Astrometry - Challenging our Understanding of Stellar Structure and Evolution

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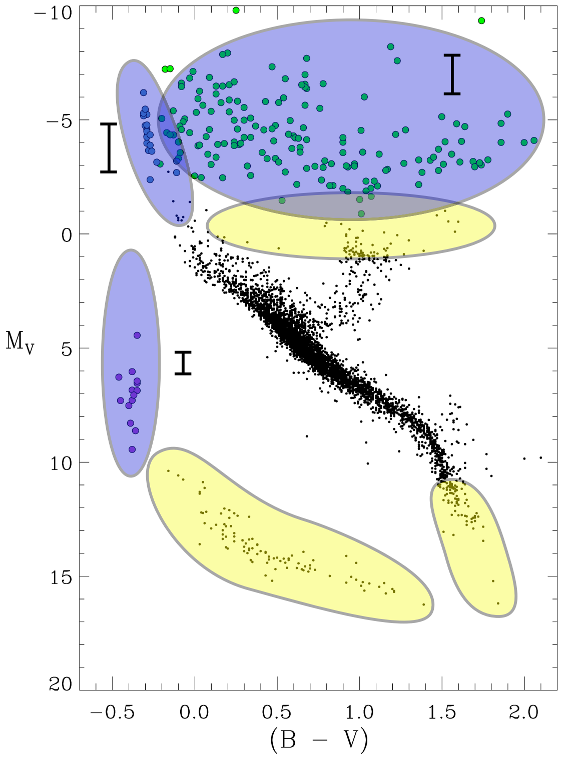

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ABSTRACT

Stellar mass plays a central role in our understanding of star formation and aging. Stellar astronomy is largely based on two maps, both dependent on mass, either indirectly or directly: the Hertzprung-Russell Diagram (HRD) and the Mass-Luminosity Relation (MLR). The extremes of both maps, while not *terra incognita*, are characterized by large uncertainties. A precise HRD requires precise distance obtained by direct measurement of parallax. A precise MLR requires precise measurement of binary orbital parameters, with the ultimate goal the critical test of theoretical stellar models. Such tests require mass accuracies of $\sim$1%. Substantial improvement in both maps requires astrometry with microsecond of arc measurement precision. Why? First, the 'tops' of both stellar maps contain relatively rare objects, for which large populations are not found until the observing horizon reaches hundreds or thousands of parsecs. Second, the 'bottoms' and 'sides' of both maps contain stars, either intrinsically faint, or whose rarity guarantees great distance, hence apparent faintness. With an extensive collection of high accuracy masses that can only be provided by astrometry with microsecond of arc measurement precision, astronomers will be able to stress test theoretical models of stars at any mass and at every stage in their aging processes.

1 Distances to Objects at the Extremes of the Hertzsprung-Russell Diagram

The HRD is generally the first figure a stellar astronomer considers to understand any given star in context. All classes of stars appear on the HRD, including supergiants, AGB stars, giants, subgiants, dwarfs, subdwarfs, and white dwarfs, as well as other exotic stars. The HRD maps a star's temperature and luminosity, which together determine the star's radius. However, placing a star on the HR diagram requires knowledge of its luminosity, thus an accurate distance measurement. Trigonometric parallax is the most reliable and straightforward method of measuring stellar distances, and is usually the most accurate method as well. Ground-based parallax efforts have pushed forward for 170 years (e.g., the summary in the Yale Parallax Catalog, van Altena *et al.* 1995). In the past 20 years, space-based efforts have made great headway, from Hipparcos results (ESA 1997; van Leeuwen 2008) to the Hubble Space Telescope (Benedict *et al.* 2007). Figure 1 shows an observational HRD. In the coming era, astrometric efforts like Pan-STARRS, LSST, and Gaia will measure parallaxes of millions of stars to unprecedented precision. Even so, there remain rare, astrophysically compelling objects at such great distances in the Galaxy that only astrometers with precision better than 10 microseconds of arc (10 μas) and heretofore unprecedented sensitivity can provide accurate luminosities.

