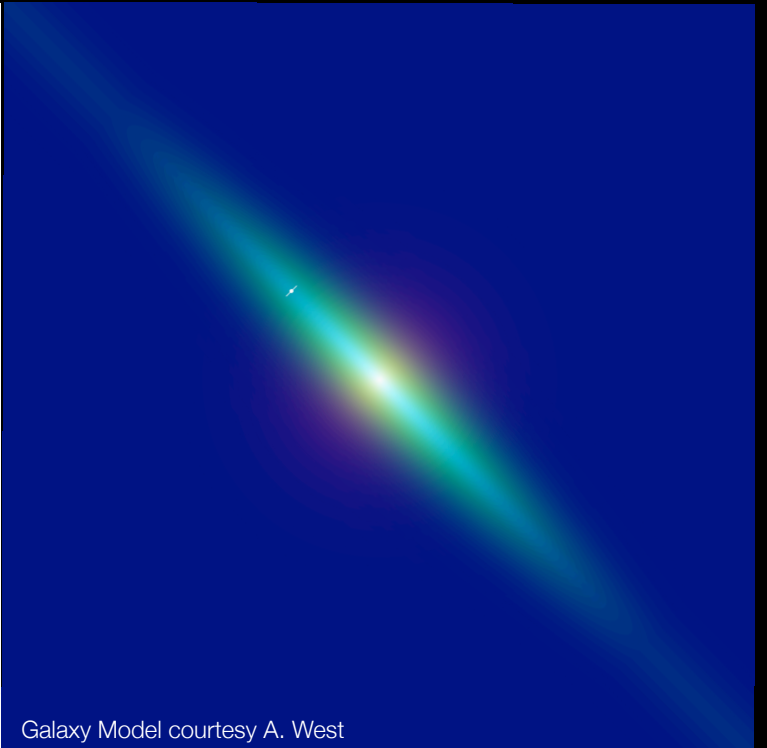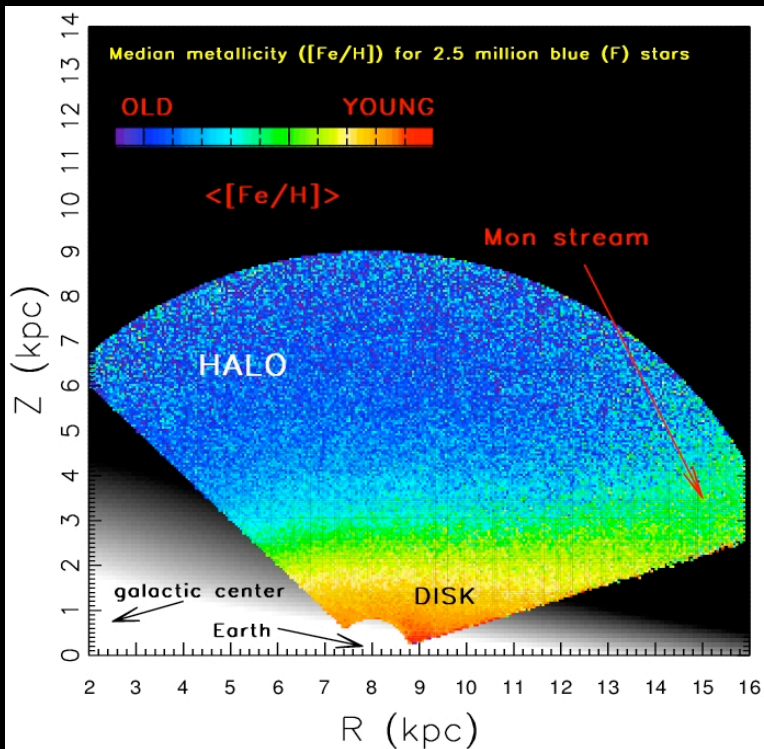# Measuring Stellar Ages & the History of the Milky Way

An Astro 2010 White Paper

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Median metallicity ([Fe/H]) for 2.5 million blue (F) stars

Galaxy Model courtesy A. West

Motivation

Robust stellar age measurements, and the star formation histories (SFHs) they enable us to derive, are powerful tools for understanding galaxy formation. Theoretical simulations show that galaxy mergers and interactions produce sub–structures of stars sharing a single age and coherent spatial, kinematic, and chemical properties[1,2]. The nature of these sub–structures place strong constraints on models of structure formation in a Λ–CDM universe[3].

