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OUTFLOW FROM THE OUTER LAGRANGIAN POINT: OBSERVATIONS AND MODELS OF 4U 2127+12 IN M15

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ABSTRACT

We present MMT observations of AC 211, the optical counterpart of the high-luminosity X-ray source in globular cluster M15. We confirm the observation of Naylor and coworkers that the He I absorption is blueshifted by $\gtrsim 100$ km s^{-1} with respect to the mean velocity of the cluster. We show that if the absorption occurs in a stream of gas outflowing from the L_2 point of a binary system, as might be expected for a common envelope binary, both the blueshift and the unexpectedly low velocity variations of the He I lines can be understood. The model predicts that the He I velocity curve is not sinusoidal.

Subject headings: clusters: globular — stars: individual (4U 2127+12) — X-rays: binaries

I. INTRODUCTION

The X-ray source in M15 (4U 2127+12) has been identified with the blue optical star AC 211 (Aurière, Le Fèvre, and Terzan 1984) by positional coincidence and by the fact that the optical (Ilovaisky *et al.* 1987) and X-ray (Hertz 1987) light curves have similar (8.5 hr) periods. Optical spectroscopy of the source (Naylor *et al.* 1986; Naylor *et al.* 1988, hereafter NCDH) showed that the He I absorption lines displayed velocity variations with a similar periodicity. However, the mean velocity of these absorption lines was found to be -170 km s^{-1} from the cluster mean (-105 km s^{-1} in Peterson, Olszewski, and Aaronson 1986). Also, the semiamplitude of the velocity variations was found to be ≈ 40 km s^{-1}, a surprisingly low value for a low-mass X-ray binary in an 8.5 hr orbit, especially since the large (1.4 mag) variations in the optical light curve suggest that the system is being viewed close to edge-on.

The 170 km s^{-1} difference between the He I absorption in AC 211 and the cluster mean is far higher than the cluster escape velocity; indeed, if AC 211 possessed a transverse velocity of this magnitude, it would be expelled from its position within a few arcseconds of the center of the cluster in $\lesssim 10^4$ yr (Bailyn and Grindlay 1987). NCDH suggest that a recent close encounter with another cluster member resulting in a high recoil velocity for the binary is responsible for the large blueshift of the absorption lines. On the assumption that the He I absorption lines arise from near the compact object, NCDH also suggest that the small amplitude of the velocity variation might imply that the binary contains a massive ($\gtrsim 8\ M_\odot$) compact object. These two suggestions are probably mutually exclusive—a binary with a mass 10 times that of an average cluster member would be difficult to eject at ≈ 200 km s^{-1} through stellar encounters.

Bailyn and Grindlay (1987) have suggested, primarily on evolutionary grounds, that AC 211 consists of a 1.2 $M_\odot$ neutron star and a 0.8 $M_\odot$ secondary which has recently left the main sequence, overflowed its Roche lobe, and undergone unstable mass transfer, thus creating a common envelope. Such a system is on the boundary of stability, so the transfer of a small amount of mass to the more massive neutron star would stabilize the mass transfer, resulting in a system with stable mass transfer, but surrounded by a common envelope. In this case, the absorption lines might be created in material being ejected from the common envelope, which would provide a natural explanation for the high blueshift. Fabian, Guilbert, and Callanan (1988) have also suggested that outflow is responsible for the blueshifted absorption, suggesting that the lines might be formed in a strong wind from an accretion disk corona.

In § II of this paper, we present observations confirming the presence of blueshifted He I absorption in AC 211. In § III we discuss the possibility of outflow from the outer Lagrangian points in AC 211 and show that this model provides a good match to both the observed mean velocity of the He I absorption and the size of the observed velocity variations; a prediction of the model is that the velocity curve is not sinusoidal. Section IV summarizes our results.

