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CE 315: A NEW INTERACTING DOUBLE-DEGENERATE BINARY STAR[1]

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ABSTRACT

We present spectroscopic observations of object CE 315 revealing a blue continuum with strong emission lines. Most of the detected lines are identified with He I or He II in emission, with a handful of faint lines of nitrogen. Notable is the complete absence of hydrogen lines. The He lines exhibit triple-peaked profiles with remarkably broad widths of ~2000 km s^{-1} (FWZP). The observations show that CE 315 is an interacting binary system with an orbital period of 65.1 ± 0.7 minutes and a mass ratio of 0.022. We conclude that the most likely scenario for this object is that of an accreting ~0.77 $M_\odot$ white dwarf with a ~0.017 $M_\odot$ helium white dwarf as mass donor.

Subject headings: binaries: close — novae, cataclysmic variables — stars: individual (CE 315) — white dwarfs

1. INTRODUCTION

During the spectroscopic follow-up of proper-motion stars in the Calán-ESO Catalog (CE; Ruiz et al. 2001), the star CE 315 ($\mu = 0''.34\ \mathrm{yr}^{-1}$, $\theta = 264°$) was found to have a spectrum consisting of a blue continuum with strong emission lines of He I and He II (weaker). The line profiles were clearly variable on timescales shorter than 5 minutes, with multiple components evident even in a low-resolution discovery spectrum. The spectrum of CE 315 is strikingly similar to that of the unique object GP Com (=G61-29), discovered by Burbidge & Strittmatter (1971).

Nather, Robinson, & Stover (1981) found that GP Com has an orbital period of 46.5 minutes and suggested that it is a double-degenerate system in which the lower mass star transfers He through an accretion disk onto the higher mass component. Evidence for carbon-nitrogen-oxygen (CNO) processed material in the accretion disk of GP Com was found by Marsh, Horne, & Rosen (1991), who detected emission in lines of N I, N II, O I, Ne I, and possibly Mg II. The relative strength of these lines indicates that nitrogen is highly overabundant with respect to carbon and oxygen compared with solar values, thus providing evidence for the action of a CNO cycle in GP Com. The enhanced abundance of C, N, O, and Mg may have its origin in the thermal pulse stage of the primary star, which later on transferred this processed material to the secondary during a common-envelope phase. More recently, Marsh (1999) published a detailed study of the kinematics of GP Com based on time-resolved spectroscopy. He found a radial velocity of the narrow component at the center of the triple-peaked He lines of 10.8 ± 1.6 km s^{-1} in phase relative to the S wave (Nather et al. 1981), consistent with an accreting white dwarf if the mass ratio of the system, $q = M_2/M_1$, is ~0.02.

The understanding of the evolutionary path of a binary system leading to a double-degenerate (DD) system, such as GP Com, is a matter of considerable theoretical interest (Iben & Tutukov 1984; Mochkovitch & Livio 1989; Branch et al. 1995). However, in spite of extensive search efforts (Robinson & Shafter 1987; Bragaglia et al. 1990), there are only a handful of interacting binary white dwarfs known so far, and thus little is known observationally about this class of objects. Here we report the discovery of an accreting DD system with a period of 65.1 minutes, which makes it the longest-period member of the AM CVn group.

2. OBSERVATIONS

CE 315 was discovered during the spectroscopic follow-up of high proper motion stars from the Calán-ESO Catalog. The discovery spectrum was obtained 1998 March 22 using the ESO 3.6 m telescope at La Silla equipped with the ESO Faint Object Spectrograph and Camera 2 (EFOSC2) and the B300b grism. This combination produces spectra with a ~16 Å resolution, covering the spectral range from 3860 to 8070 Å. A first inspection of the spectrum, taken with 1800 s integration time, showed no sign of any other lines except for the He I and He II (weak) emission lines.

