Astro2020 Science White Paper

Precision Stellar Astrophysics and Galactic Archeology: 2020

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:

The 2020s will see a major revolution in the fields of stellar astrophysics and galactic archaeology ushered in by the tremendous leaps made in the past 5 years including precision astrometry, precision photometry, massively multiplexed spectroscopy, and gravitational wave detection. It is not merely the quality, but the quantity of these data that will be fundamentally new to the 2020s. Will the US community sit on the sidelines and watch the revolution from afar? We argue here that a rich array of science is enabled by studying the stars in the Galactic neighborhood, enabling breakthroughs in fundamental physics, near-field cosmology, galaxy evolution, and comparative exoplanetology.

With ground-based facilities that are (or will soon be) scanning the skies for variable phenomena heretofore unseen (e.g. ZTF, LSST and LIGO) and space-based facilities performing photometric and astrometric measurements on huge populations of stars at a precision previously possible only for the Sun (e.g. *CoRoT, Kepler, TESS, Gaia*, and *SphereX*), we are entering a golden Era of Stars. This revolution will allow us to **understand fundamental aspects of stars**: as physical systems, planetary hosts, and the building blocks of galaxies throughout cosmic time.

1   Precision Galactic Archaeology

The most fundamental relations in stellar astrophysics are those between stellar mass, luminosity, radius, and age, which serve as key tests for models of the formation and evolution of stars. The intricate morphology of these relations provides clues about the underlying physical processes that drive stars through periods of relative stability and instability. The gross morphology of this relation allows us to measure the bulk properties of galaxies out to the very highest redshifts.

For decades, observational improvements to this relation were essentially stagnant. While stellar masses and radii can (and have) been measured to extremely high (1%) precision in multiple ways (e.g. primarily in binary systems or via microlensing or interferometry), luminosity requires a distance. Distance errors have plagued luminosity measurements since antiquity. The *Hipparcos* mission revolutionized distance measures in the mid-90s but did not probe to sufficient distances with sufficient precision for sufficiently large samples to be of great utility for understanding broad questions such as the formation history of the Galaxy. The successful launch and data releases of the *Gaia* mission in conjunction with upcoming photometric (e.g. *TESS*, LSST) and spectroscopic campaigns (SDSS-V, DESI, 4MOST, Weave) have now, or will soon, yield an unprecedented volume of the Galaxy for which **precision 6D+chemistry phase-space coordinates of millions of stars are known**. This has important implications for the formation of the Milky Way: the sheer number and distribution of these quantities will provide a high-spatial resolution, high-fidelity Hertzsprung-Russel Diagram for huge sectors of the Milky Way. This will allow us to dissect the Milky Way at a unprecedented level. It will also allow us to extract uniform and rare populations at levels previously impossible. The bulk populations reveal crucial details about the assembly history of the Galaxy, while the rare populations (for example, Helium flashing red-giants) reveal new stellar physics that is not entirely understood (See white paper by Ness et al. for more detail on this).

2   Precision Stellar Chronology

Stellar ages play a critical role in Galactic and Extragalactic Astrophysics. From questions ranging from "How Old is the Milky Way" to "How Old is the Universe," stellar ages (particularly in globular clusters) have been an important component. At this point, we are ready to ask more fine-grained questions such as "When was the last major accretion event in the Milky Way?" and "How old are the various components of the Milky Way's Bulge?" The questions do

not just have the limited scope of revealing the formation history of the Milky Way in gory detail, but allow us to compare with cosmological models of galaxy formation to understand whether other galaxies are forming in line with our expectations.

