Instrument Science Report WFC3 2005-028

The Frequency of WFC3/IR Saturations

T.M. Brown
November 15, 2005

ABSTRACT

The WFC3/IR channel will combine sensitivity with a wide field of view, such that all long exposures will contain some saturated stars, even in sparse fields near the Galactic poles. Because such saturations in IR detectors can result in persistence (particularly when a pixel is over-saturated by factors of 10 to 100), I quantify here the frequency of 1x, 10x, and 100x saturations, as a function of position on the sky. I use the 2MASS and GSC2 catalogs for this analysis, although each has its limitations for this purpose. Away from the Galactic plane, the greater depth of the GSC2 is required to quantify the frequency of moderate saturations (1-10x). If, however, one is only interested in extreme saturations (>100x), the 2MASS catalog is more appropriate, because it is sufficiently deep for such sources and it avoids the large systematic errors (by factors of 200) that can arise due to an incorrect assumption of spectral type and extinction when extrapolating from the GSC2 optical bands into the IR. Both catalogs suffer from serious incompleteness in the Galactic plane, especially toward the Galactic center, but for such fields the 2MASS catalog would still be preferred over the GSC2 when checking for saturating objects.

Introduction

The WFC/IR channel will be at least as sensitive as NICMOS but have a field of view seven times larger than NICMOS camera 3. The combination of this sensitivity and field size means that WFC3/IR images will often contain saturated stars, which can impact subsequent observations if the WFC3/IR detector exhibits significant persistence.

An infrared observer might expect that the Two Micron All Sky Survey (2MASS) would be the appropriate catalog for examining the frequency of WFC3/IR saturations, but in fact the 2MASS catalog is not deep enough for this purpose. Although the depth of the survey varies across the sky, the faint limit is typically near 15th mag in *J*, *H*, and *K* (the formal level 1 requirement of the catalog is *J*=15.8, *H*=15.1, and *K*=14.3 mag). Stars near this faint limit saturate the WFC3/IR channel in a short time. The Guide Star Catalog (GSC), currently at version 2.3, generally goes much fainter (down to 22 mag in *V*) but the extrapolation from the optical into the infrared is going to depend upon the accuracy of the spectral type implied by the optical colors and the assumed extinction (which will be a large source of systematic errors along sightlines of high extinction). Thus, neither catalog is particularly well-suited to predicting the number of saturating stars in WFC3/IR images.

Analysis

To demonstrate the limitations of the 2MASS catalog for checking the WFC3/IR saturation frequency, I obtained the 2MASS passbands (Cohen et al. 2003, AJ, 126, 1090) and “supertemplate” spectra (Cohen et al. 2003, AJ, 125, 2645). I used these data to calculate the relationship between 2MASS photometry and WFC3/IR count rates, under the assumption of both hot and cool stars. For the hot star, I used the Kurucz (1993, CDROM 13, ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid) spectrum with parameters T_{eff}=50,000 K, log *g* = 5.0, and [Fe/H]=-2, while for the cool star I used the Kurucz spectrum with parameters T_{eff}=3,500 K, log *g* = 3.0, and [Fe/H]=0. I then normalized these spectra to 15th mag in 2MASS *J*, *H*, and *K*, and calculated the count rates in the central pixel of such a source observed with each of the WFC3/IR filters, using the wfc3tp IDL tool (Brown 2003, ISR WFC3 2003-13); this tool assumes the “nominal” WFC3 performance, while in reality the WFC3/IR throughput appears to be about 15% lower than expectations (Brown et al. 2005, ISR WFC3 2005-12). I assumed the encircled energy of the central pixel was 30% for filters shortward of 1.2 microns, and 20% for filters longward of 1.2 microns (G. Hartig, private communication). The results are shown in Tables 1 through 3. The ratio in the last column gives an indication of the systematic errors that can arise from the assumption of an incorrect spectral type when transforming from 2MASS photometry to WFC3/IR count rates. Of course, extrapolating from the optical can be much more hazardous, so for completeness, I show in Table 4 the analogous information for sources normalized to 15th mag in Johnson *V*; here, the assumption of an incorrect spectral type when transforming from optical photometry to WFC3/IR count rates can produce results in error by factors of 200 or more.

