Explanatory Supplement to the 9P/Tempel 1 IRAS Survey Images

Delivered to University of Maryland

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Russ Walker

Vanguard Research, Inc.
5321 Scotts Valley Drive, Suite 204
Scotts Valley, CA 95066

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To reflect modifications needed for PDS archival purposes

Background

The bulk of the IRAS observation time was spent in the survey mode that systematically mapped the sky with a series of overlapping and confirming scans. This redundancy can be used to produce a survey with fainter limiting magnitude, such as the IRAS Faint Source Survey, or to improve the spatial resolution in the scanned fields. Construction of images from survey data is complicated by the fact that the confirming scans cross each other at varying angles. Construction of comet images also requires compensation for the motion of the comet and the changing spacecraft parallax during the relatively large time interval (>103 minutes) between the confirming scans necessary to build the image. All the images in the delivered set were constructed from survey scans. They are thus “time-averaged” images of the comet emission history.

The method for the production of comet images uses a computer algorithm based on the Maximum Correlation Method (MCM) for Image Construction (Aumann, Fowler, and Melnyk, 1990), and closely parallels the "HiRes Processing" performed at IPAC (Melnyk and Rice, 1991). The major departure from the IPAC scheme occurs in the Comet Image Preprocessor (CIPP) where the coordinates of each detector footprint (data sample) are transformed to a moving Sun-referenced coordinate system with the comet at the origin.

The Comet Image Preprocessor (CIPP) - The CIPP program reads the scan data and performs three main functions; 1) transform the coordinates of the data samples to a coordinate system that moves with the comet; 2) remove data artifacts, such as baseline, tails, and radiation hits (glitches) that tend to be magnified by the image construction processing; and 3) associate each data sample with the specific pixels in the map covered by the detector response function and their weights in the observed response. This latter information is stored in an array and is "looked up" by the processor (described below) at each iteration of the image construction.

The Comet Image Processor (CIP) - Once the CIPP has "cleaned up" the scan, the CIP program applies the MCM algorithm to construct high-resolution images of the comet from the survey scans. The spatial response functions of the IRAS detectors that were used are modified versions of those given by Moshir, 1986. They have been "de-tailed" and their response extended to 1% of the peak by approximating the point spread function of the IRAS telescope mirror with a two-dimensional Gaussian blur that contains 85% of the flux from a point source within a circle of diameter 25", 25", 60", and 100" for the 12, 25, 60, and 100 micron bands (Beichman, et al, 1988).

CIP begins with a map of uniform low level radiance, and builds an image by scanning an analytical version of the IRAS focal plane over the map, simulating the IRAS data-taking process. The analytical data samples are compared to the real scan data samples (cleaned by the CIPP) and pixel correction factors determined. Details of this process are given by Aumann, et al, 1990 and Melnyk and Rice, 1991. Building the map is an iterative process, wherein each iteration begins with the most recent estimate of map radiance. Statistics relating to pixel noise and convergence are generated at each iteration. A typical

image will converge after 15 to 40 iterations. Two image products were produced from the Tempel 1 survey scans:

A. Radiance Map - The radiance map is the surface brightness image produced by the CIP. Two radiance maps were produced for archive; 1) the map resulting from the first iteration (equivalent to the IPAC FRESCO image, see Melnyk, 1990), and 2) the high-resolution map produced at the final iteration.

B. Photometric Noise Map - This is an image of the internal photometric uncertainty (standard deviation) of the radiance in a pixel as a result of averaging overlapping detector samples. The photometric noise map may be used to estimate the error in aperture photometry of the comet, photometric profiles, and flux ratios.

