The HST Treasury Program on Eta Carinae

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THE STIS CCD CROSS-DISPERSION POINT SPREAD FUNCTION

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1. Introduction

This report to outlines the work done by the Eta Carinae HST Treasury Project to determine the properties of the cross-dispersion point spread function for the HST Space Telescope Imaging Spectrograph (STIS) CCD. In this document we will refer to the cross-dispersion point spread function by the abbreviation: XSF. The goal of this work is to give a model for the STIS/CCD XSF which can be calculated as a function of wavelength and CCD column number. The intended uses of this model include: calculating STIS CCD slit throughput corrections, re-calibrating the absolute flux scale for the STIS CCD, and deconvolving the observed cross dispersion profiles for extended sources.

The XSF is not a simple symmetric Gaussian or modified expediential function. It is complicated by a feature which appears separated from the profile maximum by 0.05” to 0.20” at 5% to 10% the peak value (i.e. Figure 2, 1 pixel = 0.05”). This feature is not to be confused with the STIS “ghost” (Hill, 2000) which manifest’s itself at a much larger separation from the XSF peak along a line connecting the peak and the optical axis of the instrument. The “ghost” and this feature may be related but that has not been determined. We have focused here on practical modeling based on high signal to noise observations of standard stars rather than working out a theoretical basis from first principles.

Scattered light also contributes to the XSF at a relatively low level which can be approximated as a constant on the order of 0.1% of the peak value across the 10 to 20 CCD rows used to fit the two peak XSF. A more detailed model of the scattered light contribution is left for another document.

2. The Model

This XSF model is composed of two squared Lorentzian peak function, one a fraction of the amplitude of the other and with their centers offset from each other. The square Lorentzian form was chosen because fits the wings of the distribution much better than a Gaussian or modified expediential function. A constant level was included in the model to account for the contribution of scattered light to the XSF. We also assumed that the flux distribution is one dimensional on the cross dispersion axis in order to avoid complicated integration of the slit profile in the dispersion direction. The resulting model takes the form:

$$f[x] = p * \left[\frac{a^4}{(a^2 + (x-z)^2)^2} + b\left(\frac{a^4}{(a^2 + (x-z+c)^2)^2} \right) + d \right]$$

Where:

a = the width of the profile
b = the fractional difference in amplitude between the main and secondary peak
c = the offset of between the peaks in pixels
d = constant background level which simulates the scattered light contribution
p = maximum peak value
z = the row number where the maximum peak value resides

Parameters a, b, c, and d are values which can be solved for as a function of wavelength, CCD column number, and date. In contrast, parameters p and z depend on the spectral flux of the source its position on the slit. An illustration of the model appears in Figure 1.

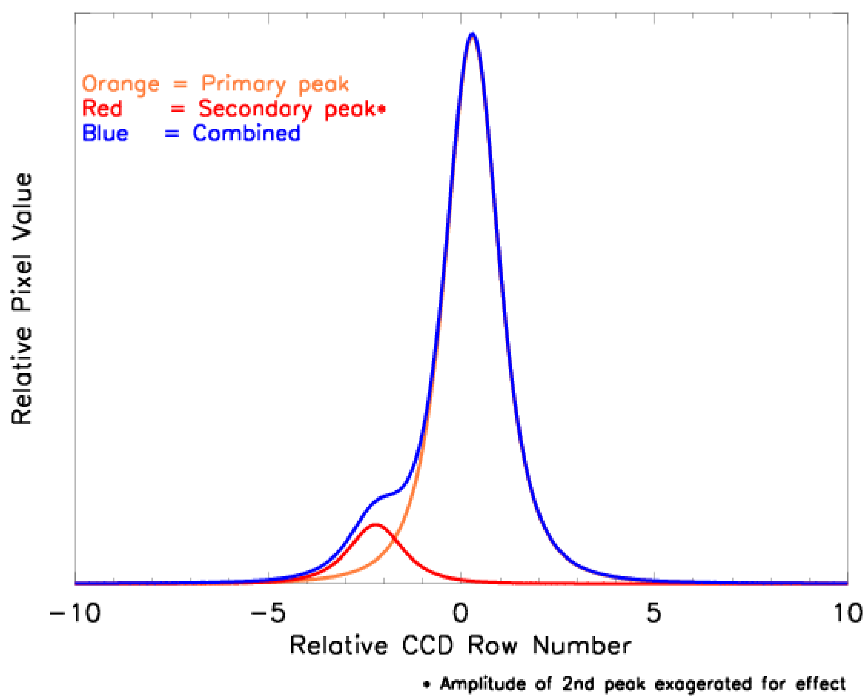

Figure 1 An illustration of how the two peak model adds up.