With these limitations in mind, I next characterized the expected frequency of saturations in WFC3/IR images as a function of Galactic longitude (*l*) and latitude (*b*) by extracting fields from the 2MASS and GSC2.3 catalogs. I extracted circular fields of 1 square degree (33.85 arcmin radius) at l = 0 degrees (Galactic center) and l = 180 degrees (Galactic anti-center) for $-90 < b < 90$ degrees in steps of 10 degrees. For each field, I determined the line-of-sight extinction through the Galaxy by interpolating the Schlegel et al. (1998, ApJ, 500, 525) extinction map, and assumed that this extinction applied to all of the objects in the field; in reality, this extinction is generally an upper limit for the extinction toward any given star in the field. Because the Schlegel et al. (1998) map increases to extremely high values in the Galactic center, where the stars would generally lie in the foreground of the attenuating dust, I clipped the map at $E(B\text{-}V) < 2.0$ mag. I then interpolated a series of spectra from the Kurucz grid, ranging from $3{,}500 < T_{eff} < 48{,}500$ K in steps of 5,000 K, with log $g = 5.0$ and [Fe/H]=0.0, and then reddened these spectra with the Fitzpatrick (1999, PASP, 111, 63) extinction curve, using the $E(B\text{-}V)$ from the Schlegel et al. (1998) map and R_V=3.1. To translate the 2MASS catalog into WFC3/IR count rates, I normalized each of the synthetic spectra to J=20 mag, and calculated the J-K color and WFC3/IR count rates as a function of T_{eff}. I then converted the measured J-K values in the 2MASS catalog to WFC3/IR count rates by interpolating on the grid of results from the synthetic spectra and normalizing to the measured J magnitudes.

To translate the GSC2.3 catalog into WFC3/IR count rates, I used a similar process, but instead I normalized to Johnson V and interpolated using Johnson B-V. The GSC2.3 catalog provides many photometric measurements, but the ones most often populated are F_{pg} and J_{pg} (not to be confused with the infrared J magnitude), corresponding, respectively, to red and blue photographic plates. Johnson B and V values are also provided on a limited basis from supplementary catalogs. The F_{pg} and J_{pg} values can be converted to Johnson B and V with the following formulae:

$$V = F_{pg} + 0.03 + 0.44\,(J_{pg} - F_{pg}) - 0.03\,(J_{pg} - F_{pg})^2 + 0.02\,(J_{pg} - F_{pg})^3$$

$$B\text{-}V = -0.04 + 0.69\,(J_{pg} - F_{pg}) \quad \text{for Declination (J2000)} < 0$$

$$B\text{-}V = -0.03 + -.73\,(J_{pg} - F_{pg}) \quad \text{for Declination (J2000)} > 0.$$

For stars without valid measurements of both F_{pg} and J_{pg}, the supplementary Johnson B and V values were used, where available. If only a Johnson B value was available, the star was assumed to be blue, while if only a Johnson V value was available, the star was assumed to be red. If neither supplementary B nor V was available, and only one of the F_{pg} or J_{pg} values was available, a star was assumed to be red if only the Fpg was available, and a star was assumed to be blue if only the J_{pg} was available.

I translated the 2MASS and GSC2.3 catalogs into WFC3/IR count rates for the four filters that should receive the most use: F105W (fat Sloan *z*), F110W (wide *J*), F125W (broad *J*), and F160W (broad *H*). Although the wfc3tp code calculates the WFC3/IR throughput under the nominal assumptions for component throughputs, I also repeated the process with two changes in these assumptions that are likely to reflect the actual flight values of the WFC3/IR channel. First, I increased the detector quantum efficiency to reflect the enhancements from thinned detectors (the current WFC3/IR detector will likely be replaced with a thinned detector before flight); second, I reduced the total throughput by 15%, to reflect the loss of throughput seen in thermal vacuum tests (due to a problem with some unknown component). Taken together, these changes create a net increase in WFC3/IR throughput at most wavelengths, especially at the short-wavelength end of the channel.

