Understanding the LMXB X2127+119 in M 15

II. The UV data

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Abstract. We present HST UV observations of the high-inclination low mass X-ray binary AC211 (X2127+119), which is located in the globular cluster M 15 (NGC 7078). We have discovered a C iv P Cygni profile in this system, which confirms the existence of an outflow from AC211. The outflow velocity as measured from the P Cygni profile is \( \approx 1500 \, \text{km s}^{-1} \). We calculate that the mass lost through this wind is too small to support a large period derivative as favoured by Homer & Charles (1998). Using new X-ray observations we have revised the ephemeris for AC211 and we find no evidence in support of a period derivative. The UV spectrum exhibits several absorption features due to O, Si and C. The very strong He i line at 1640 Å is not seen to modulate strongly with orbital phase, suggesting its origin lies in the outer parts of the system. In contrast, the eclipse of the UV continuum is short compared with the X-ray and optical eclipses.

Key words. accretion, accretion discs – stars: binaries: eclipsing – stars: coronae – stars: individual: X2127+119, AC211 – ultraviolet: stars

1. Introduction

The star AC211 was first suggested as the optical counterpart of the X-ray source X2127+119 by Aurière et al. (1984), an association primarily based on its ultraviolet excess \((U - B = -1.4)\). Their results were spectroscopically confirmed by Charles et al. (1986), making this the first optical counterpart of a globular cluster X-ray source to be identified.

Since then, there have been several studies of AC211 using optical spectroscopy (Naylor et al. 1988; Bailyn et al. 1989; Ilovaisky 1989) as well as UV observations with the International Ultraviolet Explorer (IUE) (Naylor et al. 1992). All these suffered from heavy contamination due to background cluster stars. More recently Downes et al. (1996) acquired observations with the Faint Object Spectrograph (FOS) on board the Hubble Space Telescope (HST) and were able to resolve AC211 from the background stars in the cluster. They confirmed that several spectral features observed with IUE are intrinsic to AC211. However, their spectra were of relatively low resolution. In addition, Callanan et al. (1999) have recently detected EUV emission from M 15 which could originate from AC211. If confirmed, this system would be the first persistent LMXB source detected at EUV wavelengths.

It has been recognized from the very earliest optical observations (Aurière et al. 1984) that AC211 may be an eclipsing system, and this model has been slowly elaborated, and the system is now generally accepted to be an Accretion Disc Corona (ADC) source, in which the compact object is hidden behind the rim of the accretion disc, and the majority of the X-ray come from a scattering corona (e.g. White & Holt 1982). The largest problem in this interpretation was the observation of two type I X-ray bursts (Dotani et al. 1990; Smale 2001), which implied a direct line of sight to the surface of the neutron star. This puzzle was recently solved by White & Angelini (2001) who obtained Chandra images of the core of M 15, which revealed the presence of a second X-ray source 2.7′′ from AC211. This source (M 15 X-2) was completely unresolved by the X-ray instruments flown prior to Chandra, and is now presumpted to have been the source of the X-ray bursts.

In this paper we present two sets of HST observations with the Space Telescope Imaging Spectrograph (STIS) instrument. We show that the strong He i emission must originate in the ADC, while most of the continuum emission originates in a region very close to the centre of the disc. In addition we present

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the first detection of a C iv line in this system, which exhibits a P Cygni profile and thus confirms the existence of a wind.

2. Observations and data reduction

Observations of AC211 were taken with the FUV-MAMA detector of the HST STIS spectrograph during two “visits”. Although the spacecraft is pointed towards the target for the duration of each visit, the observations are broken up by Earth occultations. Visit 1 on 1998 July 7 comprises 15 spectra with equal exposure lengths of 600 s. Visit 2 occurred 11 days later on 1998 July 18 and again we obtained 15 spectra of 600 second exposures. The grating used in both visits was the G140L, with a slit 52′′ long and 0.5′′ wide. However, only ≈25′′ of the long slit projects onto the detector. This configuration produced spectra in the range of 1150–1730 Å with a dispersion of 1.2 Å per pixel at 1440 Å. There were also a number of spectra from other sources recorded on the MAMA detector. The alignment of the slit on the sky was different for each visit and therefore apart from AC211 the additional spectra on the MAMA detector correspond to different stars for each visit.

