DISCREPANT MEASUREMENTS OF THE RADIAL VELOCITIES OF SS CYGNI: SOLUTION TO THE PROBLEM

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Abstract

We show that the discrepancies among the various measurements of the radial velocity curve of the K5 V star in the dwarf nova SS Cyg have been caused by (1) poor choices of lines for measuring its velocity and (2) large distortions in its velocity caused by heating from the white dwarf and its accretion disk. The correct K velocity of the center of mass of the K5 V star is 158 ± 3 $km\ s^{-1}$.

I. Introduction

The radial velocity curve of SS Cyg is the most carefully measured of any cataclysmic variable: It has been measured seven times – five times since 1970 (Joy 1956; Walker and Chincarini 1968; Kiplinger 1979; Stover *et al.* 1980; Cowley, Crampton, and Hutchings 1980; Walker 1981; Hessman *et al.* 1984). All the published measurements of the K velocities of the two stars in SS Cyg are listed in Table 1. The velocities do not agree at all well. The differences among the published velocities of the white dwarf are not surprising because the velocity

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Table 1

Measurements of the Amplitudes of the Radial Velocity Curves of SS Cygni

Reference	K Velocity ($km\ s^{-1}$)	
	K5 V Star	White Dwarf
Joy (1956)	115	122
Walker and Chincarini (1968)	115[a]	122[a]
Kiplinger (1979)	165[b]	85±4
Stover et al. (1980)	153±2	90±2
Cowley et al. (1980)	120±6	118±8
Walker (1981)	123±2	107±2
Hessman et al. (1984)	156±3	96±3

[a] Walker and Chincarini adopted Joy's K velocities.

[b] Kiplinger rejected this velocity because it disagreed with Joy's and because the absorption lines in his spectra were sometimes doubled.

of the white dwarf must be measured indirectly from emission or absorption lines produced by the accretion disk. It is easy to attribute the differences among the white dwarf velocities to an incomplete understanding of the accretion disk and its spectrum.

The velocities of the K5 V star fall into two groups, one near 120 $km\ s^{-1}$ consisting of the measurements by Joy (1956), by Walker (1981) and his collaborators and by Cowley, Crampton, and Hutchings (1980), and the other group near 155 $km\ s^{-1}$ consisting of measurements by Kiplinger (1979), by Stover *et al.* (1980), and by Hessman *et al.* (1984). The difference between these two groups of velocities are more troubling and harder to ignore because it is not obvious how they can arise: measurement of the radial velocity curve of the K5 V star should

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be a straight-forward and well understood process. To investigate the cause of the difference we have remeasured the the spectra of SS Cyg obtained by Walker (1981), and, following a suggestion first made by Cowley, Crampton, and Hutchings, we have investigated the effect of heating by the white dwarf and accretion disk on the apparent radial velocity of the K5 V star. We were able to resolve the discrepancies completely. Our results are given in detail by Robinson, Zhang, and Stover (1986); we summarize our results here.

II. Remeasurement of Walker's Data

Walker's data consists of electrographs taken with a Spectracon image converter mounted on the coude spectrograph of the 3-meter telescope at Lick Observatory. The plates were taken in 1970 and 1971. We remeasured the plates with the Grant measuring engine at Lick Observatory using the 4063 Å, 4143 Å, and 4404 Å lines of Fe I, and the 4226 Å line of Ca I.

Adopting a circular orbit, we found $K = 146 \pm 7\ km\ s^{-1}$. This K velocity is different from the velocity reported by Walker (1981). The difference is due entirely to differences in the spectral lines used to measure the velocity. Walker used the 4045 Å, 4063 Å, 4071 Å, 4143 Å, 4271 Å, and 4383 Å lines of Fe I. Although these lines would be a good choice for measuring the velocity of normal late-type stars, they are a poor choice for cataclysmic variables. The 4045 Å line is contaminated by Hg II from the night sky, the 4071 Å line is far too weak to be reliable, and the 4271 Å line is a blend with strong lines of CH and Cr. Walker did not use the 4226 Å line of Ca I, the strongest and most reliable line in the region covered by his plates. Thus, half the lines used by Walker were suspect, and the best line in the spectrum was not used at all.

