Period derivative of the M15 X-ray Binary
AC211/X2127+119

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Abstract

We have combined *Rossi X-ray Timing Explorer* observations of X2127+119, the low-mass X-ray binary in the globular cluster M15, with archival X-ray lightcurves to study the stability of the 17.1 hr orbital period. We find that the data cannot be fit by the Ilovaisky et al. (1993) ephemeris, and requires either a $7\sigma$ change to the period or a period derivative $\dot{P}/P \sim 9 \times 10^{-7}\text{yr}^{-1}$. Given its remarkably low $L_X/L_{\text{opt}}$ such a $\dot{P}$ lends support to models that require super-Eddington mass transfer in a $q \sim 1$ binary.

Key words: accretion disks, binaries : close, stars: individual (X2127+119/AC211), X-rays: stars

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1 Introduction

The X-ray source X2127+119 is one of the $\sim 10$ bright ($> 10^{36}$ erg s$^{-1}$) low mass X-ray binaries (LMXBs) located within globular clusters, being within 2" of the core of M15. It was the first cluster X-ray source to have an optical counterpart proposed, the $V\sim15$ star AC211 (Aurière et al. 1984), on the basis of blue colours, variability and location within the *Einstein* HRI error box (Geffert et al. 1989). The identification was spectroscopically confirmed by Charles et al. (1986), who found He ii $\lambda 4686$ and H$\alpha$ emission. AC211 is optically one of the brightest of all LMXBs, which is remarkable given its relatively low $L_X$. Consequently, it has been extensively studied (Hertz 1987, Callanan 1988, Dotani et al. 1990, Ilovaisky et al. 1987, Naylor et al. 1988, Bailyn et al. 1989, Ilovaisky et al. 1993) both in X-rays and at optical/UV wavelengths.

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However, deriving the system parameters and understanding the geometry has proven difficult. Observations have yielded a wide variety of temporal behaviour, obscuring the true binary period, and other unusual phenomena, as detailed below.

AC211 exhibits the largest amplitude optical variations of any LMXB, and \( \sim 5 \) times greater than in X-rays. Following their first photometric campaign Ilovaisky et al. (1987) detected a 8.54hr periodic modulation in their series of U-band CCD images, although there were puzzling unmodulated episodes. A reanalysis of HEAO-1 scanning data from November 1977 by Hertz (1987) revealed a consistent 8.66hr X-ray modulation. However, further optical spectroscopy by Naylor et al. (1988) gave a slightly different binary period of \( 9.1 \pm 0.5 \text{hr} \) based on a radial velocity study of the He\( \text{I} \lambda 4471 \) absorption line. More remarkably, they found that the \( \gamma \) velocity was blue-shifted by \( \sim 150 \pm 10 \text{kms}^{-1} \) with respect to the cluster. Their favoured model for the system consisted of a high-inclination accretion disc corona source, which accounts for the unusually low \( L_X/L_{opt} \sim 20 \). A variable height disc rim (greatest when close to the accretion stream impact point) would then modulate both the X-rays and optical emission from the X-ray irradiated disc. They invoked ejection of the system from the cluster core (following a close encounter with another star) to explain the high \( \gamma \) velocity. Alternative explanations were suggested; Fabian et al. (1987) proposed He\( \text{I} \) absorption in a supersonic wind from a massive corona, whilst Bailyn et al. (1989) preferred an outflow from the outer Lagrangian point as the site, requiring a common envelope system (the result of unstable mass transfer). The detection of a radius expansion X-ray burst with Ginga (Dotani et al. 1990) further complicated the picture, as clearly, in spite of the corona, the X-ray source must be directly visible for at least part of the time. Notably, this remains one of the most luminous X-ray bursts ever detected.

