DA White Dwarf Radial Velocity Measurement Postprint

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Abstract

The spectra of DA white dwarfs in the optical band are dominated by Balmer lines. Due to the relatively broad lines and asymmetric line profiles, traditional radial velocity determination methods based on line centers are very difficult. This paper introduces a method to determine the APP velocity of DA white dwarfs by selecting theoretical templates based on the effective temperature and surface gravity of the white dwarf through cross-correlation, and then subtracting the gravitational redshift of the white dwarf to obtain its radial velocity. Tests find that for low-resolution spectra (R~2000) of DA white dwarfs with Teff above 10000K, the precision is within 10km/s when the signal-to-noise ratio is greater than 20. We measured the radial velocities of the observed sample of DA white dwarfs from SDSS DR7, and statistical analysis shows that within 1000pc, the average radial velocity is close to 0.

Full Text

Radial Velocity Measurement of DA White Dwarfs

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Abstract

The optical spectra of DA white dwarfs are dominated by Balmer lines. Due to their broad and asymmetric line profiles, traditional line-center methods for determining radial velocity are extremely difficult. This paper presents a method that selects theoretical templates based on the effective temperature and surface gravity of white dwarfs to determine their apparent (APP) velocity through cross-correlation. The true radial velocity is then obtained by subtracting the white dwarf' s gravitational redshift from this APP velocity. Tests demonstrate that for low-resolution spectra (R~2000) of DA white dwarfs with effective temperatures above 10,000 K, the precision is within 10 km/s when the signal-to-noise ratio exceeds 20. We measured the radial velocities of DA white dwarfs from the SDSS DR7 observational sample and found that the mean radial velocity approaches zero within 1000 pc.

Keywords: white dwarfs; radial velocity; template matching

1. Introduction

White dwarfs represent the final evolutionary stage for the vast majority of stars in the Milky Way, with approximately 97% of all stars destined to become white dwarfs. Since nuclear reactions have ceased in their interiors, white dwarfs evolve simply through continuous cooling, becoming progressively colder and dimmer until they eventually become black dwarfs. Based on spectral classification, white dwarfs can be categorized into DA, DB, DC, DO, DZ, DQ, and other types [1], with DA white dwarfs being the most common, comprising roughly 75% of the total population. Due to their low luminosity, white dwarfs are relatively difficult to observe, particularly spectroscopically. Prior to the Sloan Digital Sky Survey [2], the largest catalog of spectroscopically identified white dwarfs was published by McCook et al. [3] in 1999, containing only 2,000 objects. This catalog provided positions, magnitudes, parallaxes, and proper motions, but due to low spectral resolution, no atmospheric parameters were available. The Sloan Digital Sky Survey increased the number of spectroscopically confirmed white dwarfs by more than an order of magnitude. In 2006, Eisenstein et al. [4] identified over 9,000 white dwarfs in SDSS DR4, Kleinman et al. [5] identified more than 20,000 in SDSS DR7, and Kepler et al. [6] discovered over 9,000 new white dwarfs in SDSS DR10 in 2015. The current sample of spectroscopically identified white dwarfs now exceeds 30,000, providing a substantial data foundation for statistical studies of white dwarf properties.

Kinematics are crucial for understanding white dwarf populations, making radial velocity measurements essential. However, radial velocity (or APP velocity) measurements of white dwarfs remain relatively scarce, primarily due to historically low signal-to-noise ratios and spectral resolution. Early kinematic studies of white dwarfs relied mainly on proper motions, simply assuming radial velocities to be zero [7]. The first relatively precise measurements of white dwarf radial velocities were conducted by Pauli et al. [8][9], but these required high-resolution spectra. Measuring radial velocities from low-resolution DA white dwarf spectra is exceptionally challenging. DA white dwarf spectra in the optical band are characterized by broad hydrogen lines and a continuous spectrum, with Stark effects causing asymmetric line profiles [10], which introduces significant errors in radial velocity measurements. To obtain radial velocities from low-resolution white dwarf spectra, this paper introduces a method that selects template spectra based on white dwarf parameters and uses cross-correlation to determine their APP velocity. Since white dwarfs exhibit both Doppler effects and gravitational redshift, we refer to the combined effect as the APP velocity.

2. Methodology

2.1 DA White Dwarf Spectra

DA white dwarf spectra have distinctive features that make them relatively easy to identify, particularly for hotter white dwarfs. Figure 1 shows a typical white dwarf spectrum compared with a main-sequence star spectrum. The green solid line represents a main-sequence star spectrum, while the black solid line shows a white dwarf spectrum, with the four hydrogen lines (H , H , H , and H) marked below. The key characteristic of DA white dwarf spectra is the presence of very few lines—only several strong hydrogen lines that are exceptionally broad. Although both spectra have the same resolution, the hydrogen lines in the main-sequence star are much narrower than those in the white dwarf. This breadth makes radial velocity determination from a single hydrogen line problematic, as the line center is difficult to pinpoint, leading to relatively large errors. Consequently, estimating APP velocity using hydrogen line centers yields unsatisfactory results.

The lower panel of Figure 1 displays enlarged views of the four hydrogen lines in the white dwarf spectrum, from top to bottom: H , H , H , and H . All four lines exhibit profile asymmetry, meaning the two sides of the line center are inconsistent. This asymmetry arises from Stark effects [10]. H shows relatively better symmetry, while H , H , and H display obvious profile asymmetry, which creates difficulties for APP velocity estimation using line centers.

2.2 Template Matching and Cross-Correlation for APP Velocity Calculation

The primary methods for calculating APP velocity are either using the centers of multiple spectral lines or employing template-based cross-correlation [11]. Given the spectral characteristics of white dwarfs, the line-center method cannot provide accurate velocities, so we utilize a template-based cross-correlation approach.

