Optimisation of an EMCCD

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ABSTRACT

Electron multiplying CCDs (EMCCDs) incorporate a charge multiplication process that reduces the read-noise to an insignificant level. As well as allowing single-photon detection, the essentially zero read-noise highlights other noise sources present in CCDs that previously have not been of importance. First amongst these is clock induced charge (CIC). This consists of stray electrons generated during the clocking of the CCD that are hard, if not impossible, to distinguish from genuine photo-electrons. Dark current can also be a significant noise source with EMCCDs if the correct operating conditions are not used. The requirement for low CIC requires that the CCD is operated in non-inverted mode which generally causes a large increase in dark current. It was found that for short exposures, however, that dark current could be temporarily suppressed, even in non-inverted mode, through the effect of ´dither´. CIC generated in the serial clocking of the CCD (an E2V CCD201 device[1]) was measured using a non-standard manipulation of the CCD´s dump gate structure and then reduced by modifications to the clock amplitudes. The mean noise charge in the EMCCD was finally reduced to 0.013e^- per pixel per frame and the rms read noise reduced to 0.025e^- rms. The cryogenic EMCCD camera used in these investigations was later used for a very demanding spectroscopic observation of a faint cataclysmic variable star where high-time resolution was combined with high spectral resolution in a way that would have been impractical with a conventional CCD camera.

Keywords: EMCCD Spectroscopy dither CIC dark current cataclysmic variable

1. Clock Induced charge as a limiting noise source

The high charge-domain multiplication gain renders the read-out noise insignificant in an EMCCD. Levels of 0.025e^- rms are easily attained and can be made even lower if the device is read out slowly. The process of clocking a CCD inevitably produces a small quantity of internally generated charge due to the high electric fields present. This charge, known as clock induced charge or CIC, is present in conventional CCDs at a level that is barely noticed and then only when the device is heavily binned. For an EMCCD this CIC is clearly visible and is the dominant noise source. For practical observations where the mean signal may be a fraction of an electron per pixel per frame it is essential to optimise the CIC levels as much as possible. The graph in Figure 1 shows a sequence of cuts through EMCCD bias frames as the camera under test was progressively optimised. Individual CIC electrons appear as spikes.

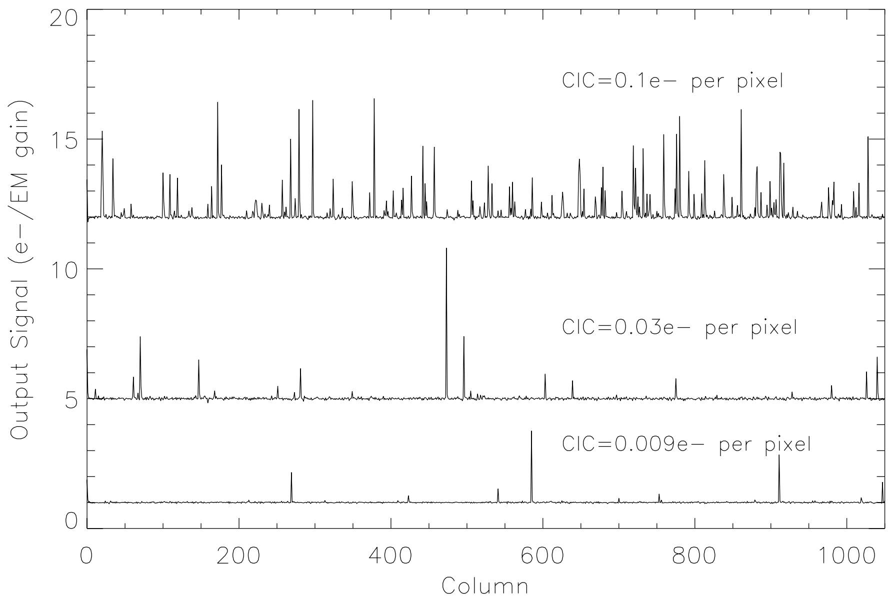

Figure 1. Appearance of CIC in bias image cuts.