II. OBSERVATIONS

Spectra of AC 211 (the summation of which is shown in Fig. 1) were obtained with the Multiple Mirror Telescope (MMT) spectrograph and photon-counting Reticon system at the MMT Observatory on 1987 June 24 (exposure time 600 s) and 25 (exposure time 400 s) and September 16 (exposure time 720 s). Because AC 211 is located near the center of the globular cluster M15, small apertures and good seeing are required to obtain useful spectra of this star. Seeing on these nights varied from 1″.0 to 1″.5, and a 1″ diameter circular aperture was used. Some of the variations in line strength which we observe are therefore likely to be due to changes in the seeing. The lack of significant He II emission in previous MMT observations (Grindlay 1988) may be due either to slight positioning errors, poorer seeing, variability in the line, or a combination of these factors. The summed spectrum shown in Figure 1*a* covers the wavelength range 4050–4850 Å with a resolution of ≈ 1.0 Å. Figure 1*b* shows an enlargement of the region near the 4471 Å He I line. Wavelength calibration and sky subtraction were carried out with the CfA Forth data reduction system. Further analysis was done at the CfA using IRAF. The spectra have not been flux-calibrated to remove the intrinsic response of the telescope/detector combination.

The heliocentric radial velocities, equivalent widths, and FWHM of the He II 4686 Å emission, He I absorption, and Balmer lines are shown in Table 1. From observations of the

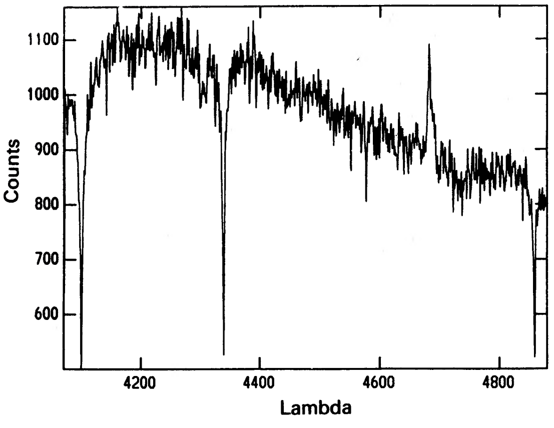

FIG. 1*a*

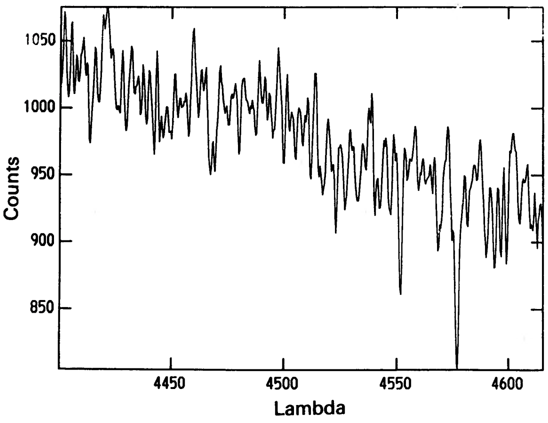

FIG. 1*b*

FIG. 1.—Combined spectrum of AC 211. (*a*) Entire spectrum. (*b*) Region around the 4471 Å He I line.

cluster horizontal branch star I51 (Sandage 1970), we find that the errors in the computed velocities due to uncertainties in the absolute velocity scale and in determining the centroids of the individual lines (done by Gaussian fitting) are ± 20 km s^{-1}. We have used a cross-correlation technique to determine the radial velocity of the Balmer lines; the errors in these velocities are ± 15 km s^{-1} (again, as determined from scatter in the observed I51 velocity).

Much of the Balmer line absorption is likely to be due to the cluster background, and the cross-correlation should therefore reflect the mean cluster velocity of -105 km s^{-1}, as confirmed by our observations. Significant variations in the radial velocity of these lines (see Table 1) may be due to seeing changes, which result in different contributions from objects near AC 211 to the observed spectrum, as well as possible changes in the Balmer features in AC 211 itself (NCDH). The He II emission is broad and variable, with widths comparable to those reported by NCDH.

