# Astro2020 Science White Paper

# The IMF at Very Low Mass using Near-IR Surveys from Space: The Need for Deep K-band Imaging

**Thematic Areas:** ☐ Planetary Systems ☑ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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**Abstract (optional):**

# 1 Introduction

The relative distribution by mass of stars that arises from a single star-forming event - the Initial Mass Function - provides one of the most readily observed windows into the physics of star-formation. Empirical determinations of the IMF have been made for a wide range of stellar environments, sampling populations of stars within our own Galaxy and in external galaxies. The shape of the IMF at high masses appears to be at least roughly invariant from region to region within our own Galaxy, and perhaps even within external galaxies of varying mass (Bastian, Covey & Meyer 2010; Myers et al. 2011; Krumholz et al. 2014). This "universality" of the IMF at high masses suggests that some single process dominates the physics in this mass regime, with competitive accretion (Zinnecker 1982) and turbulent fragmentation (Padoan et al. 1997) being the most commonly cited possible mechanisms.

The shape of the IMF and its variation with environment at low mass is a subject where much less is known. While stars and substellar objects with masses $M < 0.5\ M_{\odot}$ contribute little light and relatively little mass on galactic scales, and are therefore perhaps of less "importance" for modeling galaxy formation and evolution (Krumholz 2014), they are still the most numerous stellar class (Bochanski et al. 2010) and are important for elucidating the physical processes that govern star and planet formation. Outstanding questions include: What is the fragmentation lower mass limit for isolated star formation, and is it a function of metallicity or environment? Is there more than one pathway for producing substellar and planetary mass objects, and if so are the properties of objects of the same mass formed by different pathways different or essentially the same? Is the IMF at very low masses a function of metallicity?

The past two decades have provided astronomers with an ever-expanding set of wide-area, multi-color optical imaging surveys of the sky (SDSS; PAN-STARRS; Gaia-DR2; APASS; Sky-Mapper). These general-purpose surveys, and many more targeted imaging surveys aimed at specific science topics, have provided the source material to greatly improve our knowledge of galactic structure, stellar-populations, star-formation and the stellar IMF for $M > 0.5\ M_{\odot}$ in different environments, to name a few. Optical surveys that are already in progress or that will begin soon (ZTF; LSST; Gaia-DRn) will greatly add to this panoply of data. In the near-IR, 2MASS and WISE were for many years the primary wide-field survey that could be used to address this science. A new generation of relatively deep, wide-field, ground-based near-IR surveys is just now becoming available (UHS - Dye et al. 2018; VHS - Banerji et al. 2015) and they are providing new insights into the low-mass IMF. EUCLID and WFIRST will take the next step by providing space-based imaging for $\lambda < 2.0\ \mu$m of thousands of square degrees of the sky to very deep limits and with high spatial resolution and good astrometric accuracy.

The capability for the next generation of deep, wide-field surveys to improve our understanding of the physics of the IMF at very low masses could be dramatically enhanced by the addition of space-quality data at K-band. K-band is crucial because it allows by far the deepest search for isolated planetary mass objects (PMO's) and the cleanest sorting by metallicity for the lowest mass stars and brown dwarfs, as we detail below. We describe two specific programs which could be conducted if an appropriately equipped, wide-field, space-based facility were available and which would greatly improve our understanding of the IMF at low masses. These programs require either a modest change to one of the planned NASA missions, or funding of a new, purpose-built mission designed for deep, wide-field imaging at K-band.

# 2 The Dependence of the Low Mass Limit of the IMF on Metallicity and Environment

The first brown dwarfs were discovered only a little more than two decades ago. Now, primarily based on wide, relatively shallow infrared surveys conducted by 2MASS and WISE, there are thousands of known brown dwarfs and three new spectral types (L, T and Y) spanning effective temperature ranges from 2500K to 300K. Recent efforts have concentrated on refining the spectral classifications to account for surface gravity and metallicity, thereby allowing identification of brown dwarfs that are either young or of low metallicity (Burgasser et al. 2003; Kirkpatrick et al. 2006; Cruz et al. 2009; Allers & Liu 2013; Best et al. 2017; Zhang et al. 2017a). The number of known young or low metallicity brown dwarfs is small now, but could be expanded by 100x in the next decade if a suitable K-band imaging capability existed , enabling new quantitative tests of how the low mass IMF arises and its dependence on physical quantities such as metallicity..

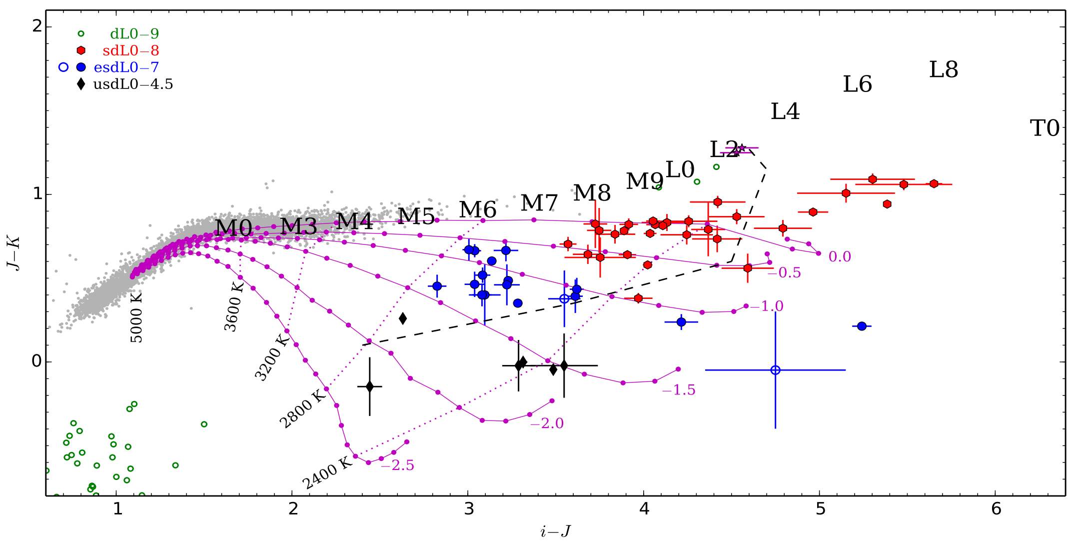


Figure 1: Color-color plot from Zhang et al. (2018), illustrating the ability to distinguish metallicity classes for late-M, L, and early T dwarfs/subdwarfs using $J - K$ color. Grey and green dots demarcate the solar-metallicity sequence from F through L spectral types. Other colored points mark the locations of known late-M and L subdwarfs. The magenta lines represent families of curves from the BT-Settl model grids (Baraffe et al. 2015) whose metallicities (in magenta) and $T_{eff}$ values (in black) are shown. If K-band data were added to the WFIRST High-Latitude Survey, a similar diagram for a volume of space 5000 times larger could be produced.

As the intermediate step between stars and planets, brown dwarfs provide insights into the fundamental physics governing the formation and evolution of both their smaller and larger cousins. However, because substellar objects are both cool and small, the existing substellar census is almost entirely representative of the Pop I disk of the Milky Way. Only about eighty subdwarf L and T dwarfs (i.e. L and T dwarfs with halo or thick disk metallicities) have been discovered (Zhang et al. 2018). By combining deep, wide-area, space-based K band imaging data with existing or planned survey data, it would be possible to not only identify a very large sample of L and T subdwarfs, but also to sort them by temperature and metallicity and thereby allow that census to provide fundamentally new data on the dependence of the star-forming process on metallicity at low mass. Figure 1 illustrates that a filter set which includes i, J and K band can be used very effectively to sort L and T dwarfs by metallicity; this is due to collision-induced $H_2$ absorption, which most strongly suppresses the K-band flux and thereby causes M, L and T dwarfs to have increasingly blue $J - K$ colors with decreasing metallicity (Linsky et al. 1969; Burgasser et al 2002; Burningham et al 2014; Borysow et al. 1997).

The largest areal survey to date for low mass subdwarfs (Kirkpatrick et al. 2016) used proper motions from the all-sky AllWISE processing (Cutri et al. 2013) to identify nine L subdwarfs that, because they are bright and nearby, serve as the prototypes of their class. The deepest survey for L subdwarfs to date (Zhang et al. 2018) used imaging of 3000 square degrees from the UKIRT Large Area Survey and SDSS, identifying 34 L subdwarfs down to K $\sim$ 17 mag (Vega) and to distances of order 100 pc. By combining i-band data from LSST, J band data from the WFIRST 2000-sq-deg HLS, and K band data matched to the HLS J-band data - e.g. 5$\sigma$ K-band detections to K $\sim$ 23.5 mag (Vega) - such survey data could identify M, L and T subdwarfs over a volume five thousand times larger than the Zhang et al. study, to distances of $\sim$2 kpc (identifying more than 500 halo and thick-disk T subdwarfs based on existing model fits).