This model describes the actual flux distribution while each pixel value is really the flux distribution integrated over the pixel's surface area. Therefore, to fit the actual observed XSF, we must integrate f[x]. This is represented by the function F[x]:

$$F[x] = \int f[x]dx = \frac{1}{2}\left[a^2\left(\frac{x-z}{a^2+(x-z)^2} + \frac{b(c+x-z)}{a^2+(c+x-z)^2}\right) + 2d(x-z) + a * ArcTan\left(\frac{x-z}{a}\right) + ab * ArcTan\left(\frac{c+x-z}{a}\right)\right]$$

Given F[x], we assumed that each pixel has a uniform sensitivity across its surface and that no significant gaps exist between pixels to arrive at:

$$Pixel\_Value(x) = F[x+0.5] - F[x-0.5]$$

3. Determining the Model Parameters

The six free parameters in the model were simultaneously fit to actual data by a modified Levenberg-Marquart method which was developed and rigorously tested in-house. The data fit are bias subtracted and flat fielded observations of BD +75 325 and AGK +81 266 obtained through the HST archive at MAST. The data was not "rectified" since any scheme which interpolates the pixels introduces noise into the data.

In a non-rectified STIS CCD image, the dispersion axis is tilted slight with respect to the CCD so that the central peak of the distribution crosses several rows as it travels from one side of the detector to the other. The observed XSF was extracted by computing the median pixel value for each CCD row in ten consecutive columns. We fit the observed XSF up to 200 times across the CCD by starting in column 10 and making cuts at intervals of 5 columns to column number 1010. The columns on the edge of the CCD were excluded because they tend to be anomalous. A typical fit appears in Figure 2.

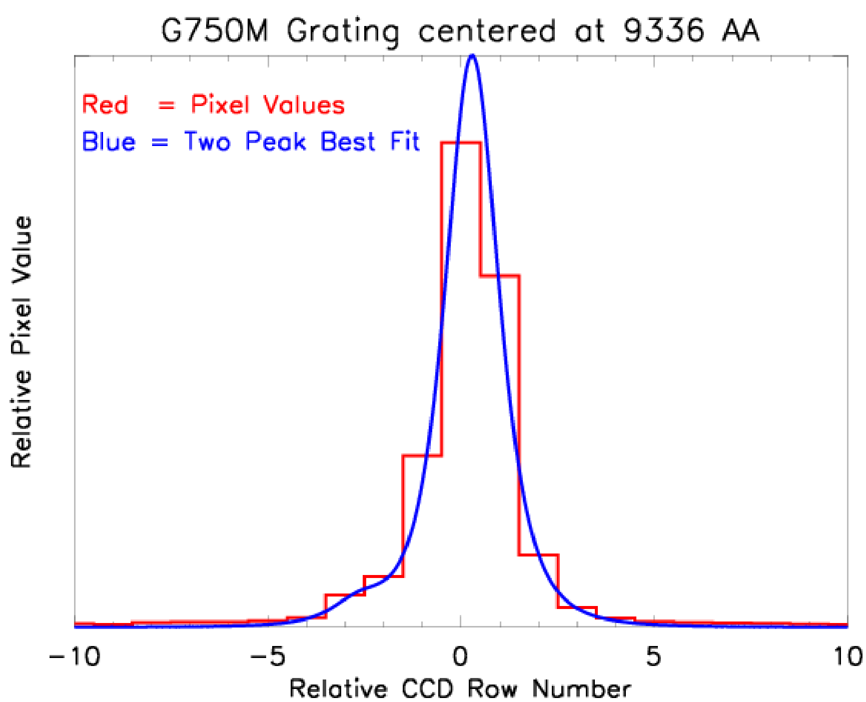

Figure 2 A fit of the XSF by the two peak model

The fits were graded with respect to quality using a chi square statistic and data from poorest quality fits were discarded. We used the best fit a, b, and c parameters to determine how they vary with relation to grating, wavelength (λ in angstroms), and CCD column (y in pixels). The relations determined for each parameter are as follows:

Peak width (a): (Figure 3 & Figure 4)

For the G230MB grating:

$$a = 1.284 - (4.06\times10^{-5})y - (1.53\times10^{-7})y^2$$

For the G430M grating:

$$a = 1.411 - (6.48\times10^{-4})y + (3.83\times10^{-7})y^2 - (1.90\times10^{-5})\lambda$$

For the G750M grating:

$$a = 2.190 - (2.74\times10^{-4})y + (1.64\times10^{-7})y^2 - (3.06\times10^{-4})\lambda + (2.41\times10^{-8})\lambda^2$$

Relative amplitude of peaks (b): (Figure 5)

If (λ >2473 Å) then $b = -0.2488 + (1.263\times10^{-4})\lambda - (1.038\times10^{-8})\lambda^2$

Else b=0.0

Separation of peak centers (c): (Figure 6)

$$c = (2.96\times10^{-4})\lambda$$

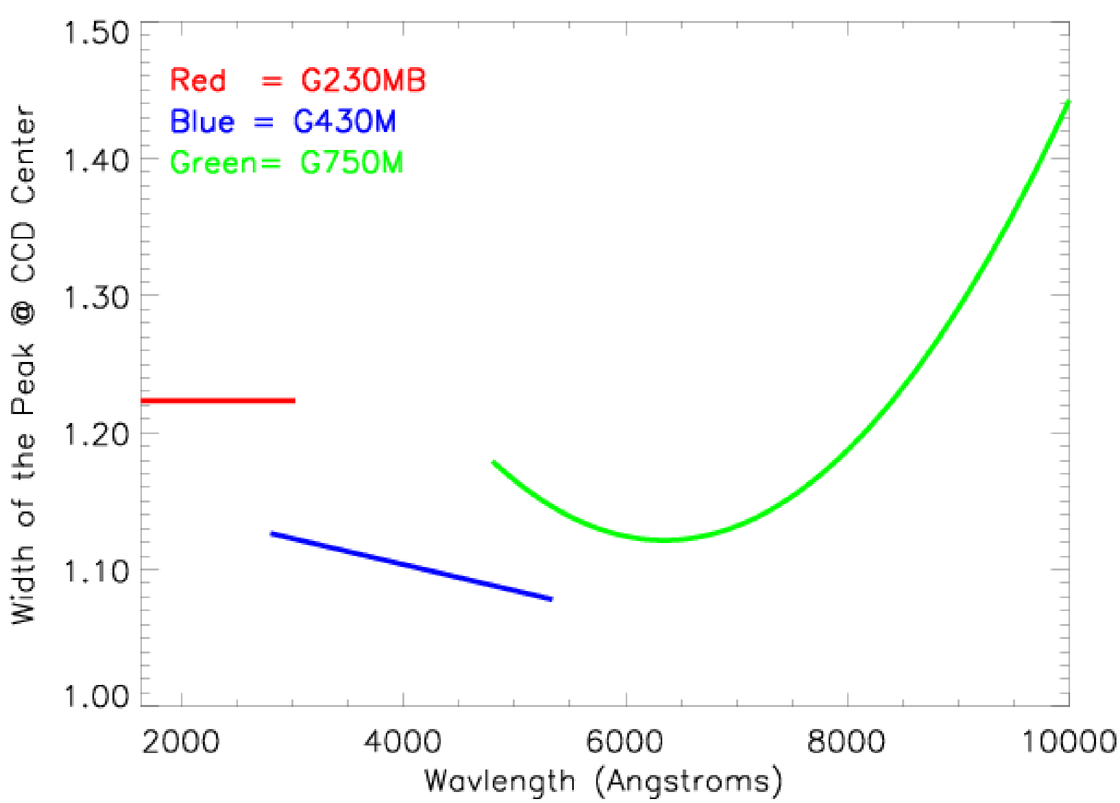

Figure 3 Width of the peak (a) as a function of wavelength at the center of the CCD for each grating.

None of these parameters have any significant trend with respect to date or detector age. In general as wavelength decreases the width of the peaks (a) and the distance between the peak centers (c) shrink until the two peaks effectively merge into one. The difference between a two peak and one peak solution is most noticeable on the G705M grating with only small differences on the G430M grating and nearly no difference on the G230MB grating. The linear relation between c and λ, which intercepts at zero, indicates that this feature is could be cause by an internal reflection. Only the width of the peaks (a) shows any trend with respect to CCD column number (Figure 4). This is explained by a slight change in focus across the CCD.