We employ theoretical white dwarf spectra as templates, calculated by Koester [12]. The model spectral library covers effective temperatures from 5,000 K to 80,000 K and surface gravities from log g = 7.0 to 9.5.

To obtain accurate APP velocities, we first select the most appropriate template spectrum from the model library. "Appropriate" means the selected template should have atmospheric parameters consistent with the target spectrum—specifically, similar effective temperature and surface gravity.

The template matching process proceeds as follows: First, both the model and observed spectra are resampled to a uniform interval of 0.1 Å. Based on the characteristics of DA spectra, we select eight continuum windows in regions without spectral lines (3862, 3939, 4035, 4219, 4490, 4693, 5025, 5254 Å). In these eight windows, we calculate the flux ratio between each theoretical spectrum and the observed spectrum, then fit a fifth-order polynomial function to the flux ratio versus wavelength. Each theoretical spectrum is multiplied by this polynomial, and the chi-square deviation is calculated between the adjusted theoretical spectrum and the observed spectrum. The theoretical spectrum yielding the minimum chi-square value is selected as our final template.

After selecting the template spectrum, we estimate the white dwarf's APP velocity using cross-correlation. The procedure is: First, we set a minimum velocity V_min, maximum velocity V_max, and velocity increment V_delt. Starting from the minimum velocity, we shift the target spectrum accordingly and calculate the correlation coefficient with the template spectrum. We increment the velocity by V_delt and repeat the calculation until reaching V_max, establishing a relationship between correlation coefficient and velocity—the correlation function. Finally, we locate the maximum value of the correlation function, and the corresponding velocity is our measured APP velocity.

2.3 Method Testing

To test the reliability of our method, we generated a series of simulated spectra. These were created by adding noise to theoretical spectra to achieve specific signal-to-noise ratios, then shifting them by assumed APP velocities. We measured the APP velocities of these simulated spectra using the method described in Section 2.2. Figure 2 [Figure 2: see original paper] shows the test results for simulated spectra with a signal-to-noise ratio of 20.

The panels in Figure 2, from top-left to bottom-right, display test results for simulated spectra with APP velocities ranging from 80 km/s to -80 km/s. The horizontal axis represents effective temperature, while the vertical axis shows velocity error. Each panel shows the error variation with temperature. Overall, errors are relatively larger in the low-temperature region, decreasing from 5,000 K to 9,000 K, with maximum errors occurring at 5,000 K. The overall error also depends on the velocity itself—larger absolute velocities yield relatively larger errors. For spectra with effective temperatures above 10,000 K, the velocity errors are less than 10 km/s.

3. APP Velocity Measurement of Observational Sample

We applied the method described in Section 2 to measure APP velocities for the DA white dwarf sample from SDSS DR7 [13]. This sample contains over 20,000 white dwarfs with provided effective temperatures, surface gravities, and masses. Approximately 2,000 DA white dwarfs have signal-to-noise ratios greater than 20. Figure 3 [Figure 3: see original paper] shows an example of APP velocity measurement for a DA white dwarf. The solid line represents the correlation coefficient as a function of APP velocity, while the dashed line indicates the velocity corresponding to the maximum correlation coefficient—this velocity is our calculated APP velocity for the white dwarf.

Figure 4 [Figure 4: see original paper] shows an example of fitting between an observed spectrum and the best-matching theoretical model spectrum. The black solid line is the observed spectrum, and the red dotted line is the corresponding best-fit theoretical spectrum.

3.1 Gravitational Redshift Calculation

Before calculating the APP velocity, we first compute the white dwarf' s gravitational redshift using the following formula:

$Vg = 0.635\ (M/R)$

where M represents the white dwarf' s mass and R its radius. Vg denotes the gravitational redshift. This formula originates from Silvestri et al. [14]. We first calculate the white dwarf' s radius from its mass using equation (1), then estimate the gravitational redshift using equation (2).

The upper panel of Figure 5 [Figure 5: see original paper] shows the distribution of gravitational redshift and radial velocity for the sample. The gravitational redshift is primarily distributed between 10-80 km/s, with most concentrated around 30 km/s, consistent with white dwarf masses predominantly around 0.6 solar masses.

3.2 White Dwarf Radial Velocity Measurement

For these 2,000 high signal-to-noise ratio white dwarfs, we measured their APP velocities. The difference between the APP velocity and gravitational redshift yields the white dwarf's true radial velocity. Figure 4 shows an example of white dwarf template spectrum determination, where the red dotted line represents the best-fitting theoretical spectrum relative to the observed spectrum (black solid line). This template spectrum is used for correlation to calculate the white dwarf' s APP velocity.

The lower panel of Figure 5 [Figure 5: see original paper] shows the relationship between white dwarf radial velocity and heliocentric distance. We calculated the mean and dispersion of radial velocities within 1,000 pc of the Sun, dividing this range into 10 bins of 100 pc each. The rectangles represent the mean radial velocity in each bin, with error bars indicating the dispersion. The results show that between 100 pc and 1,000 pc, the mean radial velocity is near zero, confirming that previous assumptions of zero radial velocity for white dwarfs were reasonable.

4. Conclusion

By selecting templates based on white dwarf parameters for matching and measuring DA white dwarf radial velocities, we can obtain accurate radial velocities for DA white dwarfs with effective temperatures above 10,000 K, with precision within 10 km/s. Analysis of over 2,000 high signal-to-noise ratio white dwarfs reveals that the mean radial velocity tends toward zero overall, indicating that previous studies assuming zero radial velocity when calculating white dwarf kinematic information were reasonably justified.

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6. References

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