Finally, to calculate the frequency of saturations, I assumed encircled energies of 30% for the two shorter-wavelength filters (F105W and F110W) and 20% for the two longer-wavelength filters (F125W and F160W), a full well of 75,000 e^-, and a typical science exposure of 1000 sec. The number of saturations in each full square degree was then normalized to the WFC3/IR field size (0.0014 square degrees). The results of these calculations are shown in Figures 1 - 4. In the top panels of each figure, I show the frequency of saturations expected from translating the GSC2.3 catalog, while in the bottom panels of each figure, I show the frequency of saturations expected from translating the 2MASS catalog. The solid curves are the saturations expected with the nominal assumptions for WFC/IR channel (i.e., the throughput assumed prior to thermal-vacuum tests), while the dotted curves are the saturations expected with the likely flight configuration (i.e., an increased quantum efficiency from thinned detectors but a loss of 15% throughput in some other component). Curves are shown for the number of objects saturating (*blue*), saturating by a factor of 10 (*green*), and saturating by a factor of 100 (*red*).

When observing away from the Galactic plane, the GSC2.3 catalog predicts many more saturating sources than the 2MASS catalog, because of its greater depth; the prediction at these latitudes should be accurate, given the faint limit of the GSC2.3. The proximity of the 1x saturation curves (*blue*) and 10x saturation curves (*green*) in the 2MASS plots is a clear indication that the 2MASS catalog is seriously incomplete at the magnitudes that result in moderate saturations. In the Galactic plane, the 2MASS catalog surpasses the GSC2.3 catalog, but we know that the 2MASS catalog is not deep enough to accurately predict the number of saturations anywhere on the sky (e.g., it seems to underpredict by a factor of ~10 when outside the plane); thus, both catalogs are seriously underpredicting the number of saturations in the Galactic plane, and the curves should be considered a lower limit at these latitudes. The true number of saturations for fields in the Galactic plane could easily be an order of magnitude higher than the predictions plotted.

If one is only interested in extreme saturations (> 100x), the 2MASS catalog is likely the more appropriate catalog to check, because it is reasonably complete at the required magnitudes at high Galactic latitudes and surpasses the completeness of the GSC2.3 in the Galactic plane. However, it is still worth noting that the 100x saturation curves (*red, bottom panels*) in the 2MASS plots, even at high Galactic latitudes, predict 2-3 times less events than the 100x saturation curves (*red, top panels*) in the GSC2.3 plots.

Conclusions

The GSC2.3 should be adequate for predicting the number of WFC3/IR saturations along sight-lines away from the Galactic plane, and thus observers should expect at least 10 saturating stars in any long exposure, even at high Galactic latitudes. In the Galactic plane, neither the 2MASS nor the GSC2.3 catalogs are sufficient for predicting the number of saturations, and thus observers should expect well over 100 saturations in long exposures. Of course, the calculations done here were for arbitrary empty fields, which are really most relevant for parallel observations; for pointed observations, observers generally look in very biased regions on the sky, which will result in many more saturated pixels than the average for that latitude (e.g., star clusters, nearby galaxies, nebulae) or fewer saturated pixels for that latitude (e.g., extremely underdense regions chosen for deep fields). If the WFC3/IR detectors show significant persistence, the saturations will result in pixels with enhanced but decaying dark rates in the hours after the saturating exposures. The effects of this persistence should be mitigated through appropriate dithering strategies. Dithering images with saturating sources will also increase the number of pixels exhibiting enhanced dark rates in subsequent exposures, but in general the number of saturated pixels should not be a significant fraction of the total pixels available.