Shortly after the discovery, during April 3 and 4 of 1998, a series of spectra were obtained with the Cerro Tololo Inter-American Observatory (CTIO) 4 m Blanco Telescope with the Ritchey-Chrétien (R-C) Spectrograph, the Loral 3K CCD, and grating KPGL No. 2. The nights were not photometric. However, what became clear from this series of observations was the variable nature of the spectrum of CE 315, with line profile changing in shape and strength on timescales of less than 300 s.

During the nights of 1999 March 19 and 20, spectra of CE 315 were obtained under photometric conditions with the 4 m Blanco Telescope at CTIO. In this opportunity we used the R-C Spectrograph with the Loral 3K CCD detector and grating KPGL No. 3, covering the spectral range between 3750 and 7000 Å with a resolution of ~4 Å. The slit was 1''.5 wide, oriented according to the parallactic angle. The seeing during the first night was ~1''.3, and during the second, 1''.5. During the first night (1999 March 19), 25 consecutive spectra of 360 s integration time each were obtained. Taking into account the reading time, the time difference between each spectrum is about 510 s. Similarly, during the second night (1999 March 20), 30 consecutive spectra of 360 s integration time were obtained.

During 1999 March 23, using the ESO 3.6 m telescope at La Silla equipped with EFOSC2 and grism 16, we obtained a sequence of 27 spectra (360 s integration each) with a 60 s

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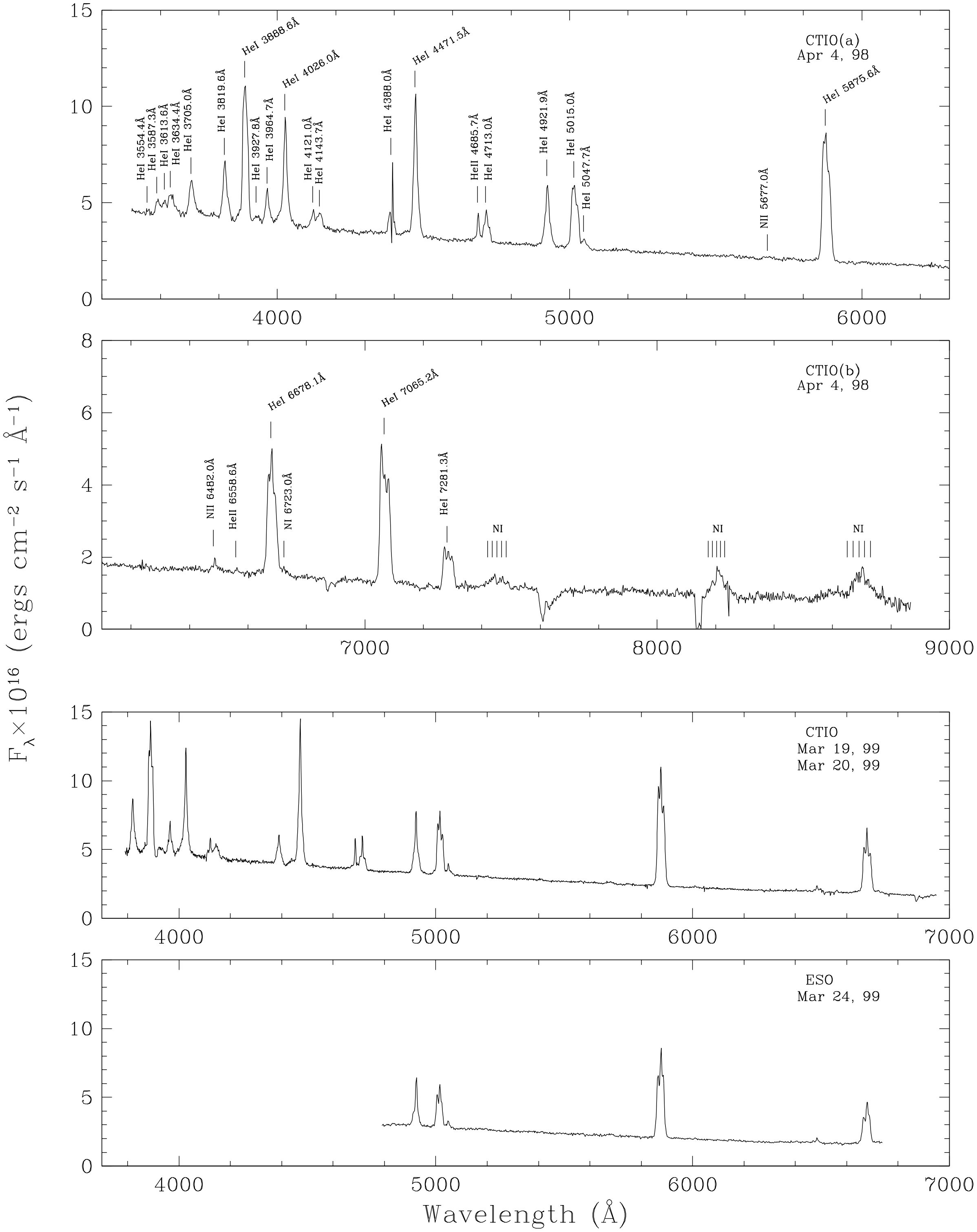

