

The SMART Data Analysis Package for the Infrared Spectrograph¹ on the *Spitzer Space Telescope*²

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ABSTRACT. SMART is a software package written in IDL to reduce and analyze *Spitzer* data from all four modules of the Infrared Spectrograph, including the peak-up arrays. The software is designed to make full use of the ancillary files generated in the *Spitzer* Science Center pipeline so that it can either remove or flag artifacts and corrupted data and maximize the signal-to-noise ratio in the extraction routines. It can be run in both interactive and batch modes. The software and users guide will be available for public release in 2004 December. We briefly describe some of the main features of SMART, including visualization tools for assessing data quality, basic arithmetic operations for either two-dimensional images or one-dimensional spectra, extraction of both point and extended sources, and a suite of spectral analysis tools.

1. INTRODUCTION

The Spectroscopy Modeling Analysis and Reduction Tool (SMART) is a software package written in IDL⁸ for the analysis of data acquired with the Infrared Spectrograph (IRS) on the *Spitzer Space Telescope* (Werner et al. 2004). The code has been developed for the UNIX/Linux operating systems. The IRS comprises four separate spectrograph modules covering the wavelength range from 5.3 to 38 μm , with spectral resolutions $R = \lambda/\Delta\lambda \sim 90$ and 600. The modules are named after their wavelength coverage and resolution: Short-Low (SL), Short-High (SH), Long-Low (LL), and Long-High (LH). The SL includes two peak-up imaging cameras that have bandpasses centered at 16 μm (“blue”) and 22 μm (“red”). For details of the IRS instrument, see Houck et al. (2004) and chapter 7 of the *Spitzer Observer’s Manual*⁹ (hereafter SOM7).

SMART has been designed specifically for IRS data, and in particular to extract spectra from observations of faint or extended sources. It has been written with an understanding of

both the available *Spitzer* IRS observing modes and a knowledge of how the contents of various files generated by the *Spitzer* Science Center (SSC) IRS pipeline can be used to maximize the signal-to-noise ratio (S/N) in the extracted spectrum. These three design factors make it a comprehensive and powerful software package for the extraction and analysis of IRS data.

SMART is primarily intended to operate on the Basic Calibrated Data (BCD; see SOM7) delivered by the SSC pipeline, but will also operate on the Browse-Quality Data (BQD; including both images and wavelength and flux-calibrated spectral tables) and two-dimensional data products from intermediate stages of the SSC pipeline (for example, the un-flat-fielded data). SMART aims to provide the routines necessary for the processing and scientific analysis of IRS data. The main goal is to simplify the tasks of visualizing, organizing, optimally combining, and extracting data. The result of this processing are fully flux and wavelength calibrated spectra. Further analysis is available within SMART. In addition, the spectra can easily be exported (in either FITS, ASCII, or IDL save set formats) to other analysis packages written, for example, in IDL or IRAF.

SMART includes software developed by two of the *Spitzer* Legacy teams. The Molecular Cores to Planet-Forming Disks (C2D) team has developed a code to remove fringes caused by interference in the detector substrate material (Lahuis & Boogert 2002). This software is an enhanced version of the code developed for the *Infrared Space Observatory* (ISO) Short Wavelength Spectrometer (Kester et al. 2003). The Formation and Evolution of Planetary Systems (FEPS) team have adapted the IDP3-NICMOS package (Schneider & Stobie 2002) to analyze image data from the IRS peak-up cameras. The spectral

¹ The IRS was a collaborative venture between Cornell University and Ball Aerospace Corporation, funded by NASA through the Jet Propulsion Laboratory and the Ames Research Center.

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⁸ The Interactive Data Language, Research Systems, Inc.

⁹ See <http://ssc.spitzer.caltech.edu/documents/som>.

analysis code is based on the inherited *ISO* Spectral Analysis Package (ISAP¹⁰; Sturm et al. 1998).

The present paper is an introduction to SMART. The SMART Web site¹¹ serves as the repository for the full listing of all functions available in SMART, in addition to details of the algorithms used. This Web site includes a comprehensive SMART Users Guide (SUG) and a set of data-reduction recipes aimed at the new user. Each recipe outlines the steps required to produce wavelength- and flux-calibrated spectra. Both the Web site and the software will be publicly available in 2004 December. In § 2 we introduce the main graphical user interfaces (GUIs) used for the interactive analysis of IRS data and briefly describe the experienced-user and batch-mode capabilities.

2. SMART GUIs

Before starting a SMART analysis session, the observers need to fetch their IRS data from the *Spitzer* archive. SMART is designed to operate on the SSC pipeline BCD FITS files. A BCD is a calibrated, flat-fielded two-dimensional image. The observer obtains a BCD image for each IRS exposure (for observing mode and pipeline details, see SOM7). In addition to the BCD file, SMART also needs two associated files for each exposure. These files are the uncertainty data and the bad-pixel mask. The bad-pixel mask has a 16 bit integer assigned to each pixel. Each bit corresponds to a given warning/error condition detected during the pipeline processing. For example, a pixel may have suffered a cosmic-ray hit or may be saturated. A Perl script searches the local directory for these three files and builds a new FITS file (“*bcd3p.fits”) for each exposure. Each new FITS file contains the data plane and two extensions: the uncertainty plane and the bad-pixel mask plane.

