White Dwarfs as Astrophysical Probes

A Whitepaper Submitted to the Decadal Survey Committee

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Science Frontier Panels:
PRIMARY: Stars and Stellar Evolution (SSE)
SECONDARY: Galactic Neighborhood (GAN)

Projects/Programs Emphasized:
1. The Large Synoptic Survey Telescope (LSST); `http://lsst.org`
2. Pan-STARRS; `http://pan-starrs.ifa.hawaii.edu`
3. Thirty Meter Telescope; `http://www.tmt.org`
4. Giant Magellan Telescope; `http://www.gmto.org`
5. James Webb Space Telescope; `http://www.stsci.edu/jwst`

1 Introduction – The Milky Way White Dwarf Population

Over 97% of all stars eventually end their lives passively, shedding away their outer layers and forming white dwarfs (WDs). These stellar cinders are the burnt out cores of low- and intermediate-mass hydrogen burning stars, and contain no more nuclear fuel. As time passes, WDs will therefore slowly cool and release any stored thermal energy into space, becoming dimmer and dimmer. Although difficult to study given their intrinsic faintness, successful imaging and spectroscopic observations of WDs can shed light on a diverse range of astrophysical problems.

The number of known WDs expanded significantly from one in 1914 (40 Eri B in Russell's first HR diagram) to $\sim$1000 in the 1970s as a result of both opportunistic discoveries and targeted searches for high proper motion stars. An order of magnitude increase in the number of known WDs resulted again, this time from a single survey, the **SDSS**. This increase produced an extraordinary improvement in our knowledge of the WD luminosity function (LF) and thus of the tempo and character of star formation and chemical evolution in the Milky Way (Harris et al. 2006). In addition, spectroscopy of this much enlarged sample led to the discovery of new and interesting species of degenerate stars (Eisenstein et al. 2006). These studies underly a significantly improved understanding of stellar evolution beyond the main sequence and the behavior of matter in extreme conditions.

In this whitepaper we outline how new observational searches for WDs, and detailed follow up, can directly impact our grasp of important astrophysical questions:

- **What is the age and star formation history of various Milky Way component?**
- **How do stellar evolution models and mass-loss rates vary in different environments?**
- **What is the (initial) progenitor mass function of evolved stars in old stellar populations?**
- **Is a significant fraction of the Galactic dark matter tied up in baryons?**
- **What is the composition of extrasolar planetary material?**
- **What is the census of massive planets around stars?**
- **How can pulsational analysis of WDs be used to probe condensed matter physics?**

Answering these questions will first require new wide-field surveys that uncover rich WD populations in the Milky Way disk and halo, and in Galactic star clusters (such as **LSST**, **Pan-STARRS**, and **SkyMapper**). Full sampling of the populations, from newly formed objects at 100,000 K to the coolest remnants in the Galaxy at 3,000 K, will also require deep, ground and space based pointings with future UV, optical (**HST** and **JWST**), and infrared (**NIRSS**, **SASIR**, and continued **Spitzer**) missions. Although the discovery of these stars alone will answer several of the questions listed above, spectroscopic follow up with 30-m class telescopes such as **TMT** and **GMT** will be required to take full advantage of these new discoveries.

2 White Dwarfs as Chronometers

The WD LF represents a powerful tool to measure the star formation history of a stellar population, and therefore can provide direct tests to Galaxy formation models. The structure in the LF, including the faint-end turnover, is directly correlated with the formation timescale and subsequent evolution of the progenitor population. Uncovering the remnant LF in Milky Way components will require sampling large populations of WDs in different environments.

2.1 The Formation Timescale of the Galactic Halo

An important goal of stellar astrophysics in the next decade will be to characterize the age distribution of stars in the Galactic halo, using techniques that are independent of main-sequence turnoff physics (see next section). The faintest WDs in the nearest globular star clusters including M4, NGC 6397, and 47 Tuc (approved cycle 17 program) have been detected with **HST** (see Figure 1), and, at $M_{\rm V} \gtrsim 16$ (Hansen et al. 2007), are a full magnitude fainter than the faintest known objects in the Galactic disk (Harris et al. 2006). This work provides very accurate, and independent, age measurements for the nearby globular clusters and suggests that these objects formed several Gyr before the Galactic disk. However, the measurement rests on a few star clusters and can not be generalized to test Galactic formation models.

Extending this initial work to larger populations would allow turnoff and metallicity-independent age measurements for a sample of clusters that have very different dynamics and abundances. This therefore permit a clean study of age-metallicity relations for these systems. For example, a delay in the formation of metal-rich vs metal-poor clusters can be sensitively probed.

