For Bruce Margon
From Anne Kinney

A Rough Photometric Calibration for FOS,BLUE,G160L,ORDER0

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1 Summary

The HST's FOS,BLUE,G160L mode is of special interest for studying rapid variations simultaneously using the 1st order reflection for ultraviolet spectroscopy and the 0th order reflection for "white-light" photometry. When using the onboard tape recorder to record a long time series, the time resolution has been set as high as 6.18s for FOS spectra in the "1/4-stepping" mode (4 pixels per Digicon diode), or 3.2s in the 1/2 stepping mode (2 pixels per diode). The G160L grating reflects Lyman alpha 1216Å light onto the Blue Digicon detector at pixels 630, 1225, and 2020 in orders 0, 1, and 2 respectively (for observations made in the 1/4-stepping mode). The first order spectrum provides useful coverage of 1150-2500Å at 9.2Å (FWHM) resolution (with 2nd-order contamination longward of 2300Å). The un-dispersed zero-order reflection gives simultaneous broadband optical photometry. For studies of fainter targets, pixels 1-500 and 750-1200 offer a simultaneous background monitor for accurate subtraction of the variable particle background. G160L's unique capability for obtaining simultaneous time-resolved ultraviolet spectra and broadband optical photometry will become increasingly important after the High-Speed Photometer is removed from the HST to make room for the Corrective Optics Space Telescope Axial Replacement (COSTAR).

Despite its importance, the spectral sensitivity curve of the 0th-order G160L light has not previously been calibrated. This report summarizes a first attempt to derive a rough photometric calibration of this mode using synthetic photometry techniques and a variety of laboratory and on-orbit data. The passband shown in Figure 2 is constructed from laboratory data and checked with on-orbit observations of two red and one blue targets. The 0th-order G160L passband has a FWHM of 1900Å, a pivot wavelength near 3400Å and produces 820 counts per second for a 1 mJy (10^{-26}erg cm^{-2}s^{-1}Hz^{-1}) point source with the 4.3 arcsecond aperture. The observed count rates are reproduced with an accuracy of order 20-percent. A 40-percent discrepancy is seen for the reddest target. Further investigation is needed to resolve this discrepancy. The order 0 passband has been installed in CDBS for use by SYNPHOT and XCAL software.

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2 Construction of the Oth-Order G160L Passband

Laboratory measurements of the G160L 0th-order reflection are tabulated in Table 1 (George Hartig, private communication).

Table 1. G160L Order 0 Reflectance Measurements

wavelength	reflectance
1219	0.029
1249	0.030
1404	0.042
1525	0.045
1669	0.047
1777	0.055
1920	0.071
2037	0.086
2150	0.106
⟨∼ 6000⟩	⟨0.54⟩

Most of these measurements are indicated to be for "full grating illumination with monochromatic unpolarized light". Unfortunately, these measurements do not extend longward of 2150Å as they were obtained in the course of measurements taken to calibrate the 1st order sensitivity curve. The estimate near 6000Å may be less reliable, and probably represents an average reflectance over range of wavelengths based on the accompanying comment "by comparison with camera mirror illuminated with internal Pt-Cr/Ne CAL LAMP".

The laboratory data do not adequately define the G160L,ORDER0 reflectance longward of 2150Å. As a trial, several points were added by hand to connect the reflectance measurements shortward of 2150 with the estimate around 6000Å. These were typed into an ASCII file ORDER0.DAT with 2 columns giving wavelength and reflectance. The resulting reflectance curve plotted by XCAL is shown in Figure 1.

To obtain the photometric passband of the G160L 0th-order light, we must multiply the 0th-order reflectance curve by the throughputs of other components along the light path through the HST and FOS, including the OTA, the science aperture, the grazing and collimator mirror reflectances, and the Digicon detector quantum efficiency curve. These additional component throughput curves are already available in the STSCI's calibration data base system (CDBS). They were based originally on pre-launch calibration measurements, and are now corrected to match the in-flight measurements of spectrophotometric standard stars. They are retrieved by the synthetic photometry software packages (XCAL, SYNPHOT) by specifying the OBSMODE parameter to be "FOS,BLUE,4.3" (e.g. for the Blue Digicon and 4.3 arcsecond aperture). This gives the product of the following throughput files

crotacomp:hst_ota_004.tab	ota throughput
crfoscomp:fos_sqr4p3_002.tab	4.3 arcsecond aperture throughput
crfoscomp:fos_rflgrzb_001.tab	grazing mirror reflectance
crfoscomp:fos_rflcolb_002.tab	collimator reflectance
crfoscomp:fos_dqeb_002.tab	blue digicon quantum efficiency

Thus to specify the product of the 0th-order reflectance curve and the other component throughput curves, we set the OBSMODE parameter to "ORDER0.DAT * FOS,BLUE,4.". The resulting passband, as shown in Figure 2, has a peak throughput of 2 percent, a FWHM of about 1900Å centered about 3400Å, and response extending from the MgF2 cutoff at 1150Å to the Blue digicon cutoff at 6000Å. XCAL indicates a pivot wavelength of 3392Å, a gaussian-equivalent FWHM of 1869Å, and a count rate of 822 counts/s for a 1 mJy source.

3 Comparison with HST Observations

What's required to check the accuracy of the above passband curve are FOS,BLUE,G160 count rates measured for several objects with known spectral energy distribution. Ideally, targets with both blue and red spectra in the wavelength region of interest (1000-6000Å) are needed to be certain that both the blue and red wings of the passband correctly defined. A single target will suffice to calibrate roughly the conversion factor between counts/s and flux units. Count rates for both a red and a blue target will test the mean wavelength of the passband. If a wide variety of target spectra are available, more details of the passband can be reconstructed, since the measurement of each unique spectrum constrains a different integral of the passband curve.