2.1. Project Manager

SSC pipeline products are read into the project manager and proceed either directly or via image analysis into the ISAP-based Data Evaluation and Analysis GUI (IDEA). Figure 1 presents a flowchart outlining the main GUIs available in SMART. At first glance, some of the GUIs may appear complex, but we remind the reader that the SUG will be available at the SMART Web site.

Figure 2 shows the project manager and data set GUIs. These form the base for launching different applications and storing the resulting data products. The project manager allows the *Spitzer* observer to load files by browsing a local directory that contains the two-dimensional images and spectral table files

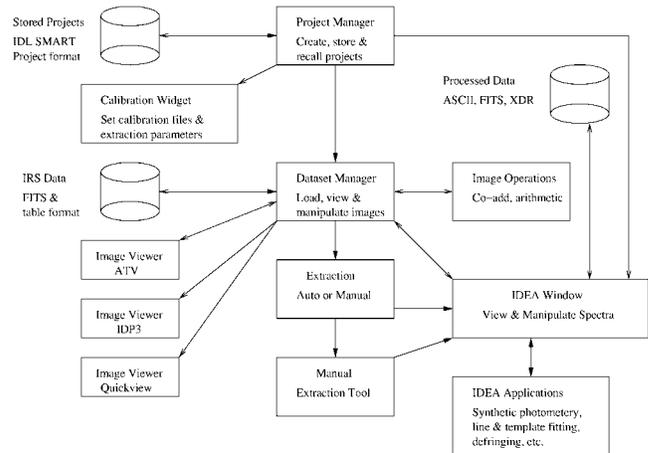


FIG. 1.—SMART flowchart.

from the archive, or to or import files from an existing local database. It is designed to handle large data sets by grouping them into sets called “projects.” BCDs within one project may or may not come from the same IRS module or astronomical target. For example, consider the simple case of a low-resolution observation of a point source covering the full wavelength range (5.3–38 μm). This requires the use of both the SL and LL modules. Each module covers its nominal spectral range in two orders via two subslits. The default observing mode will obtain two spectra of the target source per subslit, resulting in eight separate exposures. The resulting spectra from this observation would consist of two sets of four spectra that are 5.2 to 8.7 μm (SL2), 7.4 to 14.5 μm (SL1), 14.0 to 21.3 μm (LL2), and 19.5 to 38.0 μm (LL2) from the target source. The IRS low-resolution observations always obtain data simultaneously in the two subslits, so there are an additional two sets of four spectra (with the same wavelength coverage as above) of the background sky. Entire projects can be saved to disk as IDL save sets, which can be imported into new SMART projects. Alternatively, individual files can be exported from the project in either FITS or ASCII table formats. The main applications launched from the project manager are described in the following sections.

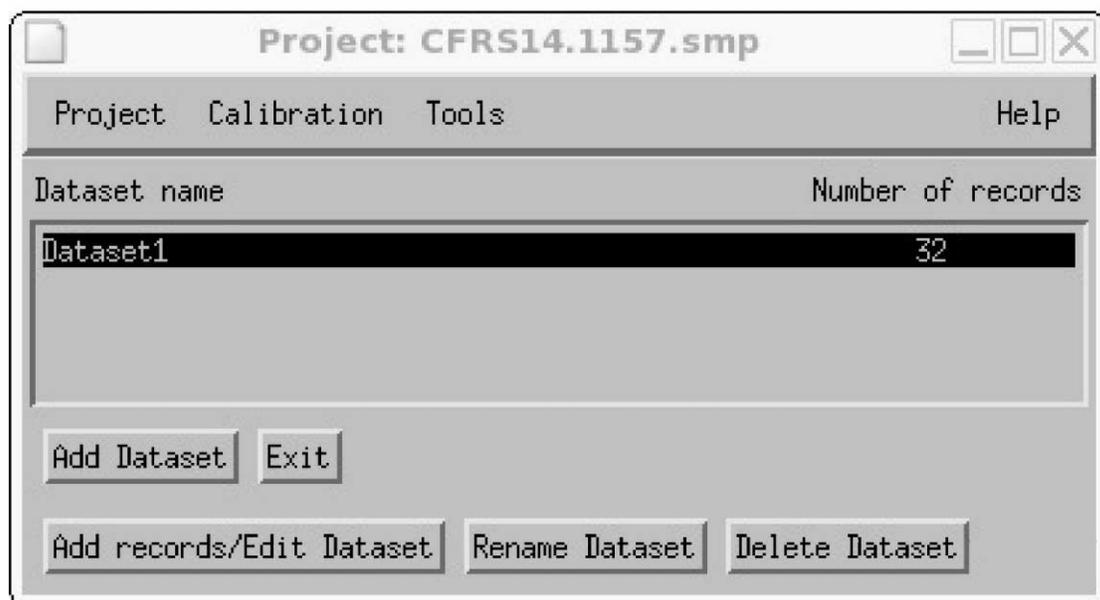
2.2. Image Display/Analysis

2.2.1. ATV-IRS

We have enhanced a version of the image display program ATV to work with our IRS spectral two-dimensional images. The ATV code was developed to visualize both two- and three-dimensional images (Barth 2001). Figure 3 shows an example of data displayed in ATV-IRS. We have enhanced the code so that an overplot tracing the curved spectral orders and the boundaries of the individual resolution elements can be displayed. The cursor position is reported in terms of pixel position

¹⁰ The *ISO* Spectral Analysis Package (ISAP) is a joint development by the LWS and SWS Instrument Teams and Data Centers. Contributing institutes are CESR, IAS, IPAC, MPE, RAL, and SRON. The ISAP software is available at <http://www.ipac.caltech.edu/iso/isap/isap.html>.

