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Article

The velocity of white dwarf stars relates to their magnitude

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SUMMARY

The relationship between the velocity of a white dwarf star and its absolute magnitude is unknown, posing unresolved questions about what characteristics a fast-moving white dwarf has compared to its slower counterparts. Using the European Space Agency's Gaia dataset, we analyzed the relationship between white dwarfs' magnitudes and proper motions. We hypothesized that older white dwarf stars may have different velocities than younger ones, possibly that stars slow down as they age. After filtering down the Gaia dataset to a set of roughly 65,000 white dwarfs, we selected the ones that had the highest proper motions. When we further filtered the high proper motion dataset to not include white dwarfs with outlier parallaxes, we were left with a dataset that was theoretically the fastest white dwarf stars in the Gaia dataset. Comparing these fast white dwarfs to the candidate dataset, we found that the white dwarfs in our filtered dataset were substantially redder and higher magnitude (traits traditionally associated with older stars) as compared to their non-fast counterparts.

INTRODUCTION

The European Space Agency's Gaia mission to conduct astrometric and spectrophotographic measurements at a previously unseen scale is groundbreaking and far surpasses previous missions. Launched in 2013, Gaia aims to create a 3-dimensional catalog of nearly 1 billion space objects, primarily consisting of stars (1). Gaia's first data release was in September 2016 and consists of observations made over the span of 14 months (2). Gaia's second data release (DR2), the dataset used in this paper, was released in April 2018 and consists of 22 months of observations between July 2014 and May 2016 (2,3). Gaia's DR2 made several improvements upon the already revolutionary success of the first, of which the most relevant to this paper was the improvement in data available for high proper motion stars (2,4).

Proper motion is a metric of how fast across the sky a star is moving in reference to the observer's line of sight. Gaia measures proper motion as a star's angular velocity in relation to the Gaia telescope. Gaia tracks how far an object moves in its field of view over a given time period and uses this information to calculate the proper motion of an object in the right ascension (ra) and declination (dec) directions. Our paper focuses on white dwarfs, examining the relationship between a white dwarf's magnitude and its proper motion, which has not been researched in depth. Since Gaia cannot directly confirm with 100% certainty whether or not a star is a white dwarf, the white dwarfs in this paper are candidate white dwarfs (4). Gaia DR2 increased the available data on stars, meaning this set is likely to include more white dwarf stars. This provides a better opportunity for us to examine the relationship between white dwarfs and proper motion.

The Gaia survey collected data on magnitude, a measure of how bright a star is, by first measuring the intensity of light emitted by an object. Gaia used the formula $m = 2.5log(intensity)$ to convert the intensity into a magnitude value (2). However, these values are apparent magnitude values, meaning that Gaia calculates the brightness of a star as seen from the Gaia telescope. Our focus is on stellar magnitude as a whole, as opposed to the magnitude from a set viewing point, so it is more helpful to measure absolute magnitude, the magnitude of a star when measured from a standard distance of 10 parsecs away, which is scaled using parallax, an astrophysical measure of displacement in the sky (6). We calculated the absolute magnitude of Gaia objects by using the formula $M = m + 5 + 5log(parallax)$, with M representing absolute magnitude and m representing apparent magnitude.

Stars are constantly undergoing nuclear fusion, the process by which two lighter nuclei combine to form a heavier one, throughout their lifetimes. However, when a star has exhausted all its nuclear fuel, it begins the process of slowly dying, which either culminates in the creation of a white dwarf or, for the most massive stars, a supernova. While a supernova entails parts of a star shooting outward, when a star becomes a white dwarf, it collapses in on itself. Though its mass is conserved, it becomes smaller in volume, meaning that white dwarfs are some of the densest objects in the universe (9).

We do not have nearly as much data on white dwarfs as other star types due to their large distance from the Earth (9). This is particularly the case with data gathered by Gaia, as the white dwarves in this dataset are consistently far away (European Space Agency). In this paper, we investigated candidate white dwarfs in the Gaia dataset. We observed their proper motions, especially the ones with abnormally high proper motion in an attempt to unpack why they might be moving so fast. This is an area of white dwarf astronomy that has not been studied in depth. We hypothesized that the slower white dwarfs we identified would be redder and fainter compared to the rest of the dataset. A star being redder and fainter has been traditionally associated with being older, and older objects have had more time to collide

