New On-Orbit Sensitivity Calibration for All STIS Echelle Modes

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ABSTRACT

On-orbit sensitivities for the 32 medium- and high-resolution STIS echelle secondary modes were determined for the first time using observations of the fundamental DA white dwarf standard star G191-B2B. Revised on-orbit sensitivities for the 12 medium- and high-resolution echelle prime modes based on observations of the same standard star are also presented. We review the procedures and assumptions used to derive the adopted throughputs and implement them into the pipeline.

Introduction

The Space Telescope Imaging Spectrograph (STIS) has four echelle grating modes, namely E140H, E140M, E230H and E230M, which provide spectroscopic coverage from 1150 Å to 3100 Å at resolving powers from R $\sim 30,000$ to R $\sim 110,000$. Through simultaneous observations of multiple orders, these modes are designed to maximize the spectral coverage achieved in a single exposure of a point source.

The sensitivity calibration of the echelle modes has been particularly challenging over the years for several reasons. An initial on-board absolute flux calibration of the 12 prime echelle medium- and high-resolution modes is presented in Bohlin (1998). Since then, several critical issues related to the echelle flux calibration have been tackled broadly and in depth. This has been possible thanks to a better characterization of the performance of the STIS instrument as a whole that has been accomplished in the meantime. Among these issues, particularly worth mentioning are a new 2-D algorithm for removing scattered light from STIS echelle data (Valenti et al. 2002), a characterization of the changes in sensitivity with time (Stys et al. 2004; Aloisi, 2006; Aloisi 2007a), and a characterization of the behavior of the echelle blaze function (shift and shape) with time and location of the spectra on the detector (Aloisi 2007b).

The secondary echelle modes have been used almost as often as the prime modes during STIS operations (started in February 1997 and suspended in August 2004 due to the failure of Side 2). However, the absolute flux calibration of these modes is still based on an extrapolation of the on-orbit sensitivities of the prime modes. Moreover, while a time-dependent sensitivity (TDS) correction based on first-order modes was implemented into the pipeline in April 2005 for both prime and secondary echelle modes (Aloisi 2007a), no attempt has ever been made to correct the secondary modes for effects related to the blaze function, in particular the well known effect of a blaze-shift due to the monthly offsets of the Mode Select Mechanism (MSM) and the passage of time on orbit (Aloisi 2007b). This is due to the fact that on-orbit sensitivity calibration data are required in order to properly apply such a correction to the secondary modes.

The on-orbit sensitivity calibration of the echelle prime modes is primarily based on observations of the hot subdwarfs BD+75°325 and BD+28°4211 (see, e.g., Table 1 in Bohlin 1998). These stars are not among the primary DA white dwarf (WD) standards used for HST, but are instead secondary standards which are tied to the primary ones (e.g., G191-B2B) through low-dispersion STIS spectroscopic observations. In addition, at wavelengths below 1900 Å, the heavy line blanketing in BD+75°325 causes errors of 10-20% in the relative flux within one order (Bohlin, 1998). This particularly affects the sensitivity determination of the two short wavelength modes E140H 1234 Å and E140H 1598 Å, since only one observation of BD+75°325 is used for this purpose. Also, the on-orbit sensitivity calibration of the most used prime modes was derived by averaging observationally heterogeneous datasets, i.e., observations of different standard stars acquired at different epochs between September 1997 and May 1999. These data have been selected to have zero MSM offsets in the most recent versions of the sensitivity calibration of the prime modes, but the shift of the blaze function from one epoch of observation to the other has never been properly taken into account.

In this ISR we report the first on-orbit sensitivity calibration (and correction for the blaze-shift) of the 32 secondary echelle medium- and high-dispersion modes. A revision of the on-orbit sensitivity calibration of the 12 prime modes is also presented in light of the availability of new better suited observations and in light of an improved understanding of the above mentioned issues related to the absolute flux calibration of the echelle data.