Although the GSC2.3 is deeper than the 2MASS catalog at most latitudes, the 2MASS catalog is likely the catalog of choice for investigating the possibility of extreme saturations (> 100x) in a given field; it is reasonably complete at these magnitudes, and translating its infrared photometry into WFC/IR count rates is less uncertain than extrapolating from the optical bands of the GSC2.3. It would be prudent for observers to check the 2MASS catalog when planning their observations.

Table 1. Rates in central pixel for sources normalized to 2MASS *J*=15 mag

Filter	Cool star count rate (e^-/s)	Hot star count rate (e^-/s)	hot rate / cool rate
F093W	818	2307	2.8
F098W	657	1515	2.3
F105W	1450	2542	1.8
F110W	3075	3985	1.3
F125W	1487	1442	1.0
F126N	71	67	0.9
F127M	360	326	0.9
F128N	80	70	0.9
F130N	83	70	0.8
F132N	83	67	0.8
F139M	397	267	0.7
F153M	640	277	0.4
F160W	2577	1083	0.4
F164N	217	68	0.3
F167N	202	62	0.3

Table 2. Rates in central pixel for sources normalized to 2MASS *H*=15 mag

Filter	Cool star count rate (e^-/s)	Hot star count rate (e^-/s)	cool rate / hot rate
F093W	313	2620	8.4
F098W	251	1720	6.8
F105W	554	2886	5.2
F110W	1175	4525	3.9
F125W	568	1637	2.9
F126N	27	76	2.8
F127M	138	370	2.7
F128N	31	80	2.6
F130N	32	80	2.5
F132N	32	77	2.4
F139M	152	303	2.0
F153M	245	314	1.3
F160W	985	1230	1.2
F164N	83	77	0.9
F167N	77	71	0.9

Table 3. Rates in central pixel for sources normalized to 2MASS *K*=15 mag

Filter	**Cool star count rate (e^-/s)**	**Hot star count rate (e^-/s)**	**cool rate / hot rate**
F093W	266	2804	11
F098W	214	1841	8.6
F105W	472	3089	6.5
F110W	1000	4842	4.8
F125W	484	1752	3.6
F126N	23	81	3.5
F127M	117	396	3.4
F128N	26	85.1	3.3
F130N	27	85	3.2
F132N	27	82	3.0
F139M	129	324	2.5
F153M	208	336	1.6
F160W	839	1317	1.6
F164N	71	82.4	1.2
F167N	66	75.5	1.2

Table 4. Rates in central pixel for sources normalized to Johnson *V*=15 mag

Filter	Cool star count rate (e^-/s)	Hot star count rate (e^-/s)	cool rate / hot rate
F093W	25372	1144	0.045
F098W	20382	751	0.037
F105W	44968	1261	0.028
F110W	95348	1976	0.021
F125W	46104	715	0.016
F126N	2190	33	0.015
F127M	11177	162	0.014
F128N	2475	35	0.014
F130N	2577	35	0.014
F132N	2583	33	0.013
F139M	12296	132	0.011
F153M	19860	137	0.0069
F160W	79919	537	0.0067
F164N	6735	34	0.0050
F167N	6250	31	0.0049