¹¹ The SMART Web site can be accessed at <http://isc.astro.cornell.edu/smart>.



Name	Object	BCDID	Aorkey	Expid	Icenum	Module	RA	DEC	Type
IR SX002600_bcd_0267_0003763968	IS015 1418 9		3763968	2	0	LL	214,4140000	52,4771767	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 10		3763968	2	1	LL	214,4140100	52,4771690	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 11		3763968	2	2	LL	214,4140100	52,4771652	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 12		3763968	2	3	LL	214,4140100	52,4771652	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 13		3763968	2	4	LL	214,4140100	52,4771652	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 14		3763968	2	5	LL	214,4140100	52,4771652	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 15		3763968	3	0	LL	214,4349400	52,4689445	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 16		3763968	3	1	LL	214,4349400	52,4689445	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 17		3763968	3	2	LL	214,4349300	52,4689484	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 18		3763968	3	3	LL	214,4349400	52,4689445	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 19		3763968	3	4	LL	214,4349400	52,4689445	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 20		3763968	3	5	LL	214,4349300	52,4689484	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 21		3763968	4	0	LL	214,4138200	52,4772263	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 22		3763968	4	1	LL	214,4138200	52,4772263	IMAGE
IR SX002600_bcd_0267_0003763968	IS015 1418 23		3763968	4	2	LL	214,4138200	52,4772301	IMAGE

Fig. 2.—*Top*: SMART project manager GUI. *Bottom*: SMART data set GUI.

(x,y) and flux (pixel value), in addition to sky coordinates (R.A., decl.) and spectral wavelength. This is very useful for assessing whether weak features in a spectrum are emission lines or are caused by cosmic-ray hits to the detectors. The viewer can also display the uncertainty and bad-pixel mask planes, returning the same information for the cursor position. Additional pixels can be flagged at this stage by editing the bad-pixel mask. In addition to displaying a single BCD, one can make a movie of a stack of images or make a single mosaicked image. A table containing the pixel information can also be inspected. If a stack of images is selected, the statistics on the cube of

pixel data can be displayed in a table. Images from an external archive can also be added to the project manager and viewed in ATV-IRS.

2.2.2. IDP3-IRS

The Image Display Paradigm 3 (IDP3) is a sophisticated photometry software package. It is written in IDL and is designed for the analysis of the *Hubble* NICMOS data. The IRS has imaging capabilities provided by the two peak-up cameras, each with an ~ 1 arcmin² field of view. The blue IRS peak-up