Method

The new on-orbit absolute flux calibration of all STIS echelle modes is based only on observations of the primary spectrophotometric standard star G191-B2B (Bohlin, Colina, & Finley 1995). It is derived with an empirical method similar to the one used by Bohlin (1998) in an earlier calibration of the echelle prime modes. This method mainly consists in dividing the observed count rates by the known flux of the standard star. While Bohlin (1998) made use of FOS spectra of the standard stars as templates and had to contend with the lower resolution of such spectra, here we instead adopted

a theoretical model of G191-B2B at the proper resolution. The model of the nearly pure hydrogen atmosphere of this standard star is the same discussed in Bohlin (2003) and Bohlin & Gilliland (2004). In principle, the theoretical spectrum should be first convolved with the effects of the instrumental line-spread function, but for most STIS high- and medium-resolution echelle settings, the sensitivity and standard star flux vary sufficiently slowly with wavelength that this refinement can be neglected. The hydrogen Lyman α line at 1215.67 Å is in fact the only spectral feature in the G191-B2B model spectrum over the whole echelle wavelength region.

Observations

Prime Modes

Only observations of the primary spectrophotometric standard star G191-B2B were used for the revised on-orbit sensitivity calibration of all STIS echelle prime modes. These observations are listed in Table 1 and were obtained as part of several calibration programs (i.e., 7657, 8067, 8421, and 8915) during the period going from December 1998 to September 2001. All data were acquired with the $0.2'' \times 0.2''$ aperture following standard peak-up target acquisition.

Some of the observations used to calibrate the sensitivity of the prime modes were obtained with non-zero MSM offsets, as indicated in the last column of Table 1 which reports the x- and y-offsets in the dispersion and cross-dispersion direction, respectively. However, for every mode we only averaged together data taken at the same epoch within the same program, i.e., with the same MSM offset. This allowed us to avoid uncertainties in the average throughput curves due to variations of the spatial or temporal component of the blaze-shift among different observations. Since the data used to infer the on-orbit sensitivity of a certain mode also define the zero point of the pipeline blaze shift correction for that mode [1] , the non-zero MSM offset of some prime modes only results in a different zero point compared to previous versions of the sensitivity curves.

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[1]The shift of the echelle blaze function (BSHIFT) varies linearly with the position of the spectra on the detector and with the passage of time on orbit. This shift is currently corrected within the pipeline for both prime and secondary echelle modes. During the processing of an echelle dataset, the following parameters are first determined from the x1d file: wavelength (OBSW), cross-dispersion position (OBSY), and dispersion (DISP in Å/pix) of the reference spectral order REFORD at pixel x = 512. The shift in pixels is then computed using the formula:

$$\text{BSHIFT} = \text{BSHIFT\_VS\_X} * \Delta x + \text{BSHIFT\_VS\_Y} * \Delta y + \text{BSHIFT\_VS\_T} * \Delta t + \text{BSHIFT\_OFFSET} \text{ ,}$$

where $\Delta x = (\text{REFWAV} - \text{OBSW}) / \text{DISP}$, $\Delta y = \text{OBSY} - \text{REFY}$, $\Delta t = \text{OBSDATE} - \text{REFMJD}$, and OBSDATE is the Modified Julian Day (MJD) of the observation. REFWAV and REFY are, respectively, the wavelength and cross-dispersion position of the reference spectral order REFORD at pixel x=512, and REFMJD is the MJD of the observations used to infer the sensitivity of the echelle mode. An average of these parameters is taken if more than one reference observation is available for a certain mode. The linear coefficients BSHIFT_VS_X and BSHIFT_VS_Y relative to the spatial component of the blaze-shift, vary with the grating used. The linear coefficients BSHIFT_VS_T and BSHIFT_OFFSET referring to the temporal component of the blaze-shift, vary instead with the grating, order, and side of STIS operations (Side 1 or Side 2). See Aloisi (2007b) for details.

Table 1. Observations of the standard star G191-B2B used to revise the sensitivity of the echelle prime modes.