The Pop I disk is rotationally supported; the halo is mostly pressure supported. Therefore, halo stars in the solar neighborhood have streaming motions in the direction of the disk rotation of order 200 km s$^{-1}$. Thick disk stars are intermediate in their kinematics, but still have a quite large streaming motion relative to the Pop I disk. A single-band second epoch of the WFIRST HLS taken several years after the original HLS could essentially identify every halo and thick-disk star in the HLS survey area via its proper motion, but deep K-band imaging is needed to sort these stars by metallicity. Specifically, at a distance of 2 kpc, 200 km/s corresponds to about 20 mas/yr if the motion is in the plane of the sky. This can be compared to the expectation[1] that the HLS will be able to produce proper motion accuracies of order 0.1 mas/yr for a baseline of 5 years for stars brighter than magnitude 23.

Intriguing additional science is also possible. The luminosity function of old populations should show a gap between the bottom of the stellar sequence and the most luminous substellar objects. The gap should increase as the population ages. Measuring this gap as a function of metallicity class (surrogate for age) in a K-band supplemented, dual-epoch HLS, could provide a direct measure of the cooling timescale for high mass brown dwarfs. The recent discovery that the inner halo of our galaxy is dominated by debris from ingestion of a Magellanic Cloud-sized galaxy about 10 Gyr ago, and that that event may have significantly affected the dynamics of the MW thick disk (Helmi et al. 2017) suggests that a subdwarf census such as envisioned could allow comparison of the low-mass IMF of the MW and the Gaia-Enceladus collider.

# 3 The Low-Mass Fragmentation Limit for Star-Formation

What is it that defines the lower mass limit for the star-forming process? Are their multiple paths to produce objects near this mass limit (and if so, which one is dominant)? If there are multiple paths to the creation of objects with M $<$ 10-15 $M_{Jup}$, can one identify which objects were formed by which mechanism?

[1] https://conference.ipac.caltech.edu/wfirst2016/system/media_files/binaries/29/original/WFIRST_Astrometry_Spergel.pdf

The bottom of the IMF was originally defined to be the mass below which fragments from the collapse of a molecular cloud should be sufficiently optically thick to their own thermal radiation that they could not radiate away their gravitational binding energy in a free-fall timescale (Rees 1976; Low & Lynden-Bell 1976). Typical estimates for this mass limit are around 10 $M_{Jup}$.

Because objects near the fragmentation limit are small and cool, attempts to identify them must be made when they are quite young. Lodieu et al. (2007, 2013) have conducted the most stringent search to identify the fragmentation limit for formation of free-floating PMO's by obtaining deep, near-IR imaging of 13 square degrees of the $\sim$10 Myr old Upper Sco association. Figure 2 shows the result of this survey, which appears to have identified more than a dozen planetary mass members based on their color-magnitude diagram position, proper motions consistent with Upper Sco membership, and spectroscopic confirmation for 12 of the faintest 15 objects (which shows that they are young L dwarfs) . The faintest objects have $K \sim 17$ mag and estimated mass of about 6 $M_{\rm Jup}$, with no evidence that the sequence has ended.

A space-based J and K band survey of the entire Sco-Cen association ($>$ 1000 square degrees), plus perhaps additional regions in Orion and Taurus, could identify 50-100 times more $K < 17$ planetary mass objects and go more than 5 magnitudes fainter at $K$, to a mass well below 1 $M_{\rm Jup}$. With two epochs of $K$ imaging separated by five years, and one epoch at both $J$ and $K$, such a survey could provide much better proper motion membership data (relative to ground surveys), a much larger sample, and definitively measure the fragmentation limit or show that it is below a Saturn mass. Because Upper Sco's proper motion is about 30 mas/yr, the proposed data would easily prove or refute membership based on kinematics. If these solivagant planetary mass objects have space motions of a few km/sec relative to their stellar counterparts (because they have been ejected from a forming disk, for example), that would also be within the grasp of these data (1 km/s at 150 pc corresponds to 1.3 mas/yr motion). A $K$-band filter is required for this science because the planetary mass objects of most interest – with masses 0.5 to 10 $M_{\rm Jup}$ – should have temperatures in the range 1200-2000 K at ages of 5-15 Myr (appropriate for Sco-Cen); they should thus have L dwarf spectral types and be *very* red, with $V - K \sim 10$ mag and $J - K \sim 2$ mag or more. In fact, these planetary mass, very young objects have been found to be even redder than old L dwarfs of the same spectral type (see the RHS of Figure 2) - possibly due to enhanced dust formation at low surface gravities (Bowler et al. 2017).

# 4 Other Benefits of a K-Band Capable Space Telescope

The IMF we observe is the result of many processes, each of which may significantly affect the resultant distribution of stellar masses. Low mass stars attain their final mass primarily from disk accretion - but it is still unknown what fraction of the accreted mass arises from slow, steady-state accretion and what fraction arises from short-duration, high mass-accretion rate episodes (FU Ori events). Among high mass stars, binary star mergers may significantly affect the final IMF slope. Time domain astronomy (TDA) is one way to address each of these topics.