File Designations and Content

The delivered data set includes radiance and noise images, processing logs, aperture photometry files, the scan list, and a file of the osculating orbital elements used for Tempel 1. IRAS scans are identified by a satellite operations plan (SOP) number. The images are identified by a "mean" SOP number, since several scans are used to make an image. The IRAS observations were made in four spectral bands centered nominally at 12μm, 25μm, 60μm, and 100μm. Images are supplied for the first iteration (01) and the final iteration (xx) determined by the convergence of the flux in all the pixels in the scanned path. Thus, the following file names:

Radiance and Noise Maps in /data/survey/images/:

Radiance Maps (40) – sSOP_Band_Iteration#_radiance.fit
Noise Maps (40) – sSOP_Band_Iteration#_noise.fit

Radiance and Noise Photometry Tables in /data/survey/phot/:

Radiance Photometry Files (20) – sSOP_Band_Iteration#_radiance.tab
Noise Photometry Files (20) – sSOP_Band_Iteration#_noise.tab

Processing Logs (20) – /calib/survey/proclogs/sSOP_Band_log.txt

The numbers in parenthesis above are the number of files that PDS-SBN received.

In addition, there is an ASCII file of the orbital elements (/calib/survey/tempel1_elements_used.txt) and an ASCII file, which lists all the scans that were used to create the images along with some useful data concerning the circumstances of the comet and the geometry of the scan (/calib/survey/survey_scans_used.txt). See the notes at the end of the file.

For convenience, there are files of the spectral response of the IRAS detector bands: /calib/filter/filWWWum.tab, where WWW is the nominal wavelength at band

center. The files give the wavelength in microns in the first column and peak-normalized response in the second column.

The Radiance and Noise Maps are in FITS image format. They have extensive headers that provide all the data that you need to use the images. The following is an example from a 100μm image that converged after 16 iterations.

```
SIMPLE  =                    T / Written by IDL:  27-Dec-2000 17:25:50.00
BITPIX  =                  -32 / IEEE single precision floating point
NAXIS   =                    2
NAXIS1  =                  150 / Fastest varying axis
NAXIS2  =                  075 / Slowest varying axis
BSCALE  =              1.00000 /
BUNIT   = 'Watts/cm2/sr'       /
BZERO   =             0.000000 /
OBJECT  = '9P/TEMPEL 1'        / Target
DATAMAX =          3.15750E-10 / Watts/cm2/sr  (in-band radiance)
DATAMIN =          0.00000E+00 / Watts/cm2/sr  (in-band radiance)
CRVAL1  =             96.94210 / Solar elon of target via orbital elements
CRPIX1  =                   77 / X-axis origin, pixel at comet max
CDELT1  =                   24 / X-axis pixel width (arcsec)
CTYPE1  = 'ELONGATION'         / Angle between IRAS line of sight and Sun
CRVAL2  =            359.40880 / Solar incl of target via orbital elements
CRPIX2  =                   37 / Y-axis origin, pixel at comet max
CDELT2  =                   24 / Y-axis pixel width (arcsec)
CTYPE2  = 'INCLINATION'        / Angle between ecl plane, E-S plane and obs dir
COMMENT COMET Tempel 1 1983 XI
COMMENT FLUX MAP
COMMENT Iteration 016
COMMENT Converged Pixels 09741
COMMENT  Jan 2003, PDS Small Bodies Node modified the header:
COMMENT    1) Corrected several keywords and values to standards.
COMMENT    2) Added keyword comments for clarification.
COMMENT    3) Removed peak flux comment line per R.Walker.
COMMENT    4) Added observation-specific keywords at end of header.
COMMENT    5) Image size is 1.0 degree by 0.5 degree.
COMMENT    6) Pixel size is 24 arcsec by 24 arcsec.
FILENAME= 's339_100um_16_radiance.fit' / OUTPUT FILE NAME
COMETMAX=          1.15603E-11 / Watts/cm2/sr  (in-band radiance)
WAVE    =                  100  / Wavelength (microns)
MEAN_JD =          2445529.789 / Mean Julian date of combined observations
MEANDT  = '1983-07-14'         / Mean UTC date of combined obs
MEANTM  = '06:56:09.600'       / Mean UTC time of combined obs
MEAN_RA =            205.57081 / deg
MEAN_DEC=            -11.23130 / deg
SOP     =                  339 / Scan Orbit
NOBS    =                    7 / Number of observations
RHO     =                1.492 / Sun-Comet distance (AU)
DELTA   =                0.976 / Earth-Comet distance (AU)
PHASE   =               42.566 / Phase angle (S-T-O) (deg)
TOBS    =                  336 / Summed time of observations (sec)
UTCSTART=         2445529.6202 / UTC at start of obs (Julian date)
UTCSTOP =         2445530.0499 / UTC at end of obs (Julian date))
STARTDT = '1983-07-14'         / UTC date at start of obs
STARTTM = '02:53:05.360'       / UTC time at start of obs
STOPDT  = '1983-07-14'         / UTC date at end of obs
STOPTM  = '13:11:47.180'       / UTC time at end of obs
SCSTART =          79843985.36 / IRAS time at start of obs
```

```
SCSTOP  =          79881107.18 / IRAS time at end of obs
END
```