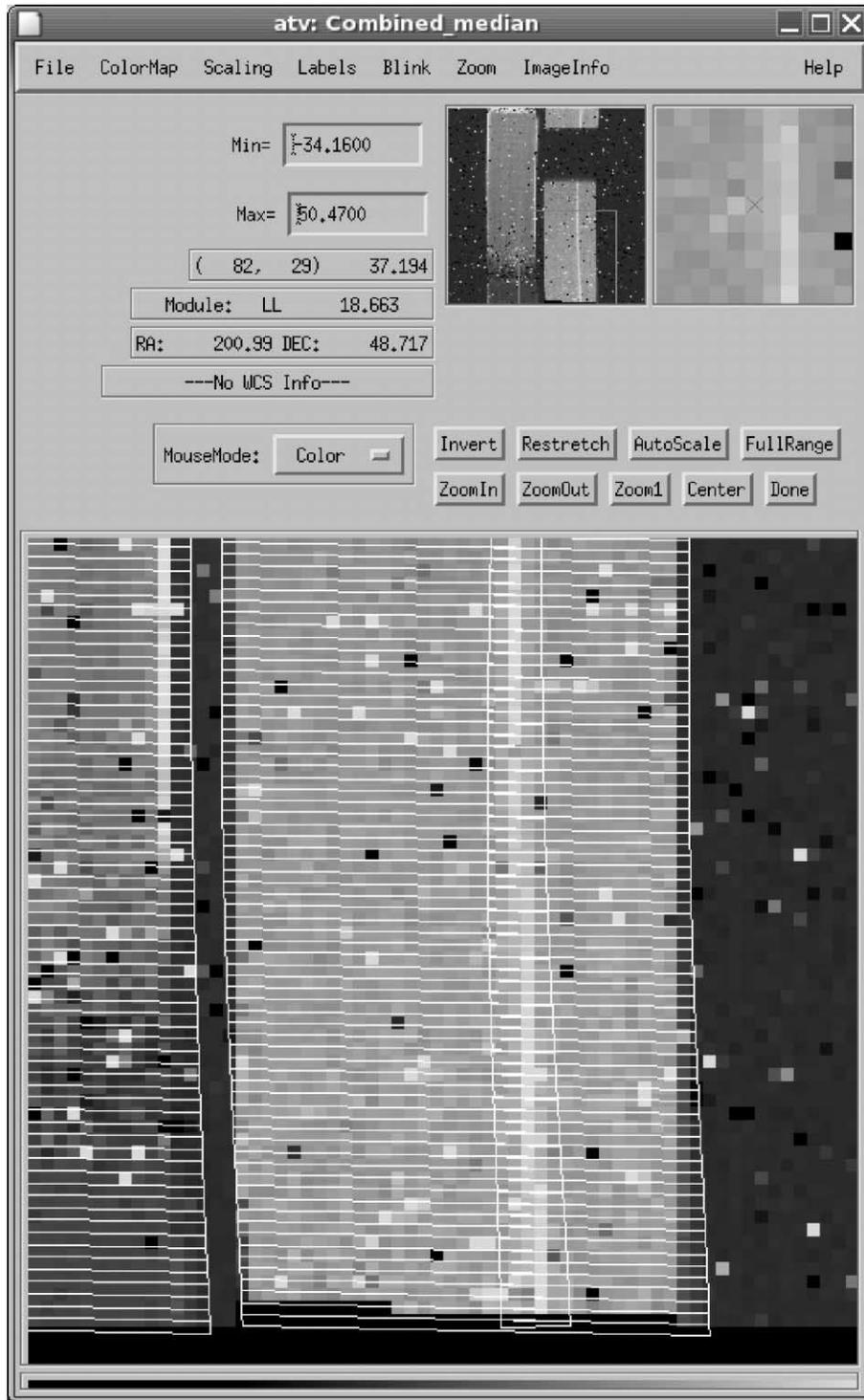


FIG. 3.—SMART ATV-IRS GUI. Data from IRS LL2 are displayed. The resolution elements overplotted are the column that has been selected for spectral extraction.

camera fills a gap in the wavelength coverage of the *Spitzer* imagers at 16 μm . Both the red (22 μm) and blue cameras are used for many observations. Elizabeth Stobie at the University of Arizona provided a modified version of IDP3, known as IDP3-IRS, which is optimized for analyzing sources observed in the IRS peak-up mode.

2.2.3. Quick Look

Quick Look takes a BCD file and collapses the spectral orders along the dispersion direction to produce an average intensity profile across the source. This provides a convenient tool to search for either extended emission or weak secondary point sources in the low-resolution data, which have slits that are 57" (SL) and 168" (LL) in the cross-dispersion direction. Figure 4 shows an example of a serendipitous detection of a weak source located close to the slit center in LL1. The negative stripes in LL2 are caused by the sky subtraction in LL1 using data that have the target source in LL2 (see § 2.4 for a discussion of sky subtraction).

2.2.4. Image Operations

The standard image operations—averaging, median filtering, division, addition, and subtraction—are available in SMART. In addition to operations weighted by the uncertainty data, pixels can be discarded according to their bad-pixel mask value. This offers a powerful means for discarding corrupted data and improving the S/N. For example, consider the median of 10 BCDs. First the pixels flagged by a bad-pixel mask value are excluded from the calculation of the median value for each pixel in the 128 \times 128 array. A new bad-pixel mask is generated for the median data by using the “or” operator on all the bad-pixel mask values associated with the data used to estimate the median. Automatic co-adding and differencing are available for SL and LL data. The images are sorted by slit and position within the slit (i.e., nod position) and then co-added. The co-added “on-source” and “off-source” images can then be differenced.

2.3. Spectral Extraction

There are currently four extraction routines available in SMART. All methods use a look-up table supplied by the SSC that traces the spectral orders on the BCD image. This table is converted into an IDL structure known as the “wavesamp.” The extraction routines use the wavesamp in order to subset the relevant group of pixels in each resolution element on the array. An example of the wavesamp trace is shown in Figure 3, where the curved spectral order has been subdivided into spectral resolution elements. The curvature results in fractional pixels being assigned to a given resolution element. The value of each fractional pixel is scaled by its geometrical area. The BCD data is in units of $e\text{ s}^{-1}$. Each routine estimates the total number of $e\text{ s}^{-1}$ in each individual resolution element. The final step is to apply the flux calibration (i.e., $e\text{ s}^{-1}$ to

Janskys) and stitch the orders together into a single spectrum, using the pipeline “fluxcon” tables.

2.3.1. Full-Aperture Extraction

This is the standard extraction method for SH and LH data. It can also be used for extended objects that fill the SL and LL apertures. The pixel values in each resolution element (as defined by the wavesamp) are summed, while accounting for fractional pixels. Prior to extraction, pixel values that are set to NaN (not-a-number) in the pipeline or flagged by the bad-pixel mask are replaced with an average value that is estimated from the values of the pixels in the same resolution element as the bad pixel.

2.3.2. Column Extraction

For SL and LL observations of point sources, the standard extraction method is column extraction. A column of pixels centered on the point source is extracted. Figure 5 is an example of the aperture used for a column extraction in LL2. The column traces the spectral order, and its width in the cross-dispersion direction is scaled with the instrumental point-spread function. The user should only override the default width after careful consultation of the manual and help pages.¹² The user-defined width is scaled with wavelength and requires additional on-the-fly calibration (see § 3). The pixels in the column in each resolution element are summed, while accounting for fractional pixels. Prior to extraction, pixel values that are set to NaN or flagged by bad-pixel mask values are replaced with an average value that is estimated from the pixels in the column within the same resolution element as the bad pixel.