Unlike for the globular clusters, the study of WDs in the Galactic field halo has been limited to very nearby objects (e.g., the **SDSS** was too shallow to uncover large numbers of halo remnants – Harris et al. 2006). If this population is uniformly older than the Galactic disk, the remnants should be cooler and the LF turnover should be fainter. Characterization of both the WD LF of globular clusters, and of the field halo, can not only help answer when the first structures in our Galaxy formed, but also shed light on the formation processes themselves through comparative measurements (e.g., test in-situ formation vs accretion theories).

2.2 The Age and Structure of the Milky Way Disk

Harris et al. (2006) comment on the lack of a precise age measurement ($\sigma \sim 2$ Gyr, Leggett, Ruiz, & Bergeron 1998; Hansen et al. 2002) for the Galactic disk based on WD cooling theory given the low numbers of low-luminosity WDs in the **SDSS** sample. Improving the statistics of this LF will require wide-field observations that are significantly deeper that the **SDSS**. Such data will lead to an accurate age measurement for the oldest stars in the Galactic disk, and also map its complete star formation history. Epochs of enhanced star formation in the disk's history will leave imprints on the WD LF in the form of brighter peaks. The luminosity, and width, of these peaks can be inverted to shed light on the formation time and timescale of the star forming events.

Detailed knowledge of the structure of the Milky Way disk can also be leveraged from multi-epoch observations of WDs. This permits a kinematic analysis of faint WD populations through proper-motion studies. Dependencies of the WD LF in the disk with the population's velocity can constrain age differences between the thin and thick disks. The velocity may also be correlated with other Galactic parameters, such as metallicity, to give indirect age-metallicity estimates. Alternatively, dependencies of the LF (and therefore age) may exist with scale height above/below the Galactic plane and therefore feed into our understanding of the disk structure.

2.3 Facilities Required

A combination of next generation space-based studies and ground based wide-field surveys will be required to characterize the WD populations of globular clusters and field components, respectively. For example, the $F070W$ and $F090W$ filters on **JWST** can extend precise WD cooling ages to a set of ten globular clusters with a range of metallicities and dynamical parameters. For the field disk and halo, wide-field surveys such as **LSST**, **Pan-STARRS**, and **SkyMapper** have limiting magnitudes up to 3 – 4 mags fainter than the **SDSS** and can improve the census of the WD population in the

Milky Way disk and halo by several orders of magnitude (e.g., **LSST** would detect 20 million WDs with $r < 24.5$). Such surveys would completely sample the brightest WDs in our Galaxy (with $M_V \sim 11$) out to beyond 20 kpc, and therefore provide the first LF for field *halo* WDs and improve the statistics of the disk WD LF by over an order of magnitude. Finally, the time-series, synoptic nature of these surveys is an important requisite to fully leverage kinematic information from these studies as discussed above.

In addition to these optical studies, the census of the oldest (and coolest) WDs in the Milky Way will greatly benefit from future near-infrared observations with satellites such as **The Near-Infrared Sky Surveyor** (24th magnitude in J, H, and K) and ground-based systems like **SASIR** (23rd magnitude in Y, J, H, and K). For example, a 3500 K helium atmosphere WD at an age of 10 Gyr is optically faint, M_V = 18, but has a color of $V-H$ = 4 and would therefore be seen out to 1 kpc with such imaging.