2. Inverted-mode operation and its effect on dark current

A CCD enters inversion when the parallel phase voltages are sufficiently negative to attract holes from the channel stop structures. These holes populate the surface of the CCD where they effectively "mop up" any dark current generated in that region. Additional dark current generated deeper in the CCD structure and known as bulk dark current is unaffected. Since surface dark current is generally two orders of magnitude higher than the bulk, the effect of inversion is to cause a huge drop in dark current signal. The exact parallel clock voltage at which inversion occurs was measured for the E2V CCD201 device. The result is shown in Figure 2. Note the abrupt drop in dark current once the clock voltages fell below -7.5V (measured with respect to the substrate).

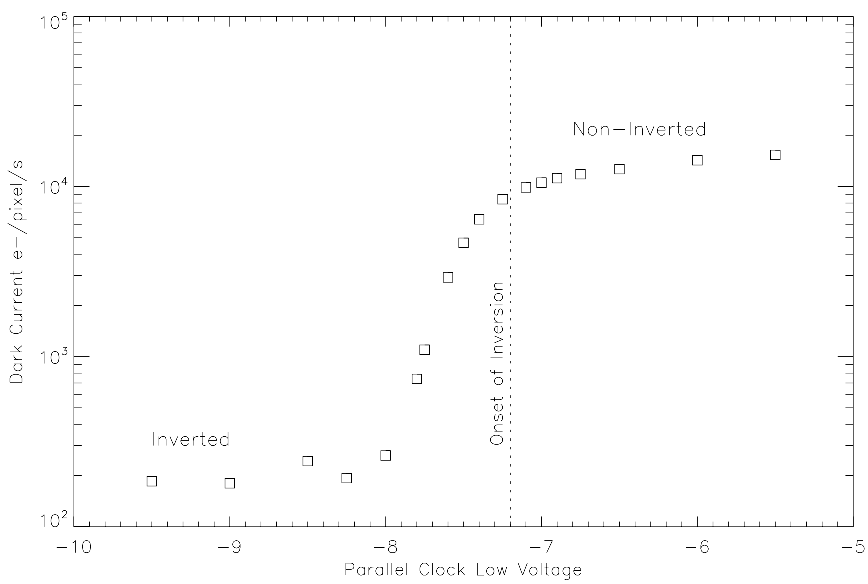

Figure 2. Measurement of the inversion point

3. Effect of Inverted mode operation on parallel CIC

The presence of holes at the surface of the CCD, whilst having a beneficial effect on the dark current, unfortunately produces a large increase in CIC. The reason for this is illustrated in Figure 3. The top of the figure shows a cross section through a pixel during integration of the image. Photo-charge can be seen accumulating at the pn junction and holes can be seen at the surface. The lower figure shows what happens as the readout of the image begins and the parallel electrode switches to a positive voltage. The holes at the surface are repelled down into the bulk of the CCD where impact ionisation creates a spurious electron. This then contributes to the photo-charge of the pixel. Long series of bias frames were co-added, both in inverted and non-inverted modes in order to measure accurately the parallel area CIC. This was done by subtracting the mean value in the serial over-scan region from the mean value in the image area. In the case of the CCD201 the inverted mode CIC was $0.2e^-$ per pixel whilst in non-inverted mode it fell to such a low value that it was un-measurable, i.e. the mean signal from CIC in the serial over-scan was equal to that in the image area. This mean signal was not zero, however, since additional CIC was generated in the serial register through which both image and over-scan pixels subsequently passed.