FIG. 1.—Average of individual spectra taken during each observing run. The upper panels show the spectrum obtained with the 4 m telescope at CTIO in 1998 April, covering the spectral range from 3750 to 8830 Å (the spike at 4388 Å is a defect in the CCD). The lower panels show the average spectra obtained in 1999 March with the CTIO 4 m and ESO 3.6 m telescopes, respectively.

R image taken between each spectrum. The spectral coverage was from 4700 to 6755 Å at a resolution of 13 Å. The slit was 1″ wide, oriented according to the parallactic angle.

In all spectroscopic runs described above, we observed spectrophotometric standards and obtained HeAr frames in order to flux- and wavelength-calibrate the data using IRAF packages.

Photometry of CE 315 was obtained in 1999 April 12 at the CTIO 0.9 m telescope using a CCD (Tek 2K No. 3), under photometric conditions. The following magnitudes were obtained: $B = 17.23$, $V = 17.67$, $R = 17.47$, and $I = 17.27$ (Kron-Cousins). The series of *R* images taken with the 3.6 m telescope, described above, clearly showed that the object is photometrically variable on timescales of minutes. Therefore, given that the integration times used for obtaining the photometry with the 0.9 m were 1200 s in B, 900 s in V, and 660 s in R and I, the above magnitudes are only an average. The observed variations in R occurred in timescales of 2 to 3 minutes and with amplitudes up to 0.2 mag.

On 1999 March 21, using ESO 3.6 m telescope and EFOSC2, a direct He I (6678 Å) image of CE 315 was obtained with an integration time of 1200 s. The point-spread function shape and size of CE 315 were similar to the rest of the stars in the frame, indicating that, as in GP Com (Stover 1983), there is no resolved He emission surrounding CE 315 that could be attributed to mass ejections during previous evolutionary phases.

3. RESULTS

3.1. *Average Spectra*

Figure 1 presents the average of all the individual spectra taken in a given observing run. The upper panels show the average spectrum obtained from the CTIO observations made during 1998 April 4, covering the spectral range from 3750 to 8830 Å. The lower panels show the average spectra obtained from the observations made in 1999 March at CTIO and ESO, respectively. Most of the detected lines can be identified with either He I or He II lines in emission, with a handful of faint lines of N I. Notable is the complete absence of hydrogen emission lines.