The 4471 Å He I absorption line is weaker in our spectra than in those of NCDH, reflecting the superior seeing and detector resolution with which their observations were taken. Indeed, in our observation of 1987 June 24, an accurate centroid cannot be measured. The other two observations, and more convincingly the combined spectra from our three observations (shown in Fig. 1), confirm that this line is significantly ($\gtrsim 100$ km s^{-1}) blueshifted from the cluster mean.

III. A MODEL FOR AC 211

The blue color ($U-B = -1.2$) and strong He II emission of AC 211 suggest that most of the optical light in the system comes from very hot gas. The orbital modulation of the optical light (and He II emission; cf. NCDH) implies that this hot gas is associated with the primary, and is periodically eclipsed. The He I absorption must originate in cooler gas. Our model assumes, with NCDH, that the intrinsic X-ray luminosity of the source is $\gtrsim 10$ times the observed value of 6×10^{36} ergs s^{-1} (which would account for the lack of observed bursts without recourse to the metallicity arguments of Fabian, Guilbert, and Callanan 1988), but that we observe the system close to edge-on. Thus we do not observe the X-ray source itself, which is obscured by the accretion disk; rather, the X-rays we see are those which have been scattered by an accretion disk corona (see, e.g., Grindlay 1988). The optical continuum and emission features originate in the disk. The structure of the disk changes with phase, accounting for the observed optical varia-

TABLE 1

VELOCITIES AND WIDTHS OF H AND He LINES

Parameter	1987 June 24 11:02 UT	1987 June 25 9:54 UT	1987 September 17 5:14 UT	Sum
He II λ4686 Emission				
Equivalent width (Å)	1.9	1.8	1.2	1.7
FWHM (Å)	5.7	12.3	7.7	9.7
Radial velocity (km s^{-1})	−220	−50	−112	−125
He I λ4471 Absorption				
Equivalent width (Å)	...	0.1	0.3	0.3
FWHM (Å)	...	1.3	2.3	3.3
Radial velocity (km s^{-1})	...	−240	−200	−220
Balmer Lines				
Radial velocity (km s^{-1})	−99	−102	−130	−113

NOTE.—The errors in equivalent width and FWHM are ~0.1 Å. Velocities for the He I absorption are not given for June 24 because the line was not detected. Errors on individual velocity measurements are ± 15 km s^{-1}.