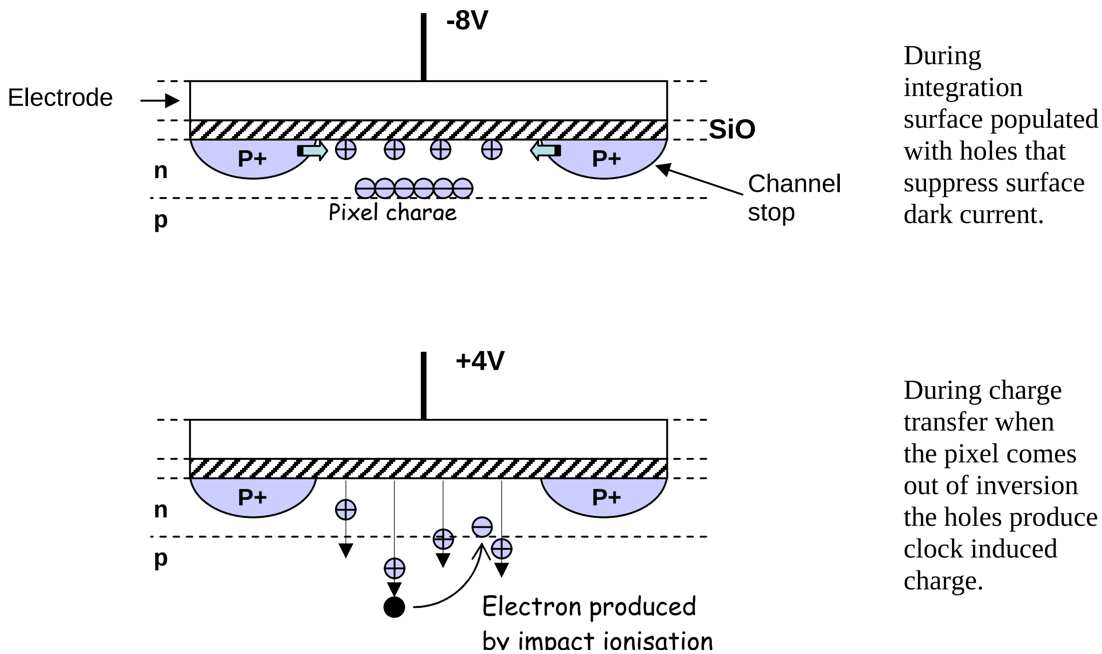

Figure 3. Inversion and CIC generation

4. Non-linear dark current and the effect of "Dither"

There was clearly a strong preference to use non-inverted mode, given the large drop in CIC that it gave. The question was now if the accompanying large increase in dark current would neutralise this advantage. Two dark current measurement runs were performed during camera cool-down from room temperature. In one of these runs the clocks were inverted during integration, in the other the clocks were non-inverted. In the case of the non-inverted run, dark frames of 60s duration were used. For the inverted run, where the signal was much lower a variety of exposure times were used increasing to many minutes at the lower end of the temperature range. Figure 4 shows the results compared with two manufacturers models for surface dark current and bulk dark current. The bulk model follows the inverted mode data well at higher temperatures before diverging quite widely at about 230K. The surface model has a close fit to the non-inverted mode data down to 190K. Below this temperature something very interesting happens and the non-inverted mode dark current suddenly drops by almost two orders of magnitude, approximating to the levels attained in inverted mode.

The explanation for the sudden drop in dark current is the phenomenon of "dither". This gives a non-linear dark current where the relationship between accumulated dark charge and exposure time is not constant. Instead the dark current for shorter exposures is much less than that for longer exposures. Note that this is only seen in non-inverted mode operation, with inverted mode the relationship is linear. Dither is due to holes being injected into the surface of the CCD during the clear operation which precedes each dark frame. These holes have a finite lifetime which increases as the temperature decreases[2]. Whilst they persist they act to suppress the surface component of the dark current. At typical CCD operating temperatures it can be greater than an hour. Figure 4 suggests that at 190K the hole lifetime is around 60s. So, for exposures of shorter than this it was possible to use non-inverted mode for low CIC and at the same time achieve the low dark currents normally experienced in inverted mode.