In practice, the G160L 1st-order spectrum can be combined with an FOS,PRISM observation to adequately define the spectral energy distribution of any target. We have used our GO data which include FOS,BLUE,G160L and FOS,BLUE,PRISM observations of the cataclysmic variable AE Aqr and the quiescent soft x-ray transient A0620-00. These are discussed below. It would of course be better to base this calibration on observations of spectrophotometric standard stars, but such observations as have so far been taken are exposed appropriately for the 1st-order spectrum and so tend to saturate the counts in the 0th order light.

3.1 A0620-00 data

A0620-00 is a binary system consisting of a K5V companion star and a quiescent accreti disk around a 5 solar mass primary that is probably a black hole. A reddening of E(B-V)=0.35 was measured during the 1975 outburst when the source was bright. The source is not eclipsing, and is not highly variable in its present quiescent state. It does exhibit ellipsoidal variations on a 7.75-hour binary period at the 10-15 percent level in the optical due to the tidal distortion of the Roche-lobe filling companion star.

A0620-00 is a faint target for HST – in fact it was barely detected in the 1st-order G160L data, but clearly detected in our 0th-order G160L, and BLUE,PRISM data. We therefore had to be very careful about background subtraction procedures. The background signal is due partly to Cerenkov radiation by energetic particles and partly to wide-angle scattering of the object's light at the grating. The pipeline employs a simple model for the variation of the background count level which is found to be inaccurate often to a factor of 2. To improve this background model, we first scaled the background spectrum that is normally used in the CALFOS pipeline by a time-dependent factor to make it fit the observed background counts in pixels 1-300 and 901-1200. The 0th-order counts/s are then obtained by summing over pixels 600-660 the observed total counts/pixel/s minus the scaled background correction.

The light curve of the 0th-order G160L data from 6 consecutive HST orbits is shown in Figure 3. The target is seen to be variable at the 10-percent level. A mean count rate of 44 ± 2 is adopted for the following analysis.

To construct a spectral energy distribution for A0620-00, we averaged the 186 individual 1-minute exposures to obtain a mean 1st-order G160L spectrum. We similarly averaged 20 1-minute BLUE,PRISM spectra taken at 4 epochs interspersed with the G160L data. The two spectra match within their uncertainties in the overlap region, and were patched together around 2300A, Figure 4a shows the resulting spectrum, along with the predicted and observed fluxes for the G160L,ORDER0 passband. Here, the observed flux (0.054 mJy) is the observed count rate (44 counts/s) divided by the sensitivity (820 counts/s/mJy). The predicted count rate is 45 percent lower than the observed count rate. The predicted distribution of detected photons is shown in Figure 4b. This large discrepancy is discussed further below.

3.2 AE Aqr

AE Aqr is a highly-variable cataclysmic variable star consisting of a K4V companion star losing mass to a magnetized white dwarf that spins with a 33s period. The variability of this target allows us to isolate several different spectral components to work with.

The light curve of AE Aqr over 8 HST orbits is shown in Figure 5a for the order 0th-order G160L data and in Figure 5b for the 2000-2300A band of overlap between the G160L and PRISM spectra. AE Aqr exhibits both quiet periods and intervals of very large flares of unknown origin. The BLUE,PRISM observations are those taken during the last HST orbit, during which AE Aqr was apparently in a moderate flaring state. We have carefully selected a pair of G160L and PRISM spectra in order to match fluxes in the overlap region. The corresponding 0th-order G160L count rate is then taken from the light curve in Figure 5a.

Figure 6a shows the spectrum of AE Aqr formed by patching the G160L 1st-order and PRISM spectra, along with the observed and predicted count rates for the 0th-order passband. The predicted distribution of detected counts is illustrated in Figure 6b. The agreement between observed and predicted counts is much better for AE Aqr than for A0620-00, even though both have rather similar red spectra.

3.3 AE Aqr oscillations

AE Aqr also has a strong coherent oscillation with two maxima per 33s period. The oscillation results from two hot spots located on the rotating white dwarf. The very blue spectrum of these oscillations permits us to check the blue side of the G160L,ORDER0 passband. Fortunately, we find that the pulse profile and amplitude of the oscillations are independent at the 10-percent level of the very large flares which are seen in Figure 5. To construct the spectrum of the oscillations, we fold the data on the known oscillation ephemeris to construct a mean pulse profile at each wavelength, then fit a simple model (sinusoidal curves) to the pulse profile (the light curve obtained by folding data on the 33s pulse phase), and finally compute the root-mean-square amplitude of the fitted model in flux units at each wavelength. A similar computation yields an rms amplitude of 103 ± 1 counts/s for the oscillation in the 0th-order light curve.

Figure 7a shows our spectrum of the oscillations together with the observed and predicted fluxes for the 0th-order G160L passband. The oscillations have a very blue spectrum, which is well determined in the G160L region but rather noisy in the PRISM region longward of 2300Å. The predicted amplitude is about 20-percent lower than observed. This is satisfactory agreement given the uncertainties in determining the red part of the oscillation spectrum and the uncertainty due to non-simultaneous measurement of the PRISM and G160L observations. The predicted distribution of detected photons for this blue spectrum is illustrated in Figure 7b.

4 Discussion

The observed and predicted count rates for the trial G160L,ORDER0 passband are collected in Table 2.

Table 2. Observed and Predicted Count Rates in G160L 0th-Order

observed (counts/s)		predicted (counts/s)	target
44	± 2	25.4	A0620-00
1.6	$\pm 0.1 \times 10^4$	1.51×10^4	AE Aqr
103	± 1	82	AE Aqr oscillation

From the reasonable agreement between observed and predicted count rates for the red spectrum of AE Aqr and the blue spectrum of its oscillations, we infer that the total area and mean wavelength of the trial passband are roughly correct. On this basis we recommend using 820 counts/s/mJy to convert observed count rates to absolute fluxes.

For A0620-00, however, the predicted count rate is 40-percent lower than that observed. This could indicate that the red tail of the passband is substantially too low. But this is puzzling because A0620-00 and AE Aqr have quite similar spectral energy distributions. Data on additional targets needs to be analyzed to clarify the nature of this discrepancy.

