The gravitational redshift of solar-type stars from \textit{Gaia} DR3 wide binaries

Kareem El-Badry$^{1,2,3}$

$^1$Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA
$^2$Harvard Society of Fellows, 78 Mount Auburn Street, Cambridge, MA 02138
$^3$Max-Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany

ABSTRACT

Light escaping from a gravitational potential suffers a redshift with magnitude proportional to the depth of the potential. This “gravitational redshift” is easily measurable in dense stars such as white dwarfs, but is much weaker and has evaded unambiguous detection in main-sequence stars. I show that the effect is directly measurable in the \textit{Gaia} DR3 radial velocities (RVs) of the components of wide binary stars. In a sample of $\sim$500 wide binaries containing a solar-type main-sequence star and a red giant or red clump companion, the apparent RV of the giant is on average $0.49 \pm 0.02$ km s$^{-1}$ lower than that of the main-sequence star. This owes primarily to the giants’ weaker gravitational fields and is in reasonably good agreement with the value expected from general relativity.

1. INTRODUCTION

General relativity predicts that light emitted from the surface of a massive object undergoes a redshift with magnitude proportional to the depth of the potential. For a star of mass $M$ and radius $R$, the amplitude of the induced apparent RV in the weak-field limit is

$$v_{\text{GR}} = \frac{GM}{Rc} = 0.64 \text{ km s}^{-1} \left( \frac{M}{M_{\odot}} \right) \left( \frac{R}{R_{\odot}} \right)^{-1}.$$ (1)

This velocity is large and easily detectable in white dwarfs, where values of about 30 km s$^{-1}$ are typical (e.g. Falcon et al. 2010). In neutron stars, it is enormous (of order 0.3c; e.g. Cottam et al. 2002). In main-sequence stars, it is smaller, but still comfortably within the capabilities of modern spectrographs.

An obvious challenge in measuring gravitational redshifts is that stars are not stationary, but have quasi-random velocities along our line of sight, with typical amplitudes of tens of km s$^{-1}$. This stymies detection of weak gravitational redshifts unless the star’s true radial velocity can be determined through external information. Wide binary stars offer precisely the required external information: their orbital velocities are small, such that to first approximation, the two stars in a wide binary have the same RV, and any difference between their observed RVs can be attributed to gravitational redshift. This allowed Greenstein & Trimble (1967) and many subsequent works to measure gravitational redshifts and masses of white dwarfs in wide binaries with main-sequence companions.

The situation is more complicated for binaries containing two main-sequence stars, because (a) the gravitational redshifts of both components are expected to have similar magnitude, and (b) the orbital
velocity and surface convective shift both have comparable magnitude to the expected gravitational redshift. This can complicate attempts to precisely measure genuine RV differences in wide binaries (e.g. Loeb 2022), but it also suggests that the effects of gravitational redshift should be detectable in a large sample of wide binaries. This has recently become possible thanks to the Gaia mission, which both enables selection of pure wide binaries samples using astrometry, and measures RVs for the component stars.

The most straightforward approach is to compare the RVs of giants and dwarfs, as the giants are expected to have much smaller (usually negligible) redshifts. Pasquini et al. (2011) compared the mean RVs of a large sample of dwarfs and giants in a star cluster, where the peculiar velocities should average out. However, they were unable to detect the gravitational redshift statistically, attributing the non-detection to the confounding effects of surface convection. More recently, Gutiérrez & Ramos-Chernenko (2022) did detect a gravitational redshift signal in the RVs of star cluster members, but only when combining data from many different clusters and fitting a global model. Similarly, Moschella et al. (2022) recently found tentative evidence of gravitational redshift in main-sequence wide binaries selected from Gaia DR2 data, but the effect was not obvious because Gaia DR2 contained RVs for both components of only a few giant/dwarf binaries.

Gaia DR3 (Gaia Collaboration et al. 2022) includes precise RVs to stars ≈ 2 magnitudes fainter than DR2, leading to a much larger usable sample of giant/dwarf binaries. Here, I leverage these new RVs to measure a visually obvious signature of gravitational redshift in the velocity difference of wide binaries’ components.

2. METHODS

From the wide binary catalog constructed by El-Badry et al. (2021), I selected binaries satisfying the following cuts:

- The position of the primary (the brighter component) in the color-magnitude diagram suggests it is a giant or red clump star, satisfying $M_G < 2 \times (G_{BP} - G_{RP}) - 1$. I corrected for extinction using the 3D dust map of Green et al. (2019) in the north and that of Lallement et al. (2019) in the south.

- The position of the secondary suggest it is a dwarf, with $M_G > 2 \times (G_{BP} - G_{RP}) + 0.5$.

- The pair is likely to be gravitationally bound, with a chance alignment probability below 10% ($R\_chance\_align < 0.1$). In practice, almost all the selected binaries have $R\_chance\_align < 0.01$.

- Both stars have a RV measurement reported in Gaia DR3, with radial_velocity_error $< 2$ km s$^{-1}$.