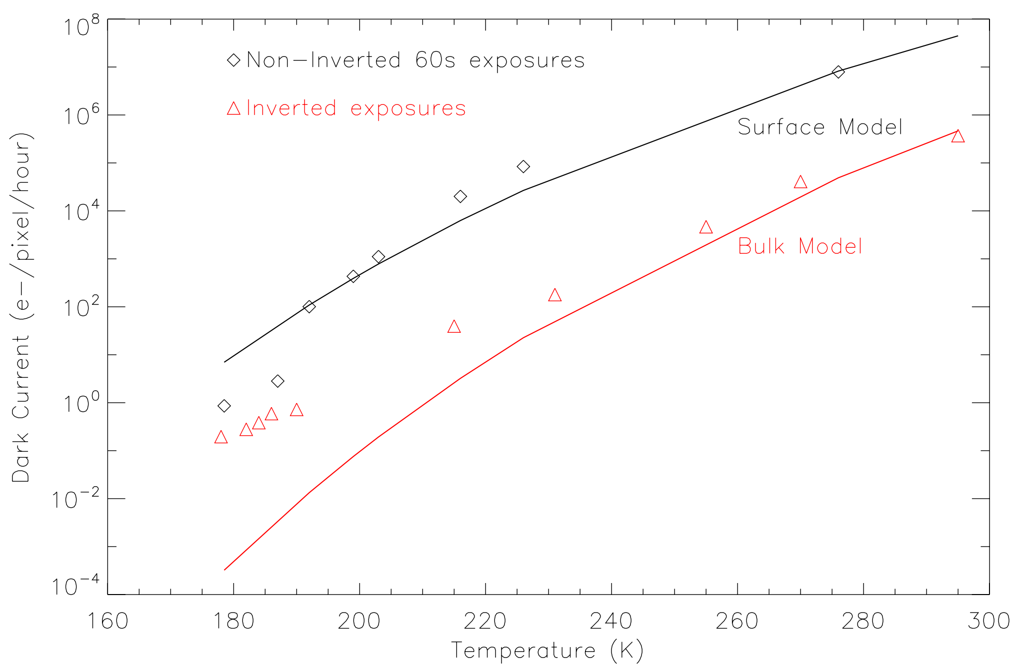

Figure 4. Comparison of dark current with manufacturers models

5. Measurement of serial register CIC using the dump-gate

Having optimised the parallel area CIC and dark current, the focus was now moved to reducing the CIC generated within the serial register. This was done using an unconventional manipulation of the dump-gate structure that lies alongside the serial register and can be used to clear its contents. The CCD201 EMCCD was clocked in a way that the entire serial pipeline was read in each line-read. Before each line-read the dump gate was pulsed high to empty the serial register part of the pipeline. This had the effect of producing a gradient in the amount of CIC present in the resultant bias image. This is explained graphically in Figure 5. This gradient directly gave the CIC per pixel transfer generated within the serial register. The effect of making small changes to the serial clock waveforms could then be quickly measured. It was found that a reduction of the serial clock high-voltage from 10V to 8.5V (substrate was 4.5V) made a significant reduction in the CIC. Further reductions in clock voltage were not possible since it caused loss of charge transfer efficiency. Figure 6 shows actual horizontal cuts through bias frames in which the CIC gradient produced by the dump gate operation is clearly visible. After this stage of optimisation the CIC charge stood at 0.013e$^-$ per pixel per readout.

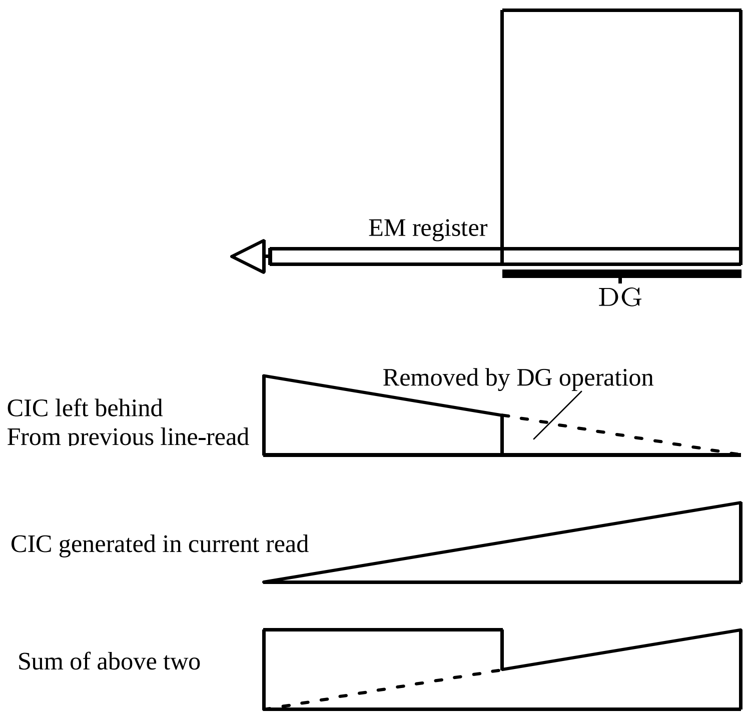

Figure 5. Explanation for how a gradient in the CIC can be induced by use of the DG.