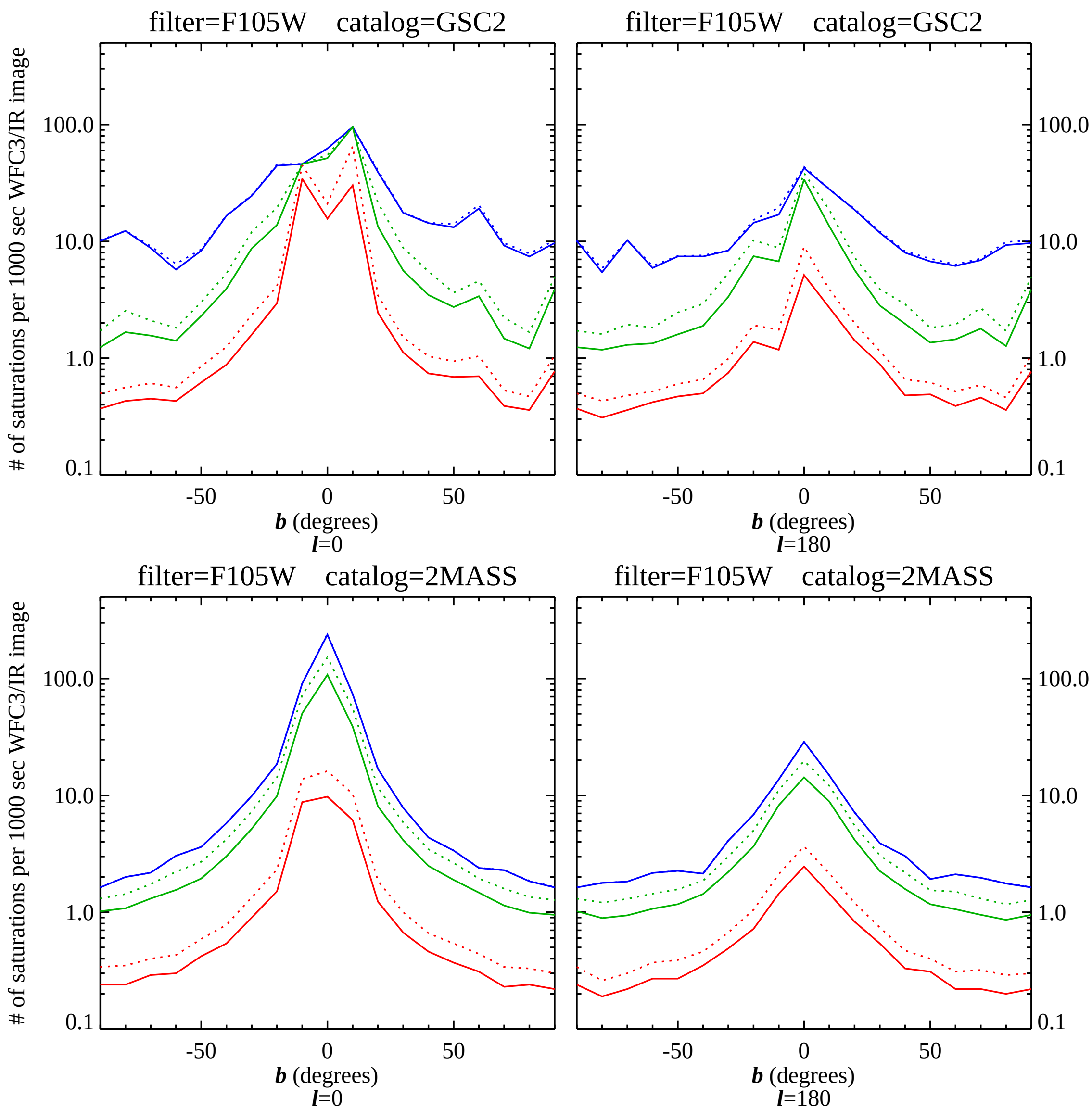

Figure 1: The expected frequency of saturations on the WFC3/IR detector in 1000 sec exposures through the F105W filter, as a function of Galactic latitude, at Galactic longitude 0 degrees (left panels) and 180 degrees (right panels), calculated using the GSC2.3 (top panels) and 2MASS (bottom panels). Curves for the nominal WFC3/IR performance (pre-thermal vacuum testing) are shown by solid lines, while curves for the likely flight performance are shown by dotted lines. For each assumed detector, three curves are shown, representing the expected number of 1x saturations (*blue curves*), 10x saturations (*green curves*), and 100x saturations (*red curves*).