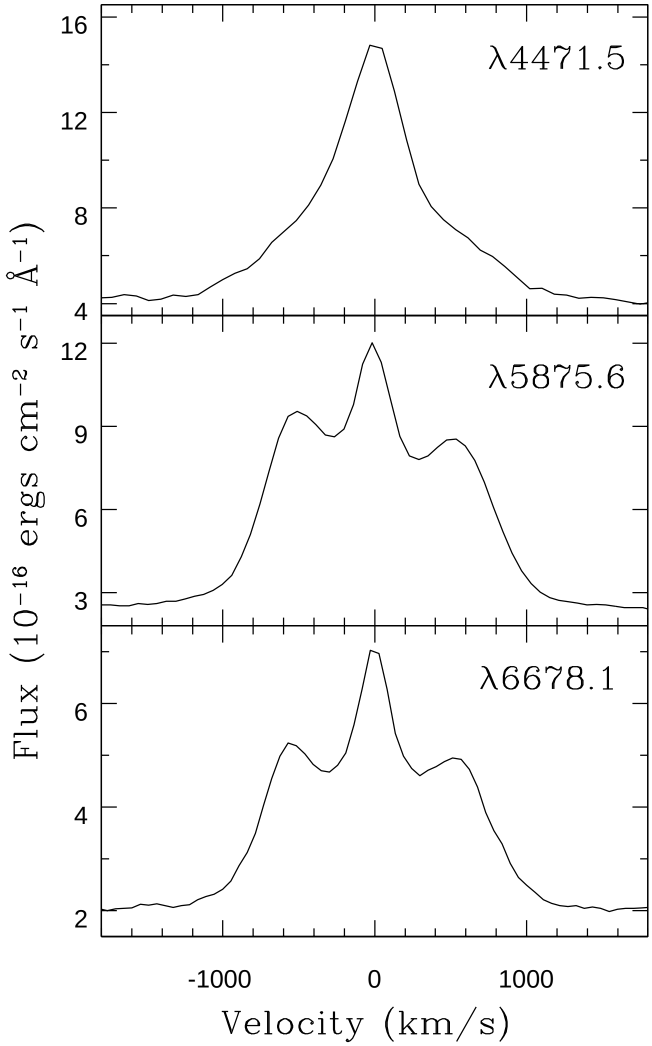

FIG. 2.—Profiles of the 4471.5, 5875.6, and 6678.1 Å lines. The difference in the relative intensities of the central and disk component between the 4471.5 Å line and the other lines is evident.

TABLE 1

EMISSION-LINE INTENSITIES

ELEMENT	λ (Å)	F_λ (ergs cm^{-2} s^{-1}) Disk	Central
He I	3819.6	2.522E−15	2.770E−15
He I	3888.6	9.409E−15	6.218E−15
He I	3964.7	1.090E−15	1.465E−15
He I	4026.0	5.589E−15	3.685E−15
He I	4388.0	1.247E−15	1.895E−15
He I	4471.5	5.472E−15	7.201E−15
He I	4713.1	2.328E−15	1.175E−15
He I	4921.9	3.44E−15	2.687E−15
He I	5015.7	6.653E−15	2.240E−15
He I	5875.6	1.588E−14	4.929E−15
He I	6678.1	8.434E−15	2.617E−15
He II......	4685.7	9.529E−16	1.015E−15

3.2. *Line Profiles*

He I lines from CE 315 show triple-peaked profiles, although in a few cases the emission from the central component almost completely dominates the spectrum. This is illustrated in Figure 2, which shows the profiles of the 4471.5, 5875.6, and 6678.1 Å lines of He I. The relative intensities of the outer and central components differ from line to line, implying that the line profiles are made up of emission that originates from two independent sources. We suggest that the emission from the outer components of the line profiles arises from an accreting disk (double-peaked profiles are characteristics of disk emission), whereas the central component has a different origin.

The profiles of the He I emission are remarkably broad, covering a velocity range of about 2000 km s^{-1} (FWZP). FWHM line widths, determined by simultaneously fitting three Gaussian components to the observed profiles, are typically 500 km s^{-1} for the blue disk feature, 580 km s^{-1} for the red disk feature, and 345 km s^{-1} for the central feature.

The above characteristics suggest that CE 315 is a binary system with the lower mass star transferring mass by way of an accretion disk. In what follows we present the determination of observed parameters of this system.

3.3. *Orbital Period*

For the determination of the orbital period of the system we followed the method devised by Nather et al. (1981), in which the profile of each line is divided into a blue and a red wing region, and the difference between the integrated intensity in the two bands is analyzed for periodicity.

