A New Flight Model of the HRC-I MCP Quantum Efficiency

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6th August 2002

1 Introduction

We present a new HRC-I MCP Quantum Efficiency (QE) model, created in three steps from broad band calibration measurements taken on-orbit, the original HRC-I QE flight model,[1] and a QE model for the HRC-S.[2]

We first combined the broad band orbital data with the original flight model - used as a relative response curve - to produce a composite measurement of the HRC-I's flight configuration response. This composite measurement was then averaged with the original flight model using an uncertainty-based weighting to generate v. 2.0 of the micro-channel plate (MCP) QE. Finally, using the latest HRC-S QE model as a shaping factor below 626 eV, we created v. 2.1 of the QE model.

In Section 2, we discuss the generation of the composite measurement from flight data. This approach was necessary because of the very low energy resolution of the HRC in imaging mode. Section 3 discusses the averaging of the composite flight measurement with the original flight model as well as the generation of the final uncertainties. Section 4 discusses the inclusion of the relative response of the HRC-S at low energies.

2 The Composite Measurement

2.1 Data Analysis

The composite measurement is based on repeated observations of three sources whose X-ray spectra are in generally distinct energy regimes. G21.5-0.9 radiates at energies above 1 keV, Cas A is prominent in the range of 0.7 to 2.5 keV, and HZ 43 emits from 0.06 to 0.2 keV.

Background subtracted source count rates for each observation were determined from level 2 event files using encircled energy data and the exposure time determined from the header of the event list. Because the filtering included in standard level 2 processing of HRC-I data results in the loss of 2-5% of true x-ray events,[3] the rates found in this way were increased by 2.5%. We chose this value as a conservative correction that minimized differences with the original flight model. This introduces an uncertainty in the measurement of approximately 1%, which has been included in the systematic error estimates for our final analysis of the detector response.

2.2 Normalizing to Fit the Orbital Data

The observed count rates determined above were compared with count rates predicted by convolving the source models with the canonical HRMA effective area, UVIS transmission, and original flight model of the MCP QE. From this comparison, we generated a set of varying scale factors to normalize the original flight model to match the

[1]Version 1, produced in 1999 by D. Patnaude from ground calibration data.
[2]Version 2.1, produced in December 2001 by D. Pease from in-flight calibration and lab flat fields.
[3]Juda, Mike. Private communication, 2002.

orbital data. In the 1.0-2.5 keV range, the normalization was constrained to optimize agreement with observations of both Cas A and G21.5-0.9.

Over the nominal energy range of the QE model of the detector, 100 eV to 10 keV, we find that the response should be decreased on average by a factor of 0.93 relative to the original flight model in order to agree with the on-orbit measurements. The bulk of this change occurs below 277 eV, where the response must be reduced by an average factor of 0.84 in order to correctly predict the observed count rates. From 11 eV to about 120 eV (1100-100 Å), the "out of band" response of the detector is also reduced by a factor of 0.68 for reasons discussed below. From 277 eV to 1.488 keV, the response appears to be greater than originally modeled by a factor of 1.13, while from 1.488 to 10 keV, it is less than modeled by an average factor of 0.92.

When the first versions of the HRC-I QE model were created, the X-ray calibration data could not be fit well with any single response function. Therefore Patnaude *et al.*[4] fit the data with separate quadratic components in several energy regimes. In our modifications of the response to improve agreement with observation, we have used continuous scale factors that are smooth within these coherent sections of the response curve, to avoid introducing any additional discontinuities. The exact factors we have used to modify the HRC-I response to create the composite measurement are shown in Figure 1. A comparison of the flight data with predictions developed using the composite measurement and the source models is given in Table 1. The new composite measurement, though by definition in excellent agreement with the flight data, is in moderate disagreement with the ground data - in the form of the original flight model - collected at the XRCF and during sub-assembly testing. The composite measurement of the detector response is plotted - alongside the original flight model, with its associated uncertainty envelope, and the pre-launch calibration data points - in Figure 2. Note that the error envelope of the original flight model and the composite measurement overlap for all but one energy band. In that band, between 0.85 and 1.2 keV, they are discrepant by less than 5%.