In the meantime, the new passband has been installed in the STScI passband database in CDBS where users of the synthetic photometry software (XCAL,SYNPHOT) can retrieve it by setting the OBSMODE parameter to "FOS,BLUE,G160L,ORDER0,4.3" for observations in the 4.3 arcsecond square aperture. For other apertures, simply change the 4.3, for example, to "FOS,BLUE,G160L,ORDER0,1.0" for observations in the 1.0 arcsecond aperture.

Figure Captions

Fig. 1. The adopted reflection curve for 0th order reflection from the G160L grating. This is based on lab measurements shortward of 2500Å, and a rough measurement around 6000Å

Fig. 2. The total sensitivity curve for 0th order G160L observations in the 4.3 arcsecond square aperture, based on the grating reflectance curve of Fig. 1 and the throughputs of other components as calibrated from in-flight measurements of spectrophotometric standard stars.

Fig. 3. The observed light curve for the 0th order light on the black-hole binary A0620-00. From this we adopt a mean count rate of 44±2 counts/s.

Fig. 4. a) The solid line shows the uv/optical spectrum of A0620-00 based on FOS/Blue 1st-order G160L and FOS/Red Prism measurements. The dotted curve shows the sensitivity curve of the 0th order G160L passband. The two open circles with horizontal error bar give the observed flux (based on the observed count rate) and the predicted flux (based on the observed spectrum). b) The wavelength distribution of detected photons from A0620-00 for observations in 0th order G160L light.

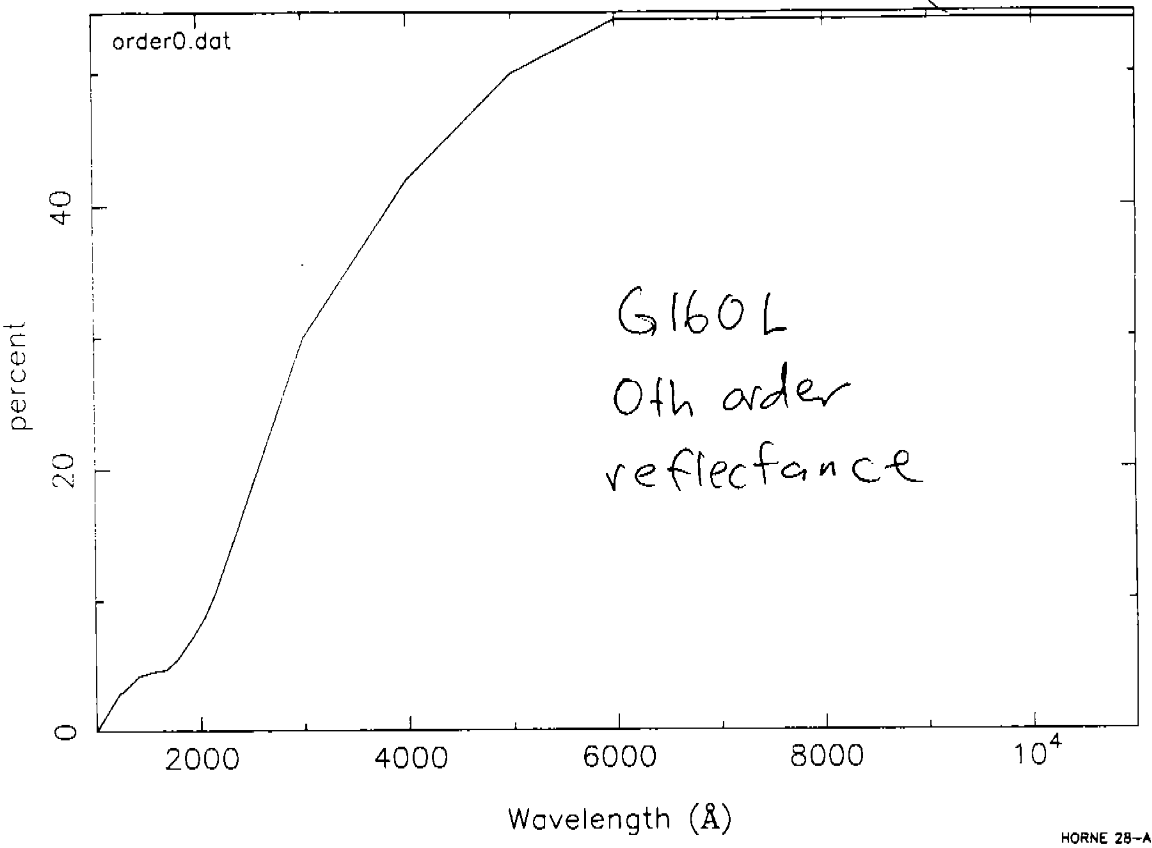
Fig. 5. a) The observed light curve of the cataclysmic variable star AE Aqr as observed with FOS/Blue detector in the 0th order G160L light. b) The light curve of AE Aqr in the 2000-2300Å region obtained from the 1st order G160L spectrum and (at the end) from BLUE PRISM measurements. The X axis is the binary cycle number E.

Fig. 6. Same as Fig. 4 but for the mean spectrum of AE Aqr.

Fig. 7. Same as Fig. 4 but for the 33s oscillations of AE Aqr.

