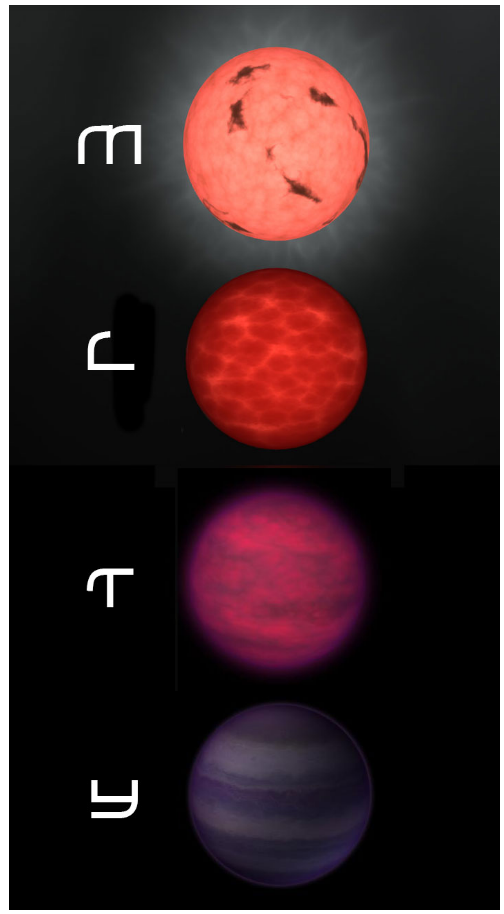
Astro2020 Science White Paper

The Need for Infrared Astrometry of Brown Dwarfs in the Post-Gaia Era



Thematic Areas

Primary: Stars and Stellar Evolution

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Abstract

Brown dwarf research in the next decade will be reliant on extending high-precision astrometry in wavelength and temporal coverage. Extending to the near- and mid-infrared enables a measurement of the low-mass cutoff of star formation as sampled across the field-age nearby brown dwarf census, allows for the discovery and characterization of cold brown dwarf analogs to cold (exo)planets, and enables predictive microlensing so that the masses of already well studied brown dwarfs can be measured directly. Extending the temporal coverage enables dynamical mass measurements for binary systems with much longer orbital periods than Gaia alone can provide. We argue also for continued access to dedicated ground-based near-infrared astrometric cameras for use on warmer brown dwarfs, whose bolometric luminosity measurements provide critical tests of theory across the full range of T_{eff}, age, and metallicity.

Overview

In April 2018, the second data release from Gaia (Gaia 2018) revolutionized astronomy and our view of the Solar Neighborhood. Within this release is a volume-complete sample of nearby stars providing *the* canonical data set against which to uncover previously missed stars and brown dwarfs (Hollands et al. 2018; Mamajek et al. 2018; Reylé 2018), determine the multiplicity of ultra-cool objects (Smart et al. 2019), enable mass measurements of nearby brown dwarf and exoplanet companions (Dupuy et al. 2019; Kervella et al. 2019), and more.

However, some nearby objects are not accessible to Gaia. Gaia works at λ<1.05 μm (Gaia 2016), so the vast majority of brown dwarfs, whose spectra peak in the infrared, are undetected. Out to 20 parsecs, for example, Gaia can completely survey only to types ~L5 (Kirkpatrick et al. 2019a). This white paper illustrates the need for continued astrometric monitoring at longer, infrared wavelengths and highlights the facilities needed for this work, whether they are currently available, already planned, or not yet envisioned.

Measuring the Low-mass Cutoff of Star Formation

Critical questions: What is the low-mass cutoff of star formation? What is the frequency of binaries at the lowest masses?

If star formation has a low-mass limit, the space density of nearby brown dwarfs will be seen to drop precipitously at a temperature corresponding to that cutoff mass at the mean age (~5.5 Gyr) of the sample (Burgasser 2004). The currently measured space density of the nearby brown dwarf sample, however, has been known to *increase* steadily throughout the late-T and early-Y dwarf sequence, which places the cutoff at <5 M_{Jup} (Kirkpatrick et al. 2019a). To probe to even smaller mass limits, additional nearby brown dwarfs at the coldest Y-dwarf spectral types are needed, as illustrated in Figure 1. As discussed in other Astro2020 white papers (Leggett et al. 2019; Kirkpatrick et al. 2019b), discoveries from the next generation of near- and mid-infrared surveys are expected to produce sizable samples of new Y dwarfs that populate the coldest bin in Figure 1, but the fundamental parameter most crucial to determining the space densities – the distance to each object – will be particularly problematic in the next decade due to the lack of capable instrumentation.