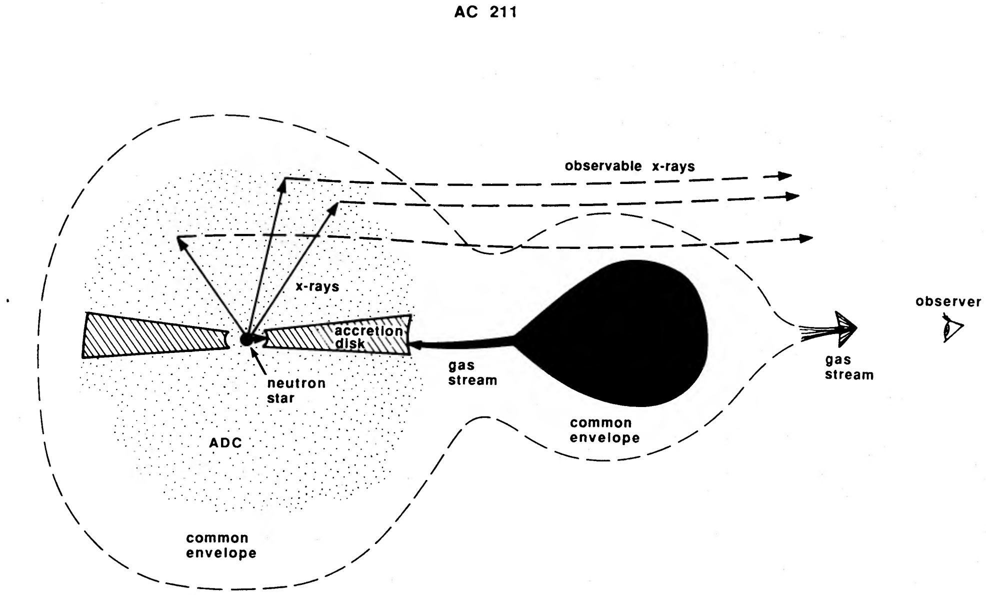

FIG. 2.—Cartoon of AC 211 (*side view*). The boundary between the accretion disk corona (ADC) and the common envelope may not be as abrupt as shown, but we have included them as two separate components to emphasize their different locations (the ADC inside the primary Roche lobe, and the common envelope in closed orbits around both Roche lobes) and their different origins (the ADC comes from material evaporated off the accretion disk, and the common envelope from material lost from the secondary too rapidly to accrete inside the primary Roche lobe). Not all X-rays will be scattered by the ADC; however, such scattering is the source of those X-rays observed from Earth, since the central source is obscured by the accretion disk.

tions. All of this is similar to the model of NCDH. We depart from this model in that NCDH assume that cool gas on the edge of the sisk is responsible for the He I absorption, whereas we propose that this absorption originates in an outflow from the L_2 point created by a common envelope. As we will show, the outflow hypothesis provides a natural explanation both for the blueshifted mean velocity of the 4471 Å He I line and for the small amplitude of the velocity variations. A cartoon of this model is shown in Figure 2.

We note that the physical situation we envisage is quite different from the common envelopes discussed by Bodenheimer and Taam (1984). In that case, the evolution of the secondary up the giant branch resulted in a massive and effectively nonrotating envelope engulfing a binary system consisting of the compact primary and the core of the giant. In our case, tidal capture has created a system close enough that mass transfer begins almost immediately after the secondary leaves the main sequence. The system may be initially unstable (Bailyn and Grindlay 1987; but see also Verbunt and Rappaport 1988), resulting in material accumulating between the secondary Roche lobe and the L_2 surface. This material should be initially close to corotating, since the spin of the secondary is presumably already synchronized with the binary system. Thus in this case material will have a chance to leave the system when it reaches the outer Lagrangian points, rather than being a nonrotating cloud which requires "spinning up" before it can be expelled.

Anderson, Lubow, and Shu (1979) have examined the structure of a gas stream emanating from the L_2 point, caused by an expanding common envelope. In general, the angular motion of the gas stream lags behind the rotation of the binary in the corotating frame. In that frame, the outflow takes the form of spiral rotating counter to the direction of the binary orbit, a result first obtained by Kuiper (1941). Anderson, Lubow, and Shu (1979) derive the angle from the line connecting the two binary components at which the flow leaves the L_2 region (defined as the small region in which the flow remains subsonic):

$$\cos 2\theta_s = -\frac{4}{3B} + \left(1 - \frac{8}{9B}\right)^{1/2}, \tag{1}$$

where

$$B = \frac{\mu}{(X_{L_2} - 1 + \mu)^3} + \frac{1 - \mu}{(X_{L_2} + \mu)^3}, \tag{2}$$

and $\mu = m_2/(m_1 + m_2)$, where X_{L_2} is the distance from the center of mass to the L_2 point in units of the binary separation.

As the gas falls away from the L_2 point, gas pressure quickly becomes small compared with the gravitational gradient, so the subsequent behavior of the gas can be computed by ballistic particle trajectories. We therefore model the proposed outflow from the L_2 point by a series of particles moving solely under the gravitational force of the two components of the binary (see Anderson, Lubow, and Shu 1979). The initial position of the particles is taken to be ϵa_{in} from the L_2 point in the direction given by equation (1), where ϵ is the ratio of the sound speed to the velocity of the orbital motion. We assume $P = 8.5$ hr for a binary system consisting of a 1.2 $M_\odot$ neutron star and a 0.8 $M_\odot$ companion (see Bailyn and Grindlay 1987), and a gas temperature of 10,000 K. In assuming this low temperature (close to that of helium recombination), we note that the L_2 point is effectively shielded from the X-ray source (since it is on the "back" side of the secondary) as well as from any optical radiation emanating from inside the Roche lobe of the primary. The test particle was given an initial velocity equal to the sound speed, again in the direction θ_s from the line connecting the two binary components.

