113. Gravitational redshift

FOR MORE than a century, stellar radial velocities have been determined spectroscopically, using the Doppler shifts of their spectral lines. But many physical effects can modify the observed wavelength and line profiles (Dravins et al., 1999). For high-accuracy work, e.g. in exoplanet studies with target accuracies of a few $\mathrm{cm\,s^{-1}}$, these small effects must be taken into account.

Causes of line asymmetries and spectral shifts include atmospheric pulsation, surface convection, stellar rotation, stellar winds, and – the effect I will focus on here – the star's gravitational potential.

The advent of high-accuracy astrometry means that stellar radial velocities can, in principle, be obtained by methods based purely on geometric principles (I have described the phenomenon of 'perspective acceleration' in the context of Gaia in essay #34). Conversely, the differences between spectroscopic and astrometric radial velocities can provide information on these sorts of stellar phenomena unobtainable by other methods.

I will look here at three classes of object for which the gravitational effects of the star's mass on the spectral line shifts are being investigated with the Gaia data: white dwarfs, open clusters, and wide binaries.

These measurements are enabling accurate mass determinations for white dwarfs (and hence tests of the mass–radius relation for degenerate objects), insights into cluster dynamics, tests of stellar structure models, and even studies of the global dynamics of our Galaxy.

ACCORDING TO General Relativity, time is dilated in a gravitational potential well, ϕ, relative to a distant observer. In the weak field regime, this leads to a spectroscopic velocity offset in the radial r direction

$$\frac{\Delta v_r}{c} = -\frac{\Delta\phi}{c^2}. \tag{1}$$

In the Newtonian limit,

$$z = \frac{\Delta\lambda}{\lambda} \approx \frac{gR}{c^2} \tag{2}$$

For photons emitted from the Sun, $z = 2\times10^{-6}$ (being a Doppler shift of $636\,\mathrm{m\,s^{-1}}$). For the Earth, $z = 7\times10^{-10}$, or an equivalent Doppler shift of $0.2\,\mathrm{m\,s^{-1}}$.

In most stars, as for the Sun, the gravitational redshift amounts to a few hundred $\mathrm{m\,s^{-1}}$, comparable to the convective blueshift in their atmospheres. But for white dwarfs, with their much smaller radius and consequently their much higher surface gravity, it reaches tens of $\mathrm{km\,s^{-1}}$. Accordingly the difference between the spectroscopic Doppler shift and the astrometric radial velocity can be used as a proxy for their mass.

Gravitational redshifts have been measured directly for white dwarfs (e.g. Greenstein & Trimble 1967; Barstow et al., 2005; Falcon et al., 2012) and also for neutron stars (Cottam et al., 2002). For white dwarfs in binary systems, specifically in the case of Sirius B, measurements have demonstrated the correspondence between the mass inferred from its gravitational redshift, and from its orbital dynamics (Joyce et al., 2018).

TURNING NOW to some of the related results exploiting the Gaia data, I will first look at two examples of the results from the studies of white dwarfs.

Pasquini et al. (2019) analysed 6 Hyades white dwarfs using archival high-resolution UVES–VLT spectra to determine their Doppler shift, and using Gaia DR2 astrometry to determine their radial velocities independently of spectroscopy. The mass estimates from the resulting gravitational redshifts were systematically smaller, by $0.02-0.05M_\odot$, than those derived from other methods. They considered this to be a significant finding for white dwarf models.

Chandra et al. (2020) used a sample of 3000 white dwarfs with data from the Sloan Digital Sky Survey and Gaia DR2. They derived *apparent* radial velocities from absorption lines, stellar radii from photometry and Gaia parallaxes, and surface gravities by fitting atmospheric models to spectra. By averaging the apparent radial velocities of white dwarfs with similar radii, and similar surface gravities, they could cancel out random Doppler shifts and, from the underlying gravitational redshift, empirically measured the white dwarf mass–radius relation across a wide range of stellar masses. They concluded that their results were consistent with the leading theoretical models of Fontaine et al. (2001).

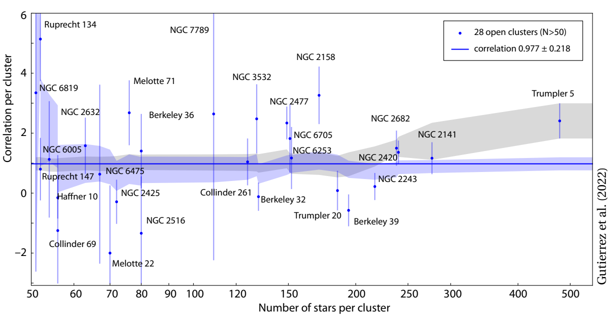
Pre-Gaia, confirmation of the gravitational redshift effect was largely limited to the Sun (where it can be separated from rotation and surface convection), and to white dwarfs (where their much smaller radii results in a much more significant relativistic effect).