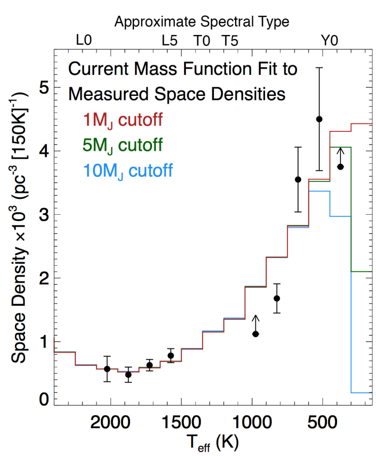

Figure 1: Space density of the (incomplete) 20-pc sample as a function of effective temperature (black points), adapted from Kirkpatrick et al. (2019a). The larger error bars on the rightmost points are caused by the much smaller volumes sampled at those T_{eff} values. Also plotted are simulations based on various forms of the mass function, for which the power-law of exponent α=0.6 (shown) provides the best fit. This model is illustrated with three different cutoff masses (10, 5, or 1 M_{Jup}). Note that the cutoff mass is best measured by the coldest bin shown, T_{eff} = 150-300K, for which a space density has yet to be measured.

Accurate distance measurements also provide a valuable tool in determining the frequency of unresolved binaries with mass ratios near one, as these objects will appear as outliers above the mean trend of absolute magnitude versus color traced by single objects (e.g., Figure 4 of Looper et al. 2008). Having this information is also critical to analysis of the mass function because companions can be more accurately accounted for in the sample. Moreover, knowledge of the binary fraction can provide an important datum with which to test rival theories of formation (Chabrier 2001; Kroupa et al. 2013; see also Burgasser et al. 2007), a topic still under hot debate (Bardalez Gagliuffi et al. 2019).

The coldest brown dwarf known, WISE 0855−0714, has $T_{eff} \approx 250K$, is at a distance of 2.3 pc, and has near-infrared Vega magnitudes of 26.4±0.3 at J and 23.9±0.1 at H (Luhman & Esplin 2014; Schneider et al. 2016). Similar objects of this T_{eff} at the volume limit of Figure 1 (20 pc) would have apparent magnitudes of J≈31.1 and H≈28.6 mag. LSST operates at shorter wavelengths for which these objects are even fainter. EUCLID operates at J and H, but is a few magnitudes too shallow for our purposes. WFIRST covers J and H and can provide the resolution needed (Stauffer et al. 2018, 2019), but integration times will be prohibitively long.

However, these objects emit their peak flux near 5 µm, so astrometric follow-up is dramatically easier there. A T_{eff}=250K object at 20 pc has an apparent 5 µm magnitude of ~18.7 mag, based on the WISE W2 measurement for WISE 0855−0714. JWST has fine-resolution imaging capability at these wavelengths, but unfortunately that telescope is simply not designed for many short-duration observations scattered all over the sky, which is what an astrometric follow-up program of very cold, nearby Y dwarfs would entail. Facilities already planned for the coming decade appear not to have the capability needed.

Measuring Masses in Multiple Systems: Orbital Dynamics

> Critical questions: What is the mass-luminosity-age relation at the lowest masses? What are the properties of exoplanet systems around brown dwarfs?

Monitoring the orbital motion of a brown dwarf allows us to constrain a key parameter: its mass. Model-independent masses can be determined if we can measure the (a) absolute astrometry, which includes the parallax, and (b) relative positions of the components, thus constraining the Keplerian orbit. If data are available for only one of these pieces, additional information such as radial velocities is needed. In the past, these techniques have lead to the extension of empirical mass-luminosity relationships from low-mass stars (e.g., Benedict et al. 2016) to cool brown dwarfs (e.g., Dupuy & Liu 2017), where resulting mass measurements have provided benchmarks to testing and refining evolutionary models (e.g., Dupuy et al. 2014). As with stellar systems (Duquennoy & Mayor 1991), large samples of brown dwarfs with determined orbital parameters make it possible to investigate their formation scenarios and dynamical histories (e.g., Dupuy & Liu 2011). Astrometric monitoring can be used to confirm, characterize, and discover planetary systems around ultracool dwarfs (e.g., Sahlmann et al. 2014), as these objects are known to host gas giants (Jung et al. 2018) and even multiple terrestrial planets (Gillon et al. 2017).

Currently, high-precision infrared astrometry for orbit determination relies on medium-sized and large ground-based telescopes and on HST. Although JWST may only be used for orbit monitoring of extraordinary targets, its highest spatial resolution mode – the NIRISS aperture masking interferometer and Kernel phase techniques – will allow us to resolve small-separation (<0.1-0.3”) binary brown dwarfs, thus providing invaluable information for mass determination. EUCLID will yield astrometric time series of ultracool dwarfs but its main surveys are pre-determined and are not well suited for follow up and orbit characterization. WFIRST's main surveys are also not well suited, and the GO program will be highly competitive and limited to a few special objects.