The image is 150 x 75 pixels (NAXIS1 x NAXIS2). The coordinate system is solar elongation, inclination. This was the natural coordinate system for IRAS. Elongation is the angle between the line of sight and the Sun. Inclination is the angle between the ecliptic plane and the plane containing the Earth, Sun, and observation direction (that is, the azimuth angle about the Earth-Sun axis). These angles are related to geocentric ecliptic coordinates by:

$$\cos(\text{elongation}) = \cos(\beta)\cos(\lambda-\lambda_o)$$

$$\sin(\text{inclination}) = \sin(\beta)/\sin(\text{elongation})$$

where β is ecliptic latitude, λ is ecliptic longitude, and λ_o is the longitude of the Sun.

The images were constructed by referencing the radiance samples to the orbital position of the comet at the time of the sample. Thus the comet (by virtue of its orbital elements) is always at pixels 75 and 37. This is the map center reference and has mean elongation and inclination as given in the header. However, as in the header above the maximum radiance of the comet (COMETMAX) did not occur at 75,37 but at 77,37. The pixel size is 24 x 24 arcsec. Also note that in this image the maximum radiance (DATAMAX) does not occur at the comet (COMETMAX). This is a map of the radiance and includes background radiance, thus DATAMIN = 0 and the comet radiance is biased up by the background radiance.

Since the images are constructed from many survey scans at different times, the mean coordinates (RA, DEC, Elongation, Inclination) were listed for the comet at the mean Julian Date (MEAN JD). Scans that occurred at nearly the same heliocentric and geocentric distances were selected. The sSOP_Band.log files and the survey_scans_used.tab contain much helpful data on this, and are self-explanatory. You will encounter the time variable UTCS. This is IRAS time. It may be converted to Julian date by

$$JD = 2445335.5d0+(UTCS - 63072000.0d0) / 86400.0d0$$

The UTCS start and stop times for each image were converted to UTC Julian dates and Gregorian dates and included in the FITS headers.

Although the images are binned into 24” pixels, the actual resolution within the image is dependent on (among other things) the number of iterations. alliterations were ran until the variations of the flux within each pixel (that was actually scanned) had converged to within the photometric noise of that pixel. There was no direct measure of the spatial resolution achieved, however, Rice (1993) measured the mean dimensions of 13 bright IRAS stellar point sources as a function of the number of iterations. The Rice (1993) results in the following table:

FWHM Cross-scan x In-scan (arcsec)				
MCM Iteration	12μm	25μm	60μm	100μm
01	256 x 64	270 x 67	301 x 121	403 x 282
05	79 x 34	72 x 36	123 x 63	182 x 134
10	51 x 28	48 x 28	86 x 50	131 x 103
20	37 x 23	35 x 23	62 x 41	98 x 80

Notes: 1. Uncertainties in the mean dimensions are less than 8%
2. The geometric detector beam is ~ 300" cross-scan and ~ 45", 45", 90", and 180" at 12, 25, 60, and 100μm respectively along the in-scan direction.
3. Little or no improvement of resolution was noted after 20 iterations.