The Milky Way Galaxy and its satellites are unique laboratories for studying these Galactic sub–structures. Detailed catalogs of stars in the Milky Way provide access to low–level substructures that cannot be detected in more distant galaxies; the Magellanic clouds provide a similar sensitivity advantage over other environments amenable to global surveys for sub–structures and SFHs. Photometric and spectroscopic surveys have identified numerous spatial–kinematic–chemical substructures: the Sag. dwarf, Pal 5's tidal tails, the Monoceros Ring, etc[4,5,6,7,8]. Additional missions will continue to mine this phase space (SDSS-3, LAMOST, APOGEE, PanSTARRS, SkyMapper), and ESO's Gaia mission will produce an order of magnitude increase in our ability to identify spatial–kinematic substructures; a white paper by Johnston & Bullock describes the potential of future studies in the Local Group.

Our ability to identify spatial–kinematic–chemical sub-structures has significantly outpaced our probe the Galactic SFH has severely lagged these rapid advances in the identification of spatial–kinematic–chemical sub–structures. **This white paper addresses two questions that define the next frontier in stellar and Galactic archeology: How well can we understand and calibrate stellar age indicators? What is the star formation history of the Milky Way, and what does it tell us about galaxy formation and evolution?** Answering these questions will require two key observational capabilities: a) a wide-field, high-precision synoptic survey, such as LSST, to measure proper motions, parallaxes and time–variable age indicators (rotation; flares; etc.) for sources beyond Gaia's faint limit, and b) sensitive, wide field, multi-object spectrographs with moderate (R$\sim$10K) and high (R$\sim$100K) spectral resolution to follow–up eclipsing binaries, monitor stellar activity, and measure precise stellar metallicities.

What we know now (or will learn shortly)

The observed components of the Milky Way trace different epochs in the formation and evolution of the Galaxy, and their SFHs provide unique insights into the history of our Galaxy. Open questions remain regarding the formation and SFH of each component:

- **The Stellar Halo** consists of a prominent population of old (12-14 Gyr[9]) globular clusters, and a distributed component first detected as high–velocity, low–metallicity field stars in the solar neighborhood[10]. The bulk of the substructures discovered over the past decade appear to be members of the halo population; the long orbital and dynamical timescales at large galactocentric radii allow accreted objects to persist as coherent substructures for quite some time.

- **Thick Disks** have been detected as distinct spatial, kinematic, and chemical structures

in our own and external galaxies[11,12,13]. These structures appear to be the result of dynamical heating of a galaxy's stellar disk, probably from minor mergers or accretion events. The oldest stars in the MW thick disk have ages of 10-12 Gyrs[14], demarcating the earliest epoch of merger activity in the Milky Way.

- **Thin disks** are a defining morphological characteristic of late–type galaxies, and the site of recent and ongoing star formation activity, as indicated by a rich population of molecular clouds, open clusters, and young associations. Studies suggest an age of at least 8 Gyrs for the Milky Way's thin disk[15]; given the predictions of standard Λ–CDM models, many investigators are struggling to understand why thin disks show little evidence significant heating by minor mergers during this period[16,17,18].

Despite the transformative effect their characterization would have on our understanding of galaxy formation, the SFHs of these Milky Way components remain poorly constrained, save for the upper and lower age limits quoted above. Age distributions of halo globular clusters, and open clusters in the Galactic disk[19], have been constructed, but the vast majority of clusters dissipate soon after their formation[20], so those that persist for t > 1 Gyr are a biased sub–sample of even the clustered component of the Galaxy's SFH.

Star formation histories of distributed populations are even more difficult to derive: in a seminal work, Twarog (1980) used theoretical isochrones and an age–metallicity relation to estimate ages for Southern F dwarfs and infer the SFH of the Galactic disk[21]. The SFH of the Galactic disk has since been inferred from measurements of several secondary stellar age indicators: chromospheric activity–age relations[22,23,24,25,26]; isochronal ages[27,28,29]; and white dwarf luminosity functions[30,31]. Despite these significant efforts, no clear consensus has emerged as to the SFH of the thin disk of the Galaxy: most derivations contain episodes of elevated or depressed star formation, but these episodes rarely coincide from one study to the next, and their statistical significance is typically marginal ($\sim 2\sigma$).

Our sparse understanding of the Galactic SFH leaves many key questions in galaxy formation and evolution unanswered: *Is the SFH of the distributed halo population identical to the SFH of halo globular clusters and Milky Way satellites? Is the thick disk a dynamically heated thin disk, and if so, what sequence of accretion/merger events did it result from? How does star formation progress in the thin disk – are there radial gradients due to the disk's dynamical timescale or the rate of gas infall?* Answering these questions will provide new insights into galaxy formation, but will require significant progress in diagnosing stellar ages.