Energy Range	Primary Object	Observed ($\frac{cts}{s}$)	Prediction with QE v. 1.0 ($\frac{cts}{s}$)	Average Modifying Factor	Prediction with Composite Measurement ($\frac{cts}{s}$)
≥1.022 keV	G21.5-0.9	0.5190	0.5441	~0.93	0.5272
0.626-1.022 keV	Cas A	88.074	82.98	~1.22	86.26
0.08-0.277 keV ≤0.08 keV	HZ 43	3.9159	5.4353	~0.84 0.68	4.0241

Table 1: A comparison of the predictions of the original flight model and the on-orbit HRC-I response measurement.

2.3 Uncertainties in the Composite Measurement

The uncertainties for this new measurement of the response are heavily dominated by the astrophysics used to model the sources and the systematics of the measurements rather than the statistical uncertainties of the data, which are less than 1% in all cases. The uncertainties in our model of Cas A are estimated at 9%. Along with systematic uncertainties - primarily that of the observed count rate correction - this leads to an error estimate of 10% in the corresponding energy range. The error in the G21.5 model is 5%, which when combined with systematic errors leads to an estimate of approximately 6% for the uncertainties in the corresponding portion of the composite measurement.

At lower energies, we have an additional complication. Due to the lack of energy resolution on the HRC-I, it is impossible to distinguish low energy X-rays from "out of band" photons. One explanation of the original flight model's over-predictions for HZ 43 is an over-estimate of the low energy response. However, because the source's spectrum extends to the extreme ultraviolet region, another possibility is that the original flight model overestimates

[4]Patnaude, D. et al. "Effective Area of the AXAF High Resolution Camera (HRC)." SPIE. 1998

Figure 1: Scale factors used to produce the composite measurement from the original flight model and the orbital data.