Aperture Photometry

The radiance (and noise) photometry files are the result of summing the radiance (and variance) from all the pixels that are within a selected distance from the pixel of maximum comet radiance. There are three columns in the files. The first is the distance (radius) that includes the pixels summed. Zero is the central pixel, etc. The second column is the summed radiance (or noise) in units of Watts cm^{-2}. The third column is the number of pixels actually included in the sum. Most of the coma flux should be contained within a few pixels radius. There is 0.846125×10^{-8} steradian per 15" square pixel.

The original photometry files delivered to PDS-SBN during December 2000 for the Survey Scan Images used the image median to estimate the background and subtract that from the image prior to photometry. This is usually a reasonable thing to do for stars, etc. However, for the comet, the dust tail may be a significant source of background (or foreground) for estimates of the coma flux (see Figure 1a). In the case of a point source in a uniform background one expects the aperture photometry curve to rise to an asymptotic value if the background has been properly subtracted (Figure 1b). R. Walker modified his photometry program to iterate the background radiance until the profile tends toward asymptotic at radii greater than 30 pixels from the maximum comet radiance. He chose to call this "coma aperture photometry" and the value of the asymptote an estimate of the total coma flux. The difference between of the original and revised methods for estimating the background is illustrated in Figures 1a and 1b. The revised fluxes for the survey scan data, generated by the "coma aperture photometry" process, and are presented in Table 1.

Photometry for the survey scan images was redone by R. Walker using the new software and radiance survey "coma" photometry files were delivered to PDS-SBN in February 2001 (data/survey/phot/).

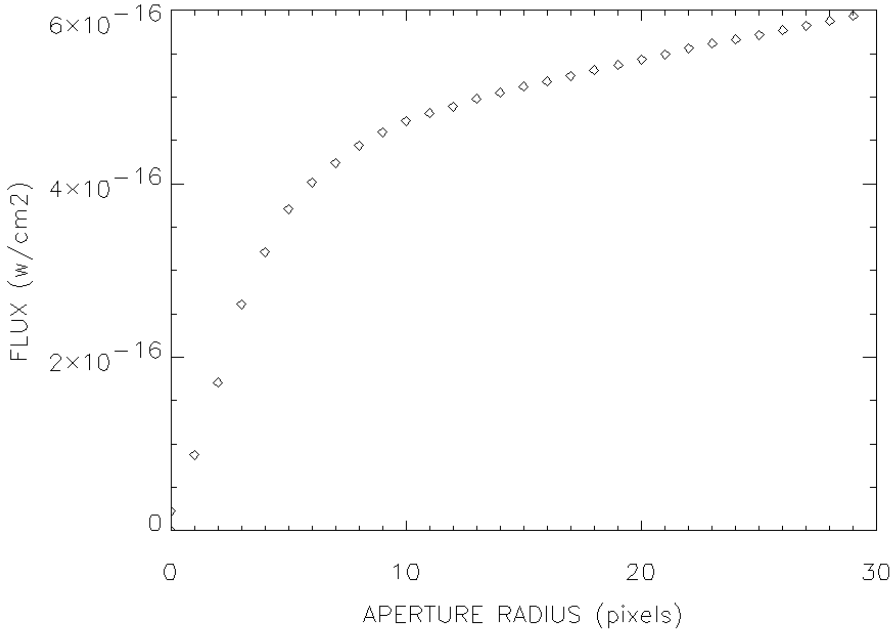

Figure 1a. Aperture photometry of the 12 μm survey radiance image #339 with median background subtraction as delivered on December 29, 2000.