Grating	Central wavelength	Dataset	Observation date	Exposure time (s)	S/N	MO (x,y)
E140H	1234	o5i010010	2000-03-16	2279.0	25.9	(3,−8)
		o5i010020	2000-03-17	3000.0	29.6	(3,−8)
		o5i010030	2000-03-17	3000.0	29.6	(3,−8)
	1416	o57u01020	1998-12-17	2040.0	29.8	(0,0)
	1598	o5i011010	2000-03-17	2284.0	18.9	(0,10)
		o5i011020	2000-03-17	3000.0	21.6	(0,10)
		o5i011030	2000-03-17	3000.0	21.6	(0,10)
E140M	1425	o4dd16020	1999-02-06	4903.0	35.4	(0,0)
E230H	1763	o5i013010	2000-03-19	2304.0	12.4	(−1,9)
		o5i013020	2000-03-19	3000.0	14.1	(−1,9)
		o5i013030	2000-03-19	3000.0	14.0	(−1,9)
	2013	o6hb20070	2001-09-18	808.0	10.9	(0,−19)
	2263	o6hb200c0	2001-09-18	101.0	4.6	(−3,−18)
		o6hb200d0	2001-09-18	609.6	11.5	(−3,−18)
	2513	o5i014010	2000-03-18	2304.0	22.6	(3,−7)
		o5i014020	2000-03-18	3000.0	25.6	(3,−7)
		o5i014030	2000-03-18	3000.0	25.2	(3,−7)
	2762	o6hb30080	2001-09-19	978.0	12.9	(−3,18)
	3012	o5i015010	2000-03-18	2304.0	13.0	(2,−9)
		o5i015020	2000-03-18	3000.0	14.9	(2,−9)
		o5i015030	2000-03-19	3000.0	14.8	(2,−9)
E230M	1978	o5i012010	2000-03-14	2304.0	34.1	(−1,9)
	2707	o5i012020	2000-03-14	2880.0	55.6	(7,−4)

Secondary Modes

Spectra of the primary standard star G191-B2B, were obtained for all STIS echelle secondary modes in September 2001 as part of the calibration program 8915 and are listed in Table 2. All data were acquired with the $0.2'' \times 0.2''$ aperture following standard peak-up target acquisitions.

All the observations of program 8915 were acquired with quite extreme MSM offsets. However, these non-zero MSM offsets are now properly taken into account within the pipeline thanks to the introduction of a blaze-shift correction in addition to the new on-orbit sensitivities of the secondary modes (see Aloisi 2007b for details).

Analysis

For each exposure the count rate as a function of wavelength within each order was measured using the standard one-dimensional spectral extraction (x1d files) produced by the IDT version of the CALSTIS pipeline as of October 2006. The IDT and STScI pipelines both sum the net counts over a standard height (7 pixels) extraction box.

The net count rate vector was divided by the WD model flux to yield the sensitivity as a function of wavelength. A multi-node, least-squares spline fit was then done to the sensitivity as a function of wavelength. The number and/or position of the spline nodes was adjusted to allow the details of each sensitivity curve to be followed while avoiding excessive oscillations of the fit. Some obvious absorption features (e.g., Lyman α) were also masked out of the fit in order not to bias the sensitivity determination towards artificially low values. When two or more exposures per mode were available, they were fitted simultaneously, with the sensitivity from each observation weighted by the exposure time. This allows measurements with different exposure times to be combined.

The detected count rates in most STIS modes are affected by time-dependent sensitivity (TDS) changes that vary with wavelength (Stys, Bohlin, & Goudfrooij 2004; Aloisi 2007a). The observation date (or an average of it when more than one observation was available) was used to correct the derived sensitivity curves for such an effect and obtain the sensitivity at a standard reference time (beginning of STIS operations in February 1997). No TDS correction as a function of temperature was applied. This correction is smaller than 0.5% for all FUV datasets used to calibrate both prime and secondary echelle modes, while there is no temperature correction for the NUV MAMA.

The TDS-corrected sensitivity vectors give the (counts/pixel)/(erg/cm^2/Å) contained within the default extraction box for observations done with the $0.2'' \times 0.2''$ aperture at each mode reference time for zero TDS losses. The PHT reference file throughput curves are, however, defined for an infinite extraction box and an infinite aperture. In order to transform the sensitivity vectors into throughput curves, it is necessary to add the corrections for the finite extraction box, and the aperture throughput, and to divide by the collecting area of HST. When the resulting throughput curve is used to calibrate an actual observation, the tabulated corrections for the particular aperture and extraction

Table 2. Observations of the standard star G191-B2B used to determine the on-orbit sensitivity of the echelle secondary modes.