The data returned from STScI included the fully reduced one dimensional spectra, as well as the two dimensional reduced spectral images. However, we noticed that in some cases the reduced data showed a poor subtraction of the geocoronal Lyα emission and in a single case the reduced spectrum corresponded to a different object. We thus re-extracted the data. We took the flat fielded and bias corrected data from the STScI pipeline and used an optimal extraction technique (e.g. Horne 1986) to extract the spectra from the 2-dimensional images.

We used the wavelength calibration determined by STScI. We then created a response curve by dividing one of our extracted spectra with a reduced spectrum from the STScI pipeline and fitting the resulting points with a spline curve. We then used this curve for our flux calibration. The resulting spectra exhibited a much better geocoronal Lyα subtraction. Although in some cases the signal to noise was improved significantly, the overall signal to noise in the mean spectrum from both visits was less (S/N ≃ 25) than the one produced from the STScI pipeline (S/N ≃ 35). Table 1 lists all the individual exposures obtained and the corresponding orbital phase at the middle of each exposure.

3. The mean spectrum

Our observations covered from phase 0.69 up to the main eclipse at phase 0.0 for visit 1, and from phase 0.88 through eclipse to phase 0.18 for visit 2. The combined mean spectrum produced from both visits can be seen in Fig 1. The main features are strong HeⅡ (1640 Å) emission, weak Nv (1247 Å) emission, a broad Lyα absorption region around 1180–1240 Å and a weak C iv (1550 Å) P Cygni line. There are also three absorption features superposed on the Lyα line. These are Cn (1176 Å), SiⅡ (1192 Å) and Nv (1202 Å). There is a line at 1260 Å which could be either Si or S and a feature at 1300 Å which could be due to either Si or O, Cn (1335 Å) absorption is present well as the Siiv (1400 Å) absorption doublet. In addition several narrow lines are also present in the spectrum like Si (1528 Å), FeⅡ (1610 Å), CⅡ (1658 Å) and AlⅡ (1672 Å), which we believe are interstellar in origin (see Sect. 8). Several of these spectral features including Siv (1400 Å) and Cnv (1550 Å) are seen for the first time in this system. Table 2 lists all the identified lines along with measurements of their equivalent widths and fluxes.

4. The UV continuum and eclipse

The average value of our continuum flux measurements is about $3 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, but modulations by a factor of 2 are observed above and below this value. Even our brightest measurement is below that observed by Downes et al. (1996) with the HST FOS (8 × 10$^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$), which
could be indicative of long term variability. However, their observations were taken at phases around 0.4 and investigation of the X-ray light curves presented in Ioannou et al. (2002) (hereafter Paper I) shows that phases around 0.4 also show the highest X-ray flux.

Figure 2 shows the modulation of continuum flux with orbital phase as observed from both visits. The eclipse close to phase 1.0 is evident. We attribute the drop in continuum flux around phases 0.7–0.85 to vertical structure in the accretion disc as discussed in Paper I. The data were folded on the ephemeris which is discussed in Sect. 7.

Despite the fact that our spectra are of poor orbital coverage during and around eclipse, we have attempted to compare the radial extent of the UV emitting region with that of the X-ray and optical emitting regions. In Paper I we derived a radius for the X-ray emitting region of $R \approx 0.8 R_{L1}$, where $R_{L1}$ is the distance from the centre of the disc to the inner Lagrangian point. That modelling assumed all of the X-ray flux originated from AC211, but varying the amount of contaminating light from M 15 X-2 does not change the derived radius. This is because it is the width (not the depth) of the eclipse which constrains the size of the eclipsed object. Using the same system parameters for the inclination and mass ratio of the system as in Paper I we find that the extent of the UV emitting region on the orbital plane of the binary must be about $0.3–0.4 R_{L1}$. The reason for this difference in the derived size is driven by the eclipse widths, which has a $FWHM$ of 0.15 in phase in the X-ray data (Paper I) compared with about half this value in the UV (see Fig. 2).