The most recent piece in the puzzle arose from the continuation of Ilovaisky and co-workers’ photometric campaign. Ilovaisky et al. (1993) (hereafter Il93) analysed all their U-band data from 1984-89 as a single set, using a phase dispersion minimisation (PDM) search method (Stellingwerf 1978). This yielded a preferred period of 17.11 hr, double that previously accepted. This was able to explain the strange unmodulated observations and was found to be consistent with all the X-ray data up to that date. Using the minima in their lightcurve combined with that of the 1977 HEAO-1 data gave an ephemeris of \( \phi = 0.0 \) for JD 2447790.963 \( \pm 0.018 + n \times (0.713014d \pm 0.000001d) \).

Nevertheless, the AC211 system remains an enigma. A high mass transfer rate, leading to significant mass loss from the system is a distinct possibility. Important constraints can therefore be placed by the measurement of any corresponding period change. Now that 9 years have elapsed since the last period and ephemeris determination we decided to make use of the opportunity
Table 1
A Journal of the X-ray/optical observations of X2127+119/AC211.

| Observatory | Detector | Date (UT) | Time | Energy | \(L_X. \left( \frac{d}{10 \text{ kpc}} \right)^2 \) |
|-------------|----------|-----------|------|--------|---------------------------------|
| HEAO-1      | A-1      | 19.11.77  | 23.11.77 | 96.4 hr | 0.25-25 | \(\sim 9.5 \) |
| EXOSAT      | ME       | 30.06.84  | 30.06.88 | 11.48 hr | 0.9-9 | \(\sim 8 \) |
|             |          | 22.10.84  | 22.10.84 | 15.27 hr | \(\sim 8 \) |
|             |          | 20.10.85  | 20.10.85 | 7.17 hr | \(\sim 8 \) |
| Ginga       | LAC      | 20.10.88  | 24.10.88 | 84.0 hr | 1-28 | 6.4 |
| ASCA        | SIS      | 16.05.95  | 17.05.95 | 26.3 hr | 0.4-12 | 4.2 |
| ASCA        | GIS      | 16.05.95  | 17.05.95 | 26.3 hr | 0.7-10 | 4.2 |
| RXTE        | ASM      | 23.02.96  | 14.03.97 | 384.6 d | 2-10 | 4.2 |
|             |          | 14.03.97  | 02.04.98 | 384.5 d | 3.4 |
| Optical     | CCD      | 28.07.84  | 22.09.89 | 1881.4 d | U-band | - |

presented by over 2 years of Rossi X-ray Timing Explorer All SKY Monitor (RXTE/ASM) observations to revisit AC211.

### 2 Determination of the revised ephemeris

#### 2.1 Data acquisition

The HEASARC maintains comprehensive databases of past and present X-ray missions, from which we obtained the EXOSAT, ASCA/SIS and GIS lightcurves and the definitive dwell RXTE/ASM data on X2127+119. Unfortunately, the HEAO-1 and Ginga products are not readily usable, hence we simply digitised the data presented in the published lightcurve plots of Hertz (1987) and van Paradijs et al. (1990) (their Fig. 1 in both cases). Lastly, the CCD U-band data were only available in their published form, so we digitised the folded data as presented in Fig.8 of Il93. In spite of the relatively poor temporal sampling of the RXTE/ASM dwell data, we found that the extensive coverage provided good phase sampling if taken over a sufficiently long time period. We chose to consider these data in two halves (as divided by time), hereafter referred to as ASM1 and ASM2. A log of all the data used is given in Table 1.
Fig. 1. Upper and lowest left panels: X-ray and optical lightcurves of X2127+119/AC211 respectively, folded (and binned) on the Il93 ephemeris and period of 0.713014 d. Lowest right panel: Sample of the X-ray lightcurves overlaid in chronological order (earliest lowest), with the flux units normalised and a vertical offset of 0.26 introduced between each dataset for clarity. Note the clear change of minimum phase over time.