2.3.3. Extended Source Extraction

Here a column of pixels centered on the extended source is extracted. The column traces the spectral order, and its width is constant with wavelength. Again, the pixels in each resolution element within the column are summed, while accounting for fractional pixels. Pixel values that are set to NaN or flagged by bad-pixel mask values are replaced using the method outlined above for column extraction.

2.3.4. Gaussian Extraction

Gaussian extraction should only be used with care, as it requires additional on-the-fly calibration (§ 3). The data from the pixels in each individual resolution element are collapsed in the dispersion direction. The resulting one-dimensional trace is fitted with a Gaussian profile. The Gaussian center and width can be frozen to aid the extraction of weak sources. Pixel values that are set to NaN or flagged by bad-pixel mask values are excluded from the fit.

¹² See <http://isc.astro.cornell.edu/smart>.

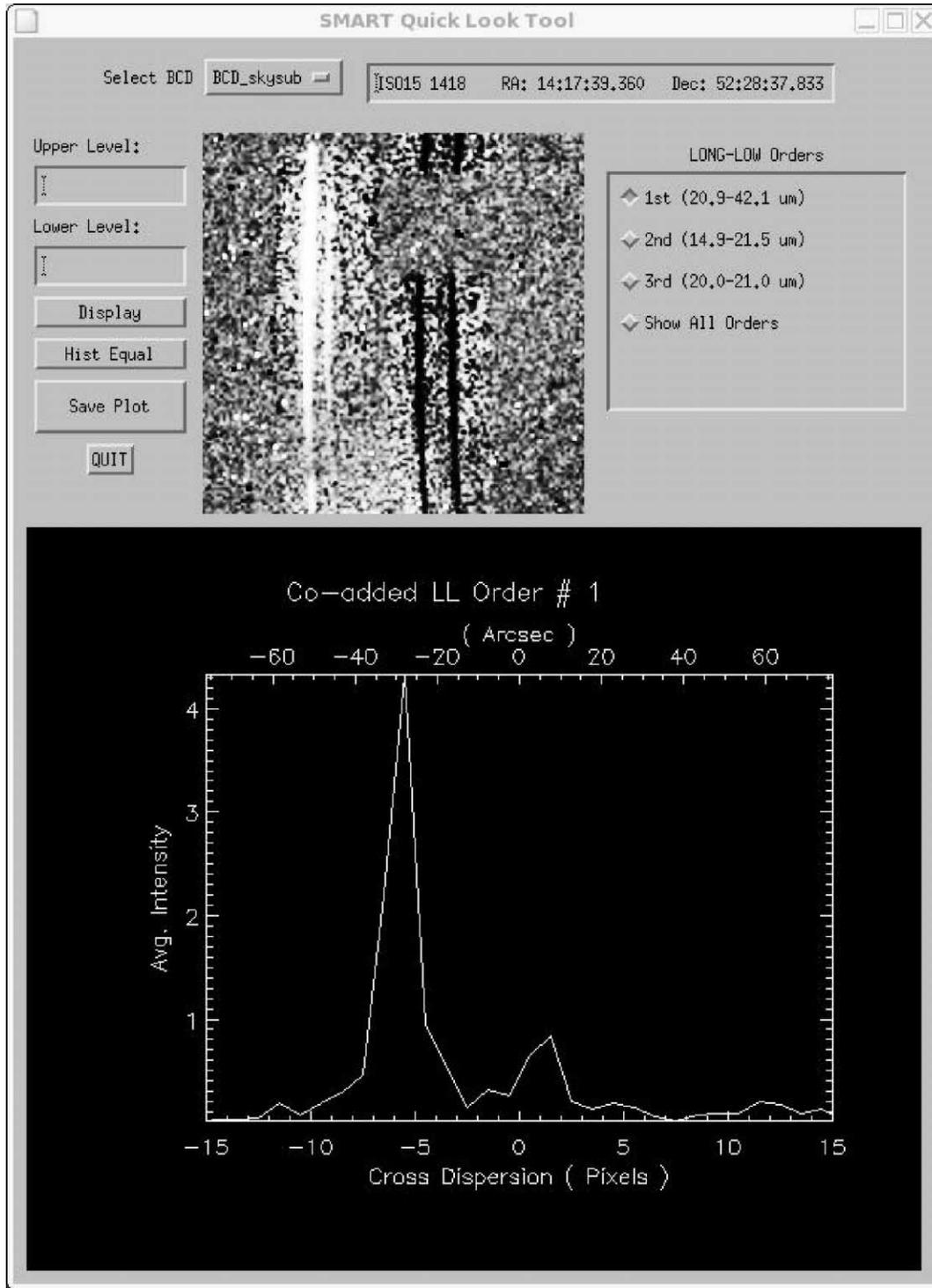


FIG. 4.—SMART Quick Look GUI. Sky-subtracted BCD data from the IRS LL are displayed in the upper image window. LL1 has been collapsed in the dispersion direction and is displayed in the plot window. A serendipitous source is observed close to the center of the slit. The negative stripes in LL2 are caused by the sky subtraction in LL1 using data that have the target source in LL2.