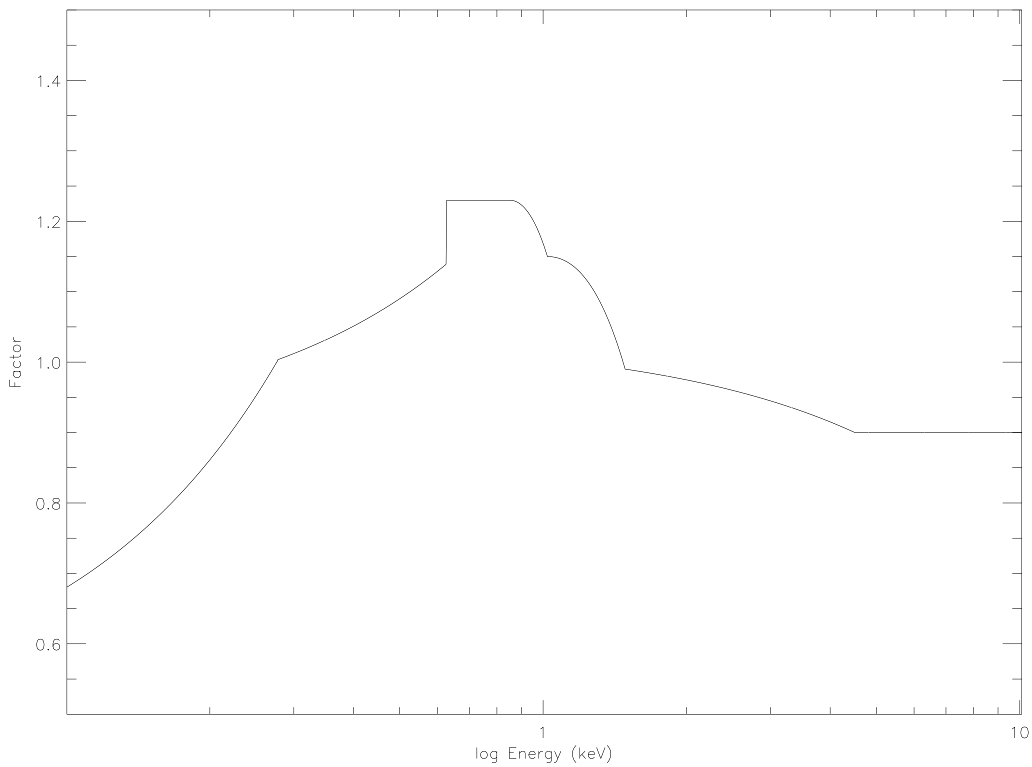
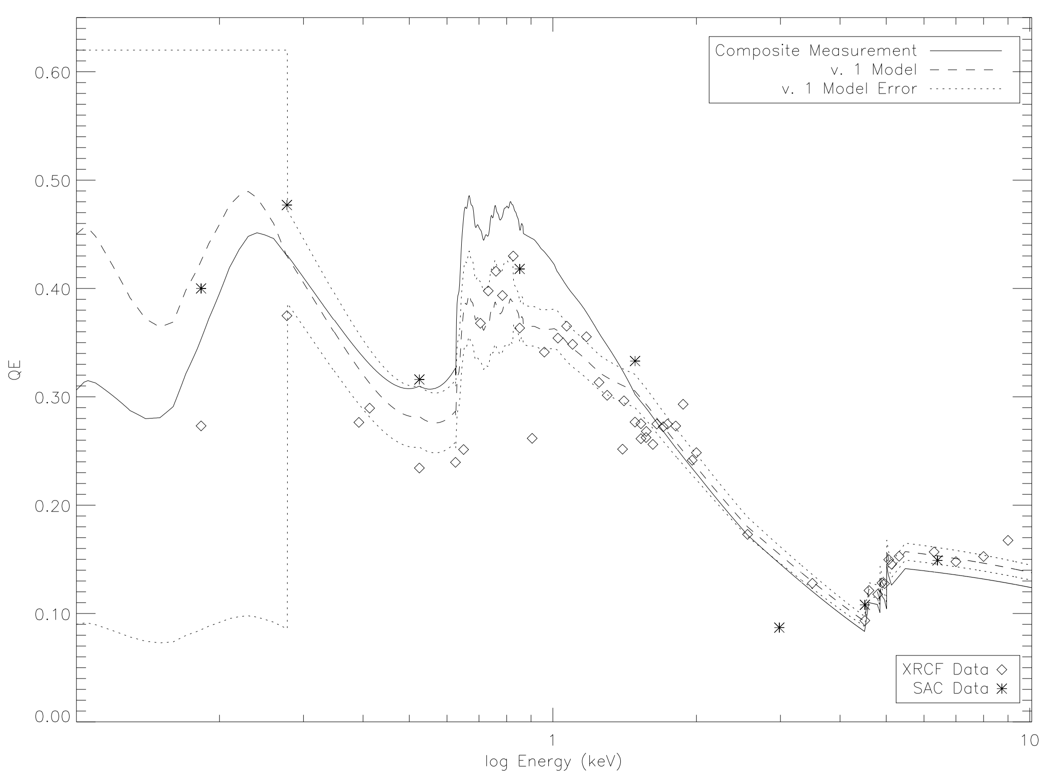


Figure 2: Comparison of the composite model and v. 1, with XRCF and SAC data



the "out of band" response of the detector. We have chosen a balanced approach and modified both the low energy and "out of band" response models. This results in comparatively greater uncertainties for the response at low energies, which we estimate to be 20% below 277 eV. While still large, this is a significant improvement over the low energy uncertainties in the original flight model. All of these uncertainties are at the one sigma confidence level.

