Astro2020 Science White Paper

White dwarfs as probes of fundamental astrophysics

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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Introduction

White dwarfs (WDs) are the remnants of all stars with initial masses less than $8M_{\odot}$, and they provide important laboratories for the study of stellar evolutionary processes and the behaviour of matter at extremes of temperature and density. As some of the oldest objects in the Galaxy they are useful cosmological clocks, placing strong limits on the ages of globular clusters and disk populations. They are implicated in the production of Type Ia supernovae, on which the cosmological distance scales and the existence of Dark Energy are predicated, even though the precise mechanism(s) remain unresolved.

The white dwarf mass-radius relation and fundamental properties of matter

The gravitational redshift of light emitted by an astronomical object was first predicted by Einstein (1916), where the size of the shift is directly proportional to the mass/radius ratio of the star.

Spectroscopic observations of WDs have provided a valuable means of accurately measuring the WD masses and mass-radius relation (e.g. Oswalt 2012, Parsons 2018). The mass-radius relation is the foundation for much of our understanding of the structure of degenerate stars. Redshift observations are best carried out on WDs in binaries with a main-sequence companion (Sirius-like system) where the radial velocity of the system can be measured from the MS star and subtracted from the gravitational redshift measurement.

Empirical verification of the mass-radius relation remains a challenge as the observational precision required was not achievable until accurate distance measurements from Gaia became available. However, despite huge improvements in precision, the results achieved with the new parallax data have highlighted the need for more accurate spectroscopic observations and improved WD atmospheric and spectral modelling, which are now the factors limiting mass measurements (Joyce et al. 2018a, Tremblay et al. 2017, Tremblay et al. 2019).

Until now, the opportunity to exploit the power of gravitational redshift measurements has been limited to a few WDs in nearby Sirius-like binary systems. A recent measurement of the redshift of Sirius B with the HST (Joyce et al. 2018b, see figure 1) demonstrated the potential for this method to achieve precision to within a few percent. Attempts to repeat this with a wider range of WDs have been hampered by the difficulty in obtaining high quality spectra uncontaminated by light from the nearby main sequence star. Measurements of several systems with the HST resulted in limited success as the light of the main sequence star can seriously affect results if present in the optical spectrum of the WD. There is a need for improved spatial and spectral resolution compared to that currently available, to resolve the WD in many more close binaries and provide redshift measurements with an accuracy of a few km/s for WDs across the full mass range. Key benefits will be a definitive test of the MRR and a vital benchmark for the thousands of spectroscopic mass determinations produced through follow-up work on Gaia white dwarf sample and future large spectroscopic surveys such as LSST.

White dwarfs as probes of variation in the fine-structure constant

It has been shown theoretically, in theories of quantum gravity, that fundamental constants, such as the fine structure constant (α) and the electron/proton mass ratio (μ) can vary in the presence of a strong gravitational field. Such variations are expected to be manifested as small shifts in the wavelengths of atomic and molecular transitions. With UV spectra containing the absorption lines of many such transitions, white dwarfs have been used to study the potential effects (Berengut et al., 2013; Bagdonaite et al., 2014) but the work is limited to a few of the very brightest white dwarfs.

Observing potential variations in the fine structure constant in white dwarf spectra is very challenging, requiring extremely high S/N and deep understanding of systematic wavelength calibration effects. Statistically, there is also benefit in observing a significant sample of objects to compare results between them. Any observed effect should be reproduced in stars of similar gravity. Furthermore, extending the sample to the extreme range of white dwarf gravities allows exploration of the dependence of α & μ on gravity, or at least places important limits which can constrain the possible range of theories.

