Fundamental Astrophysics with Open Clusters

A White Paper on High-Resolution Optical Spectroscopy for the Gemini Observatory

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Introduction

Open clusters are essential laboratories for modern stellar astrophysics. The shared age, distance, and initial chemical composition of cluster members make them ideally suited for a broad range of research efforts, including studies of stellar interiors, stellar mixing mechanisms, stellar nucleosynthesis, and Galactic chemical evolution. Below we present five science cases utilizing open clusters that will greatly benefit from a high-resolution (minimum $R \sim 45$k) optical echelle spectrograph at the Gemini Observatory.

Li Dispersion in Cool Dwarfs: Open Clusters as Probes of Standard Stellar Models and Line Formation

The order of magnitude dispersion in Li abundances of cool dwarfs of the same mass in the $\sim$100 Myr old Pleiades open cluster (Duncan & Jones 1983; Soderblom et al. 1993) presents a fundamental challenge to standard stellar models, which predict identical Li depletions in stars of the same mass, age, and metallicity (in accordance with the Vogt-Russell theorem). Observations indicating an analogous scatter in the strength of cool Pleiads λ7699 K I resonance line (Soderblom et al. 1993; Jeffries 1999), whose formation details are similar to those of the λ6707 Li I resonance line, have led some to question the attribution of Li I line strength variations to abundance variations. Instead, the observed dispersion may reflect serious deficiencies in our understanding of line formation.

King et al. (2010) have revisited line strength variations in cool Pleiads using high-resolution ($R$$\sim$60k) high-S/N ($\sim$100) echelle spectroscopy, and these observations did not reveal K I scatter as previously claimed. Ironically, however, a reconsideration of simple starspot models indicates that this does not argue for a bona fide Li abundance dispersion–there exist spot models that lead to significant Li dispersion but no dispersion in K line strengths. However, such models do predict significant dispersions in the strength of CN features and factor of $\geq$3 differences in Li abundances derived from the λ6707 Li I resonance line and the λ6104 Li I subordinate feature; the latter feature is an extremely weak feature blended in the wing of a strong Fe I line, requiring data of high spectral resolution to discern. No such dispersions or differences are seen.

These results suggest a real component to Li dispersion in the Pleiades. King et al. (2010) suggest that such dispersion is due to differential pre-main sequence (PMS) depletion caused by the effects of spot-induced radii variations. Testing this hypothesis will require further high-resolution ($R$$\geq$60k) spectroscopy in a number of young zero-age MS (ZAMS) and PMS clusters to map dispersions in Li and other line strengths and to identify radii deviations directly via spectroscopic means. King et al. (2010) also propose that their differential Li depletion mechanism may result in a distinctive Li/Be dichotomy in cool dwarfs in older (Hyades age) clusters. Because the only accessible Be features are the Be II resonance doublet at $\lambda 3130, 3131$ near the atmospheric cutoff, Be abundance determinations in such stars requires a blue-optimized spectrograph on a large-aperture telescope. High spectral resolution ($\geq$60k) is required due to the severe blending of the weak ionized features in cool dwarfs.

Stellar Nucleosynthesis in Open Clusters

As a star evolves from the MS onto the red giant branch, products of nucleosynthetic processes in the core are mixed with the pristine material of the photosphere as a result of the first dredge-up. The changes in the chemical composition of the stellar atmosphere can be investigated spectroscopically, providing valuable empirical data to test and constrain stellar evolution models. In contrast to field stars, the shared ages and initial chemical compositions of open cluster stars are particularly useful for analyzing the effects of the first dredge-up; any abundance differences between dwarfs and giants in the same open cluster can be attributed to internal nucleosynthesis and post-MS mixing.

In stars more massive than about 1.3 $M_\odot$, the CNO bi-cycle is the dominate energy source while on the MS (Arnett 1996), and thus it is the abundances of C, N, and O that can reveal the effects of core nuclear burning and post-MS mixing in these stars. A recent study of three clump giants and three MS solar-type dwarfs in the Hyades open cluster found the ^{14}N and ^{16}O abundances, as well as the ^{12}C/^{13}C ratios, of the giants relative to the dwarfs are in excellent agreement with the predictions of a standard stellar evolution model tailored to the Hyades open cluster (Schuler et al. 2009). However, the ^{12}C abundances of the giants were found to be a factor of 1.5 lower, significant at the 6σ level, than the model prediction. Independent of the model, the C+N+O abundance of the giants is lower by 21% relative to that of the dwarfs, whereas no difference is expected to result from CNO bi-cycle processing.