3 HRC-I Flight MCP QE v. 2.0

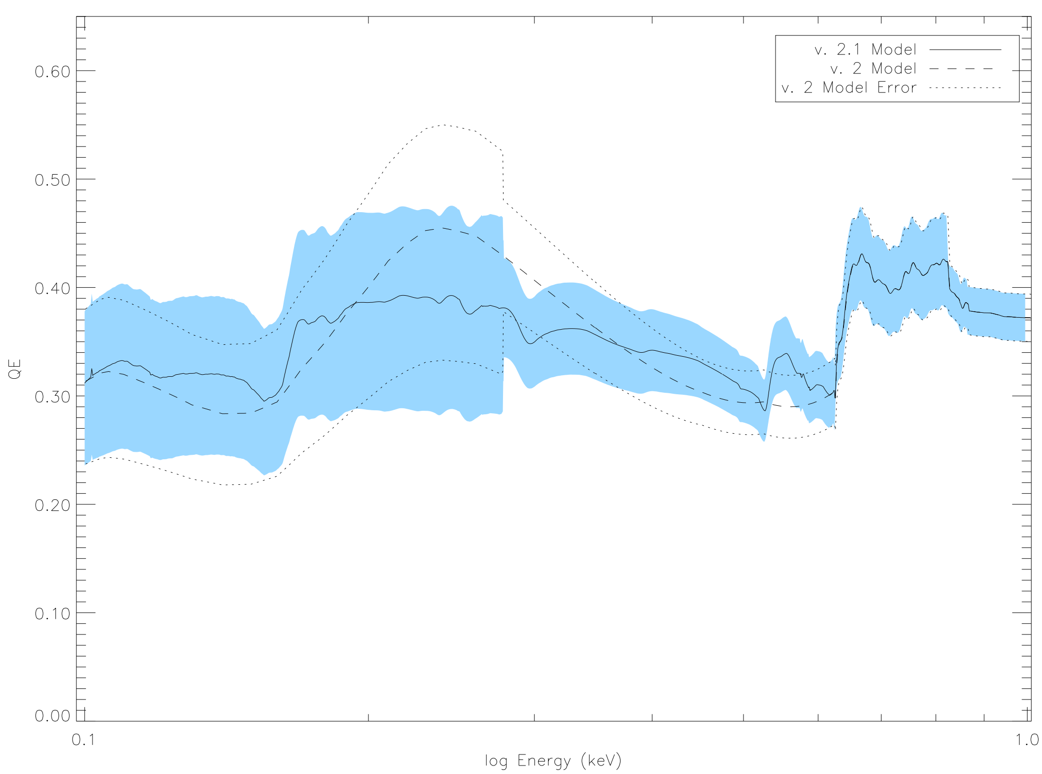
In order to combine the many discrete and well understood data points taken during ground testing with the orbital data, we combined the original flight model (v. 1) and the composite measurement of the flight response using standard error-weighted averaging techniques. This new model (v. 2.0) emphasizes the flight data at low energies, where there was a high uncertainty in the original flight model, but retains the very high resolution and quality data collected during ground testing at intermediate energies, where our new measurements are less certain. In the higher energy regime, the new model incorporates both measurements with approximately equal weight.

The uncertainty estimates for version 2.0 were calculated using the same error-weighting techniques, and most noticeably result in a large reduction of the uncertainties at lower energies relative to the original flight model.

4 The New Model - HRC-I Flight MCP QE v. 2.1

As a final refinement to the new model, we have adapted the latest HRC-S QE model (v. 2.1) for use as a shape factor at energies below 626 eV where the previous relative response of the detector was poorly known. This energy

Figure 3: Comparison of QE models versions 2 and 2.1 at energies below 1 keV



marks the lower extent of the Cas A data and the beginning of a region down to that occupied by the HZ43 data where we currently have no observational data for the HRC-I.

Given the similar shapes of the nominal QE models of the HRC-I and the HRC-S, we have normalized the HRC-S QE model to that of the HRC-I below 626 eV. The HRC-I QE model v. 2.1 is the composite of this normalization below 626 eV and the unchanged v. 2.0 model above 626 eV.[5] We show a comparison of versions 2.0 and 2.1 below 1 keV in Figure 3. No further uncertainties beyond those found in the v. 2.0 model were introduced into the error estimates for the v. 2.1 model.

The new MCP QE model (v. 2.1) is presented, with error bars and the original flight model (v. 1), in Figure 4. A new version of the total effective area was made by convolving the new QE model with the UVIS transmission and HRMA effective area models. This HRC-I Effective Area Model v. 2.1 is shown in Figure 5 with a comparison to the original effective area model.