Grating	Central wavelength	Dataset	Observation date	Exposure time (s)	S/N	MO (x,y)
E140H	1271	o6hb10030	2001-09-17	56.0	4.5	$(-6,17)$
		o6hb10040	2001-09-17	640.0	15.3	$(-6,17)$
	1307	o6hb10050	2001-09-17	654.0	17.3	$(-6,17)$
	1343	o6hb10060	2001-09-17	686.0	18.6	$(-6,17)$
	1380	o6hb10080	2001-09-17	719.0	18.1	$(-7,15)$
	1453	o6hb100a0	2001-09-17	809.0	16.6	$(-11,-5)$
		o6hb100b0	2001-09-17	229.0	8.8	$(-11,-5)$
	1489	o6hb100c0	2001-09-17	1263.0	19.3	$(-6,-16)$
	1526	o6hb100d0	2001-09-17	887.0	14.4	$(-3,-19)$
		o6hb100e0	2001-09-17	749.0	13.2	$(-3,-19)$
	1562	o6hb100f0	2001-09-17	1996.0	19.1	$(0,-19)$
E230H	1813	o6hb20020	2001-09-18	654.0	7.5	$(2,-19)$
		o6hb20030	2001-09-18	455.0	6.3	$(2,-19)$
	1863	o6hb20040	2001-09-18	997.0	10.0	$(1,-19)$
	1913	o6hb20050	2001-09-18	907.0	10.3	$(1,-19)$
	1963	o6hb20060	2001-09-18	871.0	10.7	$(0,-19)$
	2063	o6hb20080	2001-09-18	718.0	10.8	$(0,-19)$
	2113	o6hb20090	2001-09-18	679.0	11.0	$(0,-19)$
	2163	o6hb200a0	2001-09-18	640.0	11.1	$(-1,-19)$
	2213	o6hb200b0	2001-09-18	620.0	11.3	$(-2,-19)$
	2313	o6hb200e0	2001-09-18	734.3	12.6	$(-5,-17)$
	2363	o6hb200f0	2001-09-18	748.7	12.8	$(-7,-14)$
	2413	o6hb40080	2001-09-12	774.0	12.6	$(-11,-5)$
	2463	o6hb30010	2001-09-19	668.0	12.1	$(-10,10)$
	2563	o6hb30030	2001-09-19	247.0	7.2	$(-5,17)$
		o6hb30040	2001-09-19	484.0	10.1	$(-5,17)$
	2613	o6hb30050	2001-09-19	769.0	12.5	$(-4,18)$
	2663	o6hb30060	2001-09-19	992.3	13.8	$(-4,18)$
	2713	o6hb30070	2001-09-19	900.0	12.8	$(-3,18)$
	2812	o6hb30090	2001-09-19	519.0	9.0	$(-3,18)$
		o6hb300a0	2001-09-19	578.0	9.5	$(-3,18)$
	2862	o6hb300b0	2001-09-19	1232.0	12.9	$(-3,18)$
	2912	o6hb300c0	2001-09-19	549.0	7.9	$(-4,18)$
		o6hb300d0	2001-09-19	873.0	10.0	$(-4,18)$
	2962	o6hb300e0	2001-09-19	1862.0	13.2	$(-4,18)$
E230M	2124	o6hb40020	2001-09-12	353.0	15.0	$(1,-19)$
	2269	o6hb40030	2001-09-12	291.0	15.9	$(0,-19)$
	2415	o6hb40040	2001-09-12	244.0	15.7	$(-3,-19)$
	2561	o6hb40050	2001-09-12	302.0	18.2	$(-10,-14)$

box used will be applied. For the standard height extraction box and the $0.2'' \times 0.2''$ aperture, these will be the same corrections used to define the throughput curve, and so the accuracy of the extracted fluxes will be unaffected by any errors or uncertainties in the aperture and extraction box height corrections. In this case, the fluxes are directly tied to the calibration observations. However, flux values for observations done with other apertures or reduced using other than the default extraction box height will be affected by any differential errors in the tabulated values of these corrections.

Results and Accuracies

The new throughputs have generally increased compared to the values previously delivered to the pipeline. For the prime modes, at most wavelengths within each order the differences between the old and new sensitivities are modest ($< 3\text{-}5\%$). The only exceptions are the prime modes E140H 1234 Å and E140H 1598 Å, where differences as high as 5-10% are observed. Figure 1 shows an example of an average difference of the order of 5% in a portion (1239-1256 Å) of the spectrum of the flux standard star G191-B2B used to calibrate E140H 1234 Å.

In the case of the secondary modes, the differences between the new on-orbit and old extrapolated throughput curves are on average slightly larger, and may be as large as 5-8%, depending on the mode and order considered. Figure 2 shows, for example, a portion of the spectrum of G191-B2B used to calibrate E230H 1813 Å. This is a pretty favorable case for a secondary mode, since differences of the order of only 2-3% are noticeable between the two flux calibrations.