Figure 2 also allows a direct comparison between the UV and optical eclipses, the latter taken from Ilovaisky et al. (1993). It is evident that the optical eclipse is wider (its $FWHM$ is 0.15 in phase measured from the data of Ilovaisky et al.). The eclipse can only be wider if the optically eclipsed material fills more of the Roche-lobe in the plane of the orbit than the material eclipsed in the UV. Thus we find that the UV emitting region is smaller, and more centrally concentrated than both the X-ray and optical regions. We must, though, caution that AC211 is a highly variable source, and thus far we have only obtained observations of part of 2 UV eclipses.
the spectrum of AC211.

The equivalent width and flux values are from the mean weighted spectrum of both visits.

The equivalent width and flux values are the averages from individual spectrum measurements.

5. The He\textsc{i} 1640 Å line

We have measured the He\textsc{i} flux and equivalent width and plot them as functions of orbital phase in Fig. 3. The overall flux level is around a factor 3 lower than in previous observations (Naylor et al. 1988, 1992; Downes et al. 1996) which were all close to $1 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. The flux shows variations at the 50% level as a function of time, but these variations do not seem to correlate with orbital phase or between the same phases in the two different visits. Furthermore we do not observe any reduction of the He\textsc{i} flux during the eclipse. The equivalent width of the He\textsc{i} line rises sharply during the eclipse, but this is explained by a decrease in continuum flux (Fig. 2). All of the He\textsc{i} line profiles from all of our spectra can be seen in Fig. 4. It is evident that the He\textsc{i} profile is complex and changes continuously. Most importantly it does not show consistent variations with orbital phase and different profiles are observed even when spectra from the two visits correspond to the same orbital phase.

The absence of an eclipse or a strong orbital modulation of He\textsc{i} flux is an indication that the He\textsc{i} emission originates in a region of the system that is not affected by the secondary star or the accretion disc. A possible scenario is that it originates in material with a vertical extent that is larger than the secondary star and which is X-ray heated by the central source and the inner accretion disc. This is in agreement with the geometrical interpretation of Naylor et al. (1992) who suggested that the He\textsc{i} recombination line is produced in the fully ionized coronal gas of the ADC.

6. The C\textsc{iv} 1550 Å line: Estimating the mass loss

The C\textsc{iv} line exhibits a P Cygni profile with a weak blue-shifted absorption component and a stronger emission component. A P Cygni profile indicates the existence of a wind in the system, where the blue shifted absorption profile arises from the presence of cool material that is situated in our line of sight in front of the hot regions of the accretion disc and traveling towards us. Further evidence that this line comes from an extended wind region is provided by the behaviour through eclipse (Fig. 5). Despite the disappearance of the C\textsc{iv} absorption component we still see relatively strong C\textsc{iv} emission. This is indicative of the C\textsc{iv} originating in an extended region which is not occulted by the secondary star.

By measuring the extent of the blue-shifted component we can measure the wind velocity in our line of sight. It is about 1350 km s$^{-1}$ for Visit 1 and about 1750 km s$^{-1}$ for Visit 2. We also observe that in Visit 1 the emission component is sometimes absent in our individual spectra, while in Visit 2 the inverse situation exists with the emission component being stronger and the absorption component being absent in some spectra. Table 3 lists the equivalent widths fluxes and wind velocities as measured from the weighted mean spectra of each visit.

It should also be noted that Ilovaisky (1989) also found evidence of a wind by looking at H\textsc{b} absorption profiles. The wind velocities that he measured were of the order of ≃800 km s$^{-1}$. In comparison, the wind velocities found in cataclysmic variables are much faster than the wind velocities we find in AC211, with the width of the absorption component in CVs stretching to 3000–5000 km s$^{-1}$ (Warner 1995).
The behaviour of the He line with orbital phase. Plots 11a to 15d correspond to visit 1 observations and 21a to 25d to visit 2 observations. Wavelength is in Å and flux in erg cm$^{-2}$ s$^{-1}$.