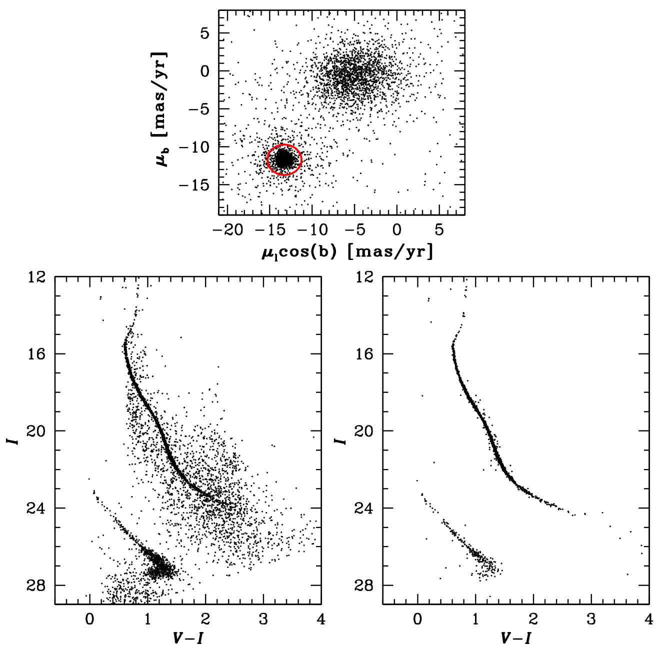

Figure 1: *The color-magnitude diagram of NGC 6397 from HST observations with ACS (see Richer et al. 2008) based on all stars (left) and proper motion members over a fraction of the field (right). The rich WD cooling sequence of the star cluster (faint-blue end) is modeled in Hansen et al. (2007) to yield an independent age for the cluster of t = 11.5 ± 0.5 Gyr.*

3 Stellar Evolution Models and Mass Loss Rates

The comparison of theoretical isochrones to observational color-magnitude diagrams has historically been used to infer the age of a nearby stellar population, provided the distance is known through independent methods (e.g., main-sequence fitting with the Hyades cluster). In practice, this comparison is often limited by our lack of knowledge of fundamental quantities (e.g., the distance and metallicity) and so the isochrones are used to estimate multiple parameters at once. When combined with the uncertainties in the microphysics of the models (e.g., the role of gravitational settling or the treatment of convective core-overshooting), the absolute uncertainty on the age of any stellar population using the main-sequence turnoff method is ∼2 Gyr for old stellar populations (D'Antona 2002). At higher redshifts, it is these same theoretical isochrones that are used to interpret unresolved light from distant galaxies into ages, metallicities and masses, and therefore form a major aspect of our understanding of galaxy formation and evolution.

It is important that the study of WDs with future blind wide-field surveys naturally extend to stellar populations such as nearby open and globular star clusters (see separate white paper by J.

Kalirai on "Resolved Stellar Populations in the Milky Way"). A survey such as **LSST** can completely map the WD cooling sequence in a 1 Gyr star cluster to 8 kpc, and therefore yield accurate ages for hundreds of systems. These age measurements are not affected by our knowledge of rotation, diffusion, overshooting, and even metallicity, and therefore can be used to test stellar evolution models in exquisite detail and constrain many of the microphysics.

Spectroscopic follow up of WDs in the nearest star clusters with 8–10 m telescopes such as **Keck** and **Gemini** have provided the masses and WD cooling ages of these remnants. With knowledge of their parent cluster age, the masses of WDs in a given cluster can be uniquely connected to that of their progenitor stars (e.g., the main-sequence lifetime of the progenitor star – and therefore its mass – is the difference between the cluster age and the WD cooling age – Kalirai et al. 2008; Williams et al. 2004, see Figure 2). This method therefore provides a way to directly map the amount of stellar mass loss that occurs through post main-sequence evolution. In turn, this improves our understanding of how stars are distributed along various evolutionary branches, and therefore impacts our ability to deconvolve the colors of distant galaxies using population synthesis methods.

Thus far, this (initial-final mass) relation has been loosely constrained with a few of the nearest clusters. Mapping the relation from [Fe/H] = -2 globulars (such as NGC 6397) to super-solar metallicity open clusters such as NGC 6791 (over a factor of 100 in metallicity) through WD spectroscopy will require multiobject spectrographs on 30-m telescopes such as **TMT** and **GMT**. The construction of this relation will enable investigation of several astrophysical problems:

- The relation will form a powerful input to chemical evolution models of galaxies (including enrichment in the interstellar medium) and therefore enhance our understanding of star formation efficiencies in these systems (Somerville & Primack 1999).

- The relation will lead to empirical estimates of the threshold mass that separates WD production from type II SNe, an important number to predict supernova rates and therefore understand energetics in galaxies and feedback processes (van den Bergh & Tammann 1991).

- For old stellar populations, the relation will allow for a study of the mass function of stars above the present day turnoff (e.g., 0.8 $M_\odot$ in a 12 Gyr population). The present day WD population and mass distribution can be mapped back to the progenitor mass distribution, and therefore yield the primordial mass function of the Galactic halo.

We note that the photometry of WDs in these new surveys will be more than three times as precise as **SDSS** photometry, particularly in the U-band which is often definitive for these stars. This greatly facilitates the matching of observed colors with predicted colors at the 1% level, making it possible to *photometrically* estimate WD temperatures, gravities and spectral types over a much wider range of parameter space then is now practical.