The Recent Thin Disk SFH: Completing the Census of Young Moving Groups

Another white paper (Feigelson et al.) reviews the detection and characteristics of distant Galactic stellar clusters; here we focus only on young stellar groups within a few hundred pcs. Several such groups have been identified within the past decade, typically with spectroscopic confirmation following their discovery in large multiwavelength surveys[32].

What have these groups taught us? First, they are not dispersed members of star formation events in present–day molecular clouds. All groups older than a few Myrs lack associated

molecular gas; it is clear that they are the spawn of a since disintegrated molecular cloud. Secondly, it appears that moving groups are heterogenous in their nature: some appear to be co–eval associations (e.g. β Pic group), but some appear to be non–co–eval "dynamical streams" (e.g. Hyades and UMa superclusters). Lastly, they have provided samples of benchmark young substellar objects with known ages and distances, critical for calibrating our models of secondary age indicators.

Multiple poor moving groups have been recently identified within 50 pc (e.g. TW Hya, η Cha, ϵ Cha, etc.), indicating that dozens more await discovery within a few hundred pcs. Gaia's exquisite proper motions will identify most of these young moving groups within the extended solar neighborhood (d$\leq$ 1 kpc in the post–Gaia era), but Gaia's poor near–infrared sensitivity will produce significant incompleteness for very–low–mass/substellar objects.

Identifying low–mass members of young moving groups discovered by Gaia will extend calibrations of stellar age indicators to the lowest masses and youngest ages. Moreover, a complete census of young moving groups will be useful for addressing a number of pressing questions concerning the recent SFH of the thin disk, such as: *What do the kinematics and age distributions of the nearest associations tell us about how star formation progresses in giant molecular cloud complexes -- do low-mass members suffer from mass segregration and/or preferential ejection? Does the low-mass end of the initial mass function vary as a function of group density or metallicity?*

The Thin & Thick Disk SFHs: Isochronal Ages, Gyrochronology And Age/Activity Relations

Isochronal Ages: The 'standard' technique for estimating stellar ages is to compare a star's luminosity and color to a grid of theoretical stellar models that have been carefully calibrated against empirical observations of globular and open clusters. Gaia's precise distances (σ_π/π =1% for solar analogs within 400 pc) and photometry will produce highly accurate colors and luminosities for field stars, greatly expanding the volume wherein we can measure the SFH of the Galactic disk from isochronal ages.

Isochronal ages enabled by Gaia parallaxes will be extremely useful, but they will not provide a definitive understanding of the SFH of the Galactic disk(s). Isochrones are unevenly distributed in color–magnitude space, so the SFHs they produce do not sample all ages equally and are subject to systematic errors. Gaia's distance errors also increase to $\sim$10% at 1 kpc for F–type turn-off stars, corresponding to an age error of $\sim$2 Gyrs; providing a well resolved SFH for the thick disk, and sampling the SFH of the thin disk at different Galactic radii, require age indicators that can be measured reliably at distances greater than 1 kpc. Finally, as isochronal ages are only effective for stars with main sequence lifetimes shorter than a Hubble time, this technique does not allow us to search for initial mass function variations over the history of the Galaxy by measuring the SFH of low–mass stars.

Gyrochronology: Since Skumanich's seminal observations in 1972[33], we have known that rotation, age, and magnetic field strength are tightly coupled for solar–type stars. This relationship reflects a feedback loop related to the solar–type dynamo's sensitivity to inner

rotational shear: fast rotators produce strong magnetic fields, giving rise to stellar winds that carry away angular momentum, reduce the star's interior rotational shear, and thereby weaken the star's magnetic field. This strongly self–regulating process ultimately drives stars with the same age and mass towards a common rotation period.