We find that the count rates predicted by the new model for all three of our sources are consistent with on-orbit measurements within the established uncertainties. Details of this comparison are show in Table 2.

Energy Range	Primary Object	Observed ($\frac{cts}{s}$)	Prediction with QE v. 2.1 ($\frac{cts}{s}$)
≥1.022 keV	G21.6-0.9	0.5190	$0.5353^{+0.0293}_{-0.0292}$
0.626-1.022 keV	Cas A	88.074	$83.38^{+4.73}_{-4.72}$
0.08-0.277 keV	HZ 43	3.9159	$4.0082^{+0.4484}_{-0.3159}$

Table 2: A comparison of the predictive properties of the v. 2.1 flight model of the MCP QE and the on-orbit HRC-I response.

5 Conclusion

We present results of the convolution of on-orbit flight data from the HRC-I with previous ground calibration data. The new model (v. 2.1) of the detector MCP response more accurately reflects our knowledge of the in-flight performance of the instrument. Further orbital data may lead to small adjustments in the normalization of the model. However, due to the low energy resolution of the detector, it is unlikely that our model of the detailed relative response of the detector will change in any significant way.

[5]The joining was actually done at approximately 623 eV because the values of the normalized HRC-S QE model and the HRC-I QE model v. 2.0 are equal at this point.

Figure 4: HRC-I QE Model Version 2.1

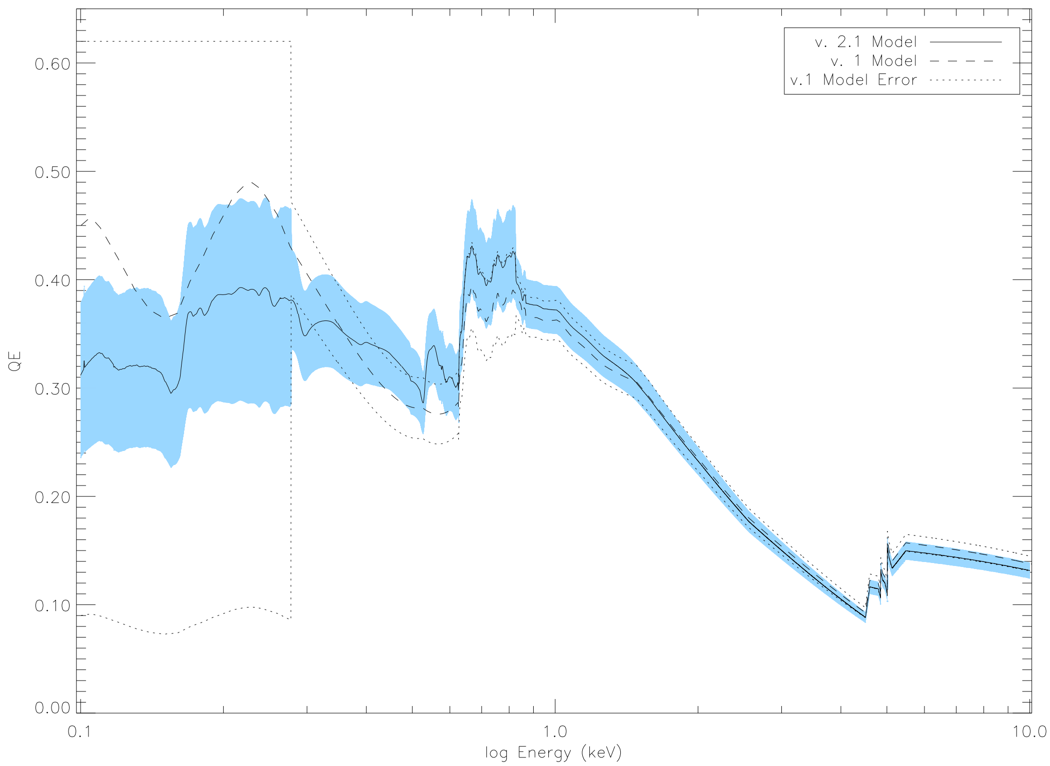


Figure 5: HRC-I Effective Area Model Version 2.1