XCAL

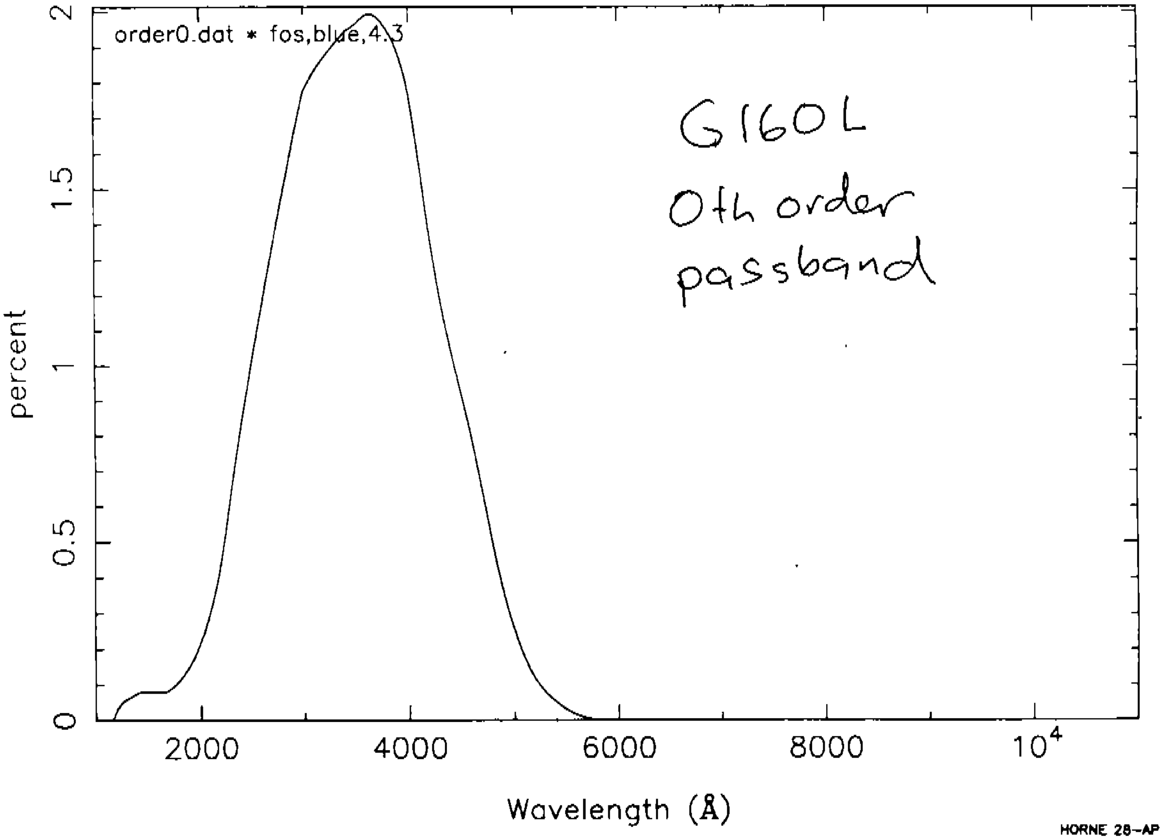
(Fig 1)



HORNE 28-APR-1993 0

XCAL

(Fig 2)



