

GRAVITATIONAL REDSHIFT FOR WIDE BINARIES IN *GAIA* EDR3

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ABSTRACT

The Doppler effect is commonly used to infer the velocity difference between stars based on the relative shifts in the rest-frame wavelengths of their spectral features. In wide binaries, the difference in gravitational redshift from the surfaces of the constituent stars with distinct compactness dominates at separations $\gtrsim 10^{-2}$ pc. I suggest that this effect became apparent for wide pairs in the *Gaia* eDR3 catalogue but was incorrectly interpreted as a possible modification of Newtonian gravity in the internal kinematics of very wide binaries.

1. INTRODUCTION

According to General Relativity, the spectrum of radiation emitted from the surface of a star is gravitationally redshifted relative to a distant observer. In the weak field regime, the spectroscopic velocity shift v_{gr} is given by (Weinberg 1972),

$$v_{\text{gr}} = -\frac{GM}{cR} = -0.636 \left(\frac{M}{M_{\odot}}\right) \left(\frac{R}{R_{\odot}}\right)^{-1} \text{ km s}^{-1}, \quad (1)$$

for a star of mass M and photospheric radius R . The observed radii of stars show significant scatter for masses $\gtrsim 1M_{\odot}$ due to stellar evolution and rotation (Torres et al. 2010), implying that redshift variations of $\sim 0.5 \text{ km s}^{-1}$ should be common in pairs of stars with different compactnesses. Attempts to measure the gravitational redshift in main-sequence stars are challenging (Pasquini et al. 2011), but recent data indicated otherwise (Moschella et al. 2021). Fluctuations as a result of surface turbulence would average out for a large enough statistical sample of stars. A larger signal of gravitational redshift had already been detected for compact stars, such as white dwarfs (Greenstein & Trimble 1967; Barstow et al. 2005; Falcon et al. 2012) and neutron stars (Cottam et al. 2002).

The mass-radius relation for main-sequence stars of up to a few solar masses follows an approximate power-law relation (Rubin & Loeb 2011), $(R/R_{\odot}) \approx (M/M_{\odot})^{0.8}$, implying,

$$v_{\text{gr}} \approx -0.6 \left(\frac{M}{M_{\odot}}\right)^{0.2} \text{ km s}^{-1}. \quad (2)$$

2. IMPLICATIONS

The circular velocity $(GM/r)^{1/2}$ of a test particle around a star of mass M falls below the velocity shift v_{gr} at orbital radii r that exceed a critical value (Loeb 2014),

$$r_{\text{crit}} \equiv \left(\frac{c^2 R^2}{GM}\right) = 10^{-2} \left(\frac{M}{M_{\odot}}\right)^{0.6} \text{ pc}, \quad (3)$$

Hence, the spectroscopic velocity difference between the stellar members of a wide binary separated by more than $\sim 10^{-2} \text{ pc} = 2 \times 10^3 \text{ au}$ could be significantly affected by the difference in their intrinsic gravitational redshifts owing to their distinct compactnesses. At separations $r \gtrsim r_{\text{crit}}$, the actual radial velocity difference could be smaller than the gravitational redshift difference, implying a constant Doppler shift *independent of separation*. Wide binaries at separations $\gtrsim 10^{-2} \text{ pc}$ are characterized by long orbital times $\gtrsim 10^5 \text{ yr}$ and low speeds $\lesssim 0.7 \text{ km s}^{-1}$, making it challenging to measure any temporal change in the radial velocities of member stars.

Eccentric binaries spend a substantial fraction of their orbital time near apocenter where their relative speed is small and the fractional impact of the gravitational redshift effect is maximized. At separations larger than $2r_{\text{crit}}$, a binary in a radial velocity catalogue may be incorrectly declared as unbound if the gravitational redshift differential is not corrected for.

At the same time, selection for a small differences in radial velocities between stars at wide separations on the sky inevitably leads to a selection bias for *gravitationally-unbound pairs* which are observed to have a small spectroscopic velocity difference between their members just because their actual radial velocity difference happens to be compensated by the difference in gravitational redshift due to their distinct compactnesses. Being gravitationally unbound, these wide pairs with small spectroscopic shifts, would have proper motions on the sky that are larger than expected for gravitationally bound systems. On average in a large statistical sample, the excess proper motion in the sky would be of the same magnitude as the gravitational redshift - given a random geometric orientation of the velocity vector for each star.