The absolute flux accuracy of the model of the standard star G191-B2B is of the order of $\pm 3\%$ in the UV spectral range. Miscentering in the $0.2'' \times 0.2''$ aperture during calibration observations introduces another uncertainty related to the global flux loss over the whole wavelength range of the echelle mode. This uncertainty is hard to quantify, but should be well below a few %. Additional local uncertanties of the order of $\pm$ 1-2% can be present in the STIS echelle calibration data due to photon statistics, small registration errors of the extraction box during the extraction of the 1D spectra, small errors in the blaze-shift correction (Aloisi 2007b) and small errors in the fitting of the sensitivities across the orders.

PHOTTAB Reference Tables

The PHOTTAB reference tables with different USEAFTER dates that implement the new sensitivity curves (and blaze-shift corrections, see Aloisi et al. 2007b) into the pipeline are qb319510o_pht.fits (USEAFTER Oct 1, 1996), qb319511o_pht.fits (USEAFTER Mar 15, 1999), and qb319512o_pht.fits (USEAFTER Jul 10, 2001) for the FUV modes, and qb319513o_pht.fits (USEAFTER Oct 1, 1996) and qb319514o_pht.fits (USEAFTER Jul 10, 2001) for the NUV modes. These tables were delivered for use in
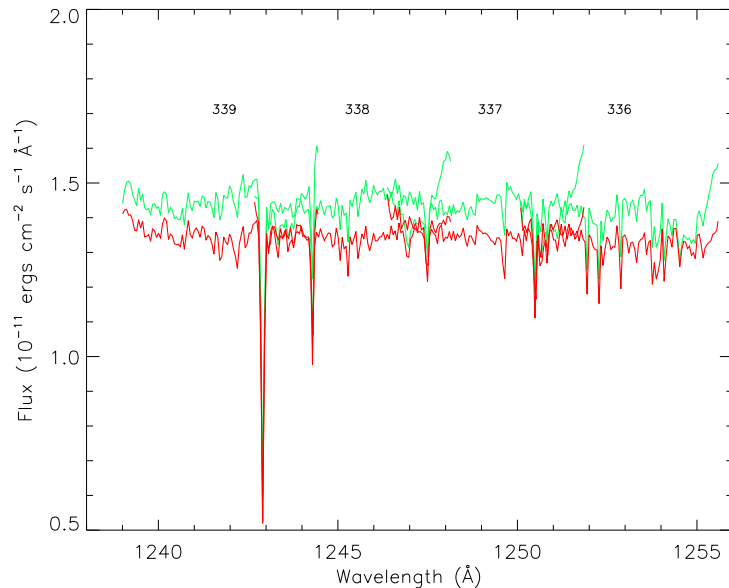
Figure 1. Spectrum of the flux standard star G191-B2B observed in March 2000 with the $0.2'' \times 0.2''$ aperture in the echelle prime mode E140H 1234 Å. Only orders from 336 to 339 are plotted, approximatively covering the wavelength range 1239-1256 Å. The red spectrum was obtained with the updated flux calibration which contains the new throughput curves discussed in this ISR and makes use of an improved blaze-shift correction as discussed in Aloisi 2007b. The green spectrum was instead obtained with the old flux calibration. Within each order, the green spectrum has an artificial S shape at long wavelengths that completely disappears in the red spectrum. The average difference between the two flux calibrations is about 5%, with peaks as high as 10% corresponding to the maxima of the S-shaped flux in the old version of the calibration. These differences are merely due to changes in the adopted throughput curves. The effects of slightly different blaze-shift corrections are noticeable at the edges of the orders and are minimal in this case.

STIS on-the-fly reprocessing (OTFR) on November 3, 2006. Calibrated data obtained from the archive after this date will use the revised throughput curves.