Future UV observations bluer than the U-band will also be crucial for understanding chemical evolution WDs, and linking that evolution to post-main-sequence processes. For example, the deficit of non-H atmosphere WDs at temperatures between 30,000 K – 45,000 K (the "DB gap", see Eisenstein et al. 2006 for newer observations) has led to a spectral evolution scenario requiring WDs to have thin layer masses which mix and settle, changing the chemical evolution along the cooling track (Fontaine & Wesemael 1987). However, this argument is opposite to results from asteroseismology determinations of the H layer (e.g., Fontaine et al. 1992, 1994) and can only be verified with UV observations of the H content.

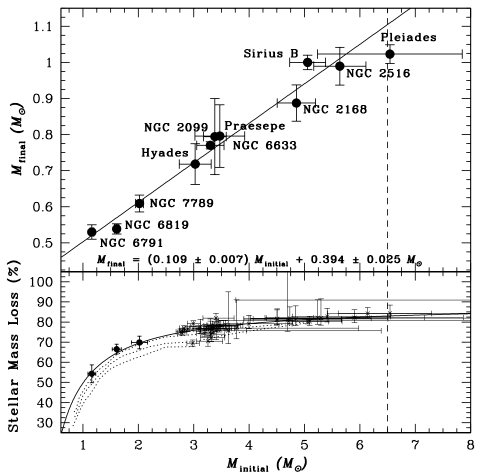

Figure 2: *Top – The initial-final mass relation from Kalirai et al. (2008), with best linear fit. The WD population of each star cluster is represented by a single data point. The relation shows a roughly linear rise in the remnant mass as a function of the initial mass. Bottom – The total integrated stellar mass loss that is suffered through standard evolution, directly constrained from the initial-final mass relation. The individual data points, except at the low mass end, correspond to individual progenitor-WD measurements.*

4 White Dwarfs as Dark Matter Candidates

The broadband study of WDs in future surveys can directly inform the overall baryon mass budget of the Milky Way. Since the MACHO experiment of detecting microlensing events towards the LMC, WDs have been suggested to possibly form an appreciable fraction of the Galactic dark matter. The MACHO results suggest that 20% of the halo of our galaxy is tied up in ∼0.5±0.3 $M_\odot$ objects (Alcock et al. 2000). Searches for these stars, e.g., in excess of the contribution from the stellar halo, have mostly failed (e.g., see § 6 of Kalirai et al. 2004 and references therein and also Oppenheimer et al. 2001). However, the searches have been limited to either wide field shallow surveys or pencil beam deep **HST** projects. Based on the MACHO results, a survey such as **LSST** will be sensitive to hundreds of dark halo WDs and therefore will definitively tell us the degree to which WDs are a component of the Galactic dark matter.

5 White Dwarfs as Exoplanetary Laboratories

WDs offer two major advantages for exoplanetary science research, which are not afforded by main-sequence, planetary system hosts. First, for $T_{\rm eff} < 25,000$ K, WD atmospheres should be free of heavy elements (Zuckerman et al. 2003), and those stars with planetary system remnants can become contaminated by small, but spectroscopically detectable, amounts of metal-rich material. Analysis of metal-polluted WDs therefore enables a compositional analysis of extrasolar planetary matter; Zuckerman et al. (2007) found that the abundances in the spectacularly metal-rich WD GD 362 are consistent with the accretion of a large asteroid with composition similar to the Earth-Moon system.

To date, metal-rich dust or gas disks, very likely produced by the tidal disruption of a large asteroid (Jura 2003; Jura, Farihi, & Zuckerman 2008), have been found around more than a dozen WDs and provide a ready explanation for the metal absorption features seen in their atmospheres. Recent **Spitzer** studies indicate that between 1% and 3% of all WDs with cooling ages less than ∼0.5 Gyr harbor warm circumstellar dust disks (Farihi et al. 2009), signifying an underlying population of terrestrial bodies that have survived post-main sequence evolution. These discoveries provide information that at present can be acquired no other way: the frequency and bulk chemical composition of minor planet systems around other stars; and the survival and dynamical evolution of planetary systems through the post-main-sequence phases of their host star. Evidence is strong that these disks evolve from the tidal disruption of minor planets: to be tidally destroyed within the Roche limit of a WD, an asteroid must be perturbed out of a much larger orbit (Debes & Sigurdsson 2002), and hence unseen planets of conventional size are expected at WDs with dusty disks.