Stellar ages have historically been crudely determined using the isochrone fitting technique. This technique has been limited however, because it requires observed quantities (luminosity and therefore distance) as well as temperatures to be known precisely. In the past decade, stellar ages could be measured to roughly 25%, with uncertainties contributed by both distance and chemical abundance errors, and this is for only the youngest ($<$100 Myr) and oldest (12 Gyr) populations with vastly higher uncertainties at intermediate ages. In the 2020s, precision distances in addition to the routine assembly of high-quality, high-resolution spectroscopy for **millions** of stars will be transformative. In the local volume, *Gaia*'s 1% distances in conjunction with high-resolution spectroscopy yield 5% ages on stars. This will allow the *first* real reconstruction of the age distribution of the solar neighborhood and the **direct** assembly history of the Galaxy.

In addition, asteroseismology from *Kepler* and *TESS* has emerged as a game changer in terms of deepening our understanding of stellar astrophysics (1). Asteroseismic constraints allow us to measure precise masses (5% uncertainty) and ages (20% uncertainty) of tens of thousands of stars *across the galaxy* (2; 3). Upcoming spectroscopic surveys will be able to provide comprehensive investigation of stellar astrophysics and of stellar system architecture over a range of 10^4 in the masses of stars that belong to binaries with orbital periods 0.5 hours to $>$12 years, up to $>$15 kpc in distance from the Sun. The overarching goal of these programs is to consistently and comprehensively measure mass, age, chemical composition, rotation, and stellar multiplicity for vast samples of stars across the color-magnitude diagram (Figure 1).

3   Precision Stellar Chemodynamics

The concept of using the "chemical fingerprint" of stars as a distinct phase-space dimension to determine the history of the Milky Way and other galaxies has been suggested for at least 50 years. The major new development here, that may at last liberate the promise of this technique, has been highly multiplexed, high-resolution spectrographs that allow detailed chemical abundance patterns to be determined for millions of objects, rather than just handfuls. In addition to the classic questions of Milky Way assembly, which will without-doubt be transformed by this data, other broad questions will be addressed. Notions such as hunting for the most extremely metal poor stars as probes of the earliest star-formation epochs have been recently developed. The current limitation is simply numbers. That will be transformed with the measurements from instruments such as APOGEE and *Gaia*.

In addition to questions of galaxy formation, fundamental atomic and nuclear physics questions can begin to be probed. For example: what is the origin of the r-process elements? Despite its critical role in producing elements beyond the iron peak (particularly in metal-poor environments) and its spectacular display in the first gravitational wave neutron star merger event, our theoretical understanding remains rudimentary. Fortunately, theoretical yields for the r-process can be greatly

improved via a combination of vast spectroscopic samples and multi-messenger follow-up. This problem has extremely wide-ranging implications from understanding the first stars and supernovae to understanding the gross properties of high-redshift galaxies. Robust conclusions are obscured by complicating factors such as the contribution of certain phases of advanced stellar evolution (e.g, the thermally pulsating AGB phase) can alter estimates of galaxy mass by factors of several. However, t is now possible to address these issues directly with chemical abundances for large samples of stars for which both photometric and spectroscopic precision well outpaces theoretical models. Advances in this area will place stellar population synthesis models on firm footing, giving us confidence when applying them in high-redshift galaxy formation regimes.

4   Precision Stellar Astrophysics

Time domain astronomy is radically changing our understanding of stars, largely through the availability of high-cadence high-precision space-based photometry (CoRoT, Kepler, TESS, WFIRST, etc.) for large samples of stars. Many stellar variables, (e.g., solar-like oscillators, γ-Doradus stars, heartbeat stars, etc.) that are nearly impossible to detect from the ground can now be discovered and accurately characterized by the thousands. The scientific impact has been historic because stellar pulsations literally let us peer past the previous limit of stellar photospheres. On the main sequence, we now have measurements of helium abundance (4), rotation rate (5; 6), convective mixing length (7; 8), and overshoot (9; 10) made from *inside* stars, eliminating some of the biggest uncertainties in stellar models. Tidal circularization timecales of binaries can be directly measured (11) and physical mechanisms can be determined from tidally excited pulsations (12; 13).

