Fundamental Stellar Physics throughout the Galaxy

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Introduction

Stars drive the chemical evolution of the universe. Our understanding of how stars form, evolve, and die is fundamental to our understanding of a wide range of topics, from circumstellar disks and exoplanets, to the life history of galaxies, cosmological distance scales, and primordial nucleosynthesis. Stars also provide the environment for planet formation, both their own and those of their neighbors in dense environments, and are one of the most important components in defining a planet's habitability. Although stars have been a primary target of astrophysical investigation for more than a century, new instruments open the door for exciting new discoveries in the field. Open clusters with well-determined membership and distances present hundreds or thousands of stars of uniform age but at a range of masses and evolutionary states. They are ideal for improving our understanding of how stars and exoplanet systems form and evolve. At present, precision spectroscopic measurements of Sun-like stars and low dispersion measurements of fainter populations (e.g. white dwarfs and M dwarfs) in exemplary clusters (e.g. M37 at 1.4 kpc) are photon-limited. Spectroscopy of stars across many clusters would provide benchmarks for models of stellar evolution, including unparalleled constraints on stellar masses, radii, rotation, dynamos, diffusion, core-convective overshoot, mass loss, the impact of binary companions, and the initial-final mass relation. The Giant Magellan Telescope (GMT), Thirty Meter Telescope (TMT), and Maunakea Spectroscopic Explorer (MSE) will offer unique opportunities to establish more powerful constraints on stellar evolution by extending cluster studies to larger, more diverse samples at greater distances and to lower stellar masses. Here, several examples illustrate how multi-object or high-resolution spectroscopy, or high-spatial resolution imaging, can revolutionize open cluster studies by targeting the faintest stars in open clusters—white dwarfs and late-type M dwarfs.

The Initial-Final Mass Relation for White Dwarfs: Low-resolution spectroscopy of the strong Balmer features in the spectra of white dwarfs provide robust measures of their surface gravities and temperatures (Tremblay et al. 2011) and enable comparisons with cooling models to determine masses and cooling ages. Comparison of the cooling age to the total cluster age yields the evolutionary lifetime of the progenitor, and by inference its initial stellar mass. This establishes the poorly understood initial-final mass relation for stars. We note that these spectroscopic measurements are well matched to the multi-object spectroscopic sensitivity and field-of-view for the blue channel detectors of WFOS/TMT and GMACS/GMT, as well as to the MSE, for open clusters at distances of 0.5 - 1 kpc. With a better understanding of the initial-final mass relation, the effects of complex processes like stellar mass loss, dredge up, convective-core overshoot, and rotation can be investigated directly. Particularly interesting, but also challenging, are the highest mass white dwarfs (> 1 M_{Sun}) because of their smaller radii and fainter magnitudes (Cummings et al. 2016). A more complete assessment of the population would better delineate the stellar mass at which white dwarf formation ends and core-collapse supernovae begin, which defines the Type II supernova rate (Horiuchi et al. 2011). This also constrains the production rate of higher-mass CO-core white dwarfs, which help predict the Type Ia supernova rate (Greggio 2010).

The use of star clusters rather than Gaia field white dwarfs (e.g., El-Badry et al. 2018) to study the IFMR provides many advantages because it is independent of the IMF or Galaxy star formation history, does not have to assume progenitor metallicity, and is less sensitive to the adopted stellar evolutionary models and white dwarf cooling models. Additionally, the Gaia-based IFMR cannot test the IFMR's sensitivity to metallicity or to variations in progenitor rotation rate.