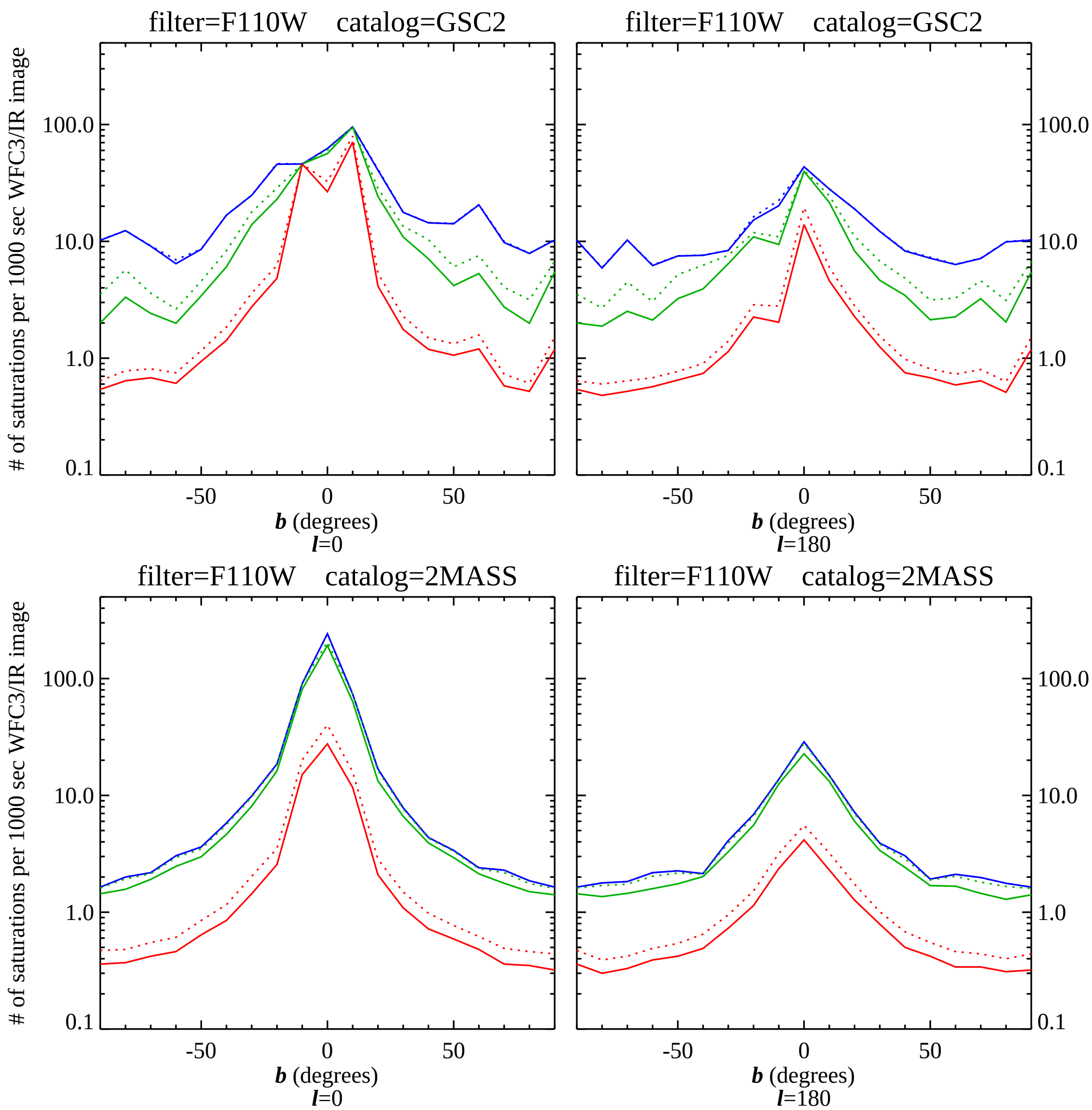

Figure 2: The same as Figure 1, but for the F110W filter.