The computations employed a fourth-order Runge-Kutta integrator. The trajectory was followed out to a distance of 20 times the binary separation from the center of mass. By integrating the same initial conditions with different step sizes, the energy error could be determined. The step size finally adopted

1989ApJ...344..786B

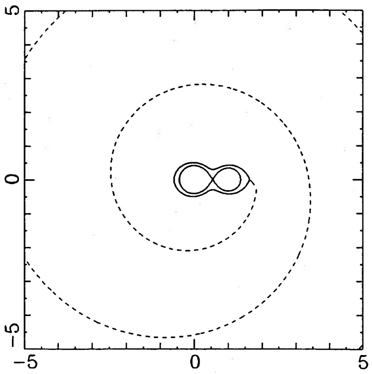

FIG. 3.—Direction of the outflow from the L_2 point from AC 211 in the corotating frame (*top view*). Axes are labeled in units of the binary separation. A stationary observer would see the system rotate counterclockwise.

has errors of $\lesssim 10^{-9}$ per step, or $\lesssim 10^{-5}$ over the whole simulation. The results of this integration are displayed in Figure 3, which shows the computed trajectory. We have also performed integrations in which a random velocity component appropriate for a 10,000 K gas is added to the initial velocity. These calculations confirm Anderson, Lubow, and Shu's (1979) finding that the spreading of the particles is small enough to preserve the identity of the first few turns of the outward spiral.

At each time step (equal to 0.006 of the binary period) the particle's contribution to the observed absorption column was computed. The absorption was calculated in each of 50 equally spaced directions, corresponding to observations made at each of 50 equally spaced orbital phases. In each direction, and thus for each orbital phase, the radial velocities of the particles with respect to the systemic center of mass were averaged. The radial velocities were weighted by $1/r$, appropriate to planar outflow (where r is the distance from the primary), thus taking into account the decrease in the number of photons intercepted with distance. To account for the decrease in density due to spreading of the material in the $\hat{z}$-direction, the velocities were further weighted by a factor of t_0/t when the time t exceeded t_0. The quantity t_0 was set equal to the assumed height of the disk, h, divided by the thermal velocity. The results changed only marginally for values of h between $0.05a_{\rm in}$ (adopted as the standard model) and $0.5a_{\rm in}$. Gas from outside the innermost loop of the spiral contributed only slightly to the integrated absorption.

Figure 4 shows the resulting variations with orbital phase of the mean radial velocity of the absorbing material. Immediately before the binary passes through phase 0.0 (defined as the mid-eclipse of the primary by the secondary), the absorption is dominated by material which has already circled the binary once (in the rotating frame) and is moving outward with considerable velocity (≈ 100 km s^{-1}). After phase 0 the absorption is concentrated in the relatively slow-moving material near the L_2 point. This material is much denser than the material just before eclipse, and one might therefore expect the shape of the absorption line to change in a manner dependent on the total optical depth, and hence on the mass-loss rate through the L_2 point. As the binary goes through its orbit to the next eclipse, the mean outward velocity of the absorbing material increases until the next eclipse. The mean velocity is ≈ 150 km s^{-1} (blueshifted from the center-of-mass rest frame), and the semiamplitude of the velocity variations is ≈ 60 km s^{-1}. This is in remarkably good agreement with the values reported by NCDH, especially since the long (1 hr) integrations required for their spectra will tend to smear the velocity variations. Note that the shape and phasing of the velocity curve in Figure 4 are quite different from the sinusoidal shape predicted by models in which the absorbing gas is associated with one or the other binary component.