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III. The Effect of Heating on the Velocity of the K5 V Star

Differences in measurement methods cannot account for the low radial velocity measured by Cowley, Crampton, and Hutchings (1980). As some of their spectra were obtained while SS Cyg was erupting, Cowley, Crampton, and Hutchings suggested that heating of the K5 V star by the accretion disk and white dwarf could change its apparent velocity. The observations by Hessman *et al.* (1984) showed that heating could, indeed, have a significant effect on the radial velocity curve. They found that the K velocity of the K5 V star increased to 195 ± 9 $km\ s^{-1}$ when SS Cyg was erupting. We have, therefore, made a more quantitative estimate of the effects of heating on the radial velocity curve.

Using the light curve synthesis program we developed to analyze the light curves of cataclysmic variables (Zhang, Robinson, and Nather 1986), we calculated the distortion in the temperature distribution across the surface of the K5 V caused by heating during ten phases of an eruption of the system. The heating changes the apparent radial velocity of the late-type star in two ways. Hotter areas on the surface of the star have a higher surface brightness and contribute more to the observed spectrum. The apparent velocity will be skewed towards the velocity of these brighter areas. If, however, the temperature of an area becomes too high, its late-type spectrum disappears altogether and it ceases to contribute to the observed absorption line spectrum. The apparent velocity will be skewed away from these hot areas.

We chose a model of SS Cyg giving an apparent K velocity of 155 $km\ s^{-1}$ at minimum light. When SS Cyg erupts, the K velocity of the model first drops to about 125 $km\ s^{-1}$ and then increases again to about 170 $km\ s^{-1}$. This behavior is easily understood. As the accretion disk and white dwarf become more luminous the side of the K5 V star facing towards them becomes hotter. Initially the heating is modest and the K5 V star retains its late-type spectrum, but since the side towards the white dwarf is brighter, the center of gravity of the late-type spectrum shifts towards the white dwarf and its K velocity is reduced. As the accretion disk and white dwarf become yet more luminous, the temperature on the side of the K5 V star towards the white dwarf becomes so high that it loses its late-type spectrum. The center of gravity of the late-type spectrum shifts away from the white dwarf and the K velocity of the K5 V star increases again. Our calculations also show that the apparent K velocity of the K5 V star at minimum light is *not* the true K velocity of the star. Residual heating reduces the velocity of the K5 V star by at least 3% even at minimum light.

Cowley, Crampton, and Hutchings (1980) obtained their spectra on several different observing runs. About half the spectra were obtained when SS Cyg was erupting. We have divided the spectra into three groups: spectra obtained when SS Cyg was at minimum light, spectra obtained when SS Cyg was in eruption but not at maximum light, and spectra obtained near minimum light at the end of an eruption. We calculated the K velocity of each group separately. At maximum light the K velocity was 103 ± 17 $km\ s^{-1}$, at the end of an eruption the velocity was 126 ± 10 $km\ s^{-1}$, and at minimum light the velocity was 141 ± 10 $km\ s^{-1}$. We conclude that the K velocity of the K5 V star depends strongly on heating and that only the data obtained near minimum light can be used to measure its K velocity.

Conclusion

The discrepancies among the various measurements of the K velocity were caused by an unfortunate choice of spectral lines to measure and by heating of the K5 V star by the accretion disk and white dwarf. The velocity is drastically affected by heating and, until much better models for the effect of heating become available, the only safe course is to measure the K velocity when SS Cyg is solidly at minimum light. Three high-quality sets of data obtained at minimum light are

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now available: our remeasurements of Walker's spectra give $K = 146 \pm 7$ $km\ s^{-1}$, the minimum light spectra obtained by Cowley, Crampton and Hutchings (1980) give $K = 141 \pm 10$ $km\ s^{-1}$, and the grand average of all the velocities obtained at McDonald Observatory is $K = 155 \pm 2$ $km\ s^{-1}$. The agreement among these measurements is not perfect, but the largest difference is now only 1.5σ and is much more satisfactory. We have, therefore, brought the disparate measurements of the radial velocity curve into reasonable agreement.

The weighted average of the three high-quality measurements is $K = 154 \pm 2$ $km\ s^{-1}$, but this is not the best estimate of the *center-of-mass* velocity of the K5 V star because it is slightly heated even at minimum light. Applying a 3% correction for residual heating, which is the least amount that can be present at minimum light, we estimate that the true K velocity of the K5 V star is 158 ± 3 $km\ s^{-1}$.

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