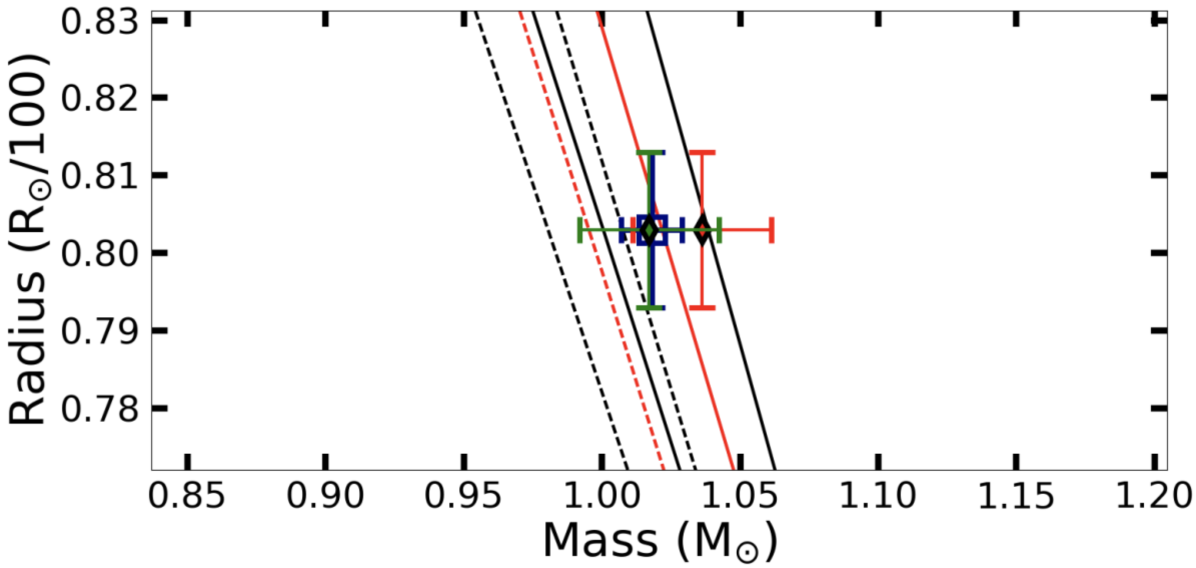

Figure 1. Mass and radius of Sirius B measured from the gravitational red-shift (red and green diamonds, corresponding to two slit positions in the STIS spectrograph) compared to the dynamical values (blue square). Solid and dashed lines represent theoretical mass-radius relations for thick and thin H-layers respectively (Red lines - T_{eff} = 25,922K for Sirius B, black either side for 10,000K and 40,000K).

We have recently conducted a number of detailed studies, using bright hot white dwarfs as targets. This work has utilized the best observations from the HST archive and new observations approved in HST cycle 25. While the results are very promising, it is most likely that we will only obtain an upper limit on the variation of α, due to the limitations of the spectral resolution (~100,000) of the STIS spectrograph. Therefore, to make progress in this work requires both increased aperture and spectral resolution in future UV instrumentation.

White dwarfs as probes of bulk exoplanet composition

In the strong gravitational fields associated with white dwarfs, it is predicted that their atmospheres should be pure H or He (depending on the prior evolution), devoid of heavier elements, which sink out of the surface layers. However, many studies (e.g. Barstow et al. 1993, 2003) have demonstrated that white dwarf atmospheres containing metals are ubiquitous. While the presence of this material was initially attributed to the effect of radiative levitation, this mechanism was unable to explain the detailed abundances or the presence of metals in cool white dwarfs, where the radiative effects are negligible. It is now evident that many white dwarfs are accreting material from extrasolar planetary debris (e.g. Jura et al., 2009, 2012; Gänsicke et al., 2012; Barstow et al., 2014 – see figure 3). Consequently, the study of white dwarf atmospheres provides a unique opportunity to determine the composition of these bodies.

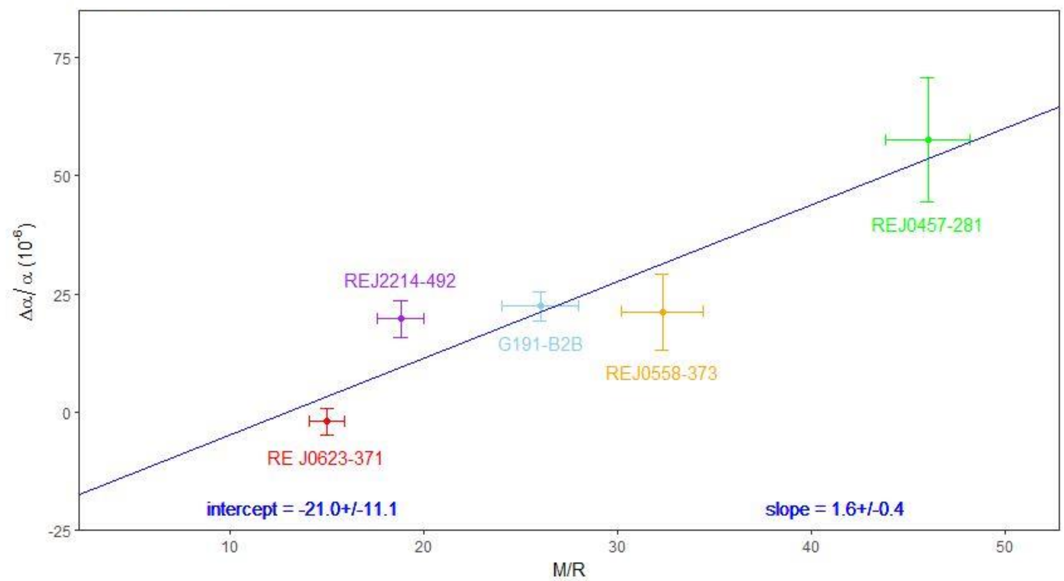

Figure 2. Limits on the variation of the fine structure constant as a function of "compactness" (M/R) for five hot H-rich DA white dwarfs, obtained through UV spectroscopy with HST.

Priorities in exo-planet research are rapidly moving from finding planets to characterizing their physical properties. Of key importance is their chemical composition, which feeds back into our understanding of planet formation. Mass and radius measurements of transiting planets yield bulk densities, from which interior structures and compositions can be deduced (Valencia et al. 2010). However, those results are model-dependent and subject to degeneracies (Rogers & Seager 2010; Dorn et al. 2015). Transmission spectroscopy can provide insight into the atmospheric compositions (Sing et al. 2013; Deming et al. 2013), though cloud decks detected in a number of super earths systematically limit the use of this method (Kreidberg et al. 2014). For the foreseeable future, far-ultraviolet spectroscopy of white dwarfs accreting planetary debris remains the only way to directly and accurately measure the bulk abundances of exo-planetary bodies. Significant progress will be made through the acquisition of a large sample of high-resolution UV spectra to provide these measurements.

Instrumentation Requirements

White dwarfs have been studied extensively in the UV for around 40 years, initially by IUE and then HST. While this work has yielded many important and exciting scientific results, it has generally been limited to a small and heavily biased sample. White dwarfs are Earth-sized, and hence intrinsically faint, and even with the improved throughput of the Cosmic Origins Spectrograph on HTS, high-resolution ultraviolet spectroscopy can only be obtained for either very nearby (<20pc) or young (<100Myr) and, therefore, hot white dwarfs, severely limiting our understanding of the underlying physics, and the wider diagnostic power of these stellar remnants.

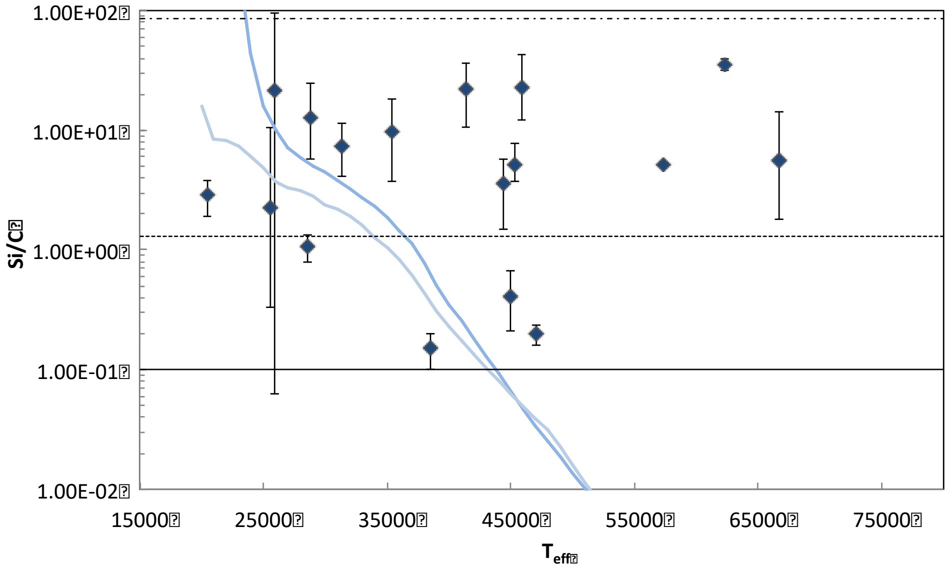

Figure 3. Si to C ratio for a sample of 17 white dwarfs observed in the far UV by FUSE. Most stars show evidence for accretion of rocky material (solid line – solar abundance, dotted line – CI chondrite, dot-dash line – bulk Earth).

A large UVOIR telescope in the 8-16m aperture range will enable high S/N observations of several thousand white dwarfs, increasing potential sample sizes for the above programmes by 1-2 orders of magnitude. In addition, the dramatic improvement in the diffraction limited resolution enabled by the larger aperture, coupled with coronagraphic capability for the most extreme luminosity ratios, will open up the possibility of resolving binary systems with smaller separations and/or at greater distances.

There is a clear need for enhanced spectral resolution compared to current instruments to obtain better dynamical information for the systems observed and to press hard on the potential for determining possible variations in fundamental physical constants in strong gravitational fields.

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