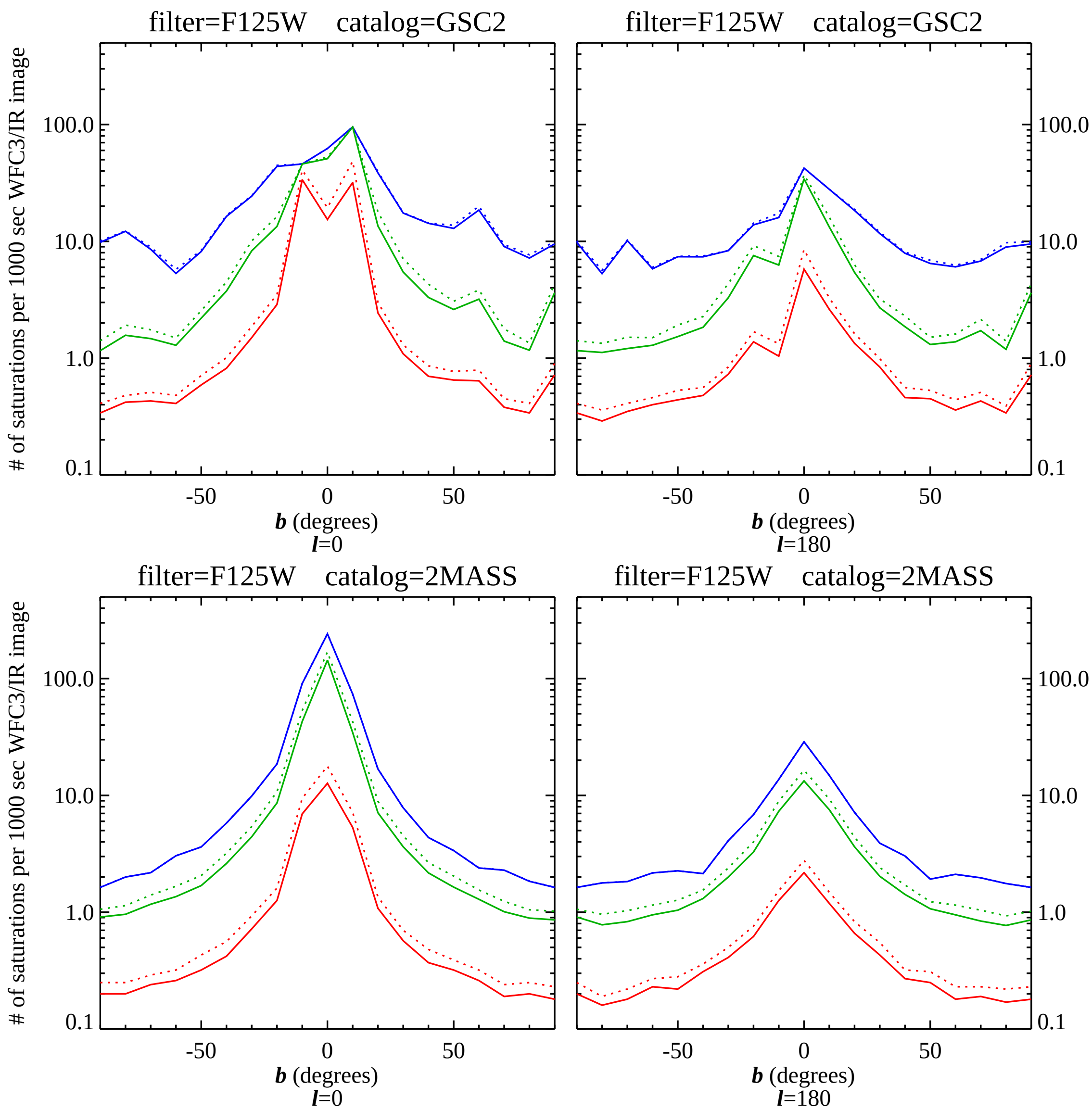

Figure 3: The same as Figure 1, but for the F125W filter.