2.2 Measurement of the ephemerides

All the data were folded on the ephemeris and period given in Il93, and binned, in order to increase the signal-to-noise. We used 40 phase bins, except for the HEAO-1 data (where we used 20), with each bin covering 0.05 (or 0.1) in phase and hence each overlapping the adjacent bins by $\pm 0.025$ ($\pm 0.05$). This provided both good phase resolution, and some smoothing to reduce noise. These folded lightcurves are presented in Fig. 1.

As expected, given its probably different physical origins, the optical lightcurve (labelled CCD) is different in shape to the X-ray, although both clearly demon-
Fig. 2. O-C plot for the orbital ephemerides of X2127+119/AC211 for each X-ray observation and the one optical dataset; as determined by a Gaussian fit to each minimum (upper panel), and cross-correlations (lower panel).

The eclipse by the secondary star. However, it is clear that the X-ray lightcurves also show considerable morphological evolution over time. The energy ranges (see Table 1) are in fact similar for all the X-ray observations and so the changes must be intrinsic to the source. Whilst the EXOSAT and ASM data are similar, the intervening Ginga observation shows a totally different shape.

In order to determine the relative orbital ephemerides for each observation, we adopted the same approach as Il93. They found the extended eclipse, or minimum, to be the only stable feature of the lightcurve, and so we used a simple Gaussian fit to determine the time of minimum in each case. Due to the poor phase coverage of the minimum in the EXOSAT data, we were forced to base our estimate on the sharp egress from minimum flux. The results are plotted in the form of an O-C plot (i.e. the phase offset between the expected minimum and that observed, versus cycle number) in the upper panel of Fig.2. As a check, we also performed a cross correlation of the EXOSAT, ASM1 and ASM2 folds with the complete ASM lightcurve fold to determine their relative phase offsets (see lower panel of Fig.2; the values have been offset, such that the mean ASM results agree with those of the upper panel).
2.3 Evidence for a period derivative

A variety of model fits have been made to the O-C data: (i) a constant O-C corresponding to a linear ephemeris with the Il93 period of 0.713014 d is a very poor fit with $\chi^2_\nu = 27.1$; (ii) a linearly increasing O-C corresponding to a linear ephemeris but with a different period of 0.713021 d ($7\sigma$ larger then Il93) is statistically a good fit with $\chi^2_\nu = 1.12$; (iii) a parabolic O-C corresponding to an ephemeris with the Il93 period and a period derivative of $P = 1.75 \pm 0.90 \times 10^{-9}$ is also a good fit with $\chi^2_\nu = 0.59$. However, one may apply a one-sided $F$-test (Bevington & Robinson 1992), to test the improvement of fit for an additional polynomial term between models (ii) and (iii). $F_{\chi} = \Delta \chi^2 / \chi^2_\nu = (6.752 - 2.954) / 0.59 = 6.43$ corresponding to a 95% confidence level that the parabolic fit is better than the linear one. Moreover, the hypothesis of a linear ephemeris is undermined by the need for a $7\sigma$ increase in the period, which is apparent in the discrepancy between the model and the HEAO-1 point. Comparison with the cross correlation results (lower panel) confirms that the data require a significant change to the Il93 ephemeris, whilst demonstrating that the ephemeris change derived from the minima times is if anything on the conservative side. We therefore consider that the evidence points towards a constant period derivative, with $\dot{P}/P \sim 9 \times 10^{-7}$ yr$^{-1}$.