The velocities are similar to those in Wolf-Rayet (WR) stars (van der Hucht 2001), including the WR X-ray binary Cyg X-3 (van Kerkwijk et al. 1996), but the mass loss rate we derive below for AC211 is orders of magnitude lower than in WR stars.
Table 3. Equivalent width, flux and measured wind velocities for each visit from the C iv 1550 Å line. The measurements were made using the weighted mean spectra of each visit.

<table>
<thead>
<tr>
<th>Component</th>
<th>Visit</th>
<th>(W_i)</th>
<th>Flux ((\times 10^{-15}))</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption</td>
<td>1</td>
<td>0.51 ± 0.12</td>
<td>1.43 ± 0.34</td>
<td>1350</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.43 ± 0.34</td>
<td>1.36 ± 0.34</td>
<td>1750</td>
</tr>
<tr>
<td>Emission</td>
<td>1</td>
<td>1.58 ± 0.18</td>
<td>4.42 ± 0.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.72 ± 0.17</td>
<td>5.46 ± 0.54</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. The above figure shows the absence of the absorption component of the 1550 Å C iv line during eclipse. The spectra in the lower two panels are the weighted mean averaged spectra created from the observations closest or during eclipse. The top panel shows the weighted mean spectrum of all our observations with the absorption component clearly visible.

We have used the method employed by Hassall et al. (1983) to estimate the mass loss rate, \(M_L\). The mass loss rate inferred from a C iv line showing a P Cygni profile for a wind with spherical geometry can be determined according to the equation:

\[
M_L = 1.1 \times 10^{-18} \frac{\tau R u^2 C}{f/A} M_0 \text{ yr}^{-1}.
\]  

(1)

Here \(\tau\) is the optical depth and is determined from the blue shifted absorption component, \(R\) is the effective radius in units of solar radii, \(u\) is the wind velocity in km s\(^{-1}\) as measured from the extent of the absorption profile, \(A\) is the abundance of the line element, \(A_0 = 1550\) Å is the rest wavelength of the line and \(f\) is the line oscillator strength. The value for the constant \(C\) is determined from the blue shifted absorption profile (Conti & Garmany 1980) and like Hassall et al. (1983) we have chosen a value of \(C = 0.3\). \(f_i\) is the fraction of the carbon element in the form of C iv in the wind. Assuming that all of Carbon in the wind is present as C iv we have used a value of \(f_i = 1\). We have set the effective radius equal to the accretion disc radius \((R = 1.7 R_\odot)\) determined in Paper I. The value for the oscillator strength \(f = 0.2303\) was taken from Morton (1991) and we also assume a solar abundance of carbon and use a value of \(A = 0.0004\) (Morton 1991). Using the above values we find a mass loss rate of \(7 \times 10^{-12} M_0 \text{ yr}^{-1}\) for Visit 1 and \(1 \times 10^{-11} M_0 \text{ yr}^{-1}\) for the higher wind velocity corresponding to Visit 2.

These mass loss rates are a factor of \(10^4\) smaller than those suggested by some models for AC211. Homer & Charles (1998) found evidence of a period derivative in the orbital period of AC211 of the order of \(9 \times 10^{-7}\) yr\(^{-1}\). To explain this change in period they concluded that the mass loss rate from the system must be of the order of a few \(10^{-7} M_0 \text{ yr}^{-1}\). Bailyn et al. (1989) also suggested a similar amount of material was being thrown out of the system from the \(L_2\) point in order to explain the large blue shift of \(\pm 100\) km s\(^{-1}\) of the He i line as originally reported by Nayler et al. (1988).

In an attempt to reconcile these mass-loss rates we examined the assumptions we had made. The use of the C iv profile to determine the mass loss rate in AC211 requires that we know the value for the abundance of carbon in the system. The metallicity of M 15 has a value of \([\text{Fe}/\text{H}] = -2.17\) (Djorgovski 1993). However, even by lowering the carbon abundance by two orders of magnitude we still do not get the very high mass loss rates of \(\sim 10^{-7} M_0 \text{ yr}^{-1}\). In addition we know that the value of \(f_i = 1\) is only an approximation, since a C iv (1176 Å) line is present at certain phases in our individual spectra. However, it is evident even by this crude determination of \(M_L\), that the wind giving rise to this C iv profile cannot produce the mass loss required by Homer & Charles (1998) and Bailyn et al. (1989).