Figure 3 shows the difference in red and blue integrated intensities ($R-B$) versus time for three of the most intense lines within the observed spectral range and for three different nights. These nonuniformly spaced time series were investigated using the periodogram analysis for unevenly spaced data devised by Scargle (1982) and developed in Press et al. (1992). The resulting power spectra are also shown in Figure 3. The periods determined using the data

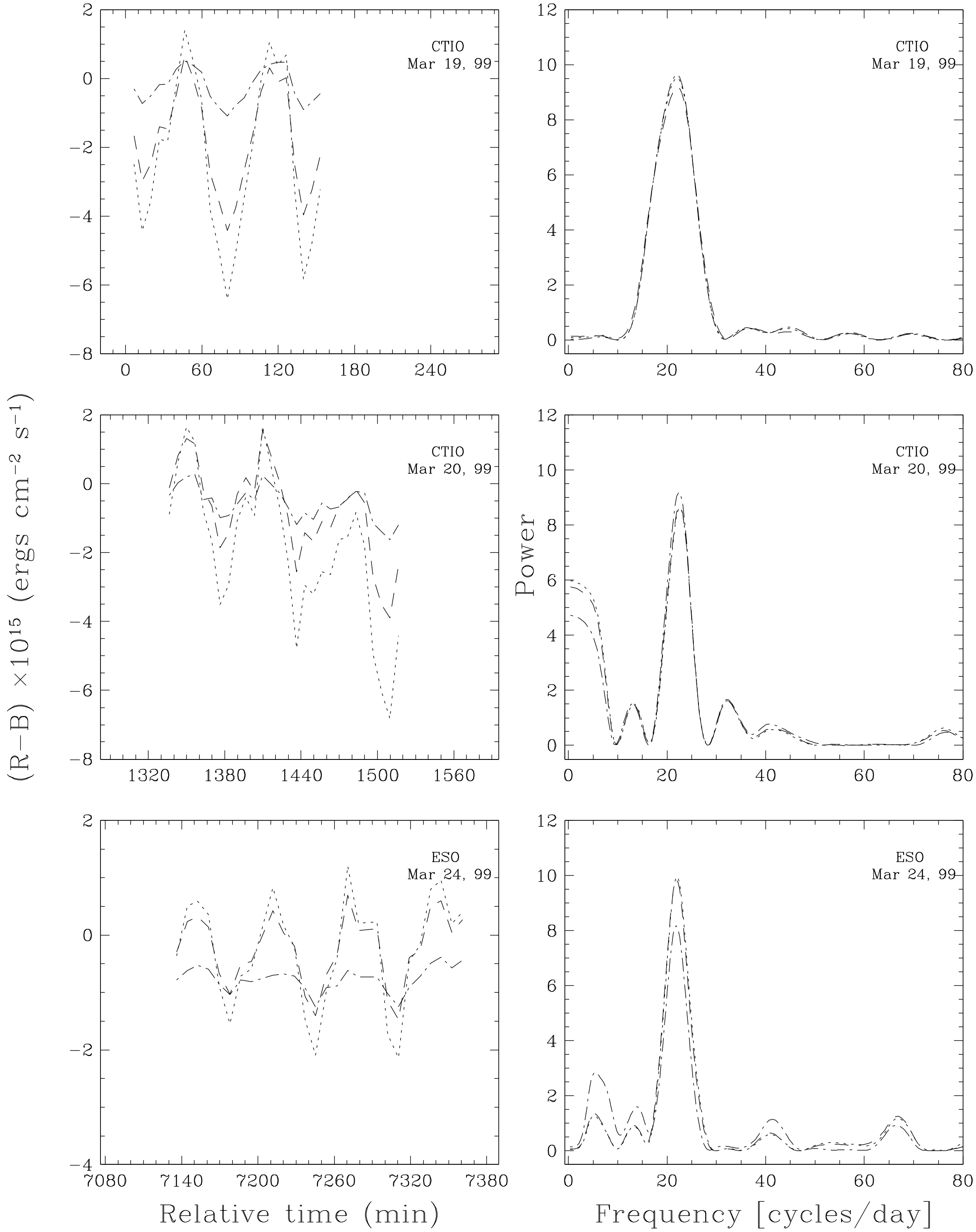

FIG. 3.—*Left*: Red minus blue ($R-B$) integrated line intensities vs. time for three of the most intense lines (*dotted*: λ6678.1; *dashed*: λ5875.6; *dot-dashed*: λ5015.7) and for three different nights. *Right*: Power spectra obtained using a periodogram analysis of the data in the left panels. The derived periods are 65.2 ± 0.9 minutes (1999 March 19), 64.4 ± 1.1 minutes (1999 March 20), and 65.7 ± 1.2 minutes (1999 March 24).

taken on 1999 March 19, March 20, and March 24 are, respectively, 65.2 ± 0.9, 64.4 ± 1.1, and 65.7 ± 1.2 minutes. In what follows we adopt a period for the system of 65.1 minutes.

3.4. *The* S *Wave*

An inspection of the line profiles shows that the dominant form of the modulation is due to changes in intensity of the line profiles. To study this modulation in more detail, we subtracted from each individual spectrum an average spectrum and analyzed the resulting spectra as a function of phase. Figure 4 presents trailed spectra using the data obtained during March of 1999 at CTIO, showing that most of the modulation is due to an emission feature that wanders in velocity between the blue and red velocity of the disk component. Because of its appearance on single-trailed