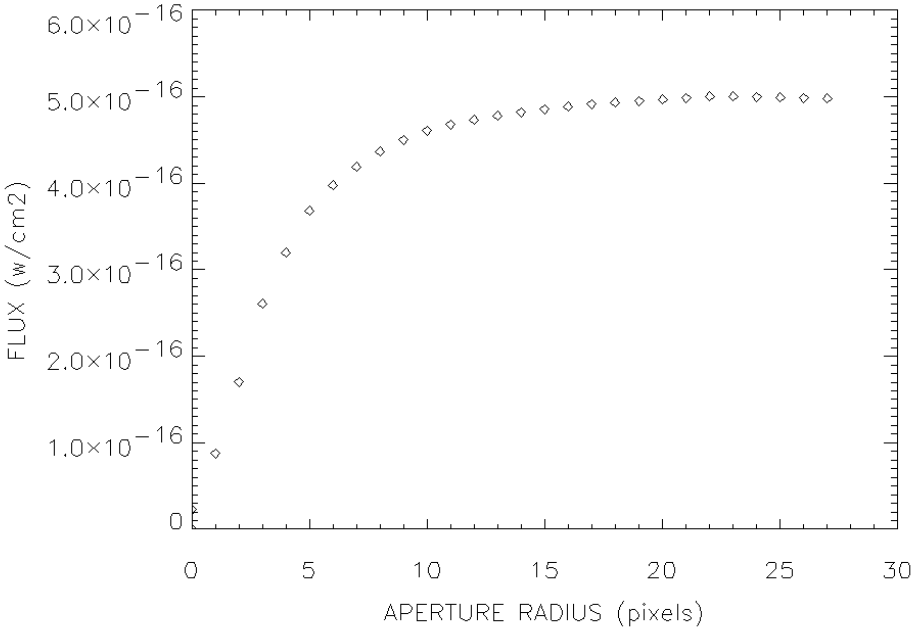

Figure 1b. Aperture photometry of the 12 μm survey radiance image #339 with iterative background subtraction (coma photometry).

Table 1. Results of "Coma" Aperture Photometry on the Survey Observations						
SOP	OBS	RHO (AU)	DELTA (AU)	BAND (μm)	FLUX (w cm^{-2})	REMARKS
339		1.491	0.976	12	4.99×10^{-16}	
				25	3.97×10^{-16}	
				60	7.03×10^{-17}	
				100	7.16×10^{-18}	Noise/Background Structure
368		1.503	1.064	12	4.14×10^{-16}	
				25	3.55×10^{-16}	
				60	6.63×10^{-17}	
				100	8.79×10^{-18}	Noise/Background Structure
389		1.521	1.138	12	3.65×10^{-16}	
				25	2.86×10^{-16}	
				60	6.05×10^{-17}	
				100	6.90×10^{-18}	Noise/Background Structure
421		1.561	1.265	12	2.96×10^{-16}	
				25	2.69×10^{-16}	
				60	(6×10^{-17})	Background Structure
				100	?	Noise/Background Structure
493		1.695	1.624	12	(1.8×10^{-16})	Crowded Field
				25	(1.3×10^{-16})	"
				60	$>5.3 \times 10^{-17}$	"
				100	?	Noise/Background Structure

Comments on Colors and Flux Measures

One can convert the in-band radiance (w cm^{-2} sr^{-1}) to flux density units (Jy sr^{-1}) by dividing the in-band radiance by (13.48, 5.16, 2.58, and 1.00) x 10^{-18} for the 12, 25, 60, and 100μm bands respectively. This must then be corrected for the spectrum of the source, for example: for a blackbody at 250K the flux densities must be divided by 0.87, 1.11, 1.19, and 1.07 for the 12, 25, 60, and 100μm bands respectively. It is recommended that model spectral radiances be integrated over the IRAS spectral response and

compared to the observed in-band radiances rather than converting the observations to flux densities.