Also, it should be noted that our above estimates where made with the assumption that the wind has a spherical geometry. If the wind in AC211 is bipolar then higher mass transfer rates would be possible.

7. Is there a period change in AC211?

The low mass-loss rate estimates calculated from the C iv P-Cygni profile are in direct contrast with the large mass-loss rate calculated by Homer & Charles (1998). Their extremely high mass-loss rate was based on their conclusion that AC211 has a large period derivative. This prompted us to re-investigate the ephemeris question. We combined the original eclipse timings of Homer and Charles (1998) with additional X-ray observations (Paper I) and recalculated the ephemeris of AC211. We based our ephemeris calculation solely on the X-ray eclipse timings and we removed the optical CCD points that were originally used by Homer & Charles. However, we emphasize that it is the addition of the new X-ray points and not the exclusion of the CCD optical points, which is responsible for the difference between the two ephemerides. Table 4 lists all the points used in our ephemeris calculation. We found that the data could be folded on the following linear ephemeris, with the uncertainty in the last figure shown in brackets.

\[
T_0 = \text{HJD} 2447484.371(5) + 0.71301(2) \times E.
\]  

(2)
The above ephemeris is in very good agreement with the ephemeris of Ilovaisky et al. (1993). Our ephemeris residuals (O-C values) are shown in Fig. 6. We also attempted a quadratic fit to the data. The best quadratic fit found corresponds to the following ephemeris (in days).

$$O-C = 1.4 \times 10^{-4} - 1.3 \times 10^{-7} \times E + 2.3 \times 10^{-11} \times E^2. \quad (3)$$

However, the above quadratic term is significant only at the 7% level! Thus our expanded data set provides no statistically-significant evidence for a period change in AC211.

8. Which lines are interstellar?

Apart from AC211 the STIS MAMA detector recorded the spectra of a number of other field stars. Comparing AC211 with the brightest other star on each visit, we can make a selection of which lines are due to the interstellar medium and which are intrinsic to AC211. We find that apart from the Hei, CIV, SiIV and NV lines all the other lines which are present in AC211 are also present in the spectra of the two other field stars. The profiles of SiII, FeII and AlIII are narrow, which is indicative of interstellar lines. However, Lyα, as well as the absorption features at 1261 Å (SiII or SiIII), 1303 Å (Oi and SiIII blend) and 1336 Å (CII) have a broader profile in AC211 than in the spectra of the background field stars. This indicates that some of the absorption seen in these lines is intrinsic to AC211; indeed the Lyα profile varies with phase.

Since the SiII absorption line at 1528 Å shows none of these problems, we can use it to estimate the column of Si towards AC211. Savage & Sembach (1991) show that the apparent column density per unit velocity is given by:

$$N_a = \frac{3.766 \times 10^{14}}{f \lambda} \int \ln \left( \frac{I_0(u)}{I(u)} \right) du \quad (4)$$

where $f$ is the absorption oscillator strength of the line, $\lambda$ is the wavelength in Å and $I_0(u), I(u)$ are the unabsorbed and absorbed line intensities respectively. $N$ is given here in units of atoms cm$^{-2}$ km s$^{-1}$. Savage & Sembach (1991) also show that apparent column densities calculated in this fashion are instrumentally blurred but non-the-less accurate as long as the line is resolved or unless the integration in Eq. (4) is performed over an entire line which has no saturated components. Normalizing our absorption profile to the continuum level and using an oscillator strength value for SiII of $f = 0.2303$ (Morton 1991), we calculate a value for $N_{SiII} = (1.4 \pm 0.1) \times 10^{15}$ cm$^{-2}$ towards AC211.