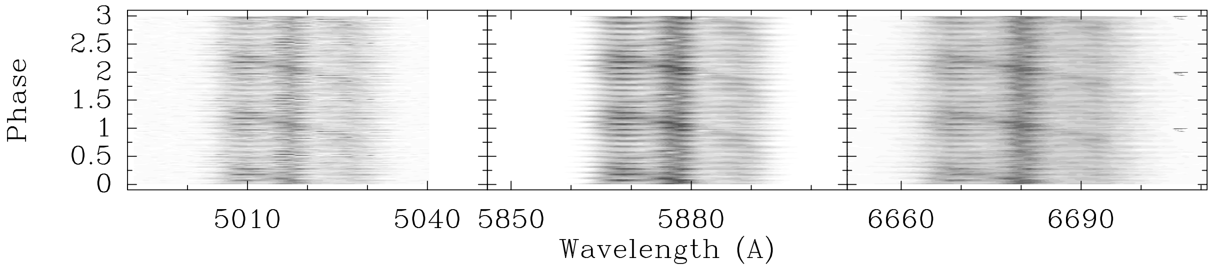

FIG. 4.—Trailed spectra of the CTIO 1999 observations phase-folded and with the same cycle repeated three times. A lowest-flux spectrum has been subtracted. The intensity is displayed on a logarithmic scale. This figure shows that most of the modulation observed in Fig. 3 is due to a feature that wanders in velocity between the blue and red velocity of the disk component, called the S wave.

spectra, this feature is usually labeled as the S wave. The S feature is thought to mark a bright region of enhanced emission where the gas stream from the donor hits the accretion disk. In the reference frame rotating with the binary system the bright spot is fixed in position, but the velocity of the gas in the spot is similar to the velocity of the disk at that position. The velocity variation shown in Figure 4 is well fitted by a sinusoidal function with a semiamplitude of 630 ± 15 km s^{-1}. This suggests that the hot spot is located at a radius of about 0.7 times the radius of the outer edge of the disk and that it is undergoing circular orbital motions. Similar to what is observed in GP Com, in CE 315 the intensity of the S wave is noticeably weaker when moving from blueshifted to redshifted velocities, which is probably due to effects of the inclination of the system.

3.5. *Disk and Orbital Velocity of the Primary Component*

The projected rotational disk velocity, $V_d \sin i$, can be determined from the half-separation of the outer peaks. From the profiles in the 5875.6 and 6678.1 Å lines observed with the CTIO telescope during 1999 March, which are the lines with the largest velocity resolution, we derive a half-separation of 510 ± 10 km s^{-1}.