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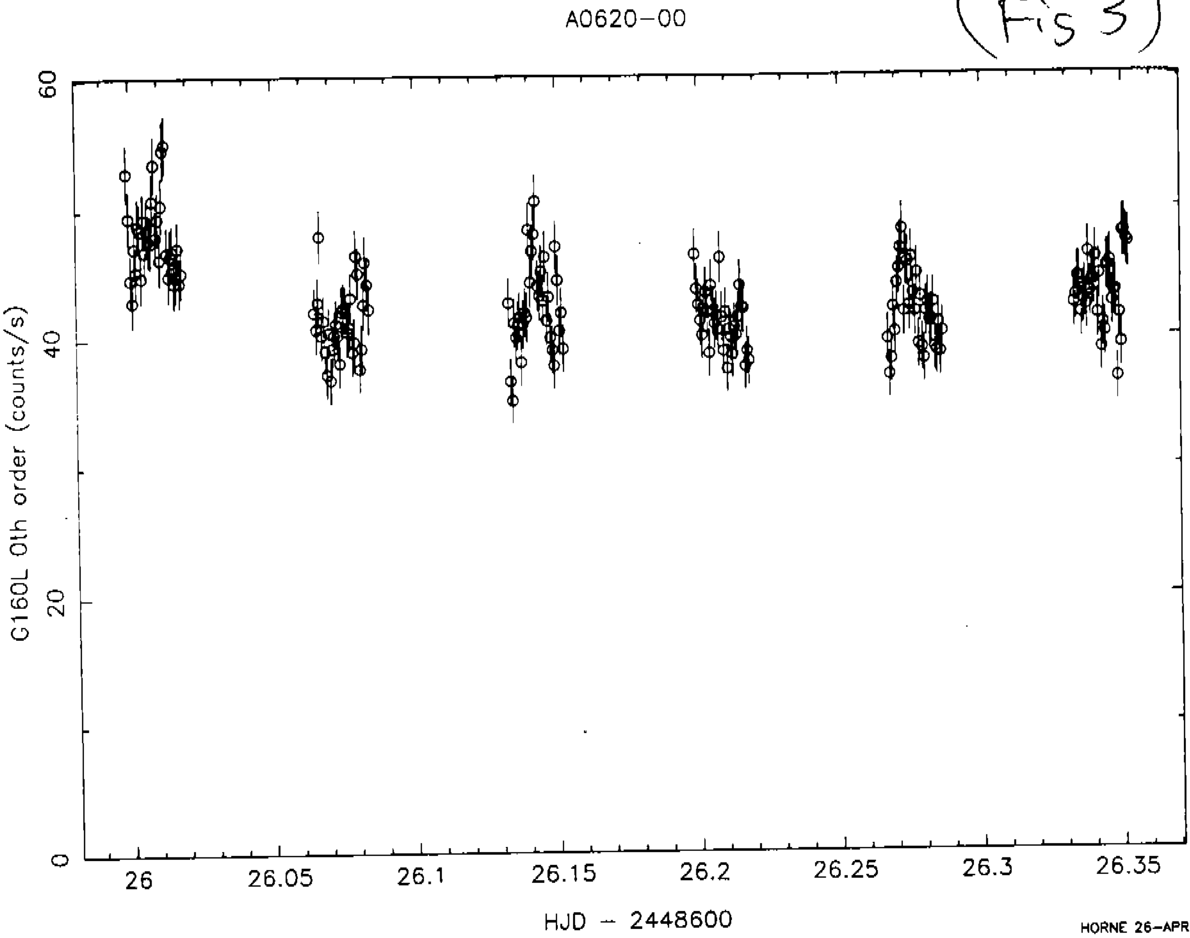
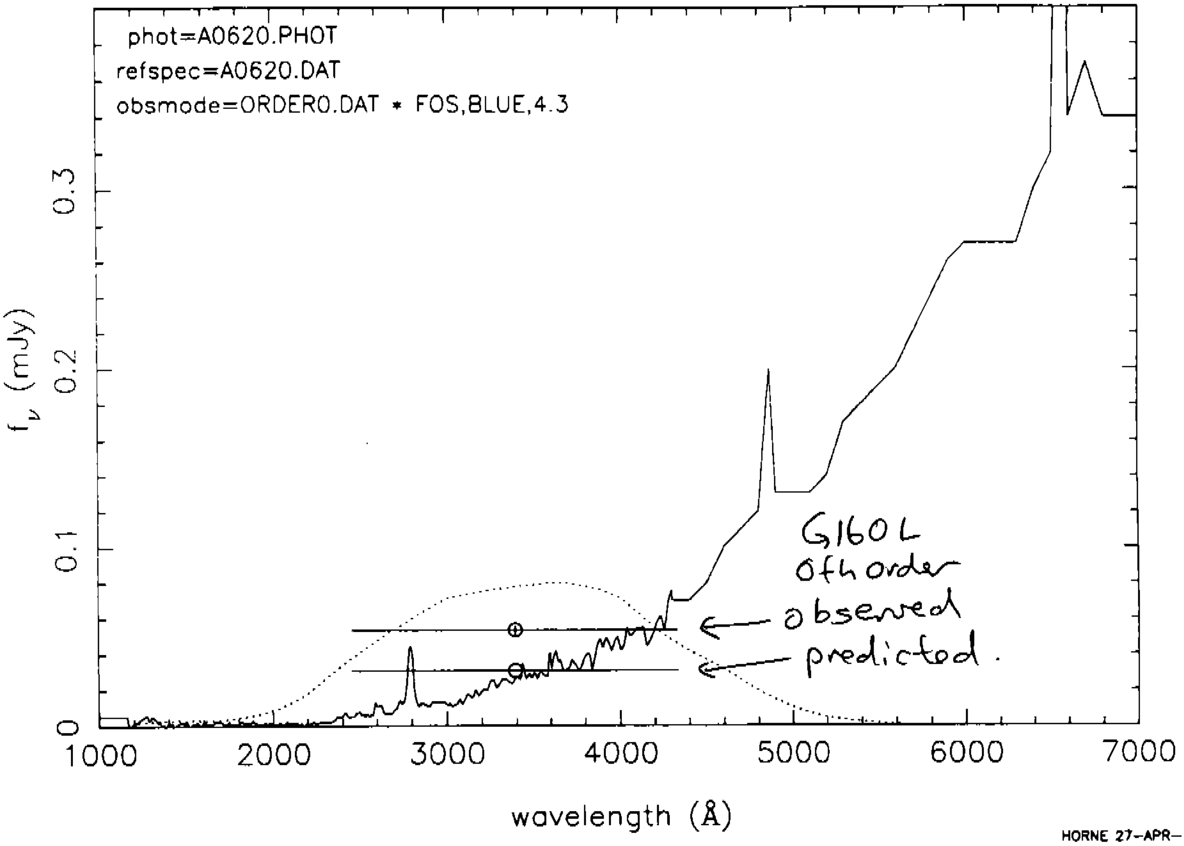
(Fig 3)



HORNE 26-APR-1993 14

XCAL

(FIG 4a)



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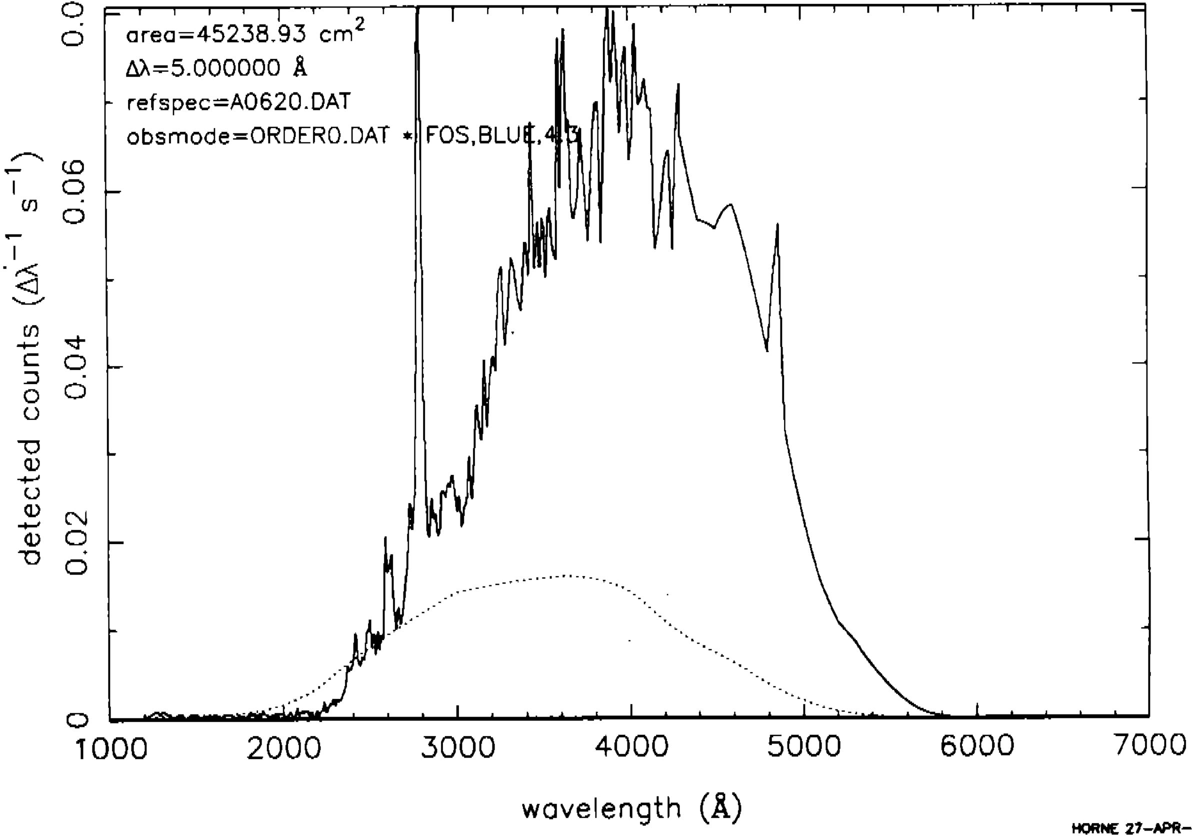
XCAL