Over the past decade, the first calibrations of the mass–dependent relationship between stellar rotation and age have been produced[34,35,36]. These calibrations depend on rotation periods measured for members of young clusters (t < 700 Myrs) and the Sun, our singular example of an old (t ∼ 4.5 Gyrs), solar–type star with a precise age estimate. The space–based Kepler satellite will soon acquire exquisite photometry for solar–type stars in NGC 6819 and 6791, providing rotation period measurements for moderate samples of stars with ages of 2.5 and 8 Gyrs, respectively, and placing these 'gyrochronology' relations on a firmer footing for ages greater than 1 Gyr.[37]

Well calibrated gyrochronology relations will enable robust ages to be assigned to individual Galactic field stars, providing a fundamentally new method for investigating the SFH of the Milky Way. From what we currently know, next generation synoptic surveys will be able to measure rotation periods for solar–analogs to ∼2.5 Gyrs (∼20 day periods and 0.005 mag amplitudes[38]). *Measuring photometric rotation periods for thousands of field stars in a variety of Galactic environments will enable gyrochronology relations to map out the SFH of the Galactic disk over the past 1-2.5 Gyrs.* It would also be extremely useful to obtain rotation periods in additional Galactic clusters over the next decade, extending gyrochronology relations to lower masses and improving their time resolution.

Age–Activity Relations: Age–activity relations tap the same physics underlying the gyrochronology relations[39,36], and provide an opportunity to sample the SFH of the Galactic disk at ages inaccessible to gyrochronology. Single–epoch measurements of chromospheric emission (such as R'$_{HK}$[40]) can be measured more efficiently than rotation periods, particularly with access to wide–field, multi–object spectrographs such as LAMOST. Stellar flares, which trace the strength of the star's magnetic field, are another photometric proxy for stellar age, though inherently intermittent and aperiodic. The same cluster observations that calibrate gyrochronology relations will indicate how the frequency and intensity of stellar flares vary with stellar age and mass, allowing the SFH of the Galactic disk to be inferred from flares detected by wide–field time domain surveys. The primary limit on the lookback time of a SFH derived from age–activity relations is the timescale when which activity signatures become too minimal to serve as a useful proxy for stellar age. We do not yet have a calibration of what this lifetime will be, but early explorations suggest even the latest M dwarfs become inactive after ∼5 Gyrs[41,39].

THE SFH OF THE GALACTIC HALO: TRACING THE FIELD POPULATION WITH ECLIPSING BINARIES, WHITE DWARFS, AND STELLAR METALLICITIES

Halo objects are ∼0.5% of the stars in the local solar neighborhood, so the ages of nearby high velocity stars provide a first glimpse of the halo's SFH. The highly substructured nature of the Galactic halo, however, argues strongly for sampling its SFH in situ to understand

the full accretion history of the early MW. The stellar age indicators described above are not feasible for probing the distant halo: direct parallax measurements will not be available as required for isochronal ages, and stellar activity indicators (rotation, flares) will be undetectable for typical halo ages. We describe below additional age indicators that will enable an in situ sampling of the SFH of the Galactic halo.

Isochronal Ages From Distant Eclipsing Binaries: Eclipsing binary stars are one of nature's best laboratories for determining the fundamental physical properties of stars. Detached, double–lined eclipsing binaries (hereafter EBs) yield direct and accurate measures of the masses, radii, surface gravities, temperatures, and luminosities of the two stars. These physical parameters are measured directly via combined analysis of multi-band light curves and radial velocity measurements[42,43].

Standard isochronal ages are derived in color–magnitude space, and require an independent distance measurement to calculate the star's luminosity. The wealth of information that can be derived for eclipsing binary systems, however, enable the derivation of *distance independent* isochronal ages by comparing to models in different parameter spaces, such as the mass–radius plane. Binary components with $M > 1.2$ $M_\odot$ typically appear co–eval to within 5%, suggesting the age estimates of the individual components are reliable at that level as well[44]. Lower mass binary components have larger errors, likely due to the suppression of convection by strong magnetic fields[45]; efforts to include these effects in theoretical models are ongoing, and should allow for accurate ages to be derived for lower–mass binaries as well. *Mapping out the SFH of the halo with EBs will require photometric detection and spectroscopic follow–up for hundreds, if not thousands, of systems.*

White Dwarf Luminosity Function: White dwarfs (WDs), the final remnants of low– and intermediate–mass hydrogen burning stars, are unique astrophysical laboratories, and are described in more detail in a companion white paper ('White Dwarfs as Astrophysical Probes'; Jason Kalirai). The most interesting and pertinent characteristic of WDs in this context is their utility as an outstanding Galactic chronometer. Due to WDs simple structure, and the well defined nature of their thermal evolution, theoretical models have proven quite successful at reconciling WD ages in clusters with those assigned to the population based on standard isochronal fitting[46].