Shull & van Steenberg (1985) calculated galactic interstellar abundances using IUE for 244 early type stars for which a number of them (68) are halo objects. Of these, 25 lie in the direction of M15 ($l = 65, b = -27$). Plotting the log($N_{SiII}$) against the log($N_{HI}$) values of the 25 stars and by fitting a straight line through the points we determine a value of $N_{HI} = (3.5 \pm 0.2) \times 10^{20}$ cm$^{-2}$. This is in excellent agreement with the $N_{HI}$ value calculated in Paper I using an interstellar reddening value of $E(B-V) = 0.05$ from Djorgovski & Meylan (1993).

Using the same method, we have also measured the silicon and hydrogen column densities by for two other stars, whose spectra were also recorded on the MAMA CCD detector (the brightest, aside from AC211, on each visit). All the equivalent widths and derived column densities are given in Table 5.

9. Discussion

The HST STIS observations show that AC211 has a strong UV continuum with a host of absorption lines, many of which are
interstellar in origin (Sects. 3 and 8). In addition there is highly variable emission from He II and a Crv P-Cygni profile (Sects. 5 and 6). Since the Hen line is uneclipsed, we conclude it must come from a relatively large volume above and below the disc (Sect. 5). From the Crv line we can estimate the mass-loss from the system as $\sim 10^{-11} M_\odot$ yr$^{-1}$ (Sect. 6) much lower than that suggested by the orbital period derivative of Homer & Charles (1998). However, the inclusion of new data implies the period derivative is no longer significant, and thus that the derived mass-loss rate is probably correct (Sect. 7). These facts all fit nicely within the normal expectation for an X-ray binary. To progress further, we must accept that AC211 is a high inclination eclipsing system, in which the X-ray source is hidden behind the rim of the accretion disc, and that the X-rays originate from an accretion disc corona. This has long been the standard model for AC211, albeit with problems. The discovery of M 15 X-2 removes the major objection to this model, which is how such a system could show an X-ray burst (see, for example, the discussion in Paper I). The simplest assumption now is that M 15 X-2 was responsible for the burst, and that the compact object in AC211 is indeed hidden.

At first sight the eclipses seem to fit easily into this model. The optical eclipse is wide, as one would expect from the eclipse of an accretion disc, since the entire disc will be X-ray heated to temperatures which emit significant radiation in the optical. The UV eclipse is narrower, again expected as only the inner regions of the accretion disc emit significant UV light. Finally, the X-ray eclipse is wide, since it is again of an extended object, the corona. We note in passing that the flux at the bottom of the X-ray eclipse is consistent with that from X-2, i.e. it could well be that the eclipse of AC211 is total. Although this means the accretion disc corona is smaller than previously thought, it does not mean the X-ray source is point like. If it were, the eclipse ingress and egress would be vertical, instead their slopes imply the X-ray emitting region is similar in size to the secondary star. The problem with the UV eclipse is twofold. First, it is not total; one would expect a small, compact UV region to be totally eclipsed. This is backed up by the fact that the UV ingress and egress is not vertical, but our poor phase coverage make this result uncertain. Second, one might not expect to see the inner disc at all; it should be hidden behind the disc rim. Thus it appears that the UV emitting region is significantly extended, but how, or why remains unclear. The only way around this conundrum would be to invoke variability, since the X-ray, optical and UV eclipses are not simultaneous. Such a solution is is unsatisfactory, though, since the X-ray and optical eclipses are relatively stable in width (Paper I and Ilovaisky et al. 1993), and the phases in common between our two HST visits are give similar UV fluxes.

10. Conclusions

The STIS UV observations presented here have shown that, although the eclipse in AC211 implies that the UV source is more centrally concentrated than either the X-ray or the optical source, it cannot be explained by a simple disc model.

The interstellar UV lines imply an $N_H = 3.5 \pm 0.2 \times 10^{20}$ cm$^{-2}$, whilst the Crv P Cygni profile implies a mass-loss rate of $M_L \sim 1 \times 10^{-11} M_\odot$ yr$^{-1}$. This is at variance with the mass-loss rates implied by Homer & Charles (1998), but the addition of new X-ray data to the ephemeris calculation removes the need for a large period change, which in turned implied the high mass-loss rate.

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