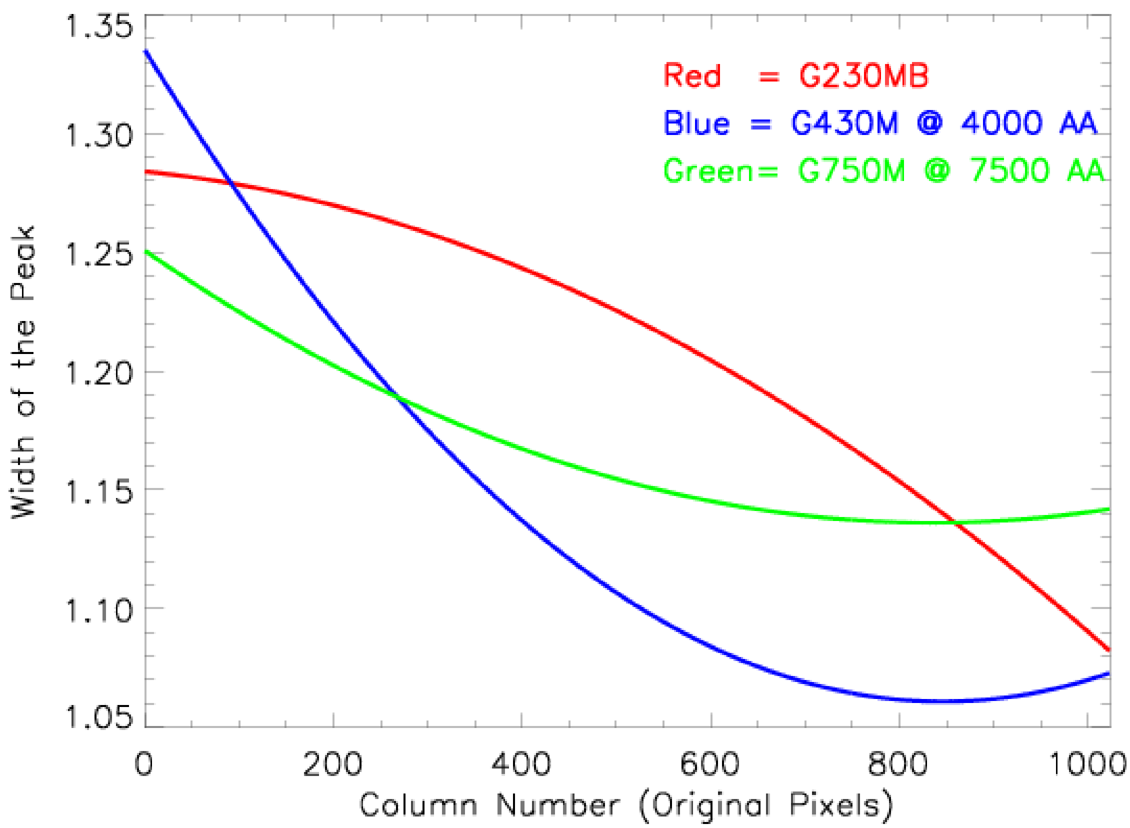

Figure 4 Width of the peak (a) as a function of CCD column for each grating

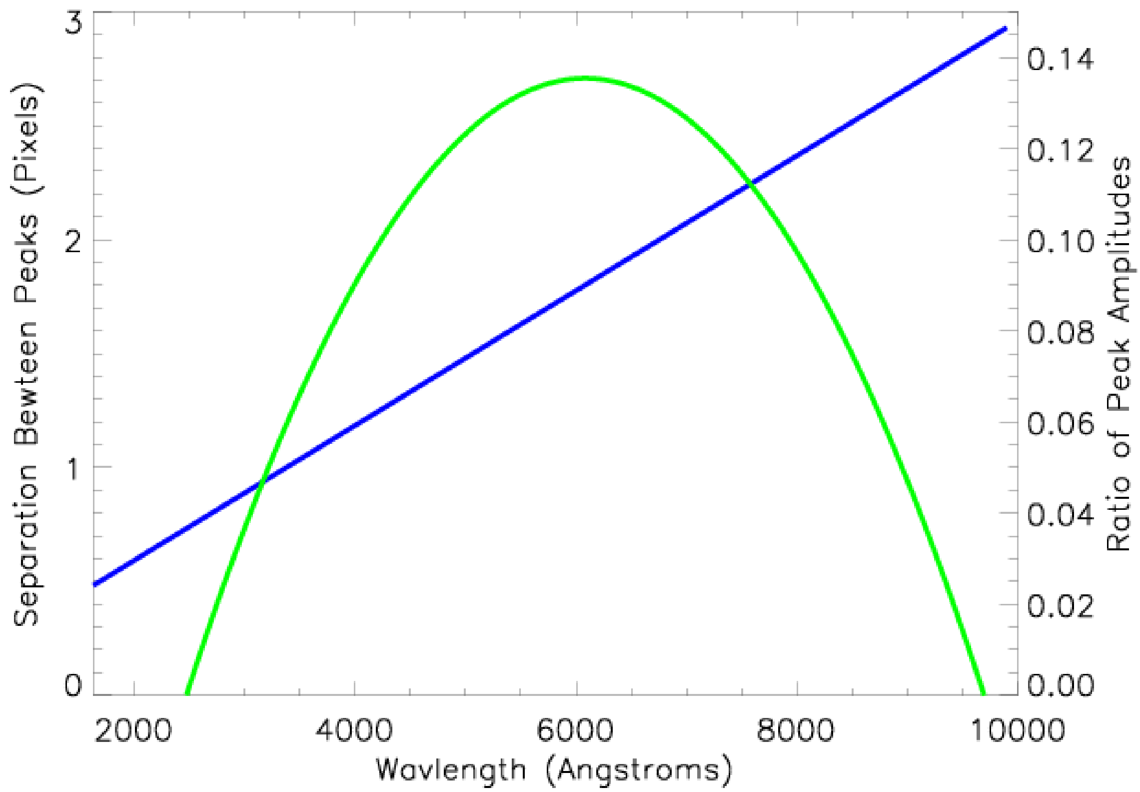

Figure 5 Separation between peaks (c, blue, left axis) and ratio of peak amplitudes (b, green, right axis) as a function of wavelength.

4. Squared Lorentzian Blurring Function

One advantage of using with Gaussians to model the XSF is that a Gaussian convoluted with a Gaussian yields a Gaussian. This makes it easy to blur one profile to match another in order to, for example, correct for a change in focus across the CCD. Unfortunately, Gaussian functions do not do a good job fitting the tails of the observed XSF. Therefore, we need to determine the blurring function that can be convoluted with a squared Loretzian and yield a squared Loretzian.

Assuming two squared Loretzians, one with a peak width of "a" and another with a wider peak width of "b" which have equal areas under their curves (same total flux), what function can be convolved with the first to yield the second? This problem is far less complicated in Fourier space where the quotient of the Fourier transforms of the first and second squared Loretzians is equal to the Fourier transform of the unknown blurring function.

Remember that we are also constraining the area under the curve of the first squared Loretzian to be equal to the area under the curve of the second squared Loretzian. This constraint is constructed in order to conserve total flux, which is a reasonable assumption for an XSF that is being "defocused."

This method yields the blurring function:

$$B[x] = \frac{(b-a)}{\pi((b-a)^2 + x^2)} \times \left[\frac{\log\left(\frac{-i}{a}\right) - \log\left(\frac{i}{a}\right)}{\log\left(\frac{-i}{b}\right) - \log\left(\frac{i}{b}\right)} \right]$$

Where the current width of the profile is a and the target width of the profile is b. The term in square brackets reduces to unity in every circumstance one is likely to encounter with the STIS CCD. The remaining function can be used to blur the XSF while conserving the total flux.

5. References

Hill, R.S, 2000, "Geometry and Approximation of Correction of STIS CCD Window Ghosts," Goddard STIS Team SMOV Report #65

Gull, T., Lindler, D., Tennant, D., Bowers, C., Grady, C., Hill, R.S., and Malumuth, E., 2002, "The STIS CCD Spectroscopic Line Spread Functions" presented at the 2002 HST Calibrations Workshop. (S Arribas, A Koekemoer, and B. Witmore, eds.)