3 Discussion

3.1 Physical origins of the X-ray and optical modulations

It is profitable to compare the lightcurve of X2127+119/AC211 with those of the dipping sources X1822-371 and X0748-676 (Parmar et al. 1986), as shown in Fig.3. The X-ray lightcurve of X1822-371 clearly shows a broad minimum preceding, by 0.25 in phase, a deeper partial eclipse by the companion star, which is coincident with the optical minimum. The eclipse is only partial as the central source of this high inclination system is hidden by the disc and the X-ray scattering ADC is never fully occulted. To model the broad dip, White & Holt (1982) required a thickened region of the disc $\sim 100^\circ$ upstream of the line joining the companion and compact object. X0748-676 is essentially very similar, but has a lower inclination, thereby enabling the central source to be seen. Here, the almost total X-ray eclipse is always preceded by complex dip structure, which varies from cycle to cycle, although there appears to be a stable dip present at about $\phi = 0.65$. This latter feature is once again probably due to a thickened region of the disc. Considering the lightcurves of
Fig. 3. The folded 1-10 keV EXOSAT/ME lightcurves of X1822-371 and X0748-676, using the period and ephemerides as given in White et al. (1981) and Parmar et al. (1986) respectively. The count rates have been normalized and the curves offset by 1 for clarity.

X2127+119/AC211 in Fig.1, the primary minima of every X-ray dataset are coincident with the optical minimum, but intervals of lower flux of variable duration are visible during phases $\phi = 0.4 - 1.0$. This varying dip structure is certainly similar to X0748-676. The origin of the raised rim of the accretion disc is most probably the impact of the accretion stream. The understanding of this process remains incomplete, with a number of possible results from simulations, as outlined in Armitage & Livio (1998) and references therein. In addition to a bulge at $\phi = 0.8$, where the initial impact occurs, a reimpact following deflection and then reconvergence of the stream at $\phi = 0.6$ has been seen (Lubow 1989), but the azimuthal extent of these regions is unclear.

If this interpretation is correct, then care clearly must be taken when determining the ephemeris of the binary motion from the times of primary minima, as the dip structure will contribute to a varying degree to the flux reduction. This may well account for the changes seen in the asymmetry of the minima. Further observations, in order to both increase the base line of the ephemeris and to better model the details of the X-ray modulation are obviously needed to more accurately measure the period derivative.
3.2 Inferred mass transfer rate

For this last section we will assume that \( \dot{P} \) is within at least an order of magnitude of our estimate. The proposed evolutionary scenario for AC211 involves a neutron star capturing a star close to the main sequence turn-off point in M15, which soon evolves towards the giant branch and turns on mass transfer by overflowing its Roche lobe (Bailyn & Grindlay 1987). Hence, one may apply the properties of a stripped giant to the secondary, which depend only on the mass of its helium core \( M_c \) and not its total mass \( M_2 \).

The secondary radius \( R_2 \) (in \( R_\odot \)) and luminosity \( L_2 \) (in \( L_\odot \)) are given by the relations (King 1988):

\[
R_2 = 12.55 \left( \frac{M_c}{0.25} \right)^{5.1}, \quad (1)
\]

\[
L_2 = 33 \left( \frac{M_c}{0.25} \right)^{8.11}, \quad (2)
\]

where \( M_c \) is in \( M_\odot \) and similarly for \( M_2 \) and \( M_X \) below. Using the Paczyński (1971) approximation for the Roche lobe radius:

\[
R_L = 0.462a \left( \frac{M_2}{M_2 + M_X} \right)^{1/3} \quad (3)
\]

then eliminating the binary separation \( a \) by use of Kepler’s law and applying \( R_2 = R_L \) for the mass transfer condition yields:

\[
\left( \frac{M_c}{0.25} \right)^{7.65} M_2^{-0.5} = 0.0609 \left( \frac{P}{d} \right) \quad (4)
\]

Taking the time derivative and dividing by (4):

\[-0.5 \frac{\dot{M}_2}{M_2} + 7.65 \frac{\dot{M}_c}{M_c} = \frac{\dot{P}}{P} \quad (5)
\]

The rate of change of \( M_c \) with respect to \( M_2 \) is governed by nuclear evolution and for \( q = M_2/M_X < \frac{5}{6} \) (King 1988):

\[-\frac{\dot{M}_2}{M_2} = \frac{5.1}{\frac{5}{3} - 2q} \frac{\dot{M}_c}{M_c} \quad (6)
\]