In addition to the IMF survey science potential, a wide-field, space-based 2-3 meter telescope at L2 or similar orbit enabling deep K-band imaging would make for a powerful and unique capability for TDA in the near-infrared. If equipped with current generation IR arrays, the K-band capability could be coupled with much better spatial resolution than LSST or Spitzer, a critical advantage for exploring the transient source populations in the Galactic plane.

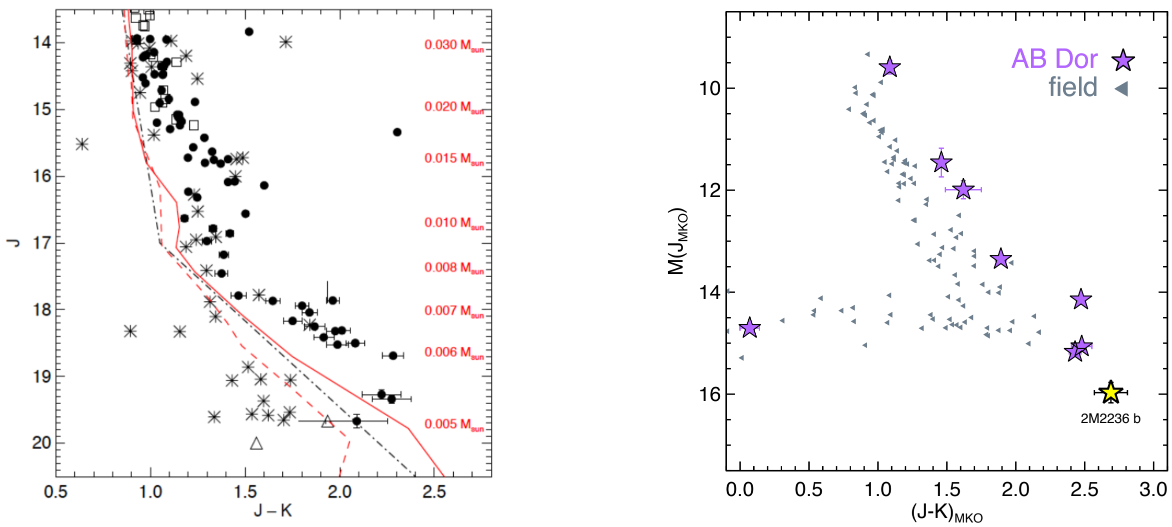


Figure 2: (LHS) $J$ vs. $J-K$ color-magnitude diagram from Lodieu et al. (2013) for a 13-sq-deg region within the Upper Sco association (distance ∼150 pc; age ∼10 Myr). A sequence of planetary mass candidates extends to the faint limit of the survey, with the lowest mass objects likely being about 8 $M_{Jup}$ (filled dots: likely Upper Sco members; asterisks: photometric non-members). A deep, space-based survey of the entire Sco-Cen association could extend these searches to objects well below 1 $M_{Jup}$. (RHS) Similar color-magnitude diagram for low mass members of the ∼100 Myr age AB Dor moving group (Bowler et al. 2017). The yellow star shows the location of an 11 $M_{Jup}$ late-L dwarf member of AB Dor; it is also very red and faint relatively to the field sequence.

A multi-epoch K-band survey of the most active star-forming regions in the Galactic plane would provide the data needed to identify and characterize the explosive events in high-mass star-forming regions that have only recently begun to be detected (Bally et al. 2015; Hunter et al. 2017). These events have been found in very crowded, heavily embedded regions (and thus outside the capabilities of LSST), requiring good spatial resolution and the longest wavelength filters possible. Do young high mass stars grow primarily from mergers or from intermittent, high accretion rate bursts from their circumstellar disks? The same survey would also provide the most sensitive survey for FU Ori events among low-mass YSO's in the same Galactic-plane fields.

# 5 Requirements and Needed Resources

The IMF science proposed here requires a 2-3 meter space-telescope with a wide-field camera, detectors with red cutoff near 2.5 $\mu$m, small pixels (for good astrometry), and an operating temperature cool enough to allow deep imaging with a $K_s$-type filter. NASA is already funding such a telescope - WFIRST - but the current design does not include a K-band filter. The cheapest way to accomplish the IMF science we advocate would be to add a K-band filter to WFIRST. Alternatively, NASA could fund a new mission whose thermal performance is optimized for 1-3 $\mu$m wide-field imaging, allowing fundamental advances on many topics, including the IMF.

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