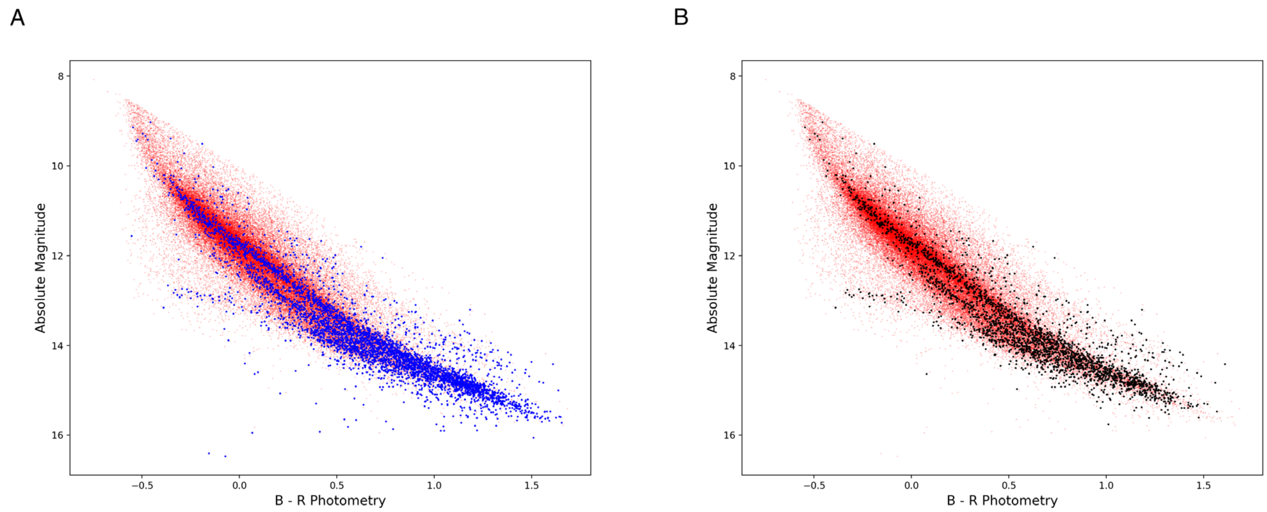

Figure 1. Hertzsprung-Russell (HR) diagrams comparing the photometry values and magnitude of the total white dwarf candidates to filtered populations. (A) HR diagram for all white dwarf candidates (red dots) and white dwarf candidates with high proper motion (blue dots). **(B)** HR diagram for all white dwarf candidates (red dots) and white dwarf candidates with high proper motion that have been filtered for normal parallax (black dots).

with and be gravitationally influenced by nearby objects, thus slowing them down. After comparing the absolute magnitude and spectroscopic qualities of "regular" white dwarfs to fast moving white dwarfs, however, we found that the relationship was actually the opposite of what we had expected – the white dwarfs that we found were moving faster were also redder and older.

RESULTS

We filtered the DR2 dataset (which contains many different types of stars) into a group of 65,000 candidate white dwarfs, which we then filtered further using conventional methods to include only the 4248 white dwarfs which we deemed to have the highest proper motion (7). We also determined whether we were, in fact, looking at the stars that were moving the fastest. If two stars are moving at the same absolute velocity, the one that is farther away will have a smaller angular velocity. As proper motion is a measurement of angular velocity, it is inherently influenced by an object's distance, and therefore its parallax. Proper motion itself is not an accurate indicator of true velocity. To rectify this, the high proper motion stars were filtered out if they had abnormally large parallax in comparison to the entire white dwarf candidate dataset. This allowed us to avoid confusing the white dwarfs closest to us with the ones that were actually moving the fastest, thus drastically increasing the accuracy of our measurements. This third and final filtration created our dataset of high proper motion white dwarfs while controlling for parallax. Implementing this filter reduced the high proper motion dataset from 4248 to only 2534 white dwarf candidates.

Figure 1 displays the dataset filtered for high proper motion overlaid atop all of the Gaia white dwarf candidates on a Hertzsprung-Russell diagram, consisting of absolute magnitude on the y axis and the magnitude of redder light (Rp) subtracted from the magnitude of bluer light (Bp) on the x axis, which we call the Bp-Rp value (**Figure 1**). The final filtered dataset, which has been controlled for parallax (**Figure 1a)**, shows a similar trend when plotted on top of the main dataset as the initial filtered dataset, which has not (**Figure 1b)**. In both cases, the high proper motion white dwarf candidates clustered toward the bottom right of the graph in comparison