3. GAIA EDR3 CATALOGUE

Recently, the kinematics of wide pairs of main-sequence stars with a total mass of $(1-2.2)M_{\odot}$ in the *Gaia* eDR3 catalogue was selected with strict data cuts on signal-to-noise ratio and radial velocities (Hernandez et al. 2022). For separations below 0.009 pc, the results showed the expected Newtonian behavior of the velocity difference between the binary members scaling in proportion to $(M_b/r)^{1/2}$, where M_b is the total binary mass. But at separations $\gtrsim 0.009$ pc, the data showed a separation-independent velocity difference of ~ 0.5 km s $^{-1}$ that scales weakly with binary mass, $\propto M_b^{0.24 \pm 0.21}$. The authors suggested that this situation is reminiscent of the deviation from Newtonian gravity in the baryonic Tully-Fisher relation (McGaugh 2020), where at low accelerations there is a need for either dark matter or modified gravity. But they also noted that the results are at odds with the predictions of Modified Newtonian Dynamics, abbreviated as MOND (Milgrom 2020), where the external field effect implies only small deviations from Newtonian dynamics.

4. CONCLUSIONS

Here I suggest that the above results reflect the selection bias induced by gravitational redshift to radial velocity cuts of spurious unbound pairs that were incorrectly identified as being gravitationally bound. This interpretation is consistent with three characteristics of the reported results: (i) the agreement between the measured asymptotic velocity of ~ 0.5 km s $^{-1}$ and equation (1); (ii) the weak dependence of the asymptotic velocity at large separations on the total pair mass, $\propto M_b^{0.2}$, as expected from equation (2); and (iii) the agreement between the transition separation of 0.009 pc and the value of r_{crit} in equation (3).

High resolution spectra of stars can be used to infer their surface gravity, GM/R^2 , and correct for the above-mentioned selection bias.

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REFERENCES

- Barstow, M. A., Bond, H. E., Holberg, J. B., et al. 2005, MNRAS, 362, 1134, doi: [10.1111/j.1365-2966.2005.09359.x](https://doi.org/10.1111/j.1365-2966.2005.09359.x)
- Cottam, J., Paerels, F., & Mendez, M. 2002, Nature, 420, 51, doi: [10.1038/nature01159](https://doi.org/10.1038/nature01159)
- Falcon, R. E., Winget, D. E., Montgomery, M. H., & Williams, K. A. 2012, ApJ, 757, 116, doi: [10.1088/0004-637X/757/2/116](https://doi.org/10.1088/0004-637X/757/2/116)
- Greenstein, J. L., & Trimble, V. 1967, AJ, 72, 301
- Hernandez, X., Cookson, S., & Cortés, R. A. M. 2022, MNRAS, 509, 2304, doi: [10.1093/mnras/stab3038](https://doi.org/10.1093/mnras/stab3038)
- Loeb, A. 2014, PhRvD, 89, 027301, doi: [10.1103/PhysRevD.89.027301](https://doi.org/10.1103/PhysRevD.89.027301)
- McGaugh, S. 2020, Galaxies, 8, 35, doi: [10.3390/galaxies8020035](https://doi.org/10.3390/galaxies8020035)
- Milgrom, M. 2020, Studies in the History and Philosophy of Modern Physics, 71, 170, doi: [10.1016/j.shpsb.2020.02.004](https://doi.org/10.1016/j.shpsb.2020.02.004)
- Moschella, M., Slone, O., Dror, J. A., Cantiello, M., & Perets, H. B. 2021, arXiv e-prints, arXiv:2102.01079, <https://arxiv.org/abs/2102.01079>
- Pasquini, L., Melo, C., Chavero, C., et al. 2011, A&A, 526, A127, doi: [10.1051/0004-6361/201015337](https://doi.org/10.1051/0004-6361/201015337)
- Rubin, D., & Loeb, A. 2011, Advances in Astronomy, 2011, 174105, doi: [10.1155/2011/174105](https://doi.org/10.1155/2011/174105)
- Torres, G., Andersen, J., & Giménez, A. 2010, A&A Rv, 18, 67, doi: [10.1007/s00159-009-0025-1](https://doi.org/10.1007/s00159-009-0025-1)
- Weinberg, S. 1972, Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity