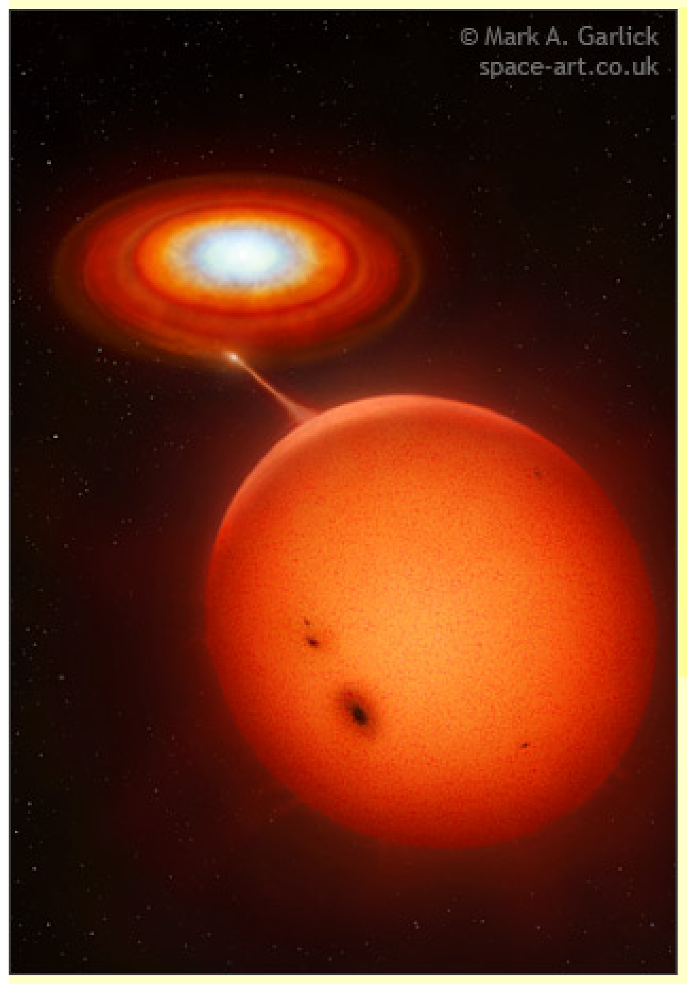
Modelling the suitability of EMCCDs in spectroscopic applications

Simon Tulloch

Isaac Newton Group, Apartado De Correos 321, 38700 Santa Cruz de La Palma, Islas Canarias, SPAIN

For very low illuminations an Electron Multiplying CCD (EMCCD) is clearly the detector of choice due to its negligible read noise. As the signal level increases another noise source known as Multiplication Noise starts to dominate. At some point this makes a conventional CCD more competitive.

A Cataclysmic Variable (CV) System

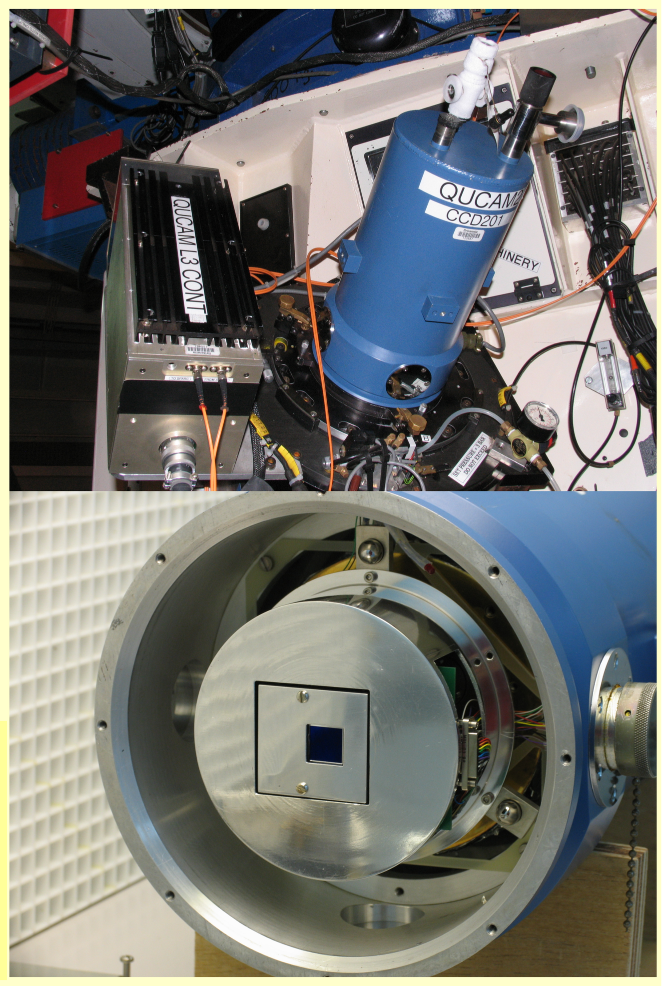


A CV consists of a White Dwarf accreting material from a fainter companion star in a close orbit. In the case of non-magnetic White Dwarfs the accreted material first forms a disc that emits most of the light of the system. The intersection of the accretion stream with the disc gives rise to a bright spot that can be detected in high time resolution spectra.

In some systems the companion star (the 'donor') eclipses the White Dwarf. High time resolution spectroscopy can then yield important information on the dynamics of the system.

Many of the newly discovered CV systems are fainter than Mag18. They are ideal targets to exploit the relatively new technology of Electron Multiplying CCDs.

The QUCAM2 EMCCD Camera



QUCAM2 is a cryogenic EMCCD camera built at the Isaac Newton Group and currently used for spectroscopy on the William Herschel Telescope. It contains a 1K x 1K pixel detector with both an electron multiplying (EM) and a conventional output. The EM output has negligible read noise.

A raw EMCCD spectrum of a CV taken with QUCAM2 on the WHT.
Magnitude 18.5 object
30 second exposure
0.22A per pixel dispersion

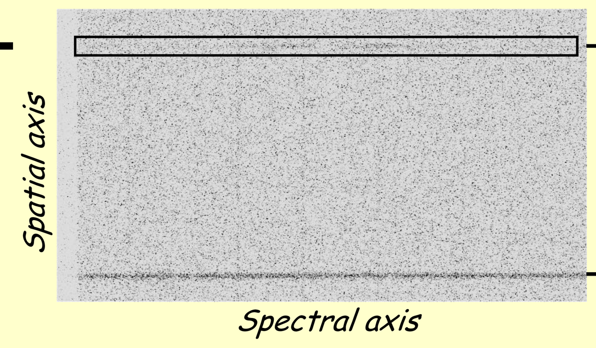
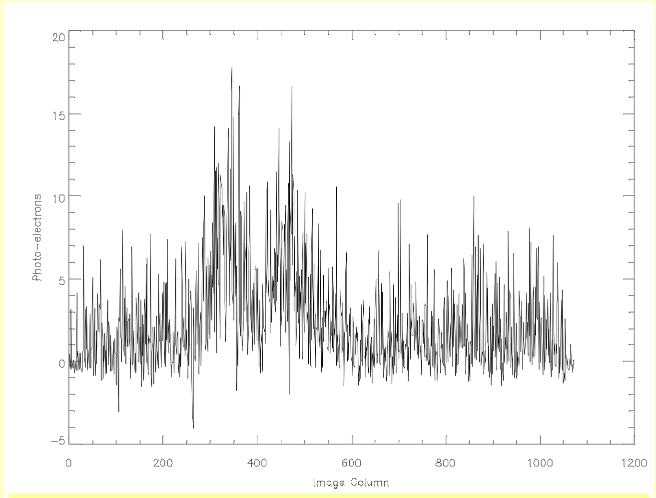
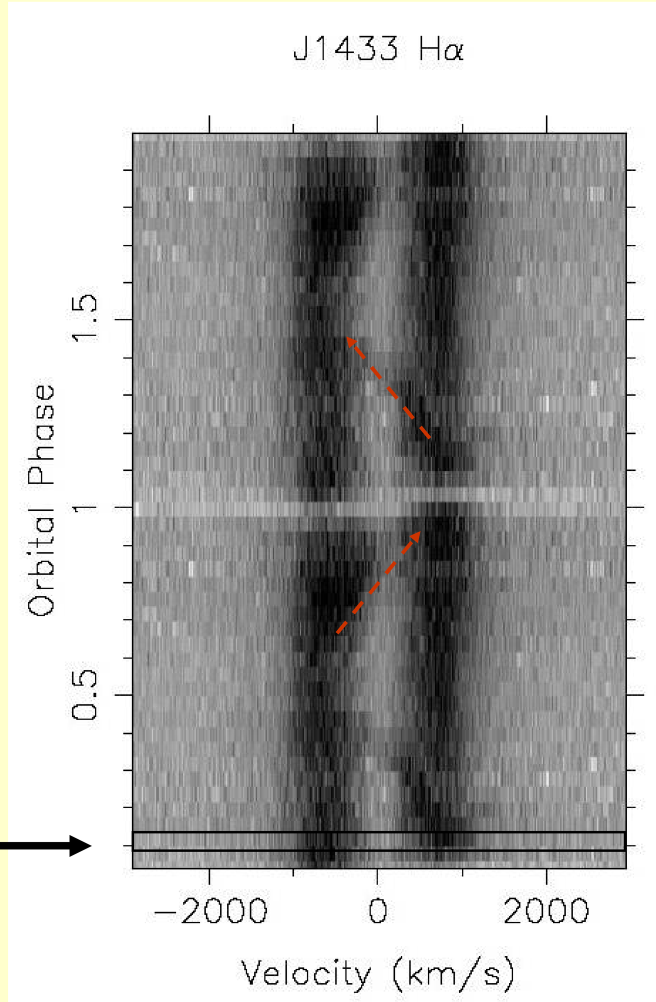


Image read out through conventional amplifier, region around the object is windowed out, spatially binned by a factor of 4 and sky-subtracted



Each 'extracted spectrum' is then stacked into a 2D trailed spectrum to highlight the motions of the CV emission lines over the course of an orbital revolution.



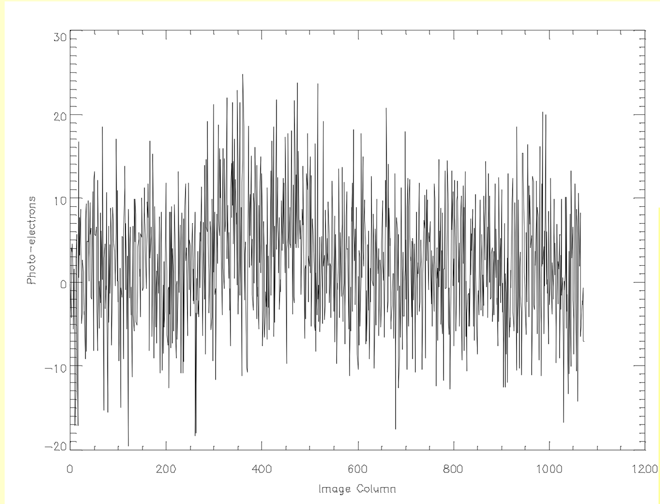
Courtesy of Pablo Rodriguez-Gil

The resultant trailed spectrum (here plotted with a horizontal axis labelled in units of km/s) can then be used to determine the dynamics of the system.

Eclipse phase when White Dwarf and accretion disc pass behind the donor star

- - - Motion of bright spot

The H-Alpha spectral line shown here is split by the rapid rotation of the accretion disc material responsible for most of the flux.



This spectrum has 6.6e of noise added to it to simulate the result we could expect by using the conventional CCD output.

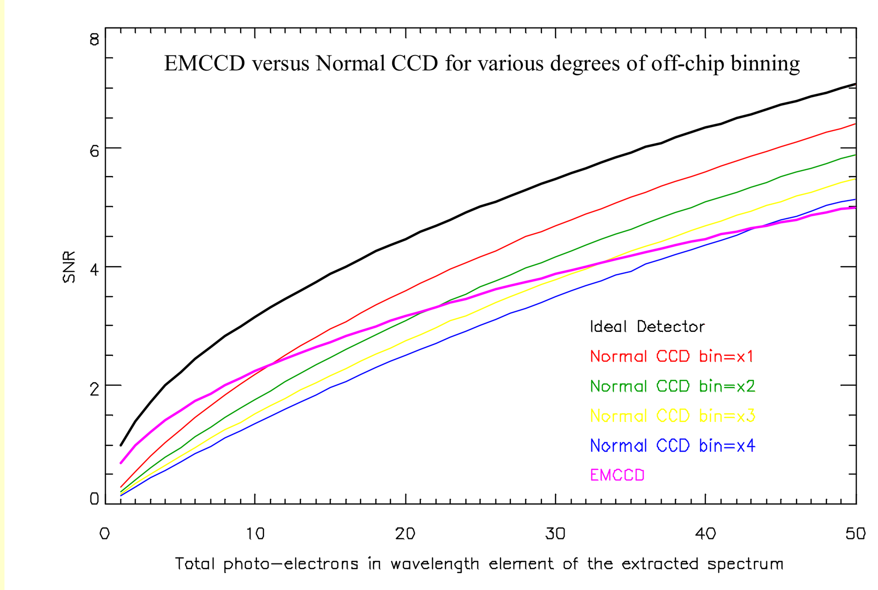
(The actual noise was 3.3e but this was effectively doubled by the 4 fold spatial bin that was needed during the extraction of the spectrum)

In this extremely challenging observation, that combined high spectral and temporal resolution with a fairly faint source on a 4.2m telescope, the EMCCD really demonstrated its worth.

The Higher Signal Domain.

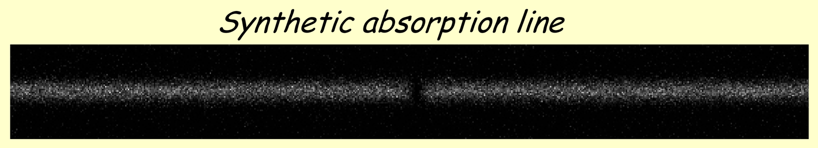
At higher signal levels we leave the read noise limited domain and the advantage of the EMCCD is diminished. In fact another noise source known as 'Multiplication Noise', which effectively amplifies the Poissonian photon noise by a factor of 1.4, actually makes the EMCCD perform worse than a conventional CCD. In this case the observer would do better to switch to the camera's conventional output.

A model of an EMCCD has been developed to show the SNR that can be expected from both its conventional and electron multiplying outputs across a range of signal levels. In the first part of the analysis, the SNR in a single wavelength element of the final reduced spectrum is calculated for both outputs. To arrive at this final reduced spectrum it will first have been necessary for the astronomer to 'spatially bin' the raw image since the light in each wavelength step will have been spread across several pixels of the detector by the effects of atmospheric turbulence. Some of this binning is generally done off-chip (i.e. post-readout) where in the case of the conventional detector it adds extra noise. The EMCCD suffers almost no loss of performance from off-chip binning so the relative merits of the two outputs is critically dependant on the binning factor.

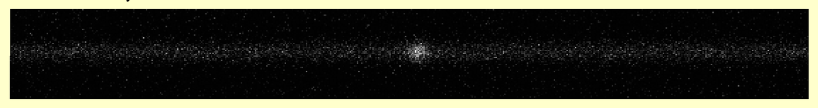


So the *single pixel* analysis suggests that for typical off-chip binning factors of 2 or 3, the observer should switch to the conventional output of the camera if the signal in the final extracted spectrum is between 20 and 30 e^-.

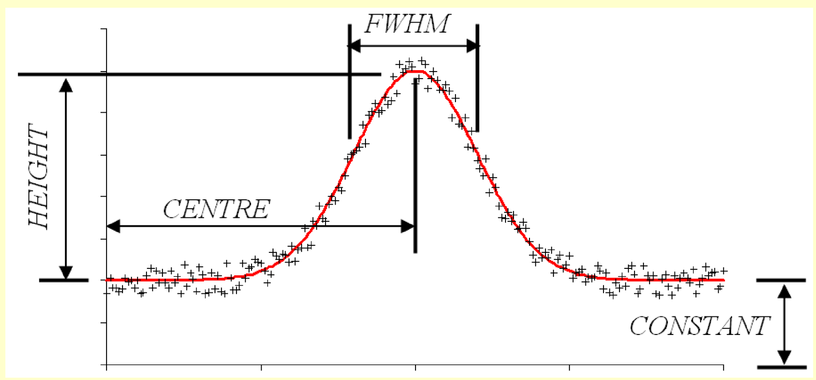
Synthetic absorption line



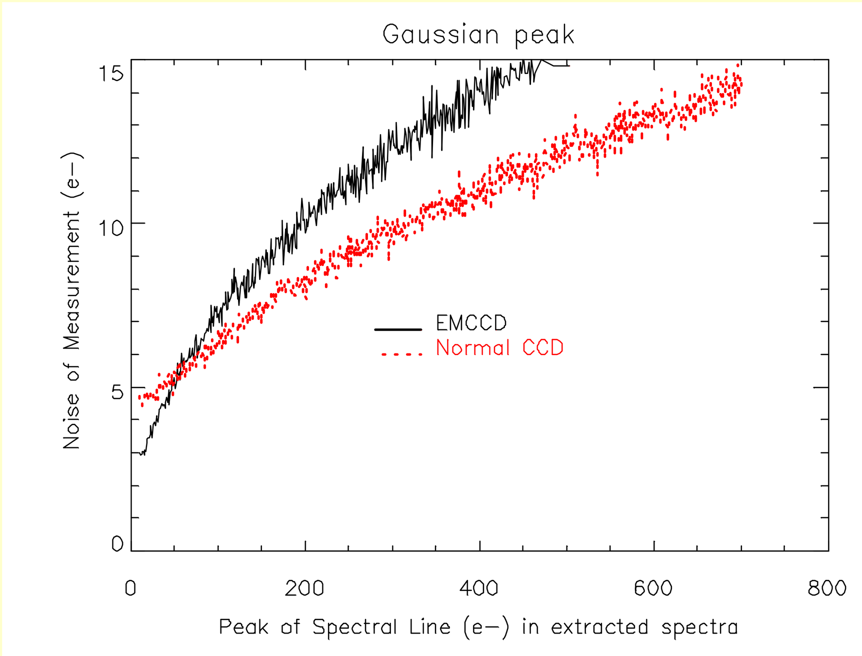
Synthetic emission line with weak continuum

