Gravitational redshifts from white dwarfs to constrain the white dwarf equation of state and composition

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White dwarfs are compact stars which are remnants of evolution of stars like our Sun (https://en.wikipedia.org/wiki/White_dwarf). Their typical masses are 0.2-1.2 Msun, but their radii are closer to the Earth's radius. They are supported against gravitational collapse by the pressure of the degenerate electron gas, giving rise to a peculiar mass-radius relation: more massive white dwarfs are smaller. The same physical mechanism (pressure of the degenerate electron gas) gives rise to the so-called "Chandrasekhar limit" (https://en.wikipedia.org/wiki/Chandrasekhar_limit), in which the white dwarf is too massive to be supported by the degeneracy pressure and has to collapse into an even more compact object (a neutron star).

There is an interesting effect of the Einstein's general relativity theory in which photons that climb out of a gravitational potential toward an observer at infinity are slightly redshifted (https://en.wikipedia.org/wiki/Gravitational_redshift). This effect is tiny for ordinary stars, but not so tiny in white dwarfs. Gravitational redshift from the surface of a spherical star is proportional to M/R, and therefore a detection of gravitational redshift provides a valuable constraint on the mass-radius relationship of white dwarfs.

How do we measure gravitational redshifts? We need features in the atmospheres of stars whose laboratory wavelengths are known (from quantum mechanics and experiments on Earth). Luckily for us, indeed white dwarfs have absorption features in their spectra, in most cases due to hydrogen atoms in the thin upper layer of the star, but sometimes due to helium or other elements (https://iopscience.iop.org/article/10.1086/133228). The problem is that when the absorption lines are shifted relative to their expected positions, we don't know whether they are shifted because of the gravitational redshift or because of the random motion of the stars in the Galaxy relative to the Solar system.

In 2020, our group made the first measurement of the white dwarf equation of state from the gravitational redshifts by averaging out the random motions of the stars and isolating the effect of the gravitational redshift (https://ui.adsabs.harvard.edu/abs/2020ApJ...899..146C/abstract). This was the first time that the gravitational redshift and the mass-radius relation was measured across such a wide range of masses (https://www.sciencenews.org/article/

white-dwarf-stars-shrink-size-gain-mass, https://hub.jhu.edu/2020/07/30/astrophysicsists-observe-gravitational-redshift-effect/).

This was a statistical measurement: we didn't know gravitational redshifts of individual stars, but we could average out the random motions. There is an alternative technique to measure gravitational redshifts without averaging. When white dwarfs are found in wide binaries with another (normal, so-called main sequence, star), the radial velocity of the main-sequence star can be used to measure the overall motion of the binary in the Galaxy and to isolate the gravitational redshift effect. This has been done, but only for a handful of objects (https://ui.adsabs.harvard.edu/abs/2018MNRAS.481.2361J/abstract, http://adsabs.net/abs/2017ApJ...848...16B, https://ui.adsabs.harvard.edu/#abs/2019A%26A...627L...8P).

There are a variety of reasons why measuring the white dwarf mass-radius relation remains an interesting thing to do. First, there should be effects of temperature which have not yet been detected: hotter white dwarfs have their degeneracy slightly lifted and they are slightly "puffier" as a result. Second, differences in core composition lead to slight differences in radii at a given mass, and measuring the core composition of white dwarfs would be an extremely interesting thing to do, albeit likely extremely difficult at the current precision.

In this project, we would like to measure gravitational redshifts of white dwarfs in about 13+ binaries. We have several datasets from which these measurements can be extracted: we obtained observations of four binaries with the Apache Point Observatory 3.5 m telescope and three binaries with the Gemini telescope, and there are 6+ binaries observed by the Sloan Digital Sky Survey that we can use (there were six as of March 2021, there could be more now). With this sample, we will more than double the number of individual white dwarf gravitational redshift measurements.

The steps in this project would be as follows:

Step 1: Learn how to measure radial velocities of white dwarfs by fitting Gaussians to the absorption lines.

Step 2: Learn how to measure radial velocities of normal stars. This is potentially more difficult depending on the stellar type because there could be "a forest" of absorption features that need to be analyzed simultaneously. Ideally we would learn modern cross-correlation techniques for doing this, but depending on the stellar type there may be easier ways.

Step 3: Learn how to measure temperatures and surface gravities of white dwarfs from a variety of techniques, including WDTools (https://github.com/vedantchandra/wdtools, https://ui.adsabs.harvard.edu/abs/2020MNRAS.497.2688C/abstract).

Step 4. Assemble the full available sample from SDSS-V. This might involve cross-correlating SDSS-V white dwarfs (we have the list available) against the catalog of wide binaries from Gaia (https://ui.adsabs.harvard.edu/abs/2021MNRAS.506.2269E/abstract) and then checking to see which companions also have spectra in SDSS or any other surveys. This is a difficult step that requires multiple catalog-processing skills. If we get to this point, the project becomes proprietary to the SDSS-V collaboration and we need to follow certain non-disclosure and project process rules.

Step 5. Measure all radial velocities and all white dwarf surface parameters for all available binaries.

Step 6. Place these objects on the mass-radius relationship and compare with models.

Step 7. Write a paper.

The easiest steps to start from are Steps 1 and 3 -- to measure the radial velocity of a white dwarf and to fit it using WDTools.

In order to do this, one needs a white dwarf spectrum to play with.

A. By reading papers above and creative googling, locate the published catalog of white dwarfs from the Sloan Digital Sky Survey, preferably one with published atmospheric parameters that you can check your work against. Pick a high signal-to-noise, DA (hydrogen) white dwarf.

B. Using right ascension / declination or another identifier as appropriate, download the spectrum (e.g., https://dr12.sdss.org/advancedSearch -> sky region). It will be in FITS format, so you would need to know how to read these data files into python. I use FV software to take a quick look at the content of the FITS data files, but it can all be done in Jupyter / python using Astropy library.

C. Fit Gaussians to the absorption lines as described here: https://ui.adsabs.harvard.edu/abs/2020ApJ...899..146C/abstract to get the total radial velocity.

D. Use WDTools (https://github.com/vedantchandra/wdtools) to measure atmospheric parameters (it gives the radial velocity, too, so it's nice to check that the result agrees with C).

E. Once you get to this point and understand steps A-D, we are in business! Then we can apply the techniques learned to the recently observed white dwarfs in binaries and proceed to measuring the radial velocities of their normal companions.