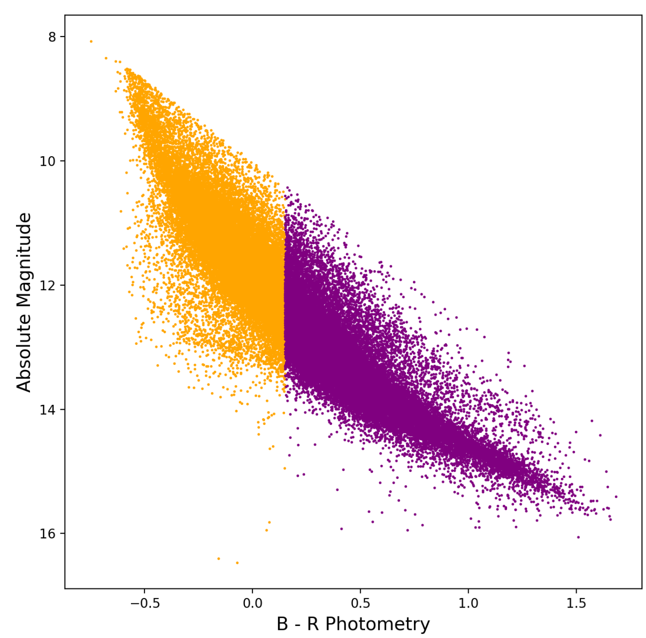

Figure 2. Hertzsprung-Russell (HR) diagrams comparing the brightest and faintest 50% of white dwarf candidates. White dwarf candidates that are above the mean difference between the values of the blue and red photometric filters (B-R photometry) are in orange and ones below the mean difference are in purple.

to the general dataset of white dwarf candidates. Fast moving white dwarfs were on average redder and possessed a higher absolute magnitude than the set of white dwarfs as a whole.

Supporting these findings, **Figure 2** shows the candidates which have Bp-Rp values above and below the mean for the entire dataset of candidates. Out of the entire set of white dwarf candidates, 56.2% had a lower-than-average Bp-Rp value, while the other 43.8% had a value higher than average value. This signifies bluer, lower magnitude white dwarfs. In stark contrast, 76.3% of the white dwarfs with a high proper motion had a higher-than-average Bp-Rp value, with only 23.7% having a below average value. This signifies a redder, higher magnitude set of stars.

Gaia DR2's proper motion measurements have been known to be slightly inaccurate (3). However, the high proper motion white dwarfs in this dataset did not have much higher error measurements than the set of candidate white dwarfs we looked at as a whole – the error differences are only 4.2 and 6.8% of proper motions in the ra and dec directions, respectively **(Figure 3a and 3b)**. These small error measurements are not high enough to be of much concern when compared to the stark differences seen in stellar magnitude and color. Additionally, the high proper motion stars with parallaxes within our range also showed little difference from the rest of the filtered datasets with the reliability of their parallax measurements (4.6%) **(Figure 3c)**.

DISCUSSION

Our analysis of candidate white dwarfs filtered from the ESA Gaia dataset using parameters outlined in Babusiaux *et al* yielded two main conclusions (7). The first was that faster moving candidate white dwarf stars were generally redder than those with low or average proper motion **(Figure 1)**. While at first it seemed that this could be due to the angular nature of proper motion, the same results were found when filtering out stars with high parallax **(Figure 3c)**. The second conclusion was that these redder, faster stars had generally higher magnitudes than the rest of the candidate dataset **(Figure 1)**. The correlation between high magnitude and redness is a consistent finding across star types in the Hertzsprung-Russell diagram. White dwarves in this dataset demonstrate this same typical relationship.

Additionally, in Hertzsprung-Russell diagrams, the redder, higher magnitude stars are usually found to be substantially older than their bluer, lower magnitude counterparts. This suggests that white dwarfs with higher proper motion, higher magnitude, and redder colors may theoretically be older than their counterparts.

These findings may be hindered by a few limitations with the dataset. The ESA has acknowledged imperfections in the Gaia DR2 measurements for proper motion in the right ascension and declination directions, despite significant improvements since DR1 (3). These inaccurate proper motions could have possibly skewed our measurements, although it is unlikely because any error in these measurements would be random and should not skew the results in either direction.

The results clearly show that our candidate white dwarfs with higher proper motion tend to be redder and higher magnitude than their slower moving counterparts. As previously stated, a strong explanation for these results would be that high proper motion white dwarfs are simply older than their counterparts with average proper motion. This would explain both the higher magnitude and redness factors found in our Hertzsprung-Russel (HR) diagrams. However, simply drawing conclusions based on HR diagrams is not a reliable method to discern the age of a star. Star age is notoriously hard to measure, and Gaia does not provide measurements of star age within their dataset. Factors (many of which Gaia does not have complete data for) such as rotation rates of these high proper motion stars would need to be explored before concluding that these results are due to the age of the candidate white dwarfs.