•The massive **O stars** are among the brightest objects observed in galaxies and they play a central role in sculpting the ISM (through their radiative and mechanical energy input), while driving the chemical enrichment of galaxies. With lives of only a few million years, they quickly burn through their fuel and explode catastrophically in supernovae. However, the fundamental parameters of these extraordinarily rare stars are still poorly known because they are generally found at large distances. Some O stars are found in clusters, but roughly 20% are runaways or field O stars while many others are found in loose associations with poorly-defined boundaries and distances, e.g., the Cep OB6 association has a 3° extent and a consequent 5% dispersion (1σ) in distance (Benedict et al 2002).

The placement of massive stars in the HRD relies heavily at present on model atmospheres. Hot stars all have essentially the same colors in the optical/IR spectral range (after correcting for interstellar reddening), so estimates of their effective temperatures are made by comparing spectral line profiles with those calculated from sophisticated models (Repolust et al 2004); the resulting temperature estimates are typically accurate only to 5%. Their luminosities are determined from their absolute magnitudes and bolometric corrections (again derived from models for the estimated temperature), but reliable absolute magnitudes are only available for O stars in clusters where distances are known from other techniques. For the majority of O stars, the absolute magnitudes are estimated from spectral classification calibrations (based upon those stars in clusters) which typically result in 25% distance errors, consequently resulting in luminosity errors approaching 50%. Thus, the observational HRD only loosely constrains modern evolutionary models for massive stars (Herrero et al 2007). Progress will clearly require better distance measurements from accurate trigonometric parallaxes.

Distances accurate to 1% will provide the accurate luminosities crucial to testing assumptions about interior structure, in particular the role of rotation and meridional circulation (Ekström et al 2008), important for the kinds of supernovae and compact remnants produced by massive stars. A 1% error also corresponds to the typical errors in luminosity from errors in effective temperature that will come from new ground based interferometric observations, and errors in angular size derived from the spectral energy distribution and errors in extinction (Fitzpatrick & Massa 2007).

• Found among the naked eye stars are many famous **supergiants**, many of which are not in clusters, so fainter stars cannot be used as proxies for determining distances. Parallaxes accurate to 4 μas will enable astronomers to (1) pinpoint supergiants' luminosities on the HRD, (2) understand how metallicities affect their positions, and (3) improve the wind-momentum-luminosity and flux-weighted gravity-relations used to derive extragalactic distances. In addition, a bright star parallax program offers a valuable public outreach opportunity — astronomers will be able to tell anyone who might ask where the stars they can see are in our Galaxy.

• Distances to **Planetary Nebulae (PNe)** are important for understanding the physics of the nebulae, the evolutionary state of the central stars (e.g., time since the ejection of material), and the space density and formation rate of PNe. At present, however, distances are notoriously uncertain, both in terms of systematic effects and for individual nebulae. Only 16 have measured trigonometric parallaxes (Benedict et al 2003; Harris et al 2007), and distances are large enough for most PNe to preclude many more being measured until we achieve μas astrometric precision. There are roughly 2000 PNe known in the Galaxy, many in and around the Galactic bulge They include a large variety of types, and understanding these different types adds scientific importance to getting accurate distances to many PNe. One additional product of μas astrometry will be the identification of binary motion for PNe central stars. One theory of the origin of bipolar symmetry seen in many PNe argues that binary central stars are common. A high-cadence μas campaign on a selected sample of bright (V$\sim$15) central stars in bipolar PNe could provide constraints on the frequency of binaries and characterize their orbits.

2 An Improved Mass-Luminosity Relation and Masses of Stars at Evolutionary Extremes

Mass is arguably the single most important characteristic of a star, as it determines a star's size and color, as well as how long it will live and what fuels it will burn. Knowing the masses of main sequence stars answers basic astrophysical questions such as, *What is the biggest star? What is the smallest star? How is the mass of a stellar nursery partitioned into various types of stars?* and, *What is the mass content of the Galaxy and how does it evolve?* To answer these and other fundamental questions requires masses to 1% accuracy. Why 1%? Our knowledge of stars consists of surface temperature, T_e; apparent magnitude; metallicity; distance, hence luminosity; and through T_e (or long-baseline interferometry), radius; and stellar mass, M. At a 5% level of mass precision, luminosities are uncertain by 12 to 22%. This luminosity uncertainty means, for example, that radii would be very poorly determined, rendering them far less useful as checks of stellar models. At the 1% level of mass precision the variation in luminosity is now only 2 to 4%. This precision of luminosity will allow choices to be made between various modeling approaches, which could include stellar phenomena such as convection, mass loss, turbulent mixing, rotation, and magnetic activity (Andersen 1998). Of the $\sim$40 stars with masses this accurately known (all in eclipsing binaries), three-quarters have masses between 1 and 3 $M_\odot$, a limited range over which to test stellar models.

The MLR's broad appeal is its applicability to many areas of astronomy. A reliable MLR lets us use a star's luminosity as a proxy for its mass, which is a valuable commodity in radial velocity, astrometric, cataclysmic binary, and extrasolar planet work. In the broader Galactic context, an accurate MLR provides benchmarks for comparisons to objects in stellar clusters, and allows us to estimate just how much of the "missing" mass is made up of the smallest stars. At the faint end of the stellar main sequence, the MLR is crucial for brown dwarf studies because measurement of a sufficiently small mass can demonstrate that a star is a *bona fide* brown dwarf. High accuracy masses are needed because (as shown in Figure 1) the width of the main sequence on the MLR is 20% or more at a given luminosity. Even though the individual stellar masses calculated to date are determined to 5% or better, they are of mixed pedigree in age and metallicity. An astrometer with μas precision is needed to measure masses accurate to 1% in myriad environments and for a suite of different kinds of stars, and stages of stellar evolution which until now have never resided in an MLR.

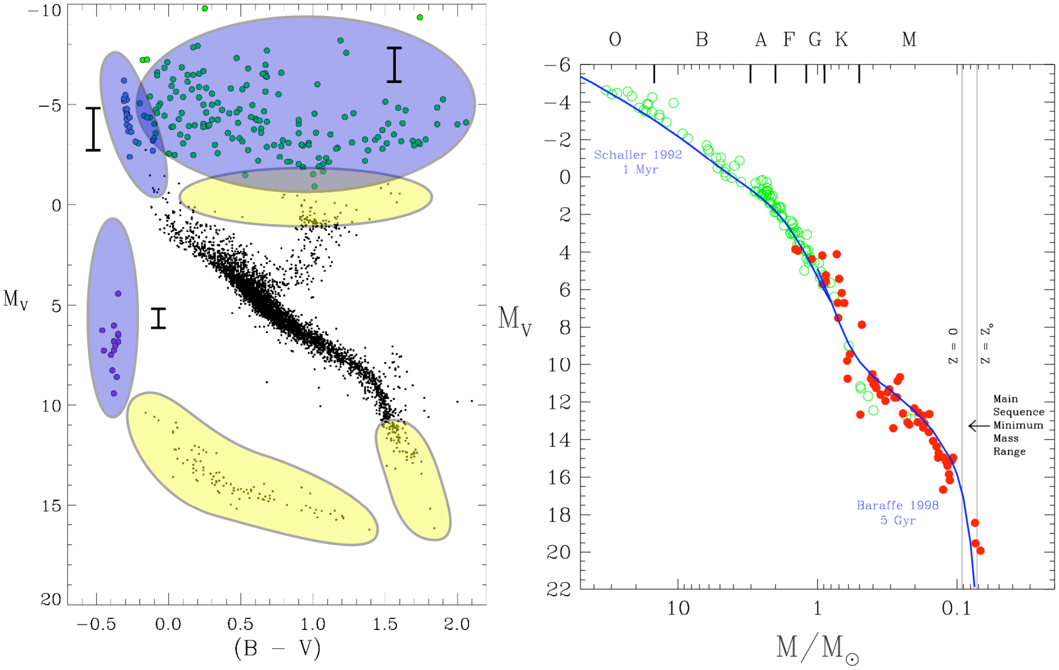

Figure 1: **Left:** Characteristic regions of the HR Diagram to be explored effectively by astrometers with $\sigma_\pi < 5\mu$as (blue) and $\sigma_\pi < 10\mu$as (yellow), with error bars representative of current knowledge near the blue regions. Supergiants are from Hipparcos, with mean parallax error 37%. A representative sample of O stars is shown, although only six parallaxes are currently available with errors less than 20%. PNe central stars with parallaxes from Harris et al (2007) are also shown, for which the average parallax error is 19%. Main sequence and giant branch data points are from Hipparcos (van Leeuwen 2007 updated to 2008) Data for white dwarfs have been taken from Bergeron et al (2001). **Right:** The mass-luminosity relation in 2008, using eclipsing binary data (open green points) from Andersen (1991) and others, supplemented with visual binary data (solid red points) from Henry (private communication). Model curves for the MLR at the indicated ages and solar metallicity are shown, from Schaller et al (1992) at high masses and Baraffe et al (1998) at low masses. Note the spread in empirical mass determinations at a given luminosity throughout the main sequence, caused primarily by different ages and metallicities.

Typically, stellar mass estimates come from measurements of the orbital motions of binary stars. The most accurate stellar masses have been inferred from studies of eclipsing spectroscopic binaries (Andersen 1991), but this method is limited. At the highest masses, only a few known eclipsing systems contain O stars (Gies 2003), and many of these are interacting systems whose members may not be representative of single stars. At the lowest masses, stars are small, so few binaries eclipse and visual binaries must be used (Henry et al 1999). Other rare, but important types of evolved stars remain almost completely unmeasured. To significantly improve the MLR at its extremes we require a combination of exquisitely accurate astrometry, faint magnitude limit, bright magnitude limit, and flexible scheduling.

The 'gold standard' method, applicable no matter what the binary geometry, consists of resolving the system and measuring the relative orbits referenced to a grid of reference stars. Resolution is particularly important for the MLR because the component luminosities must be measured to place the stars on the MLR (and on the HRD). To reach 1% mass accuracy, an inclination precision of 0.2% is required for an orbit with $i = 45°$, assuming uncertainties in other orbital parameters do not dominate. For resolvable binaries, the minimum requirement for a 1% mass determination is a 0.33% distance measurement, which corresponds to 833 pc for a 4 μas measurement.

- **White dwarf** research has far reaching implications in diverse astronomical fields, from cosmology to Galactic halo populations to nearby star studies. From the youngest WDs found as central stars in PNe to the oldest WDs from the halo, only μas faint-star astrometry brings unusual objects (with various compositions and ages) into reach for mass determinations. Nearly every aspect of WD research relies on the theoretical mass-radius relation for WDs. This relationship depends on the internal composition of the WD. Ideally, WD masses need to be known to 1% (or better) to stress test the mass-radius relation to reveal the true chemical makeup of WDs, and permit us to discriminate, for example, between different hydrogen envelope masses (Jordan 2007).

To date, empirical masses to support the theoretical mass-radius relationship are severely limited — only three WDs have dynamical mass measurements known to better than 5%, Sirius B, Procyon B, and 40 Eri B (Provencal *et al.* 2002). Other WDs with masses, such as the remaining 18 WDs that populate the mass-radius relation in Figure 13 of Provencal et al (2002), have masses gleaned from gravitational redshift studies of common proper motion systems (in which a companion is used to determine systemic parameters) or have spectroscopically inferred masses. In general, such mass determinations are rather poorly constrained, with errors of 10% or more. Through ongoing studies of double degenerate systems with Hubble Space Telescope's Fine Guidance Sensors, eight systems have already been identified that might provide masses accurate to 1% when examined by an astrometer with μas precision. At separations of a few to tens of milliarcseconds, these systems can be resolved only by long-baseline interferometry. Such a device will play a crucial role in populating the mass-radius diagram with multiple empirical checks of the theoretical mass-radius relation while providing details of the internal structures of WDs.