(Fig 4b)



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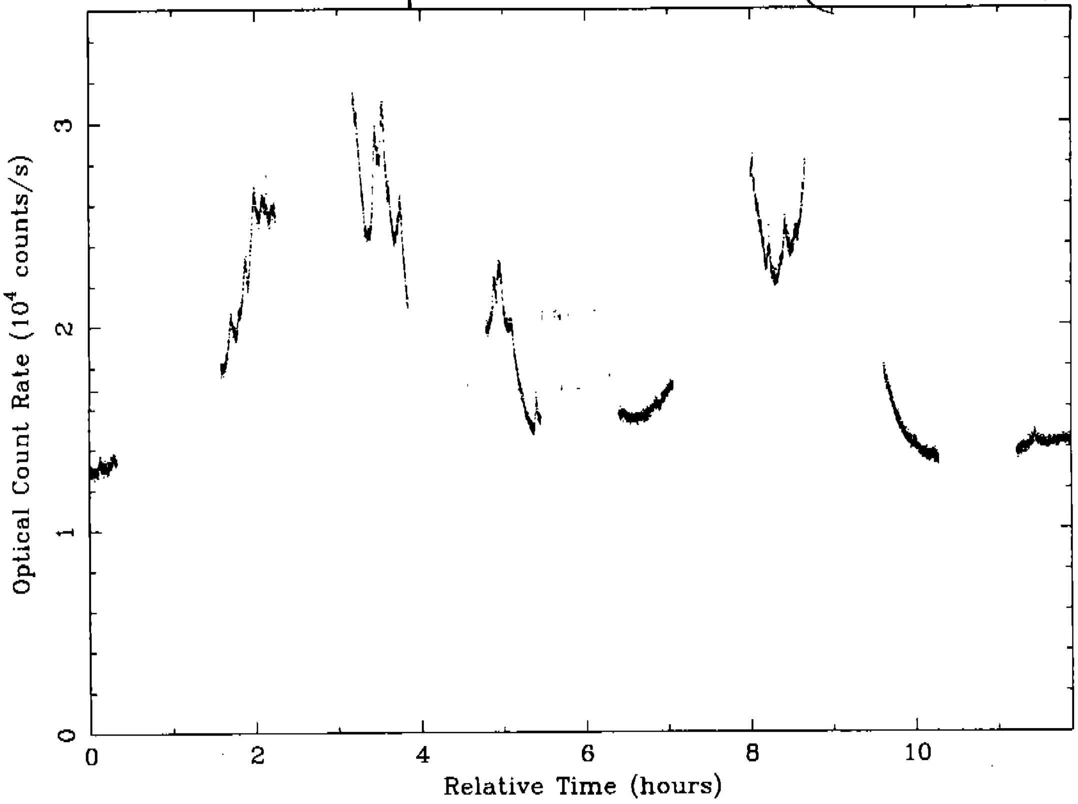
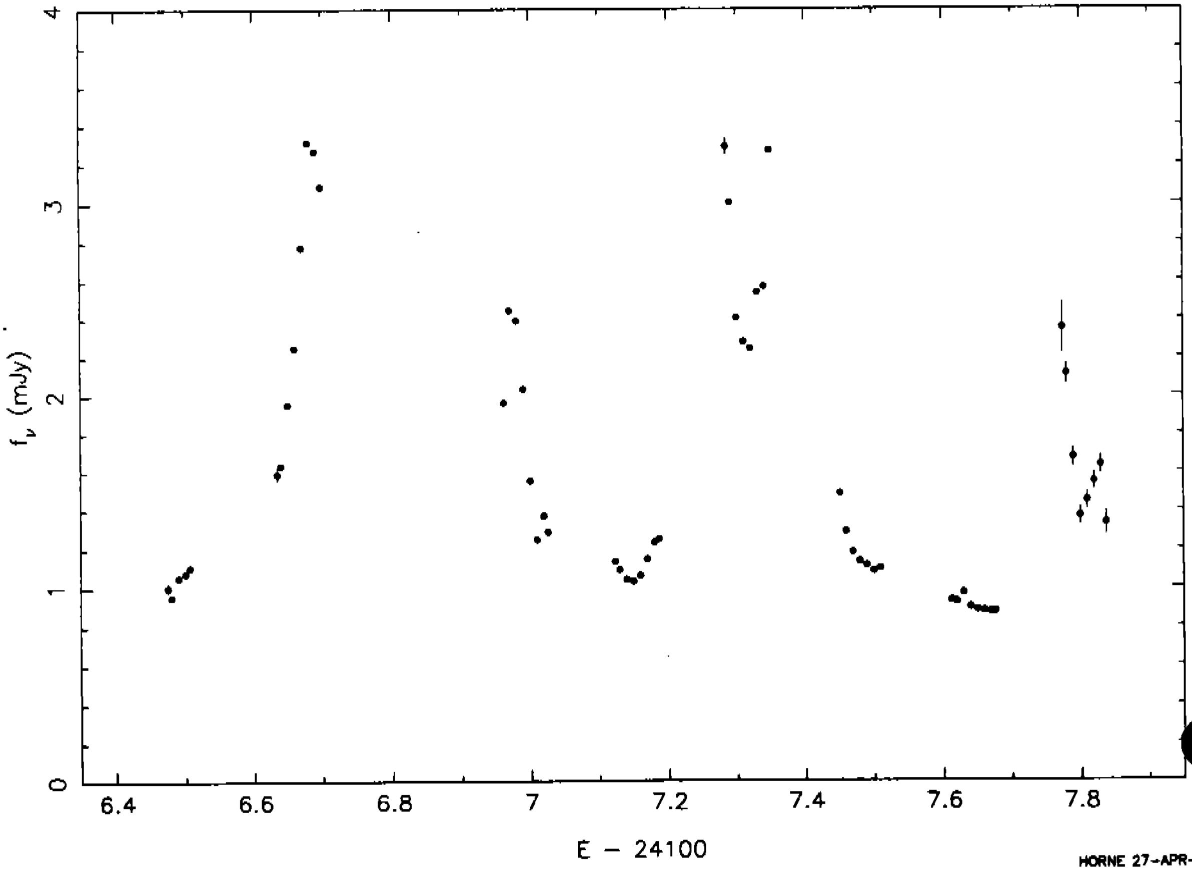
AE Aqr G160L order 0 (FIG 5a)