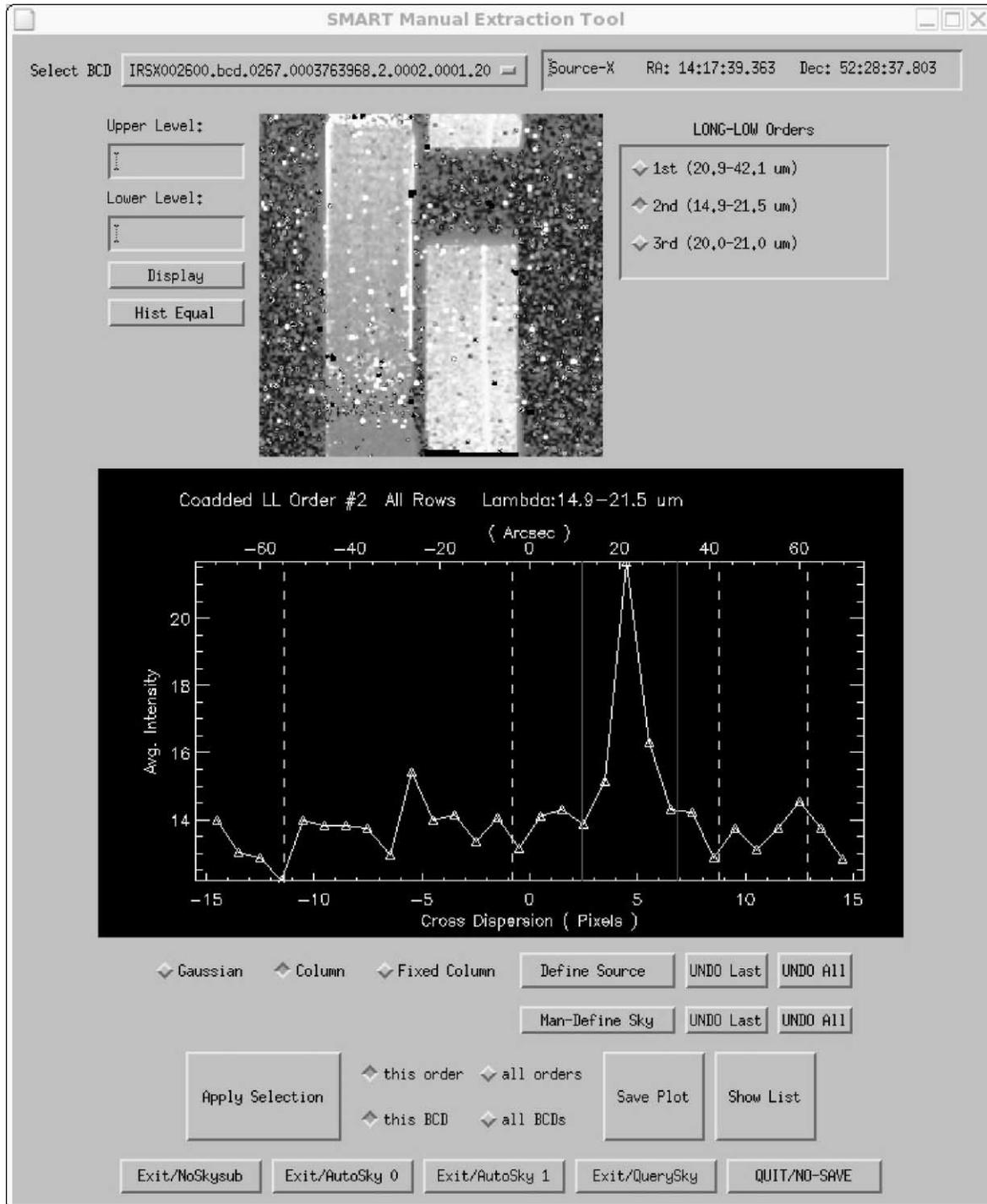


FIG. 5.—SMART Manual Extraction GUI. BCD data from the IRS long low spectrometer is displayed in the upper image window. LL2 has been collapsed in the dispersion direction and is displayed in the plot window. Overlaid on this plot are the column boundaries (*dotted lines*) and sky regions (*dashed lines*) for column extraction.