- Although extremely **massive stars** (O stars) are rare, as a group they are known to contain many binaries, with a multiplicity fraction of 75% for those found in clusters or associations (Mason et al 1998). However, mass estimates for such systems may tell us more about the evolutionary mass exchange histories of binaries rather than providing fundamental data to calibrate the properties of stars in general. For non-interacting, non-eclipsing O star binaries, masses are determined by supplementing an SB2 orbit with a precisely determined orbital inclination, or by resolving the binary and finding the shape of the orbit. Because O stars are rare and consequently distant, such measurements will require μas astrometric measurements. For example HD 93205 resides in the Carina Nebula region at a distance of 2.6 kpc. This is a 6d binary consisting of O3 V and O8 V stars (Antokhina et al 2000), and the maximum photocenter motion will be in the range of 9–16 μas (depending on the adopted flux ratio). Microsecond of arc measurement precision and flexible scheduling are required to obtain the orbital inclination and distance of this system and to obtain the mass of a star at the top of the main sequence.

- **Pre-Main Sequence Stars**. With the exception of solar mass objects, evolution of stars from birth to the zero-age main sequence is poorly calibrated (Schaefer *et al.* 2008 and references therein). Binaries in star formation regions provide an opportunity to determine precise dynamical masses in low-mass, young star systems (e.g., Prato *et al.* 2002; Hillenbrand and White 2004). Fewer than 100 pre-main sequence (PMS) spectroscopic binaries (SBs) are currently known (Melo *et al.* 2001), and even fewer eclipsing PMS SBs have been identified (Stassun *et al.* 2007). Mass determinations of a few dozen binaries among the youngest T Tauri star populations that are accurate to a few percent would revolutionize models of young star evolution. Astrometric capability at the 4 μas level is required to accurately determine the orbit of the photocenter of the shortest period (<100 days) T Tauri SBs, providing the system inclinations and hence absolute component masses to the required few percent precision for meaningful calibration of evolutionary tracks.

- **Open star clusters** are laboratories for the study of stellar astrophysics because they provide large numbers of stars with the same age and chemical composition. To date, the only cluster for which an MLR has been determined is the Hyades (Torres *et al.* 1997). However, the Hyades MLR extends only from 2.4 to 0.8 $M_\odot$ with mass errors of 5–10%. This MLR is insufficient for critical tests of the models and does not include the smallest stars, for which the age and metallicity effects are most pronounced. An astrometer with μas accuracy is needed to reduce these errors to the 1% level needed for meaningful analyses. To maintain a 1% mass accuracy beyond about 200 pc requires raw resolution and an astrometer that can be flexibly scheduled to provide coverage near crucial periastron passages to yield the most accurate masses possible. Of special interest is the production of a reliable MLR for ancient (and distant!) M67, whose constituent stars are all the same age an metallicity as the Sun. Overall, what is particularly compelling is that for a suitable astrometer target clusters span a range of 1000 in age, thereby providing a framework within which to study many aspects of stellar evolution, once accurate distances and masses are available.

3 The Coming Era of Microsecond of arc Astrometry: Gaia and SIM

Both the Gaia and the Space Interferometry Mission (SIM) efforts will revolutionize our understanding of stellar astrophysics via the HRD and MLR maps, albeit in different ways. Gaia's high precision astrometry of one billion sources will provide superb measurements of luminosities, temperatures, and masses of most of the stellar main sequence, giants, subdwarfs, and white dwarfs. More specifically, Gaia will determine distances to 1% for 10^7 stars having V=6–13 within $\sim$1 kpc (Lindegren *et al.* 2008).

SIM provides complementary depth to Gaia's astrometry in specific regimes of both magnitude and distance. SIM can effectively observe stars with V~ -1 to at least 18, adding complementary phase space at bright magnitudes to Gaia's bright cutoff at V$\sim$6 and making more accurate astrometric measurements at the faint end. Thus, only SIM can pinpoint the locations of many of famous naked-eye stars in the night sky while opening up new territory for intrinsically faint stars at tens or hundreds of parsecs. For magnitudes 6–13, SIM's wide-angle mode parallax precision of 4 μas is modestly better than Gaia's 8 μas, which will observe a far larger stellar sample. For magnitudes 14–18, SIM's precision is 3–20 times better than Gaia's (Lindegren *et al.* 2008). The combination of the ability to observe bright objects at all, and faint objects with superior precision, provides several niches important to stellar astronomy that only SIM can explore. In nearly every category Gaia will be a pathfinder for SIM, much like the Palomar Schmidt was for the 200-inch telescope.

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