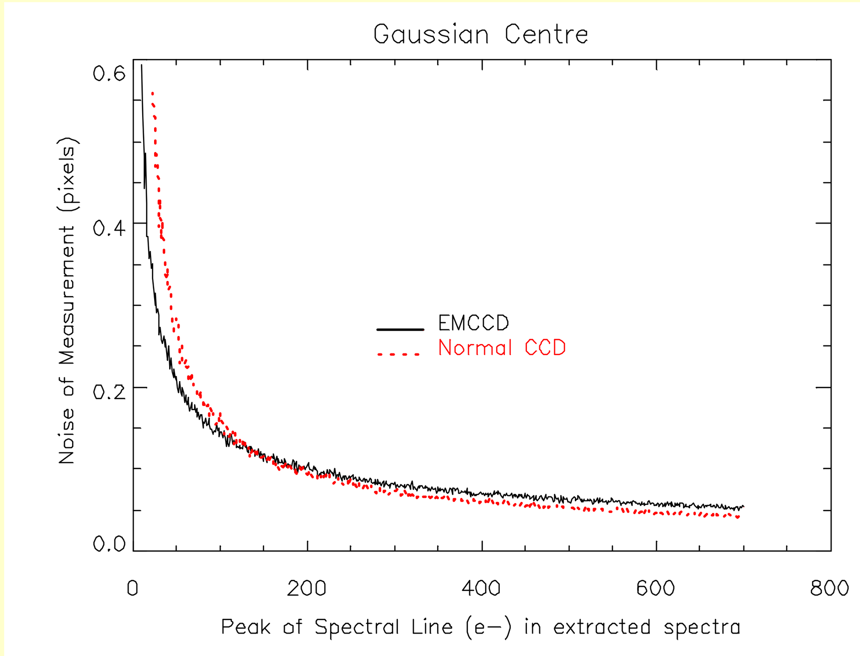


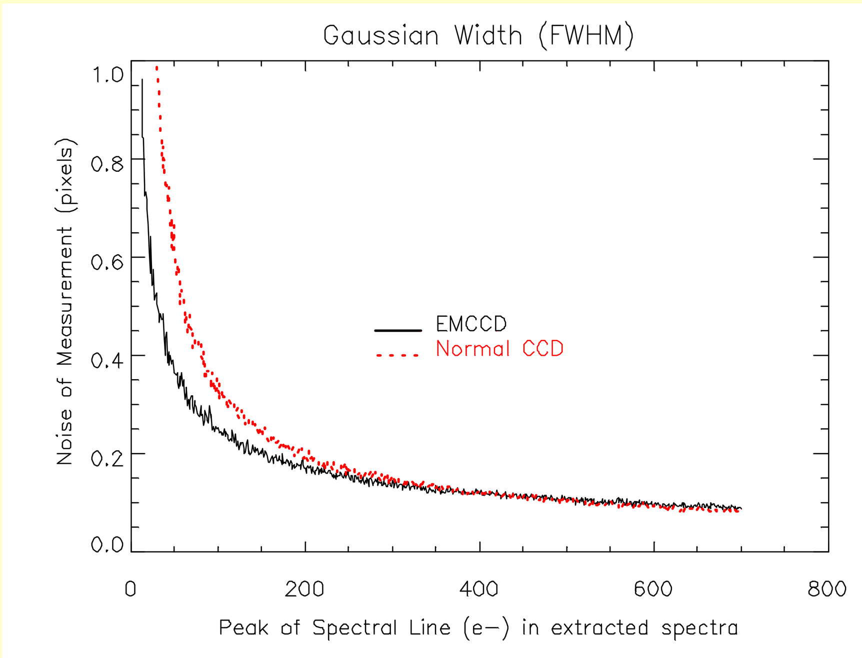
In the second part of the analysis the model was used to generate synthetic emission and absorption spectra. Two groups of spectra were created, one using the characteristics of the EM output, the other using the characteristics of the conventional output. These synthetic spectra were then Gaussian fitted and the noise in the principle parameters (height, FWHM, centre and constant) plotted against the line brightness. The measurement noise was determined by generating several thousand spectra with the same parameters using a 'Monte Carlo' algorithm and then analysing the standard deviation of the actual measured values.

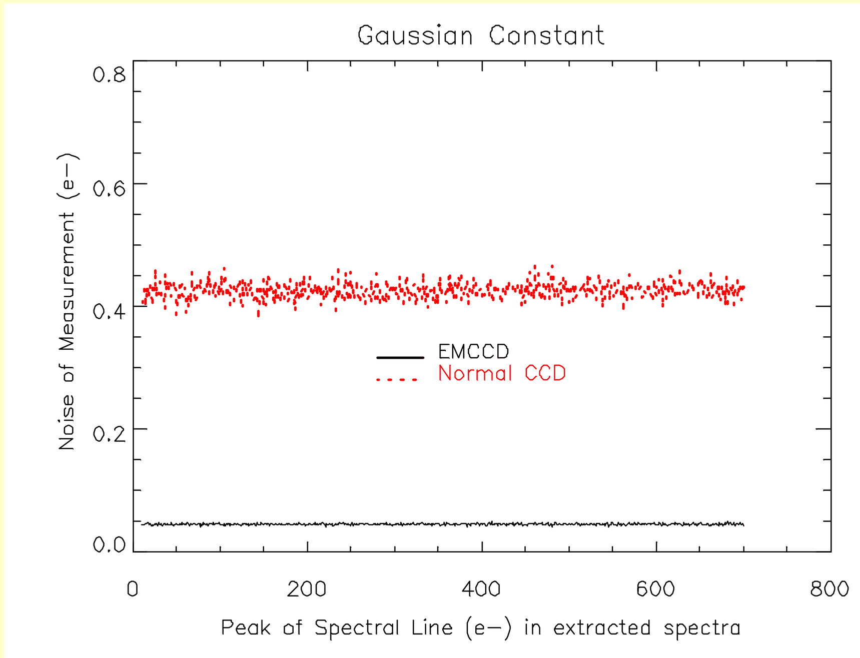


Some results are shown below for narrow emission lines with a zero continuum. Off chip spatial binning was x3. The noise of the conventional amplifier was 3.3e^-. The emission line had an FWHM of 5 pixels.









What the model shows is that in the case of a low continuum the EMCCD is competitive to higher signal levels than the earlier single pixel analysis suggests. Other simulation runs were done for broader spectral lines and lines with a higher underlying continuum. The relative performance of the two types of CCD was only weakly dependant on line width, however, the presence of even a weak continuum (>10e^-) severely reduced the benefits of the EMCCD.