Open clusters allow such studies to be extended, at least statistically, to dwarf and giant stars, exploiting their common (radial) space motions, characterised by accurate astrometry. Objectives include further tests of the equivalence principle, as well as of stellar models.

Leão et al. (2019) reported a broad study applied to 69 main-sequence stars and 2 giants in the Hyades, again based on a comparison of the spectroscopic radial velocities from HARPS, and accurate *astrometric* radial velocities based on the combination of data from Hipparcos and Gaia DR1. The spectroscopic–astrometric difference is skewed, with a dependence on right ascension consistent with a cluster rotation of $42.3\,\mathrm{m\,s^{-1}\,pc^{-1}}$. The two giants show a spectroscopic radial velocity blue-shifted with respect to the dwarfs, by $626\pm131\,\mathrm{m\,s^{-1}}$, in agreement with theoretical predictions. The standard deviation ($347\,\mathrm{m\,s^{-1}}$ for the dwarfs) is close to the expected cluster velocity dispersion.

Dai et al. (2019) used the Gaia DR2 data to derive the total 'intrinsic' redshift (gravitational plus convective blueshift) for a large number of F, G, K, and red giants (with radii estimates) within 1 kpc: some 134 000 F type, 361 000 G type, 137 000 K type, and 155 000 red giants. FGK-type stars were found to have roughly the same total intrinsic redshift, much smaller than the expected gravitational redshift, implying a contribution from the convective blueshift of several hundred $\mathrm{m\,s^{-1}}$. The red giants' intrinsic redshifts are negative, implying that their convective blueshift is, as expected, stronger than the contribution from the gravitational redshift.

A study with similar aims by Gutiérrez et al. (2022) used Gaia DR2 data on 70 000 non-degenerate stars classified as members of Galactic open clusters. Restricting the study to the best sub-sample of 28 clusters and a total of 3779 stars, and using theoretical estimates of the contribution of convective line shifts, they found a strong correlation between theory and observations of 0.977 ± 0.218, and …*'one of the more extensive validations of a fundamental prediction of gravity theories'*.



Recalling that open clusters provide a laboratory for probing the effects of gravitational redshift because of the stars' common space motion, another class of system can be similarly exploited: wide binaries.

Specifically, from the differences in radial velocities between the components of wide binaries, it should be possible to measure the combined effects of gravitational redshift and convective blue-shift of the spectral lines, by eliminating the contributions from their individual peculiar space motions. Again, because of the small amplitude of the effect, it may currently be possible to do so only in a statistical sense.

Co-moving pairs in 3d velocity space, typically wide binaries with $d>25$ au, were first compiled from Gaia DR1 by Oh et al. (2017). From Gaia DR2, 3741 pairs were identified in by Jiménez-Esteban et al. (2019), more than 50 000 within 200 pc of the Sun by El Badry & Rix (2018), and nearly 100 000 by Hartman et al. (2020).

Moschella et al. (2022) used 1682 pairs with $d>10^{-3}$ pc, and with $T_{\rm eff}$, luminosity, and radius from Gaia DR2. They found a correlation between the observed differences in Gaia radial velocities, and the differences in surface gravity and convective blueshift inferred from effective temperature and luminosity measurements, excluding a null signal at the 5σ level.

El-Badry (2022) used data from Gaia DR3 with similar goals. From 500 wide binaries containing a solar-type main-sequence star and a red giant or red clump companion, he found that the 'apparent' radial velocity of the giant is on average $0.49\pm0.02\,\mathrm{km\,s^{-1}}$ lower than that of the main-sequence star. Due primarily to the weaker gravitational fields of giant stars, the statistical result is in reasonable agreement with theoretical predictions.

I will finish with two broader implications that have been drawn from these sorts of studies.

Noting that in wide binaries, the difference in gravitational redshift for dwarf–giant components dominates at separations $\gtrsim10^{-2}$ pc, Loeb (2022) has suggested that this effect was probably incorrectly interpreted as a possible modification of Newtonian gravity in their orbital dynamics (see essay #37), most recently from studies based on Gaia EDR3 (Hernandez et al., 2022).

Studies using Gaia EDR3 suggest that the Milky Way has a nearly flat rotation curve with a local circular speed $230\,\mathrm{km\,s^{-1}}$, declining outwards by about $-1.7\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ (Eilers et al., 2019). Loeb (2022) showed that this leads to a local contribution to the gravitational acceleration of $-2.3\times10^{-10}\,\mathrm{m\,s^{-2}}$, and an associated velocity gradient $-2.4\times10^{-2}\,\mathrm{km\,s^{-1}\,kpc^{-1}}$.

In turn, this leads to an *apparent* radial migration: an apparent radial recession away from the Sun for stars closer to the Galactic centre, and a spurious radial approach beyond the Sun's Galactocentric radius.