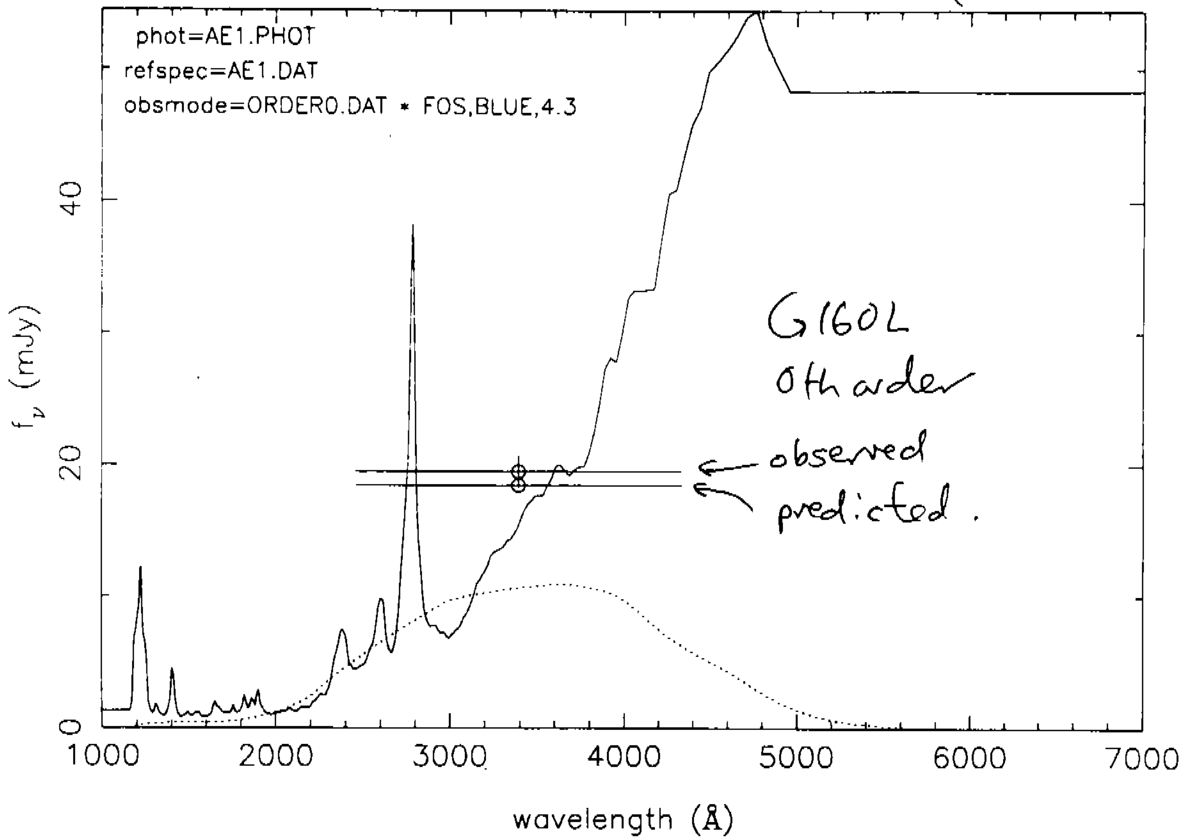
AE Aqr 2000–2300Å

(Fig 5b)



HORNE 27-APR-1993 2

(Fig 6a)