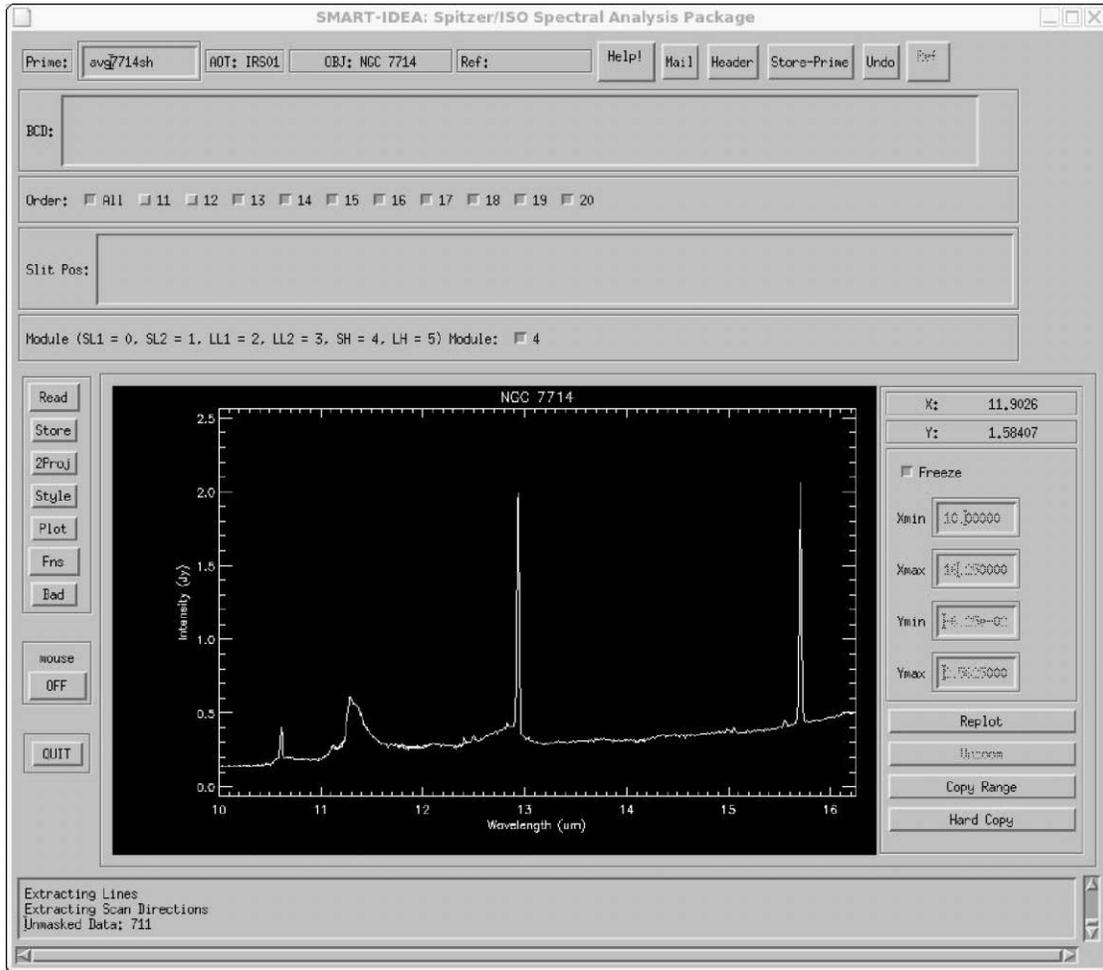


FIG. 6.—SMART IDEA GUI. This is the main GUI for viewing one-dimensional spectral data.

2.4. Sky Subtraction

The BCD images include sky emission and possible detector artifacts, which can be removed in SMART. The first method is applied before extraction, and the remaining two methods are akin to removing a baseline before measuring a line flux. If no sky image data are available, a zodiacal model can be subtracted from the spectra in IDEA.

2.4.1. Super-Sky Subtraction

The sky emission is removed by differencing an “on-source” and “super-sky” image prior to extraction. A super-sky image can be created by co-adding multiple “off-source” (i.e., sky) BCDs together. This can be done in SMART by using either the image operations GUI or one of the available scripts. This method is applicable to all four modules. For low-resolution data, the super-sky image may simply be the median of the “off-source data,” which is acquired as part of the standard

staring mode observation. For high-resolution data, separate sky observations are required.

2.4.2. Single-Sky Subtraction

The sky emission is removed during the extraction process. An “off-source” BCD is used for the sky estimate. This can be done in two ways. The first method calculates the median sky pixel value in each resolution element of the off-source BCD. In the second method, the pixel values in each resolution element of the off-source BCD are plotted as a function of cross-dispersion distance from the center of the slit. A first-order polynomial is fitted to the resulting intensity profile to estimate the sky level. For full-aperture extraction, the sky value is scaled with the area of the resolution element. For column extraction, the sky value is scaled to the area of the column within a given resolution element. For Gaussian extraction, the sky value is scaled to the width of the Gaussian.