The apparent enhanced depletion of ^{12}C in the Hyades giants may have critical implications to our understanding of stellar nuclear processes, stellar structure, and/or the chemistry of stellar atmospheres. Future high-resolution ($R \geq 60$k, necessary for the accurate measurement of weak [O I], C_2, and CN features), high-S/N (≥ 200, necessary to derive abundances to ~ 0.05 dex level) echelle spectroscopy of additional open cluster stars is vital to verify the Hyades results and to understand the potential physical or analytical mechanisms at the root of the low C abundances of the giants. While open cluster giants are generally bright and accessible to high-resolution spectroscopy with 4-m class telescopes, solar-type dwarfs in open clusters, aside from the nearby Hyades, are not. With magnitudes typically $V \geq 12$, solar-type open cluster dwarfs require an 8-m class telescope with an efficient high-resolution echelle spectrograph to obtain the high-quality spectra needed for this potentially critical research.

Overionization and Overexcitation in Cool Dwarfs: Constraints from Open Clusters

Abundance studies of main sequence dwarfs are important probes of stellar physics and Galactic chemical evolution. Open cluster stars, given their shared ages, distances, and initial chemical compositions, are uniquely valuable targets in such studies. A case in point is the recent open cluster abundance studies (Schuler et al. 2004, 2010; Yong et al. 2004) that have revealed star-to-star abundance anomalies that challenge our understanding of stellar atmospheres: abundance ratios in a given star that are excitation dependent; order of magnitude differences in abundances derived from Fe I and Fe II lines in cool ($\leq$5000 K) dwarfs; and significant trends in the abundances of elements derived from high-excitation lines that are increasing functions of decreasing $T_{\rm eff}$ in a given open cluster (Figure 1).

The results of the studies described above present a puzzle of fundamental significance regarding the derivation of cool cluster dwarf abundances, and it remains unclear if the trends are due to inadequate model atmospheres, NLTE effects, and/or age-related phenomena such as starspots and/or chromospheric emission. The role of metallicity is also unknown. Thus far, the anomalies noted above have been observed in nearby young or adolescent clusters (less than the Hyades age). Progress in

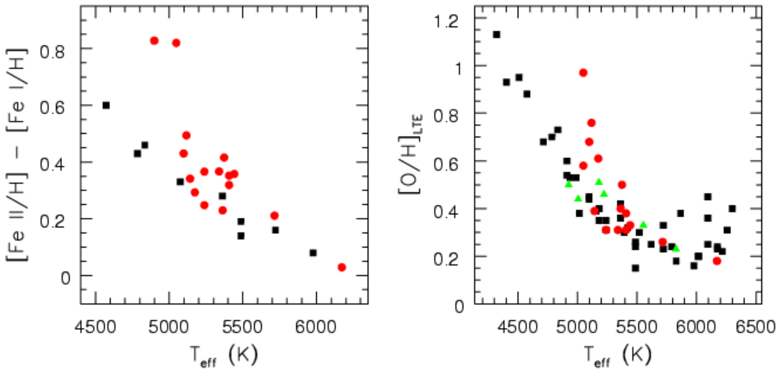

Figure 1: Left– Difference in solar-normalized Fe abundances derived from Fe II and Fe I lines as a function of $T_{\rm eff}$ for the Pleiades (red circles) and the Hyades (black squares). Right– Solar-normalized O abundances derived from the high-excitation O I triplet vs. $T_{\rm eff}$ for the Pleiades (red circles), the Hyades (black squares), and the Ursa Major moving group (green triangles).

understanding line formation in cool dwarfs depends, therefore, on high-resolution (ideally, $R \geq 60-75$k so that critical weak features can be reliably measured) and high-S/N spectroscopy of cool (faint) dwarfs in rarer (hence more distant and fainter) older open clusters. An optical high-resolution echelle spectrograph on an 8-m class telescope will allow one to explore the persistence and detailed behavior of the abundance anomalies in homogeneous stellar samples that double or triple the current age baseline of extant cluster samples. Our understanding of cool dwarf atmospheres will be limited until the age-related behavior of cool dwarf abundances is revealed.

Metallicity Gradient of the Galactic Disk from Open Cluster Abundances

Observations of the distribution of chemical element abundances at various locations in the Galaxy provide valuable constraints to chemical evolution models of the Milky Way. Open clusters, for which ages and distances can be reliably determined and for which element abundances can be determined robustly from many cluster member stars, are excellent probes of the abundance distributions of the Milky Way disk. To date, open clusters spanning the Galactocentric distance range R_{gc}∼6-22 kpc have been used to trace element abundance patterns as a function of distance from the Galactic center. These studies show that the metallicity of the Galactic disk decreases as a function of increasing Galactocentric distance out to R_{gc}∼12-14 kpc, and then "bottoms out" at [Fe/H]∼−0.30-0.50 in the outer disk (Figure 2). The abundance distributions of other elements follow a similar pattern: [X/Fe] ratios for elements such as Na, Al and the α elements are largely independent of R_{gc}, as is the dispersion in [X/Fe] ratios. Cluster element abundance distributions also appear to be independent of cluster age (Magrini et al. 2009).