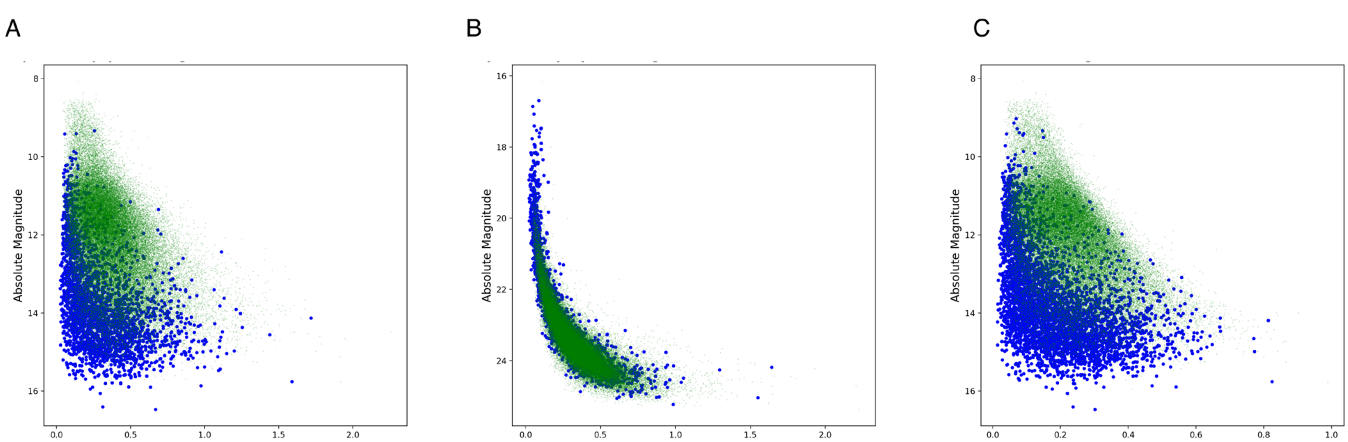

Figure 3. Comparison between the error values Gaia calculates of the full dataset of candidates (green dots) as compared to the high proper motion candidates (blue dots) for proper motion in the right ascension (a), proper motion in the declination (b), abbreviated as pmra and pmdec respectively, and parallax (c). Differences in magnitude are shown on the y axis. The differences in the error measurements as depicted on the x axis were 4.8%, 6.25%, and 4.6%, respectively.

MATERIALS AND METHODS

The ESA Gaia DR2 was filtered in the same manner as Babusiaux *et al*, 2018 while omitting the extinction filters. The entire Gaia dataset was filtered to a group of stars which were deemed to have precise photometric measurements using filters primarily pertaining to flux and magnitude. This dataset, composed of data deemed to be "quality", was then filtered down further, primarily by narrowing down the dataset to stars with photometric measurements normally found in white dwarf stars (7). As stated earlier, we converted apparent magnitude to absolute magnitude (using the formula $M = m + 5 + 5log(parallax)$), which makes sure that our magnitudes are standardized. This conversion works because of parallax, a measurement of the distance of an object from an observer. It effectively controls for the star's parallax, thus ensuring that the distance from an object to the observer is standardized. Parallax also presented the solution to a bigger issue in this project. Since proper motion is a measure of angular velocity, objects that are closer will generally have higher proper motions, simply by nature of the concept of an angular measurement. By eliminating outlier stars with high parallaxes, we were able to standardize parallax to ensure that it did not vastly alter our results. From there, the dataset was condensed further by filtering by magnitude in the previously defined Bp and Rp bands as well as the g band (consisting of visible light) in accordance with the values generally associated with white dwarfs. This allowed us to create a dataset of 65,000 white dwarf candidates. A detailed description of the numerical values of these filters as well as the validation for their use can be found in a paper by Babusiaux *et al*. (7).

The dataset created for this paper included only white dwarf candidates which had proper motions greater than 2 standard deviations above or below mean of the dataset. This new dataset, named the initial filtered dataset, consisted of 4248 high proper motion white dwarf candidates, a substantial decrease from the previous dataset of 65,000. To make the set of high proper motion white dwarf candidates more accurate, we placed a filter on the parallax of the dataset to control for parallax outliers, which created our "final" dataset of 2534 candidates.

Data availability statement

The data that support the findings of this study are available from the corresponding author, JG, upon reasonable request.

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