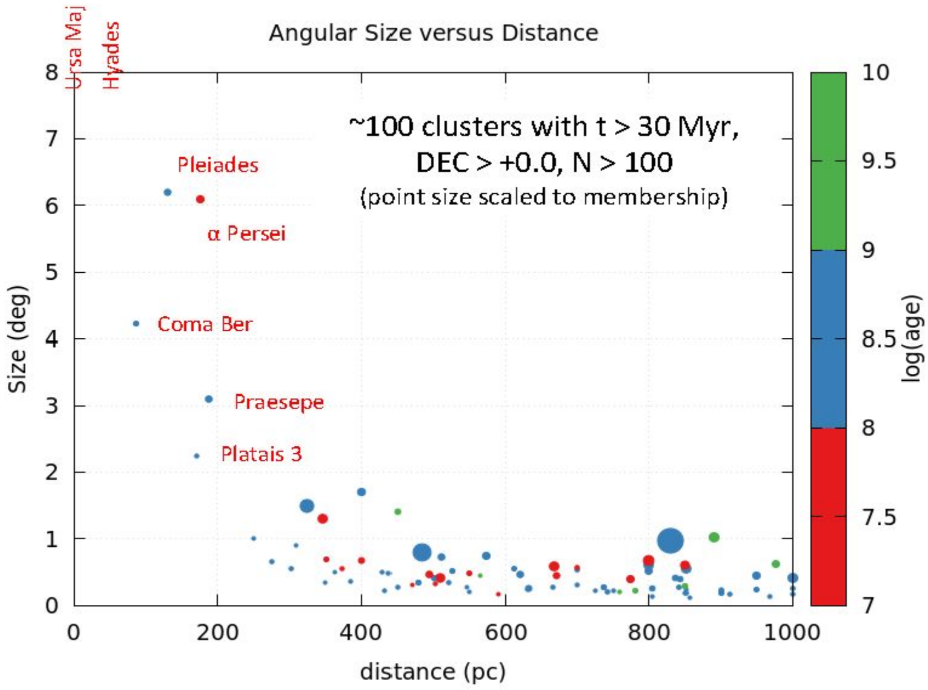

Figure 1: Angular sizes vs distances of open clusters from Kharchenko et al. (2015), restricted to δ > 0.0 (for TMT/WFOS). Point size is scaled to membership, and color indicates age; open clusters within 200 pc are labeled. Clusters further than 500 pc have angular sizes less than 1 degree and are well matched to the field-of-view of WFOS and GMACS. The closest and most compact clusters will optimize the observing program, but obtaining enough observations in clusters older than 1 Gyr will require that we can observe the faintest members out to 500 pc.

Cluster Ages from Lithium Depletion Boundaries: Despite the long-standing use of main sequence turn-off stars for measuring cluster ages, it is now known that the rapid rotation and gravity darkening associated with intermediate mass stars at the turn off point can bias age estimates by ~20% (Brandt & Huang 2016). Instead, the most robust absolute cluster ages come from the identification of the lithium depletion boundary (e.g., DÁntona & Mazzitelli 1994, Jeffries & Naylor 2001). The age is determined by identifying spectroscopically the temperature (and mass) at which the lithium depleted atmospheres transition rapidly to lithium-rich atmospheres at the lowest masses. This boundary evolves from late-M dwarfs for young clusters (< 100 Myr) to early L dwarfs for adolescent age clusters (> 500 Myr). We note that these spectroscopic measurements are well matched to the multi-object spectroscopic sensitivity and field-of-view for the red channel detectors of WFOS/TMT and GMACS/GMT for open clusters at distances of 500 - 1000 pc, and to the MSE for somewhat closer distances. Improved absolute ages for clusters would provide broad benefits to stellar and planetary astrophysics by improving the ages of clusters used to calibrate age relations like gyrochronology, cosmochronology, and chromospheric activity.

Ultra-high Precision Abundances: Ultra-high precision abundance determinations (accurate to 0.01−0.04 dex) will allow us to achieve a number of high impact goals. Among these are:

Solar Twins: The Sun has been shown to be somewhat poor in refractory elements relative to most twins in the solar neighborhood (Meléndez et al. 2009). The observed correlation between elemental abundance and condensation temperature is only observable from abundance determinations with precision better than ~ 0.02 dex. This finding has made it possible to study the conditions in the environment where the Sun was once formed, and to search for solar siblings in the Galaxy (Ramírez et al. 2014; Adibekyan et al. 2018).

Binaries: Stars in binary systems can exhibit differences in chemical composition ranging from ~ 0.02 dex to ~ 0.1 dex (Laws and Gonzalez 2001; Ramírez et al. 2011; Saffe et al. 2017; Oh et al. 2018). These differences seem to be correlated with the elemental condensation temperature. Moreover, most binaries showing these differences are known to host planets. These results demonstrate the possibility of using high-precision abundance analyses to trace fractionation of chemical elements in the early evolution of stars and planetary systems.

Cosmochronometry: There are tight, linear correlations between [Y/Mg] and [Ba/Mg] and stellar age among solar twin star in the solar neighborhood (Nissen 2015, 2016; Nissen et al. 2017; Spina et al. 2018), and Nissen (2015) proposed that the Y/Mg ratio can be used to determine precise stellar ages. It would be important to obtain precise (accurate to better than 0.04 dex) differential abundances of K giants in clusters with a range of ages and effective temperature in order to test the [X/Fe]-age relations obtained for solar twins.

Planetary Host Abundances: Solar-type stars with known massive planets are comparatively metal-rich (Gonzalez et al. 2001; Santos et al. 2001), but a similar effect for different types of stars and planetary systems remains controversial. Conversely, abundances in stars set constraints on the composition of proto-planetary disks and, hence, on planet composition.

Exoplanet Composition Constraints: The proportions of C, O, Mg, Si, and Fe determine the structure, mineralogy, and geodynamics of terrestrial planets (e.g. Bond et al. 2010; Carter-Bond et al. 2012; Unterborn et al. 2014; Dorn et al. 2015; Thiabaud et al. 2015). The C/O ratio in the Sun is 0.55 ± 0.08 (Asplund et al. 2009), but around stars with C/O ≥ 0.8 there may exist carbon planets containing large amounts of graphite and carbides instead of Earth-like silicates (Kuchner and Seager 2005; Bond et al. 2010). Similarly, while the solar Mg/Si ratio is 1.20 ± 0.14 (Scott et al. 2015), if a protoplanetary disk has Mg/Si < 1.0, terrestrial planets will have a Mg-depleted mineralogy different from that of the Earth (Carter-Bond et al. 2012). It is thus important to study stars that may host rocky planets different from the earth.

At present, high-precision abundance analyses are limited to stars that are nearby and similar to the Sun. There is the potential for future discoveries by characterizing other types of stars or more distant ones. The required precision to explore this discovery space is 0.03 dex, for which we need sufficiently high S/N and spectral resolution greater than R~50,000. We also need extended wavelength coverage to constrain the stellar parameters accurate to within $\sigma(T_{eff}) = 10K$ and $\sigma(\log g) = 0.03$ dex.

Further progress in stellar spectroscopic analysis depends critically on observations using telescopes with large light collecting area, comparatively effective spectrometers and sensitive detectors with linear response to illumination. High-resolution optical and infrared spectrometers on the GMT and TMT will provide the impetus for more precise abundances for a broad sampling of stars.

M Dwarfs: Gaia has begun to discover new and exciting features of low-mass stars, and LSST will continue and deepen this exploration. These stars, with late K to late M spectral types, lie at or near the peak of the mass function and are the most common stars in the Universe. Their atmospheres, unlike those of warmer stars, are dominated by molecular features, and many of them display strong magnetic fields, frequent flares, and other hallmarks of extreme stellar activity. Stellar models show that M dwarfs below ~ $0.35M_{Sun}$ make the transition to being fully convective, and provide an opportunity to understand the nature of convection and stellar dynamo activity. However, with absolute K magnitudes of 5.0 to 9.5 (Mann et al. 2018), they are simply too faint for even 8-10 m class telescopes to routinely collect high-resolution spectroscopy. This is particularly true for M dwarfs in open clusters, where we have the best priors on age and metallicity required for modeling both atmospheres and interiors. We cannot predict precisely which of these open questions will remain in 10 years, and which new ones will emerge in that time, but the ELTs are uniquely positioned to explore and characterize large samples of faint, low-mass stars throughout the Milky Way. At high resolution (R~50,000-80,000), we estimate that the ELTs will be able to perform high-SNR spectroscopy out to 150 pc for the lowest-mass M dwarfs, and to approximately 1.5 kpc for late-type K stars. Below we describe three interrelated research areas which ELT observations of M dwarfs have the potential to revolutionize.