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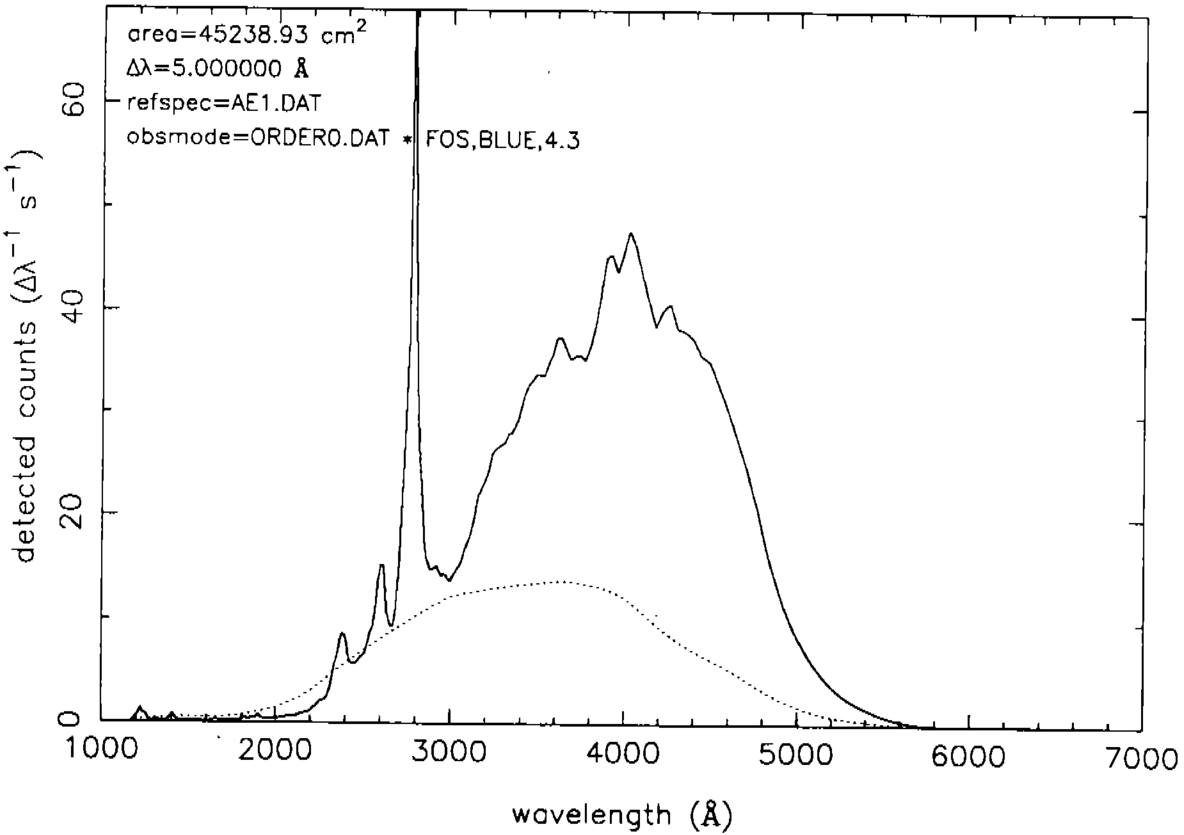
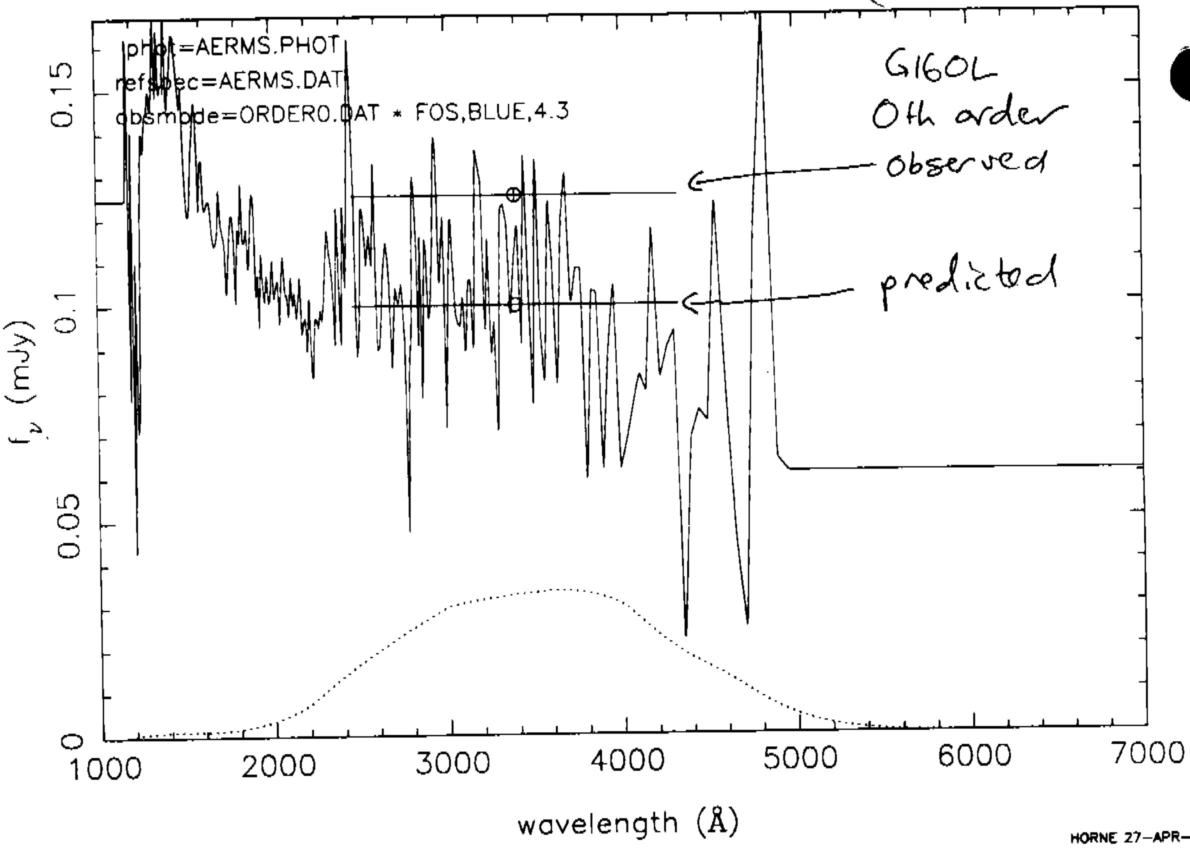
(Fig 6b)



HORNE 27-APR-1993 21

(Fig. 7a)



G160L
0th order
observed
predicted

(Fis 7b)