While these observations provide important constraints to models of disk formation and evolution, our understanding of open cluster abundance distributions can be much improved. For example, fewer than ten clusters beyond R_{gc}∼14 kpc have been subject to high resolution spectroscopy, and the element abundances for many of those have been determined from only one or two cluster members (e.g., Carraro et al. 2007). Secondly, cluster abundance uncertainties can be larger than 0.1 dex, often as a result of small sample sizes, low spectral resolution (some "high resolution" spectroscopy have relatively low $R \sim 15$k), and low (<50) signal-to-noise ratios. Lastly, while most studies determine cluster abundances for the light, α and iron-peak elements, relatively few studies provide robust determinations of neutron-capture element abundances (e.g., D'Orazi et al. 2009). The spectral features of elements such as La and Eu are often weak and blended in the spectra of cool giant stars, making their analysis difficult.

The issues outlined above can be directly addressed with a high-resolution spectrograph at the Gemini

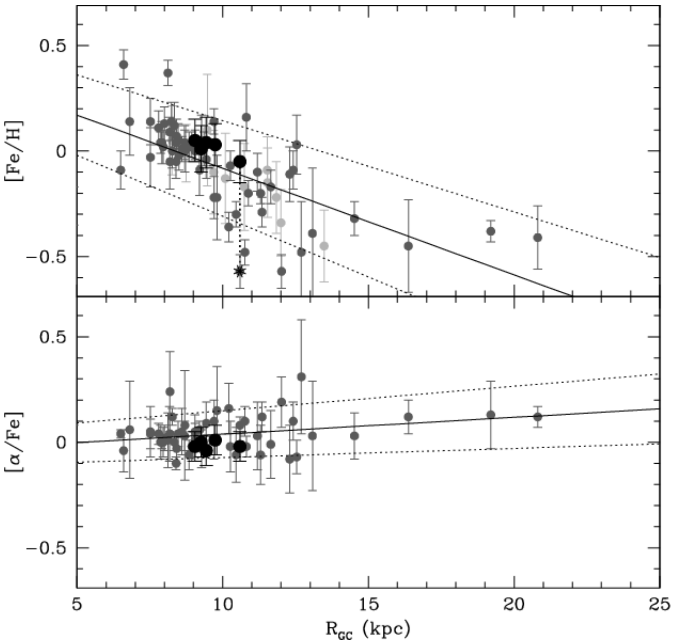

Figure 2: Open cluster [Fe/H] (top panel) and [α/Fe] (bottom panel) as a function of Galactocentric distance. Best fit lines (solid lines) with uncertainties (dotted lines) are drawn through the distributions. Note that while the [Fe/H] distribution changes at R$_{gc}$$\sim$12-14 kpc, cluster [$\alpha$/Fe] ratios are roughly independent of R$_{gc}$. Taken from Pancino et al. (2010).

Observatory. Abundances of an increased number of clusters in the outer disk can be determined more robustly with larger samples of cluster members, while $R \sim$40-50k spectral resolution will minimize line blending in evolved star spectra, decreasing abundance uncertainties and allowing for the robust determination of, e.g., neutron-capture element abundances. "Chemical tagging", the identification of different stellar populations based on their element abundance patterns, has been recognized as a powerful technique to trace galaxy formation and evolution (Freeman & Bland-Hawthorn 2002). Open clusters are the best tracers of the chemical evolution of the Milky Way disk, and only by increasing the number of clusters subject to high resolution spectroscopy, as well as the number of chemical elements analyzed, will we gain a better understanding of how the disk formed and evolved.

The Sco-Cen Complex: Star Formation and Pre-MS Evolution with Stellar Associations

While open cluster studies are arguably the "gold-standard" in stellar astrophysics, young stellar associations are proving to be similarly useful populations. The richest source of young ($<$ 20 Myr), pre-main sequence stars conducive to abundance studies is the Scorpius-Centaurus (Sco-Cen) Complex. The vexing question of lithium depletion in cool Pleiades dwarfs and the overexcitation/overionization trends observed in cool open cluster dwarfs are all astrophysically important questions that can further be addressed through abundance work with young solar-type stars in stellar associations such as Sco-Cen. Many of these outstanding problems in our understanding of stellar atmospheres are possibly related, at least in part, to the ages of the stars being considered. Unlocking the answers to these questions, therefore, requires extending studies to the younger ages that are dominantly characteristic of association members.