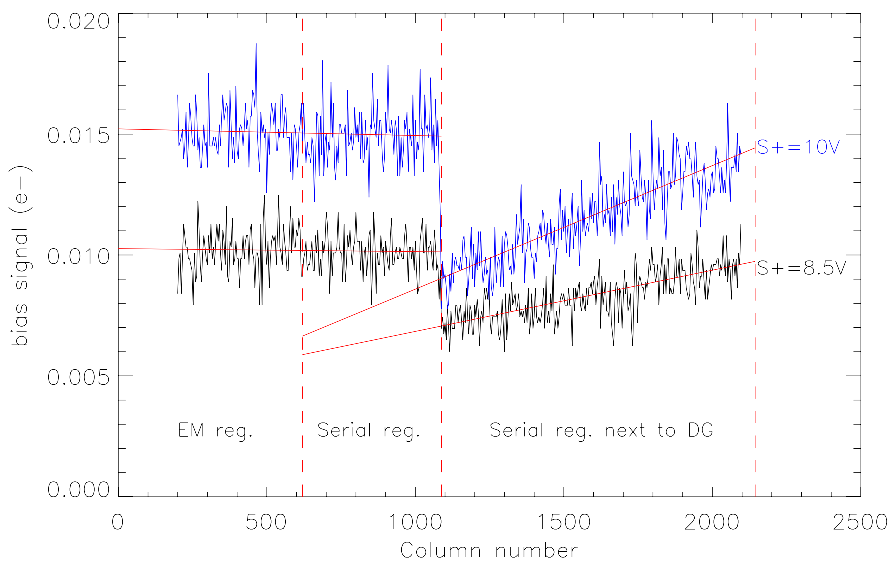

Figure 6. Actual cuts through bias frames at two values for the serial clock-hi voltage.

6. Modeling of the CIC generation

It was assumed that the majority of the remaining CIC was generated in the EM register where the higher clock voltages would make CIC generation more likely. To test this assumption a simulation was run where first the CIC appeared in a random fashion along the serial register and second where it appeared randomly along the EM register only. The histograms of the resultant model bias frames were then compared with a histogram of a stack of genuine bias frames. The three histograms are shown in Figure 7. Note that the genuine bias histogram lay very close to that of the pure in-EM register model, so the original assumption was confirmed.

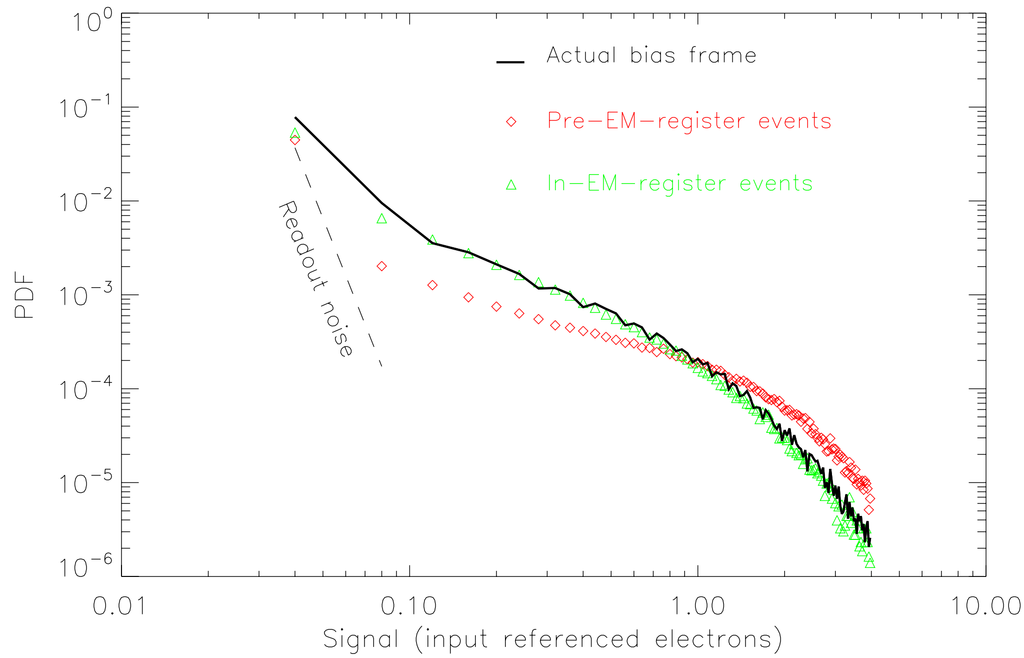

Figure 7. Model of the CIC generated both before and within in the EM register.