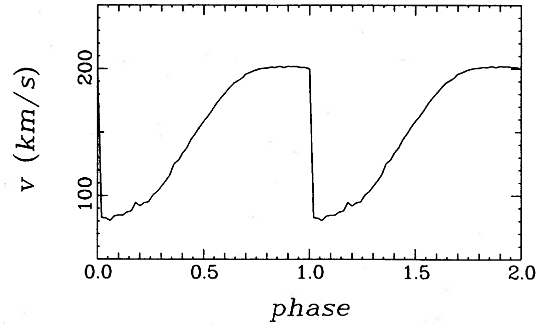

FIG. 4.—Mean outflow velocity as a function of orbital phase. The height of the disk is assumed equal to 0.05 times the inner binary separation.

Other sources of outflow in the system (e.g., from the Roche lobe of the primary as suggested by Fabian, Guibert, and Callanan 1988) or a large systematic initial velocity for the material emerging from the L_2 point may change the shape of the velocity curve significantly. However, if the absorption is predominantly created in outflow from the L_2 point, there should be a steep change in the velocity centered on the time of mid-eclipse. The data presented by NCDH, comprising 15 1 hr integrations taken over a 3 day period, are insufficient to distinguish between the shapes of the velocity curves (we note also that their spectroscopic period determination differs from the X-ray and photometric periods by $\gtrsim 5\%$). Simultaneous photometric and spectroscopic observations providing accurate phasing for the velocity curve, which would provide the best test of the outflow hypothesis, have not yet been reported.

NCDH have criticized the Bailyn and Grindlay (1987) outflow model on two grounds. First, they point out that it is difficult to obtain the observed He II emission from an outflow in which the He I absorption also originates. This is undoubtedly true, and the variations in the ratio of the He II emission to the He I absorption with orbital phase reported by NCDH further suggest that the gas responsible for the emission is not coincident with that responsible for the absorption. None of this contradicts our model, however, since we assume that the emission (and most of the observed optical luminosity) comes from hot gas inside the Roche lobe of the primary, while the absorption is created in the outflow. In this case high-resolution spectra of the He I profile might be expected to show the P Cygni profiles characteristic of outflowing winds; this may in fact be observed (S. A. Ilovaisky 1988, private communication).

NCDH also derive a minimum mass-loss rate for the outflow of $\approx 10^{-3}$ $M_\odot$ yr^{-1} on the grounds that smaller outflows would result in completely ionized material, and thus no neutral helium absorption. This value of $\dot{m}$ seems implausibly large (since the time scale suggested is comparable to that suggested by assuming that AC 211 is being ejected from the core of the cluster at 200 km s^{-1}). In deriving this value NCDH assume that, for sufficient neutral helium to be present to account for the absorption lines, the ionization parameter L/nr^2 must be less than 0.01. The origin of this criterion is not clear—indeed, NCDH assume $L/nr^2 \lesssim 60$ for their accretion disk corona model. If the requirement $L/nr^2 \lesssim 0.01$ were applied to the NCDH model, the required column density

1989ApJ...344..786B

would be 4 orders of magnitude larger than the $N_{\rm H} = 10^{22}$ cm^{-1} which they suggest.

A more plausible estimate for the necessary mass-loss rate required to produce a sufficient column of neutral helium can be derived from the following Strömgren sphere–like calculation. Consider a series of spherical uniformly expanding shells of material, with the radius of the innermost shell equal to $R_0 = R(L_2)$. Each shell expands outward at a velocity v, and material is deposited in the innermost shell at a rate of $\dot{m}$ particles per second. Since the outflow in our model of AC 211 is in the form of a disk rather than a sphere, we assume that all the particles are deposited near the equator of the innermost shell, and flow radially outward from there, forming a disk with a wedgelike profile. For convenience in this order-of-magnitude calculation, we assume that the fraction of each spherical shell inhabited by particles in the outflow is $1/4\pi$. The particle density of the material at R_0 can then be written as $N_0 = \dot{m}/(R_0^2 v)$, the density at distance r from the center of mass is $N(r) = N_0(R_0/r)^2$, and the column density $N_{\rm H}$ (integrating the density from $r = R_0$ to infinity) is $N_{\rm H} = \dot{m}/vR_0$.