In red giant stars, the asteroseismic impact has been truly exceptional. It is possible to extract precise masses and radii for thousands of these luminous stars where previously this has been infeasible (14). This permits age measurements in old stars all across the galaxy (2). An even more profound and surprising advance has arisen because the structure of red giants permits coupling between g-modes trapped in the core and p-modes typically visible in the atmosphere. This coupling creates entirely new classes of seismic observables, such as the stellar core's evolutionary state (15; 16), rotation rate (17; 18), and even the internal magnetic field (19; 20). These new diagnostics permit completely novel stellar physics and population tests. For example, the cores of red giants rotate more rapidly than their surfaces, but more slowly than predicted by models: what consequences does this imply for the core rotation of massive pre-supernova stars? For the rotation rates of the remnant black holes?

5   Precision Stellar Populations

Current stellar population models usually focus on the study of specific sub-samples of stars (e.g., 21), even though many underlying assumptions regarding the formation and evolution of stars are shared between the different models. So far no attempt has been made at self-consistently

modelling the full range of stars found within the Milky Way. The precise *Gaia* astrometry provides the first opportunity to select a *bias-free* and *complete* stellar populations to carry out exactly that experiment: the sensitivity of *Gaia* reaches the bottom of the main sequence out to $\simeq 150\,\mathrm{pc}$, and will resolve binaries with separations $10\,\mathrm{au}$. High-quality spectroscopy of this sample is required to fully characterize the physical properties of its varied constituents: stars in main-sequence & white dwarfs, single stars & stellar multiples, which may be interacting or not. Modelling this population at once will provide strong constraints on the initial mass function, the initial-to-final mass relation, the local star formation history, the binary fraction, the initial mass ratio and period distributions, and the complex physical processes of stellar interactions.

6   The No-Longer "Rare" Stars

In the previous sections we described the great revolution we expect thanks to accurate photometry, proper motion and chemical tagging of truly astounding samples of stars. Here, we focus on another dimension: samples of rare stars that will be unearthed by the current and near-future programs. Historically rare stars have contributed greatly to the advancement of astronomy. For instance, millisecond pulsars and X-ray binaries are very uncommon (their overall incidence in the Galaxy is 1 ppm) but can be identified via radio/X-ray surveys, and they have given us great insight into accretion physics, provided fundamental clues about the physics of the densest matter. The large datasets of the 2020s, combined with novel analysis techniques (e.g., machine-learning techniques such as the "Cannon", [22]) will discover unprecedented numbers of new and less conspicuous needles in the Galactic haystack. One-of-a-kind peculiarities such as "Tabby's Star" [23] and detached black holes [24; 25] will grow into entirely new classes of objects with hundreds of members [26].