Hence, we need to estimate the mass ratio \( q \). There are two limiting cases for \( M_2 \), when \( M_c = M_2 \) and \( M_c = 0.17 M_2 \). The former is obvious whilst
the latter follows from the need for \( M_c/M_2 \gtrsim 0.17 \), which is the Schönberg-Chandrasekhar limit, if the secondary is to have left the main sequence. Substitution into equation (4), with the \( 0.713014 \text{ d} \) period gives \( M_{2,\text{min}} = 0.146 M_\odot \) and \( M_{2,\text{max}} = 0.92 M_\odot \). Thus the range of masses given in Il93 of \( 0.74-0.81 M_\odot \) (based upon the M15 isochrones and the appropriate age) fit well within these limits, towards the upper end.

Finally, taking \( M_2 = 0.8 M_\odot \) as a representative value and a canonical \( 1.4 M_\odot \) neutron star (\( q = 0.57 \)) yields:

\[
\frac{-\dot{M}_2}{M_2} = 9.7 \frac{\dot{M}_c}{M_c}, \tag{7}
\]

\[
\dot{M}_2 = -0.77 M_2 \frac{\dot{P}}{P} \tag{8}
\]

and a mass transfer rate \( \dot{M}_2 \sim -6 \times 10^{-7} M_\odot \text{yr}^{-1} \).

The corresponding accretion luminosity is given by:

\[
L_{\text{acc}} = -\eta \left( \frac{G M_X \dot{M}_2}{R_X} \right) = -\eta 1.17 \times 10^{46} \left( \frac{\dot{M}_2}{M_\odot \text{yr}^{-1}} \right) \text{ erg s}^{-1} \tag{9}
\]

\[
L_{\text{acc}} \sim \eta \cdot 6 \times 10^{39} \text{ erg s}^{-1} \text{ for } \dot{M}_2 \sim -6 \times 10^{-7} M_\odot \text{yr}^{-1}
\]

The mass transfer rate is clearly super Eddington (\( L_E \sim \eta \cdot 10^{38} \text{ erg s}^{-1} \) for a neutron star accreting hydrogen) and hence the accretion efficiency \( \eta \ll 1 \). One would then expect significant mass loss from the system, after formation of a common envelope. This is just the scenario envisaged by Bailyn et al. (1989), and indeed our estimate for \( \dot{M}_2 \) above is comparable to theirs, which was based on the He i absorption features.

4 Conclusions

We have obtained X-ray and optical lightcurves of X2127+119/AC211, from the HEASARC archives and published data, which span a total of 21 years, from 1977 HEAO-1 data up to the most recent 1998 RXTE/ASM data. Folding the lightcurves on the Il93 ephemeris and 17.1 hr orbital period, we have examined the stability of this period. The lightcurves in Fig. 1 clearly demonstrate the variety of X-ray morphologies, most probably arising from changes in the vertical structure of the outer edge of the accretion disc, which is responsible for obscuring the X-ray emitting central region. As a result caution
is needed when using the folded lightcurves to check for any phase changes. However, the principal minimum (due to occultation by the secondary star) is obviously a persistent feature, and we have followed the procedure of Il93, to measure the relative ephemerides of each curve, based on its phasing. Only a non-zero period derivative applied to the original period, provides a good fit to these data, implying $\dot{P}/P \sim 9 \times 10^{-7}$ yr$^{-1}$. Modelling the secondary as an evolved sub-giant, it is possible to estimate the mass transfer rate necessary to drive such a period change. This yields $\dot{M}_2 \sim -6 \times 10^{-7} M_\odot$ yr$^{-1}$, and hence an accretion luminosity $L_{\text{acc}} \sim 6 \times 10^{39}$ erg s$^{-1}$. Lastly, as this far exceeds the Eddington luminosity, the accretion efficiency must be very low, requiring there to be significant mass loss from the system. This is consistent with the earlier spectroscopic data of Bailyn et al. (1989), and a $q \sim 1$ binary.

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