In the future, achieving these goals relies on the availability of barycentric astrometry for distances and orbits, either from a small-field, pointed, high-precision relative astrometry mission, such as a Small-JASMINE concept, or from an all-sky absolute astrometric mission, such as the European GaiaNIR concept (Hobbs et al. 2016). The spatially resolved observations needed for model-independent masses (+colors/spectra) will come from high-resolution imagers on large or extremely large ground-based telescopes and on space observatories.

Measuring Masses for Single Objects: Predictive Microlensing

> Critical questions: Measuring the mass of a single brown dwarf is possible if the object is seen to gravitationally lens a background source. How can we best position ourselves to predict such future events for known brown dwarfs?

Gravitational lensing provides an avenue via which masses of isolated objects can be directly measured (c.f., Gaudi et al. 2012, Sahu et al. 2017). Although the most common way to observe this phenomenon is via the photometric lensing effect, astrometric lensing leverages the inherent azimuthal asymmetry in the morphology of the two temporarily generated images to measure a shift in the centroid of the microlensing ``target’’ (lens + source).

The astrometric shift, $\boldsymbol{\delta}$ (Walker et al. 1995; Lu et al. 2016), and angular Einstein radius, θ_E, are:

$$\boldsymbol{\delta}_{\boldsymbol{c}}(t) = \frac{\theta_{\mathrm{E}}}{u(t)^2+2}\boldsymbol{u}(t) \qquad\qquad \theta_{\mathrm{E}} = \sqrt{\frac{4GM_\ell}{c^2}\left(D_\ell{}^{-1} - D_s{}^{-1}\right)}$$

where u and **u** represent the scalar and vector time-dependent lens-source separation in the plane of the sky normalized to θ_E, M_ℓ is the mass of the lens, and D_ℓ and D_s are the distances to the lens and source. When these equations are combined we find that (a) closer lens systems produce larger astrometric signals, and (b) if the distances to the lens and source are known, a measurement of the astrometric shift as a function of time yields the lens mass, with no further assumptions needed. Figure 2 shows the morphology of the astrometric lensing signal.

The peak magnitude, δ, for an event with a 10-Jupiter-mass lens at a distance of 10 pc lensing a background source located 2 kpc is ~1 mas. Lu et al. (2010) demonstrate that it is possible to achieve an astrometric precision as small as ~0.15 mas using Keck/NIRC2, indicating that, in principle, detecting an astrometric signal in the near-infrared from a nearby brown dwarf, and ultimately measuring its mass, given constraints on D_l and D_s, is eminently feasible.

The current measurements of parallaxes and proper motions of brown dwarfs (Kirkpatrick et al. 2019a) with median accuracy of 3 mas and 1.5 mas/yr, respectively, allow us to predict the lens-source separation with a precision of 10-20 mas, sufficient to foretell future astrometric microlensing events. However, because of the propagation of uncertainties, the accuracy of predictions deteriorates as proper motions are extended into the future, so continued monitoring of known brown dwarfs is necessary.

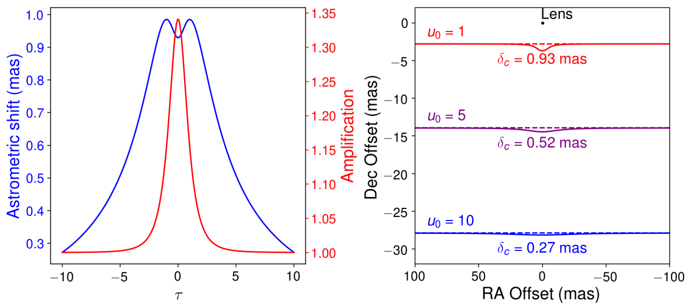

Figure 2: (Left) Comparison of the astrometric (blue) and photometric (red) signals of an event with a 10-pc, 10 M_{Jup} lens and a source at 2 kpc and a relative proper motion of 10 mas/yr. Note the offsets of the astrometric peak and its much longer signal. (Right) The relative trajectory of the source in the static frame of the lens for three different impact parameters, u_0. Observed trajectories (solid) and the trajectory in the absence of lensing (dashed) are shown.

Measuring Bolometric Luminosities

> Critical questions: What is driving the disagreement between observations and models in mass-age-luminosity space? How to we measure the luminosities of larger samples of brown dwarfs so that dependences with age, metallicity, and clouds can be further studied?

Brown dwarfs cool continuously as they age, so they never reach the main sequence where their luminosities remain constant for eons. Consequently, observational determination of the physical properties of brown dwarfs is hamstrung by a mass-age-luminosity degeneracy. Luminosities can be measured precisely when parallaxes are available (Filippazzo et al., 2015), but the age-mass degeneracy is difficult to break. Spectral features in young brown dwarfs provide rough ages (Cruz et al., 2009; Allers et al. 2013), but beyond ~200 Myr there are no reliable indicators of age for field brown dwarfs not bound to stellar primaries. As described earlier, the only current methods for determining accurate masses of field brown dwarfs are microlensing, which depends on fortuitous circumstances, and astrometric monitoring of binary orbits to measure the dynamical masses, which normally requires expensive high angular resolution observations and can take years to achieve a result. In other cases, masses are estimated from bolometric luminosities and an assumed age.