A good example can be found in the class of "double degenerate" systems, binaries consisting of two white dwarfs, which will merge within the age of Universe. Some of these merging systems may explode as type Ia supernovae, some may produce the curious R Cor Bor stars, and some be transformed into massive and highly magnetized white dwarfs. Astronomers are now geared up to robustly model the merger events and catch them *before* they merge in order to understand the merger rates and demographics. Multi-epoch spectroscopic and time domain surveys will identify an astounding number of double degenerates, even before the launch of *LISA*. Particularly interesting will be nearby and eclipsing systems (of which just a handful have been found), which can be very precisely characterized. These will then allow astronomers to use secondary approaches to measure the physical properties of the bulk of the sample (see white papers by Gaensicke et al. and Toloza et al. for more detail on white dwarfs and by Tkachenko et al. for more detail on massive stars). Probing these rapid phases of stellar evolution is now within observational reach. No longer the provenance of theory alone, we will be able to see "first contact" between theory and observation in this crucial realm of heretofore hidden phenomena.
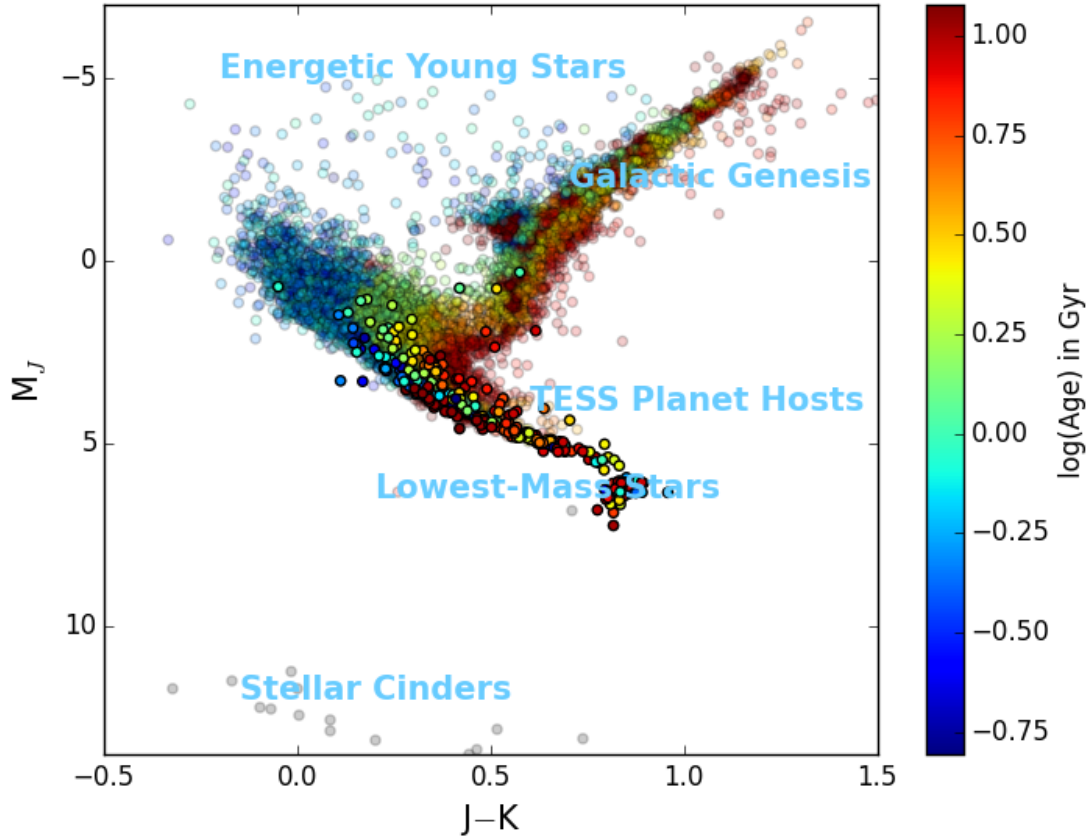
Figure 1: **Stellar astrophysical targets of the 2020s** The $(J - K)$ color and absolute J magnitude of 0.001% of the $\sim$1 billion stars that *Gaia* will observe, color-coded by their expected ages based on a Besancon Galaxy model (27). The wide range of ages of the red giants provides a perfectly-suited exploration space for Galactic Archaeology, given that we can determine their asteroseismic-calibrated ages. The luminous hot stars in the upper left ionize the gas and return metals to it, and the cool dwarfs on the lower right yield prime hunting ground for rocky planets in the habitable zone, whose host stars must be carefully characterized. The stars marked in bright colors represent those that are within 100 pc of the Sun and are part of the solar neighborhood census. The lowest-mass stars will be a major component of this census, especially since subsequent *Gaia* catalogs will have distances for much fainter stars than Data Release 1 does. The gray points with $M_J > 10$ mark white dwarfs with *Gaia* DR1 distances; the number of these "cinders" of low-mass stars will increase by a factor of 10^5 as *Gaia* continues. With knowledge of the white dwarf initial mass-final mass relation, ages can determined for these as well.

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