7. Use of an EMCCD for observation of a cataclysmic variable

The optimised CCD was then used for a challenging observation of a cataclysmic variable[3]. This is a binary star system consisting of a white dwarf primary accreting material from a less massive brown dwarf companion. The object of study was SDSSJ1433 which is 18th magnitude and has an orbital period of 76 minutes. The accreted material in this system forms a hot disc close to the white dwarf that looses energy through viscous interactions before finally impacting the white dwarf surface. The rotational velocity of this material can reach several thousand kilometres per second. Given that half this material is approaching and the other half receding from the observer, the spectral lines from material in this disc (primarily hydrogen) appear to be split. Superimposed upon this motion is a much smaller motion arising from the orbital velocity of the white dwarf (in whose frame of reference the disc material orbits) about the common centre of gravity of the whole system. It was this smaller motion that we set out to measure using high-resolution spectroscopy of the disc emission. The fact that the object was very faint, rapidly changing due to its short orbital period, and needed a high dispersion grating for good velocity resolution meant that the signal was hopelessly low for a conventional CCD. We anticipated a signal per wavelength element of approximately 1 photon every 15s. This, however, poses no problems for an EMCCD where every photo-electron is clearly visible above the read-noise. A total of 4 orbits of the system were observed and the small Doppler shift of the primary about the system centre of gravity was successfully resolved. Figure 8 shows the resultant radial velocity curve as a solid red line fitted to those data points enclosed by red squares. The radial velocity semi-amplitude was found to be 34kms^{-1}, low enough to confirm that the secondary star was a brown-dwarf with a mass below the hydrogen burning limit.

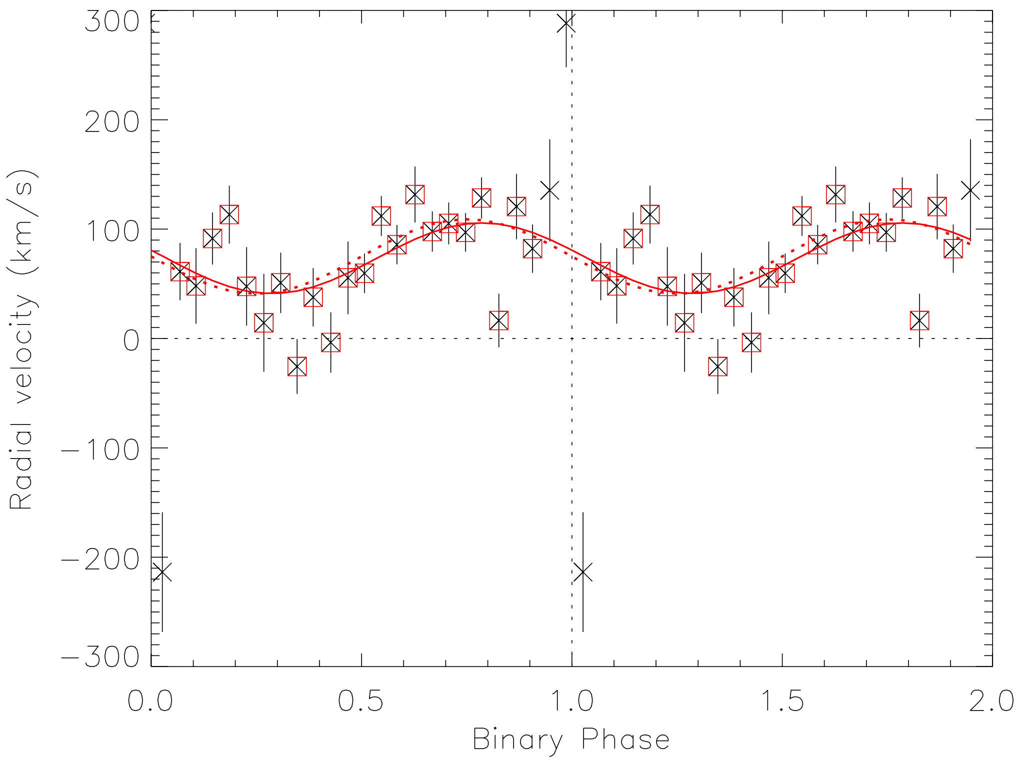

Figure 8. Radial velocity curve of a cataclysmic variable system using EMCCD data.

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