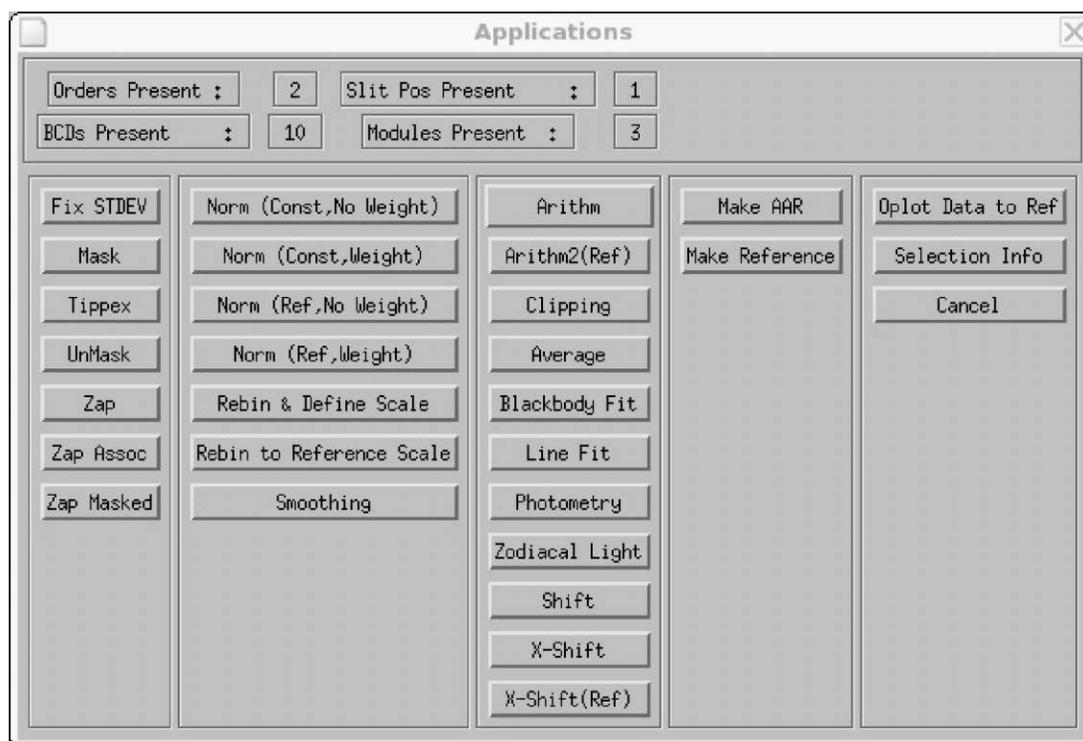


FIG. 7.— SMART IDEA applications GUI. The majority of the spectral reduction and analysis routines are accessed from this GUI.

The scaled sky value is then subtracted from each respective summed resolution element, column, or integrated Gaussian profile in the source spectrum.

2.4.3. Local-Sky Subtraction

The single-sky methods are applied to the data. However, in this instance the sky is calculated from the same BCD that contains the source data. The pixels in a given resolution element that are not part of the source column or Gaussian are used to estimate the sky value. An example of a selection of suitable sky regions is shown in Figure 5.

2.5. IDEA

IDEA is a comprehensive, one-dimensional spectral analysis package. The code includes the inherited ISAP software. ISAP was developed for the analysis of spectral data from *ISO* (SWS, LWS, PHT-S, and Cam-CVF) and provides a wealth of routines embedded in an easy-to-use graphical environment. The ability to analyze *ISO* spectra has been preserved so that direct comparisons can be made between data from the two satellites. Figure 6 shows the IDEA GUI, which has been enhanced to fit the special needs of IRS data. The applications GUI is shown in Figure 7. Processing routines include shifting, zapping low-S/N or corrupted data, defringing, rebinning, unit conversion, combining spectra with weighted means or medians, filtering,

and smoothing. Analysis routines include line fitting, line identification, continuum fitting, synthetic photometry (including the *IRAS*, *ISO*, and *Spitzer* filter profiles), zodiacal light modeling, blackbody fitting, dereddening, and template fitting routines. The spectra can be imported/exported as FITS, IDL save sets, or ASCII tables.

3. EXPERIENCED-USER AND BATCH MODES

SMART is supplied with a default set of calibration files from the SSC that can be inspected in the Calibration GUI. However, the experienced user can create her/his own set of calibration files and import them into SMART via the Calibration GUI. The extraction routines can be tailored to specific source profiles to maximize the S/N. Intermediate pipeline products (for example, the unflat-fielded data) can be substituted for the BCD image files. This can be beneficial for the extraction of faint sources and sources that have weak features. When unflat-fielded data are used, the flux calibration is performed on the fly, using a default set of calibration sources. Both the target and the flux calibrator are extracted using the same parameters. The extracted calibration source is then used to flux calibrate the extracted target spectrum. Only an experienced user should override the default calibration file selection.

SMART is also designed for efficient batch-mode process-

ing. Many of the GUI functions are available in batch mode, and we are developing a suite of scripts for the most commonly used functions. For example, both full-aperture, column, and Gaussian extraction are available in batch mode. The script includes two sky removal options. The first option is to subtract the sky during extraction. Alternatively, the sky can be removed using the super-sky method. The data from a given slit and nod position are co-added, and then the co-added “on-source” and “off-source” images are differenced. A single spectrum is then extracted from the median-filtered, sky-subtracted image.

4. SUMMARY

SMART is currently being tested by the IRS team and the participating Legacy teams. In 2004 December we will release SMART to the public. The code will be available at our Web site,¹³ where the IRS observer can find detailed instructions for

¹³ See <http://isc.astro.cornell.edu/smart>.

downloading and installing SMART. The site includes a SMART Users Guide and recipes for reducing IRS data. We plan to update and add new functionality to the code as our understanding of the IRS data analysis evolves. For example, we are currently working on an optimized extraction algorithm for both high- and low-resolution data. Updates will be posted on the Web site.

We would like to thank the following people: the IRS team and the SSC for their dedicated work in generating the pipeline-processed data and for ongoing calibration work; the ISAP team for allowing us to inherit and modify the ISAP code; and the referee, Eckhard Sturm, for his swift endorsement of this paper.

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