For the handful of brown dwarfs with known dynamical masses and strong age constraints, the evolutionary models predict luminosities that are a factor of ~2-4 lower than the measured values (Dupuy et al. 2009, 2014; Crepp et al. 2012; Wood et al. 2019). No satisfactory theoretical explanation for this discrepancy has emerged. In addition, L and T dwarfs of a given spectral type show a diversity of colors and luminosities, likely due to differences in atmospheric cloud properties, surface gravity, and metallicity (e.g., Saumon & Marley 2008; Faherty et al. 2013; Mace et al. 2013; Filippazzo et al. 2015). Careful examination of well-calibrated luminosities of brown dwarfs has enabled us to characterize young and old brown dwarf populations (Liu et al. 2016), but the sample with precise luminosities is not yet large enough to enable detailed studies of the effects of metallicity and clouds.

Large digital sky surveys such as SDSS, Pan-STARRS, 2MASS, UKIDSS, UHS, VHS, and WISE provide a wealth of multi-band photometry for brown dwarfs, and low-resolution spectra for >1500 brown dwarfs have been taken (Burgasser et al. 2017). The SPHEREx mission will obtain low-resolution spectra spanning 0.75-5.0 µm over the entire sky, providing even more precise spectral energy distributions. However, absolute calibration still requires parallaxes. The resulting luminosities will provide essential constraints for the new generation of evolutionary models that will appear in the next several years (Baraffe et al. 2015; Marley et al. 2017).

Summary: Instrumentation Needed in the Next Decade

Based on the research questions addressed in previous sections, we advocate for a continuance of dedicated infrared astrometric cameras on the ground. We also advocate for space-based facilities capable of GO astrometric follow-up or dedicated to an all-sky Gaia-like astrometric survey in the near- to mid-infrared. We note that the workhorse instrument for cold brown dwarf parallaxes, Spitzer/IRAC, is being retired in January 2020 despite continuing to be an invaluable resource for the studies discussed above (e.g., Dupuy & Kraus 2013; Luhman & Esplin 2014; Martin et al. 2018, Kirkpatrick et al. 2019a).

To measure bolometric luminosities, ground-based imagers for brighter brown dwarfs are still needed. Wide-field near-infrared imaging is needed to measure parallaxes of Gaia-invisible brown dwarfs spanning the full ranges of T_{eff}, age, and metallicity. We note with alarm that of the northern hemisphere's three most productive near-infrared imagers, UKIRT/WFCAM will be decommissioned by decade's end and CFHT/WIRCam may be decommissioned within five years, leaving only ASTROCAM on the USNO 1.55m Strand telescope.

To measure the low-mass cutoff of star formation, to uncover (and measure the parallaxes for) brown dwarfs with T_{eff} values analogous to gas giants, and to provide the astrometric precision needed to predict brown dwarf microlensing events, space-based facilities probing deeply at the correct wavelengths are needed. A minimum goal is a facility allowing us to perform accurate GO astrometric measurements (uncertainties <10%) on objects as faint as H~29 mag or, alternatively, to [5μm]~19 mag. A stretch goal is to have an all-sky infrared version of Gaia that extends to [5μm]~19 mag so that object pre-selection is not even required.

Any high precision astrometric mission will also enable an improvement of the Gaia results for common objects in the same way Gaia allowed an improvement to HIPPARCOS results. Under the assumption that systematic focal plane differences between Gaia and the new mission can be modeled, the parallax and proper motion errors improve as $\sigma_\mu \sim \sigma/(RMS_T\sqrt{N})$ and $\sigma_\varpi \sim \sigma/\sqrt{N}$, where N is the number of observations, σ is the average error in an individual observation, T is the epoch coverage, and RMS_T is the root-mean-square of the list of individual epochs. Thus, the proper motion improves directly with increased temporal coverage and both proper motion and parallax improve by root-N.

These additional observations will enable the modeling of binary system orbits with periods on the order of at least twice the total temporal coverage (Casertano et al. 2008). Also, current Gaia internal work shows acceleration solutions can be done with as little as 10% of the orbit. Hence a second mission 10-20 years after Gaia could increase the binary orbit samples from 50 to 200 years. Finally, comparing proper motions in HIPPARCOS and Gaia has shown that variable proper motions are a direct indication of orbital motion and thus unresolved binarity, allowing us to put limits on orbit sizes and companion masses (Calissendorff & Janson 2018).

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