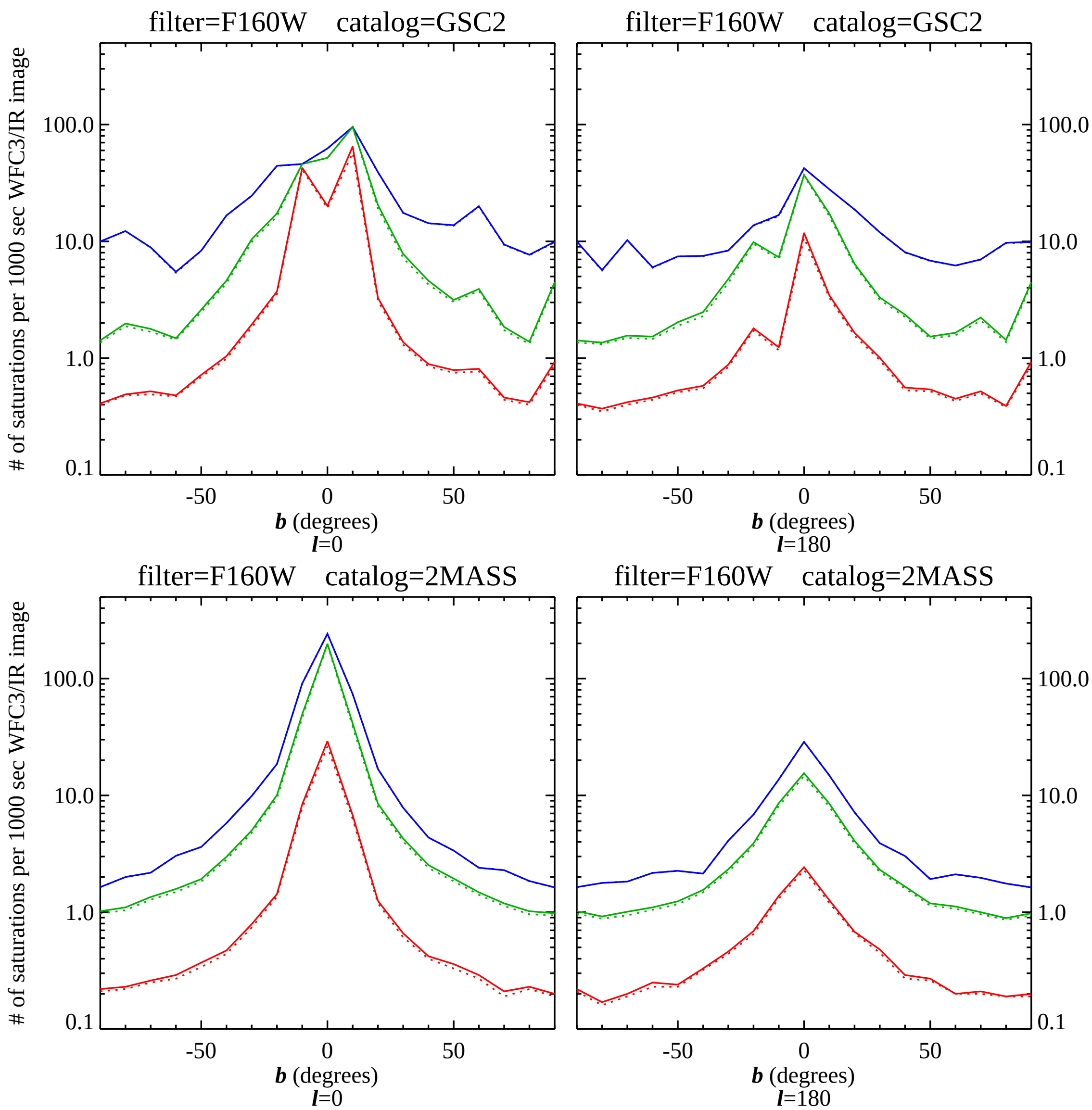

Figure 4: The same as Figure 1, but for the F160W filter.