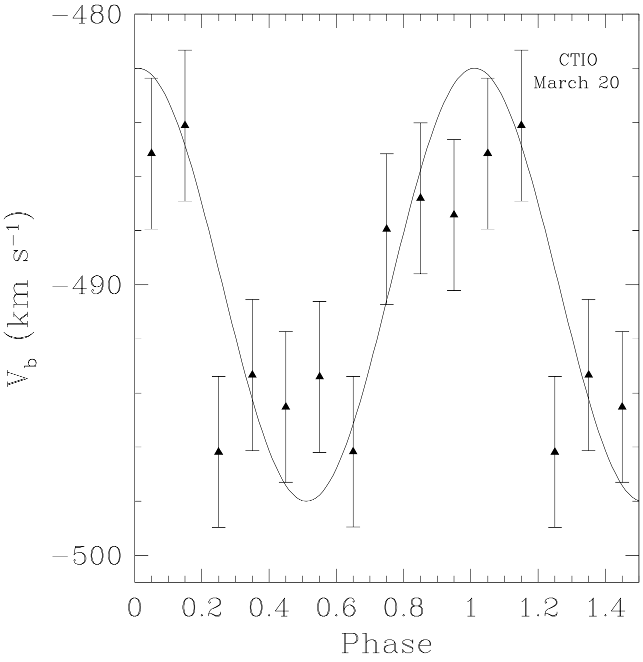

FIG. 5.—Radial velocity of the blue disk component, V_b (average of the 5875.6 and 6678.1 Å lines), vs. phase. The fit indicates a sinusoidal with an amplitude of 8 km s^{-1}.

Assuming a simple model of a Keplerian disk rotating around the primary component of a binary system, the radial velocities of the red and blue components of the disk profiles, V_r and V_b, respectively, should vary with phase, ϕ, as (e.g., Smak 1976)

$$V_{r,b} = \gamma \pm V_d \sin i + K_1 \sin \phi \ , \tag{1}$$

where γ is the systemic velocity and K_1 is the amplitude of the radial velocity of the primary component. For each line we computed $V_{r,b}$ from the observed profile using the expression

$$V_{r,b} = \frac{\int_{r_1,\, b_1}^{r_2,\, b_2} I(v) v \, dv}{\int_{r_1,\, b_1}^{r_2,\, b_2} I(v) dv} \ , \tag{2}$$

where $I(v)$ is the observed intensity at velocity v, and r_1, b_1 and r_2, b_2 are the initial and final velocities of the range of red and blue disk velocities, respectively. Figure 5 shows the dependence of the blue disk velocity with phase derived using the data taken during the night of March 20 of 1999. The blue disk velocity corresponds to an average of the individual V_b determined for the 5875.6 and 6678.1 Å lines. A least-squares fit to the observed trend gives $\gamma - V_d \sin i = -490$ km s^{-1} and $K_1 = 8 \pm 1$ km s^{-1}. The first-order velocity moment used by us as representative of the left-hand side of equation (1) should be less sensitive than other estimates to the presence of perturbations such as the S wave.

4. DISCUSSION

4.1. *The Binary System*

Given the short period of CE 315 (65.1 minutes), two candidates for the donor star are possible (see Faulkner, Flannery, & Warner 1972): (1) a helium zero-age main sequence (ZAMS) star of ∼1.7 $M_\odot$ and (2) a degenerate helium low-mass white dwarf with $M_2 \sim 0.017$ $M_\odot$ (Warner 1995). The first alternative can be easily dismissed, since in that case the light of the ZAMS star would dominate the spectrum. We therefore conclude that the donor is a low-mass helium degenerate. In addition, the large rotational velocities of the accretion disk, of the order of 510 km s^{-1}, require that the accreting star also be a collapsed star. Since CE 315 is not known to be a strong X-ray source, the accreting star is unlikely to be a neutron star or a black hole, and therefore we conclude it must be a white dwarf.