Given a central source of ionizing photons, the size of the Strömgren "wedge" (inside of which helium will be ionized) will be such that the rate of recombinations to levels above the ground level will be equal to $I_{\rm He}$, where $I_{\rm He}$ is the number of ionizations of helium per second. In a single cubic centimeter of material, the number of recombinations will be $N^2\alpha$, where α is the cross section for recombination into a state other than the ground state. For $T = 10^4$, Osterbrock (1974) gives $\alpha \approx 2 \times 10^{-13}$ for helium. Thus the outer radius of $R_{\rm S}$ of the Strömgren "wedge" $R_{\rm S}$ is given by

$$I_{\rm He} = \alpha \int_{R_0}^{R_{\rm S}} N^2(r) 4\pi r^2 \, dr = \frac{\alpha \dot{m}^2}{v^2} (R_0^{-1} - R_{\rm S}^{-1}) .$$

We can now evaluate $\dot{m}$ for given values of v, R_0, $I_{\rm He}$, α, and $R_{\rm S}/R_0$.

The observed X-ray luminosity of AC 211 is $L_x \approx 6 \times 10^{36}$ ergs s^{-1}. (We note that the X-ray spectrum of Callanan *et al.* 1987 cuts off sharply below 1 keV, so we do not expect a significant bolometric correction.) This is the appropriate value of L_x to use for this calculation, since the disk shields the outflow (as well as the observer) from the central source. Of this energy, a fraction $1/4\pi$ passes through the outflow disk, and $\approx 1/10$ of these photons will interact with a helium atom rather than with hydrogen. We assume that the available 5×10^{34} ergs s^{-1} is used efficiently for He ionization despite being initially in the form of 1 keV photons, since the excess energy will result in kinetic motion, leading to collisional ionizations. Since the ionization potential of He I is 25 eV, we find $I_{\rm He} = 1.3 \times 10^{42}$. If we adopt $R_0 = R(L_2) \approx 2 \times 10^{11}$ cm for an 8.5 hr binary with component masses of 1.2 and 0.8 $M_\odot$, $v = 150$ km s^{-1}, corresponding to the observed velocity, and $R_{\rm S}/R_0 = 1.1$ to ensure an insignificant column of ionized material, we find that $\dot{m} \approx 1.5 \times 10^{-9}$ $M_\odot$ yr^{-1}. This value for $\dot{m}$ is considerably less than the mass-loss rate of 10^{-7} $M_\odot$ yr^{-1} outflow required to yield a column of gas ($N_{\rm H} \approx 10^{23}$ cm^{-2}) optically thick to 4471 Å He I radiation. We see that the requirement that the outflow be sufficiently dense to create the observed absorption is more stringent than the requirement that the gas be neutral. Thus the outflow hypothesis allows a considerably greater lifetime for the system than does the assumption that the system is being ejected from the cluster at ≈ 150 km s^{-1}.

IV. SUMMARY

We have confirmed the result of NCDH that the He I absorption in AC 211 is blueshifted with respect to the globular cluster surrounding it by ≈ 100 km s^{-1}. We suggest that this blueshift arises because the absorption arises in an outflow originating from the L_2 point. Calculations of the velocity of such a flow as observed in various orbital phases are in good agreement with the observed mean velocity and orbital velocity shifts of the He I line. These calculations also lead us to predict that the velocity curve will be nonsinusoidal in shape. A mass-loss rate of 10^{-7} $M_\odot$ yr^{-1} would be sufficient to obtain a significant column of neutral helium to account for the absorption.

The excellent agreement between observed values of the mean velocity and the amplitude of the velocity variations of the He I absorption and those derived from the outflow model are very suggestive. Careful studies of the velocity curve can confirm or refute our L_2-outflow hypothesis. In particular, the He I velocity curve should exhibit a sudden steep change at mid-eclipse, unlike the usual sinusoidal velocity curve. If our model is confirmed, AC 211 will represent a clear example of a neutron star which has captured a main-sequence star into an initially detached orbit, only to undergo unstable mass transfer as the secondary evolved off the main sequence, as suggested by Bailyn and Grindlay (1987).

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