<u>Stellar Parameters and Atmosphere Models:</u> Comparing current generation stellar atmosphere models, which have varying degrees of line list accuracy and line strength prescriptions, with low or moderate resolution spectra yield stellar parameters and abundances with relatively large uncertainties. ELTs will provide the high-resolution (R~100,000), high-SNR optical and NIR spectra required to resolve molecular features and atomic lines from α and Fe-group elements. This will allow us to benchmark stellar atmosphere models against empirical spectral libraries in order to determine precise T_{eff}, log g, and abundance values. This procedure would benefit from the application of machine learning techniques because of the large numbers of spectra and because the spectral features, even at high spectral resolution, remain crowded.

Fully Convective Boundary: One example of new discoveries that ELTs can exploit is the "Jao gap." Recently, Jao et al. (2018) have used the exquisite Gaia DR2 data for over 180,000 M dwarfs out to 140 pc to find a previously-unknown feature in the HR diagram near spectral type M3.0 and M_G = 10. The "Jao gap" is a diagonal underdensity that dips towards lower luminosities in the red. Jao et al. concluded that it is probable that this coincidence is causal, while other investigators (e.g., MacDonald & Gizis 2018) ascribe it instead to effects of ^{3}He mixing during the merger of core and envelope convection zones. In either case, the feature clearly represents an important process in these stars. Follow-up studies should pursue measurement of accurate masses, radii, and metallicities; characterization of chromospheric activity using spectral features such as Ca II H+K, Hα, He I 10830, and the Ca II IRT; and determination of magnetic field strengths and topologies.

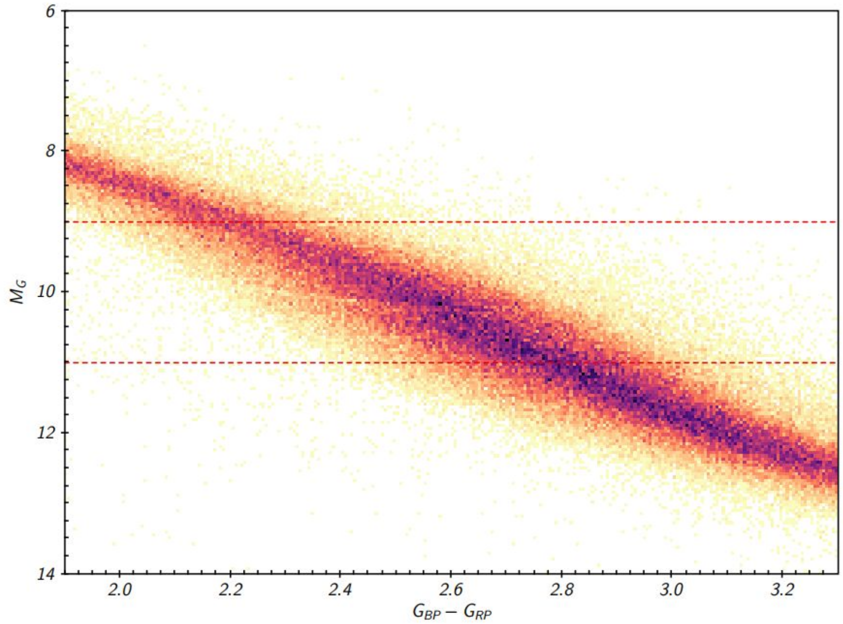

Figure 2: A portion of the observed H-R Diagram for stars within 100 pc in the Gaia DR2 dataset. The gap discussed in the text is visible near the center of the distribution; the dashed lines mark M_G = 9 and M_G = 11. From Jao et al. (2018).

Magnetic Fields: The study of magnetic fields on both M dwarfs and brown dwarfs is underdeveloped. Accurate stellar parameters help to constrain models of the dynamo mechanisms across the transition to fully convective dwarfs. For early M dwarfs, we know that inhibition of convection by magnetic fields results in main sequence models with larger radii and lower luminosity than found in models lacking magnetic fields (Feiden & Chaboyer 2012). However, our understanding becomes more limited as we move across the fully convective transition. Morin et al. (2010) used Zeeman Doppler Imaging to produce tomographic maps for six M5 - M8 dwarfs (out of an initial sample of 23) and found two distinct magnetic topologies: strong axisymmetric dipole fields and weak less-organized non-axisymmetric or toroidal ones. The intrinsic faintness of these stars, combined with the need for high-resolution NIR spectra, imply that only access to the ELTs will enable this science for a large number of targets.

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