Given the success of model-based age determinations for cluster WDs, the WD luminosity function (WDLF) is a promising tool for measuring the SFH of Galactic components. For the Galactic Disk, the Sloan Digital Sky Survey (SDSS) has spectroscopically identified over 10,000 white dwarfs and provided the first hints of structure in the luminosity function. This structure, in the form of multiple peaks, can be associated with epochs of enhanced star formation. With expanded samples of WDs, these peaks will be well established and inverted to shed light on the formation time and timescale of the underlying events. Similar studies, but reaching to fainter magnitudes and therefore larger distances, will also allow the first measurement for the age of the Galactic halo based on the WDLF. This age can be contrasted with the ages of globular clusters measured using the same technique to yield insight into the relative formation times of the halo's field and cluster populations.

SFHs from Metallicity Measurements: A detailed exploration of the Galactic halo's SFH requires knowledge of many quanities, among the most important being the overall metallicity of each star. Reliable ($\sigma([Fe/H]) = 0.25$ dex) estimates of stellar abundances (from $[Fe/H] = -0.5$ to -2.0) can be obtained by the use of well-calibrated broadband photometry (such as SDSS *ugr* or *gri*). SDSS data has already been used to produce "metallicity maps" of several million individual stars, from the disk system out into the inner halo region, to a distance of 10 kpc from the Sun. Next–generation surveys will obtain photometric errors from 10 to 100 times better than achieved by SDSS, extending the "reach" of the photometric technique well into the outer halo of the Galaxy, perhaps up to 100 kpc away, and permit metallicities to be measured extending down to $[Fe/H] = -3.0$ to -3.5, and perhaps lower.

The efficient photometric identification of very low metallicity stars allows one to more easily identify the very rare stars that exhibit large over-abundances (by a factor of 10 or more relative to solar ratios) of elements associated with production by the r(apid) neutron-capture process. These so-called r-II stars bring the possibility of obtaining direct nucleo-cosmo-chronometric age estimates (presently accurate to on the order of ~ 2 Gyr), based on observations of their Th (and sometimes U) abundances[47,48]. The combination of such information with proper motions, parallaxes, and (at least for a subset of the stars) radial velocities, will revolutionize astronomers' ability to probe the history of the assembly and evolution of the Galactic stellar populations that are recognized today.

THE MAGELLANIC CLOUDS: THE BEST LABORATORIES FOR COMPLETE, GLOBAL SFHS

In contrast with the Milky Way, stars in external galaxies can be assumed to lie at the same distance, making isochronal ages very useful; the large distances involved, however, limit the technique to relatively bright stars. The Large and Small Magellanic Clouds present fortuitous laboratories, however, because at distances of $\sim$50 kpc (LMC), and $\sim$60kpc (SMC), their main sequence stars are accessible to wide field imaging from the ground.

The Clouds are the only systems larger and more complex than dwarf spheroidals outside our own Galaxy where we can reach the MS stars. Recent experiments show the presence of LMC main sequence stars beyond 15 kpc from the LMC center[49]. Not only are MS stars the most numerous, and thus the most sensitive tracers of structure, but they *proportionally represent stars of all ages and metallicities*. Knowledge of the distribution and population characteristics in outlying regions of the LMC/SMC complex is essential for understanding the early history of these objects and their place in the Λ–CDM heirarchy. Analysing the ages, metallicities, and motions of these stars is the most effective and least biased way of parsing the stellar sub-systems within any galaxy, and the understanding the history of star formation, accretion, and chemical evolution on galaxy–wide scales.

SUMMARY & RECOMMENDATIONS

In recent years, solid foundations have been laid for a variety of techniques to estimate stellar ages. These methods promise the first comprehensive measurements of the SFH of the Milky Way and the Magellanic Clouds, which will in turn provide a transformative new view of galaxy formation and evolution in a λ–CDM universe.

Calibrating these stellar age indicators, and using them to derive SFHs for the full range of Galactic components and environments, will require two key observational capabilities:

- **Sensitive, wide–field, multi-object spectrographs:** Spectroscopic measurements are crucial for several of the age estimates described above, such as characterizing halo eclipsing binary systems, calibrating age–metallicity and age–activity relations, and performing nucleo-cosmo-chronometry on extremely metal poor stars. Sampling the SFH of sub–structures within the halo will require large samples of faint targets, such that multi–object spectrographs will provide large efficiency gains.

- **A wide–field time–domain survey with high astrometric precision:** accurate parallaxes and proper motions will enable distance–dependent isochronal ages and identify young moving groups; multi–epoch data will sample time–variable age indicators (rotation, flares, etc.) and identify halo eclipsing binaries which provide distance independent age estimates; co–adding multiple epochs will provide deep photometry for identifying halo white dwarfs and mapping the SFH of the Magellanic Clouds.

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