Abundance work in stellar associations also provides a unique environment with which to study small scale chemical enrichment. A pioneering series of investigations (e.g., Cunha & Lambert 1992, 1994) studied the chemical enrichment of B, F, and G-type members of the Ori OB1 association and found stars in the youngest subgroup showed oxygen abundances that were 40% enhanced over abundances in the older subgroups. They suggested that this enhancement, in stark contrast with the common abundances across other elements (Fe, C, N), provided evidence of self-enrichment by core-collapse supernovae explosions within Ori OB1. Building on this pioneering work, future studies of small scale chemical enrichment will benefit from the well-constrained membership of the Sco-Cen complex. Using a Salpeter IMF and total inferred masses for the Sco-Cen subgroups, de Geus (1992) has approximated that a dozen core-collapse supernovae have occurred within the two oldest Sco-Cen subgroups within the past ∼15 Myr, resulting in an expected enhancement in O mass fraction of ∼35 % (∼ 0.13 dex) based on published supernova yields (Woosley & Weaver 1995; Kobayashi et al. 2006).

Within the Sco-Cen subgroup, only the most massive stars ($\geq 18\ M_\odot$) will have had sufficient time to explode and enrich their environments. Consequently, it is the intermediate mass elements (O, Na, Mg, Si, S, Al, Ca and Ti), produced in the largest amounts by core-collapse supernovae, that will provide suitable diagnostics for exploring enrichment. Precise chemical abundance analyses of these elements with high-resolution (R≥ 60k), high-S/N (∼ 200) spectroscopy of solar-type (F, G and K) stars in Sco-Cen will allow for determination of abundances at the ∼ 0.05 dex level, which is needed to confidently identify the predicted enrichment levels. High-resolution and high-S/N spectroscopy on an 8-m class telescope are vital for this research to accurately measure weak lines and minimize blending in these cool, pre-MS stars.

General Requirements for a High-Resolution Spectrograph for the Gemini Observatory

To meet the observational needs of the science cases described herein, a high-resolution optical spectrograph at the Gemini Observatory should have capabilities similar to those at other world-class observatories, such as Keck (HIRES), Subaru (HDS), HET (HRS), VLT (UVES), and Magellan (MIKE). The instrument should be an efficient (fast) echelle spectrograph with broad wavelength coverage, ideally spanning from the atmospheric cutoff in the blue (∼ 3000 Å; possibly technically infeasible at the IR-optimized Gemini telescopes) to 1 μm, with the minimum coverage from Ca II H & K (∼ 3900 Å) through the O I triplet (∼ 7775 Å). A working spectral resolution of $R \sim 60$k corresponding to a slit width matching the median seeing is also ideal; a range of resolutions (from a minimum of $R \sim 45$k to a maximum of $R \sim 100$k) with adjusted slit widths would also be acceptable.

References

Arnett, D. 1996, in Supernovae and Nucleosynthesis (Princeton: Princeton Univ. Press), 190
Carraro, G. et al. 2007, A&A, 476, 217
Cunha, K. & Lambert, D. L. 1992, ApJ, 399, 586
Cunha, K. & Lambert, D. L. 1994, ApJ, 426, 170
D'Orazi, V. et al. 2009, ApJ, 693L, 31
de Geus, E. J. 1992, A&A, 262, 258
Duncan, D. K. & Jones, B. F. 1983, ApJ, 271, 663
Freeman, K. & Bland-Hawthorn, J. 2002, ARA&A, 40, 487
Jeffries, R. D. 1999, MNRAS, 309, 189
King, J. R., Schuler, S. C., Hobbs, L. M., & Pinsonneault, M. H. 2010, ApJ, 710, 1610
Kobayashi, C., Umeda, H., Nomoto, K., Tominaga, N., & Ohkubo, T. 2006, ApJ, 653, 1145
Magrini, L. et al. 2009, A&A, 494, 95
Pancino, E. et al. 2010, A&A, 511, 56
Schuler, S.C., King, J.R., Hobbs, L.M., & Pinsonneault, M.H. 2004, ApJ, 602, L117
Schuler, S. C., King, J. R., & The, L.-S. 2009, ApJ, 701, 837
Schuler, S. C., Plunkett, A. L., King, J. R., & Pinsonneault, M. H. 2010, PASP, 122, 766
Soderblom, D. R., et al. 1993, AJ, 106, 1059
Woosley, S. E. & Weaver, T. A. 1995, ApJS, 101, 181
Yong, D., Lambert, D.L., Allende Prieto, C., & Paulson, D.B. 2004, ApJ, 603, 697