- The pair is separated by at least 5 arcsec, to minimize the effects of blending on the RVs (Katz et al. 2022). The median projected physical separation of the sample is 6,000 AU, corresponding to a typical orbital RV difference of order 0.5 km s$^{-1}$ (with no preferred sign).

I next “corrected” the Gaia RVs using the empirical magnitude-dependent RV zeropoint derived by Katz et al. (2022, their equation 5). The magnitude of this correction is $< 0.1$ km s$^{-1}$ for a majority of the sample.
These cuts yielded 538 binaries, which are shown on the color-magnitude diagram in the left panel of Figure 1. The median apparent magnitude of the giants is $G \approx 8.3$, and that of the dwarfs is $G \approx 12.0$. The dwarfs are mostly solar-type stars with masses $0.5 \lesssim M/M_\odot \lesssim 1.5$. A majority are near the main sequence, but a few subgiants are also included in the sample. A majority of the “giants” are not strictly on the giant branch but are core helium burning red clump stars, with $R \approx 10 R_\odot$ and (most likely) $M \approx 1 R_\odot$. The median distance to the sample is 350 pc.

The main result is shown the center and right panels of Figure 1: there is a not-very-subtle difference in the mean RV of dwarfs and giants. The inverse-variance weighted mean RV difference is $\approx 0.49 \text{ km s}^{-1}$, both for the full sample (center column) and for the subsample in which both components have radial velocity uncertainties below $1 \text{ km s}^{-1}$ (right column). The observed RV difference distribution is narrower for latter subsample because the RV differences for individual binaries are still dominated by measurement uncertainties.

The expected RV difference due to gravitational redshift is $\Delta v_{\text{GR}} = \frac{G}{c} (M_{\text{giant}}/R_{\text{giant}} - M_{\text{dwarf}}/R_{\text{dwarf}})$. Assuming $R_{\text{dwarf}} \approx R_\odot (M_{\text{dwarf}}/M_\odot)$, $M_{\text{giant}} \approx 1 M_\odot$, and $R_{\text{giant}} \approx 10 R_\odot$, this translates to an expected typical $\Delta v_{\text{GR}} \approx 0.58 \text{ km s}^{-1}$, pleasingly close to the observed value.

3. CONCLUSION

I have shown that the different gravitational redshifts of main-sequence and giant stars leads to an unambiguous shift in their apparent relative RVs in wide binaries observed by Gaia. I have not attempted to account for star-to-star variation in $M/R$ within the dwarf and giant samples, or for the effects of convective shifts that can lead the mean RV of the photosphere to differ from that of a star’s center of mass. The fact that the observed mean RV offset is close to the value predicted due to gravitational redshift suggests that these simplifications are tolerable at the $\lesssim 20\%$ level, at least in a population-averaged sense, but a more detailed investigation is certainly warranted.
Given the uncertainties in RV calibration and the still poorly understood effects of convective shifts, this approach seems unlikely to yield precise tests of GR in the near future. It is, however, a nice demonstration of the gravitational redshift phenomenon and of the precision and stability of the Gaia DR3 RV data.

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REFERENCES

Cottam, J., Paerels, F., & Mendez, M. 2002, Nature, 420, 51, doi: 10.1038/nature01159
El-Badry, K., Rix, H.-W., & Heintz, T. M. 2021, MNRAS, 506, 2269, doi: 10.1093/mnras/stab323
Falcon, R. E., Winget, D. E., Montgomery, M. H., & Williams, K. A. 2010, ApJ, 712, 585, doi: 10.1088/0004-637X/712/1/585
Gaia Collaboration, Vallenari, A., Brown, A., Prusti, T., & et al. 2022, arXiv e-prints, arXiv:2206.XXXXX.
https://arxiv.org/abs/2206.XXXXX
Green, G. M., Schlafly, E., Zucker, C., Speagle, J. S., & Finkbeiner, D. 2019, ApJ, 887, 93, doi: 10.3847/1538-4357/ab5362
Greenstein, J. L., & Trimble, V. L. 1967, ApJ, 149, 283, doi: 10.1086/149254
Gutiérrez, C. M., & Ramos-Cherenko, N. 2022, ApJ, 929, 29, doi: 10.3847/1538-4357/ac5a59
Katz, D., Sartoretti, P., Guerrier, A., et al. 2022, arXiv e-prints, arXiv:2206.05902.
https://arxiv.org/abs/2206.05902
Lallement, R., Babusiaux, C., Vergely, J. L., et al. 2019, A&A, 625, A135, doi: 10.1051/0004-6361/201834695
Loeb, A. 2022, Research Notes of the American Astronomical Society, 6, 55, doi: 10.3847/2515-5172/ac5ea9
Moschella, M., Slone, O., Dror, J. A., Cantiello, M., & Perets, H. B. 2022, MNRAS, doi: 10.1093/mnras/stac1427
Pasquini, L., Melo, C., Chavero, C., et al. 2011, A&A, 526, A127, doi: 10.1051/0004-6361/201015337