From the observed projected rotational velocity of the disk and the orbital velocity of the primary component, it is possible to compute the mass ratio of the binary system, $q = m_2/m_1$, using the expression (Smak 1976)

$$\frac{q}{(1+q)^{1/2}} = \left(\frac{K_1}{V_d \sin i}\right)\left(\frac{a}{r_d}\right)^{1/2} , \tag{3}$$

where a is the separation of the system, and r_d the disk radius. Using $V_d \sin i = 510$ km s^{-1} and $K_1 = 8$ km s^{-1} and assuming $r_d/a = 0.5$, we obtain $q = 0.022$. The last assumption is based on the computations of Lin & Pringle (1976), who found that the accretion disk is comparable in size to the Roche lobe of the primary. Assuming $M_2 = 0.017\ M_{\odot}$, the derived mass ratio implies that the accretor mass is $\sim 0.77\ M_{\odot}$.

4.2. *Origin of the Central Component*

The emission from the central component of CE 315 is barely resolved, exhibiting a line width of ~ 350 km s^{-1}, broader than that of the central feature in GP Com, which is ~ 120 km s^{-1} (Marsh 1999). The ratio of intensities of the central to the disk component differ from line to line, increasing for higher excitation lines. In particular, in He II λ4686 the emission from the central component dominates over that of the disk (see Table 1). These results suggest that the emission from the central component arises from a region with a temperature higher than that in the disk, high enough to ionize helium.

Our direct He I (λ6678) image of CE 315 shows that the helium emission is unresolved; thus, it is unlikely that the emission from the central component arises in a nebular shell, produced by mass ejections during a previous evolutionary phase. Furthermore, the small radial velocity variation of the central feature makes it unlikely that it arises in the mass donor. Thus, we suggest that the central emission originates near the accreting white dwarf. Possible sites are (1) the inner boundary layer produced by accretion onto the white dwarf and (2) the region of inflow from the Alfvén surface to the star for a magnetized white dwarf (see Frank, King, & Raine 1992). In the first case, the temperature of the boundary layer is about 6 times larger than that of the disk and implies that CE 315 should be a soft X-ray source. An interesting difference between CE 315 and GP Com is that, in CE 315, the radial velocity of the central component is similar to the mean radial velocity of the double peaks, whereas in GP Com the central component is significantly redshifted with respect to the latter.

4.3. *Evolutionary Stage of CE 315*

Following the same line of argument that led Nather et al. (1981) to conclude that GP Com is an evolutionary descendant of a system like AM CVn, we propose that CE 315, having an almost pure He emission-line spectrum and a longer period, is also a descendant of an AM CVn system, but at a slightly more evolved stage than GP Com.

The number of double-degenerate systems detected in different systematic searches (see Robinson & Shafter 1987; Foss, Wade, & Green 1991; Bragaglia et al. 1990; Provencal 1995) have turned out to be very small. In an effort to explain this observational fact, Hernanz, Isern, & Salaris (1997) estimated the expected population of DD systems in the solar neighborhood, taking into account the scale height of these objects and the white dwarf's cooling time. As a result, they find that the predictions from the models are in agreement with the observed scarcity of DD systems. In particular, they predict a number density of DD systems with a period of 65 minutes (like CE 315) between 10^{-5} and 1.4×10^{-5} pc^{-3}, depending on whether the stellar formation rate is compatible with the models of chemical evolution of the Galaxy or with the white dwarf's luminosity function. Unfortunately, the distance to CE 315 is not known, which prevents us from deriving a density to compare with model predictions. An accurate determination of the distance to CE 315 (and GP Com) through trigonometric parallaxes would allow us to calculate the number density of DD systems in the CE survey, with well-defined limits in $m_R \sim 19.5$ and $\mu = 0\farcs2$ yr^{-1}, which would be crucial to test model predictions, thus making an important contribution to a better understanding of the evolutionary phase of this class of objects.

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