Missing/Additional Orders

Due to the non-zero MSM offsets of the new observations used to calibrate the echelle sensitivities of most prime and secondary modes, a few edge orders that were present in the previous calibration observations, have now dropped off the detector. As a consequence, these orders are now missing from the new PHOTTAB reference tables. Similarly some edge orders that were off the detector in the previous calibration data, are now falling onto the detector. However, not all of these orders were extracted, used for the flux calibration, and inserted into the new PHOTTAB reference tables. This is
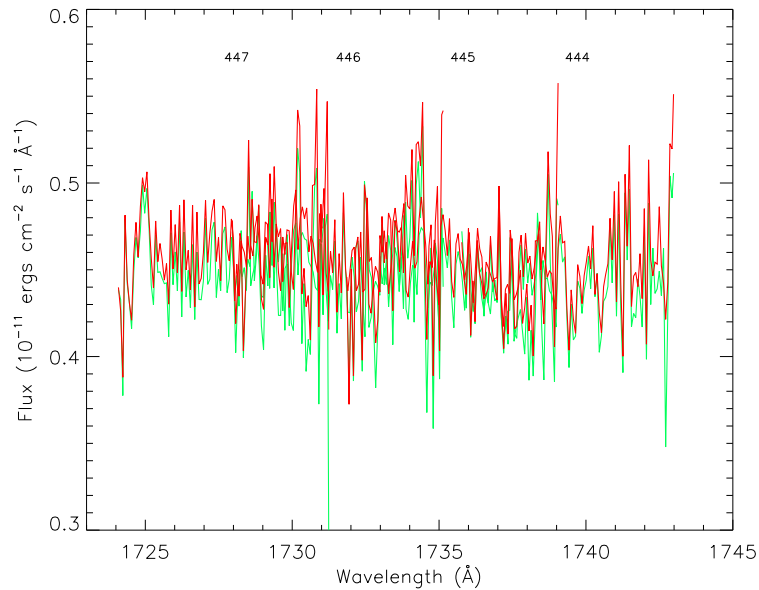
Figure 2. Spectrum of the flux standard star G191-B2B observed in September 2001 with the $0.2'' \times 0.2''$ aperture in the echelle secondary mode E230H 1813 Å. Only orders from 444 to 447 are plotted, approximatively covering the wavelength range 1724-1743 Å. Fluxes are color-coded as in Fig. 1. The observed differences of the order of 2-3% are attributed to differences in the adopted sensitivities. Due to a favorable combination of MO and epoch of observation, the blaze-shift correction of this spectrum was approximatively zero in the old version of the flux calibration. No flux errors were therefore introduced at the order edges, despite the fact that the old calibration was not applying a blaze-shift correction for secondary modes.

due to the fact that many of them are still missing from the SPTRCTAB reference files (spectrum trace tables which contain the nominal location and distorted shape of the spectra for each order of the echelle modes), thus could not be found and extracted as 1-D spectra. To conclude, the new PHOTTAB reference tables contain additional orders that were not possible to calibrate before, but their number is much smaller than the number of orders that are now missing (see Table 3 for a complete list of all missing and additional orders).

Users working on data of a certain echelle mode acquired with a quite different (e.g., zero) MSM offset compared to the observations used to calibrate that mode, may still be interested in extracting and calibrating the orders that are now missing from the PHOTTAB tables. If this is the case, they may resort to older versions of the tables with the caveats that (1) the older on-board sensitivities of the prime modes have higher systematic uncertainties, (2) the older sensitivities of the secondary modes are based on an extrapolation of the prime mode on-orbit sensitivities, and (3) the blaze-shift correction is not optimal for the prime modes and is not applied at all to the secondary modes.

Table 3.   Missing/additional echelle orders in the new PHOTTAB reference tables.

Grating	Central wavelength	Missing Orders	Additional Orders
E140H	1234	...	...
	1271	309-310	...
	1307	300-301, 352	...
	1343	291-292	...
	1380	284-285	...
	1416	...	...
	1453	270-271	...
	1489	303-304	...
	1526	295-296	...
	1562	253, 288-289	...
	1598	249	282
E140M	1425	...	...
E230H	1763	474	406
	1813	394-395	...
	1863	384-386	...
	1913	375-376	...
	1963	365-367	...
	2013	359	411
	2063	349-350	...
	2113	342-343	...
	2163	335-336	...
	2213	328-329	...
	2263	322	363
	2313	315-316	...
	2363	308-309, 348	...
	2413	302-303, 340	...
	2463	296, 332-333	...
	2513	291	...
	2563	285, 318-319	...
	2613	280, 311-312	...
	2663	306-307	...
	2713	271, 300-301	...
	2762	...	267
	2812	262, 290	...
	2862	257, 284	...
	2912	278-279	...
	2962	249, 274	...
	3012	...	268
E230M	1978	...	86
	2124	80-81	...
	2269	75-76	...
	2415	72	...

Table 3.   (cont'd)

Grating	Central wavelength	Missing Orders	Additional Orders
	2561	68-69	...
	2707	...	...

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