The second exoplanetary scientific advantage offered by WDs is that they are earth-sized, and their low luminosities permit the direct detection of infrared emission from self-luminous, substellar companions such as brown dwarfs and massive jovian planets. The improved luminosity contrast between a typical WD and a substellar companion is a factor of 10^4 compared to a main-sequence A star. For sufficiently young targets (e.g. the Hyades), photometry of WDs from telescope/instruments such as **Spitzer/IRAC** would be sensitive to infrared excesses from 5 $M_{\rm J}$ companions at arbitrarily close separations (Farihi et al. 2008; Mullally et al. 2007).

6 Rare White Dwarf Species and the Physics of Condensed Matter

In addition to future deep imaging and spectroscopic observations, accurate time-series photometry will be crucial towards several important applications of WDs. For example, the temporal coverage of surveys such as **GAIA** and **LSST**, in multiple filters, will lead to exciting discoveries of exotic stellar species including eclipsing short period double degenerate systems, pre-CV/post-common envelope systems, highly magnetized WDs, and carbon-rich degenerates. In the UV, time-series observations of pulsating WDs can lead to the identification of time-variant absorption lines in the spectrum as the stars become hotter. Mapping these changes in the thermal structure of the atmosphere can yield crucial information on the pulsation mechanisms themselves.

Eclipsing short period double-degenerate systems are especially of great interest for direct determinations of WD radii and astrometric masses, and therefore can constrain the degenerate mass-radius relation. It is the catastrophic merger of these double degenerate systems that is believed to be one potential source of type Ia supernova events. Identifying, and monitoring, such systems through their eclipse signals could reveal the gravitational decay rate of the mutual orbit, and therefore these systems may be linked to specific gravitational wave signals from **LISA**.

The study of pulsations (”asteroseismology”) of WDs has (and will continue) to yield the most information on the internal structure of any stars other than the Sun. This knowledge has improved our fundamental understanding of how matter behaves in extreme (and degenerate) pressure environments, including a better understanding of 1) the core C/O ratio, and thereby the C(alpha,gamma)O reaction rate (Metcalfe 2003), 2) the physics of crystallization (Montgomery & Winget 1999), 3) the equation of state of C/O at extreme densities, 4) the efficiency of stellar convection (Montgomery 2005), and 5) the thickness of the surface H and He layers (Bradley & Winget 1994; Metcalfe et al. 2005). Furthermore, a subset of the pulsators are extremely stable, and measurements of the small shifts in their oscillation periods due to cooling can be used to 1) infer their neutrino cross-section and loss rates (Winget et al. 2004) in the case of the DBVs (helium-rich photospheres), and 2) place constraints on their production rates of axions, one of the viable candidates for dark matter (Bischoff-Kim, Montgomery, & Winget 2008) in the case of the DAVs (hydrogen-rich photospheres).

Future asteroseismology of WDs may also help unravel the mystery of WDs with carbon atmospheres (spectral type DQ, Dufour et al. 2007), which may be the remnants of some of the most massive stars to form WDs (e.g., Williams et al. 2006). The recent discovery of variability in these stars (Montgomery et al. 2008) opens the door to new exploration of their interior composition, should these be true pulsating stars. The first discovery of strong magnetic fields in one of these (likely) pulsating DQs (Dufour et al. 2008) may hold important clues for understanding the creation of magnetic fields in WDs and their behaviors in dense plasmas.

The identifications of large numbers of pulsating WDs will also help characterize the boundaries of existing pulsation strips and possibly uncover new strips. The characterization and purity of these strips is related to the structure of the evolving star, and are often explored with follow-up spectroscopy to measure the gravity and temperatures of the pulsating stars. Future studies of these strips must also leverage UV observations of these WDs, where trace amounts of H can only be seen. The presence of H can change the number of electrons, and hence pressure in the atmosphere, causing DB WDs (those with He I lines) to be incorrectly characterized (see Beauchamp et al. 1999).

Coupling this pulsational analysis with deep, accurate LFs as discussed earlier can allow self-consistent tests of the physics governing WD structure. The processes within the star, such as the release of virial energy sources as the internal structure is rearranged through crystallization, temporarily retard the star's cooling rate and therefore should produce signatures in the LF. This can therefore constrain transitions from the Mestel cooling regime to the Debye regime, which directly impacts the use of WDs as chronometers to date stellar populations (as discussed earlier).

In summary, we stress that WDs are important astrophysical probes and their characterization through future imaging and spectroscopic surveys can benefit many new avenues of research. These observations will require both new space-based facilities in the UV, optical, and IR, and deep, ground-based surveys sampling large portions of the sky. Equally important are dedicated follow up projects to the new discoveries in these surveys (e.g., pulsating stars) with 4 – 6 m class optical telescopes

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