Colors (flux ratios) are a more complicated problem. Even after running the MCM high-resolution process the spectral bands have different resolutions. Ratios made from the 12μm and 25μm bands will have meaning since these two bands have virtually the same resolution at all iteration steps. However, if one wants to compare radiance ratios, say, R(12μm)/R(60μm), R(25μm)/R(60μm), etc. he will not obtain the desired result due to the different beam sizes involved. There are two sophisticated ways to approach this problem: 1) *Cross-band simulation* wherein a new set of images is made by scanning the high-res images with a simulation of the IRAS focal plane, running MCM on these new images to produce images that have the same resolution and can then be ratioed. 2*) Prior-knowledge* technique wherein say the 60μm high-res image is used as the starting point for constructing a 100μm image and vice versa. This technique results in an image of higher resolution than the cross-band technique. Both of these methods are described by Fowler and Aumann (1994).

A simple approach would use the beam-size information in the above table to estimate the two-dimensional gaussian beam profile necessary to convolve with the higher resolution image to produce an image at the resolution of the lower resolution image. These can then be ratioed for comparison to calculated spectral ratios. For example: one wishes to ratio a 20 iteration 12μm image with a 10 iteration 60μm image; the FWHM of the gaussian kernel would be 1) cross-scan: sqrt(86^2 - 37^2) = 77.6 and 2) in-scan: sqrt(50^2 – 23^2) = 44.4. The 12μm map is then convolved with the 77.6 x 44.4 kernel and the two maps ratioed. Values for other numbers of iterations and band combinations can be interpolated in the table. The assumption that the output PSF of MCM is gaussian is not really a bad one.

In addition, the noise images are good measures of the relative noise from one part of an image to another. They are poor estimates of the absolute noise level. The photometric noise map indicates the internal photometric error of the detector samples resulting from the averaging of overlapping samples. It does not include absolute errors such as calibration errors. This applies to both the survey and additional observations (AO) data. Beichman, et al (1988) estimates that the absolute errors in the IRAS absolute calibration are 2%, 5%, 5%, and 10% at 12μm, 25μm, 60 μm, and 100μm respectively due to uncertainty in the models used. These numbers should be RSSd with 3% uncertainty in the standard stars used and 4% uncertainty for spectral bandpass errors. I have removed some systematic errors by re-calibrating IRAS in accordance with Cohen, et al (1992). Thus an estimate of the uncertainties of the radiance data can be had by combining the above absolute errors with the noise map values in the root sum squared sense.

Some Interesting Plots

Figure 2 is a plot of the "coma" fluxes from survey scans in Table 1 and additional observations (AO) in Table 2. "Coma" fluxes from the tables are divided by the pre-perihelion "coma" flux (s287 o13). Curvature in these plots is an indication of spectral variations at differing heliocentric distances. The heliocentric distances are labeled on the plot. One expects the spectrum to change due to variations in grain temperature, size distribution, and possibly composition.

Table 2. Results of "Coma" Aperture Photometry on the AO Observations

SOP	OBS	RHO	DELTA	BAND	FLUX (w cm^{-2})	REMARKS
287	13	1.507	0.853	12	5.89×10^{-16}	
				25	4.07×10^{-16}	
				60	6.78×10^{-17}	
				100	8.98×10^{-18}	
407	12	1.541	1.204	12	3.63×10^{-16}	
				25	2.60×10^{-16}	
				60	4.02×10^{-17}	
				100	4.88×10^{-18}	Noise/Structure
407	43	1.541	1.206	12	3.56×10^{-16}	
				25	2.67×10^{-16}	
				60	4.53×10^{-17}	
				100	4.91×10^{-18}	Noise/Structure
509	40	1.735	1.725	12	?	Source Confusion
				25	?	"
				60	?	"
				100	?	"
510	22	1.737	1.730	12	?	Source Confusion
				25	?	"
				60	?	"
				100	?	"

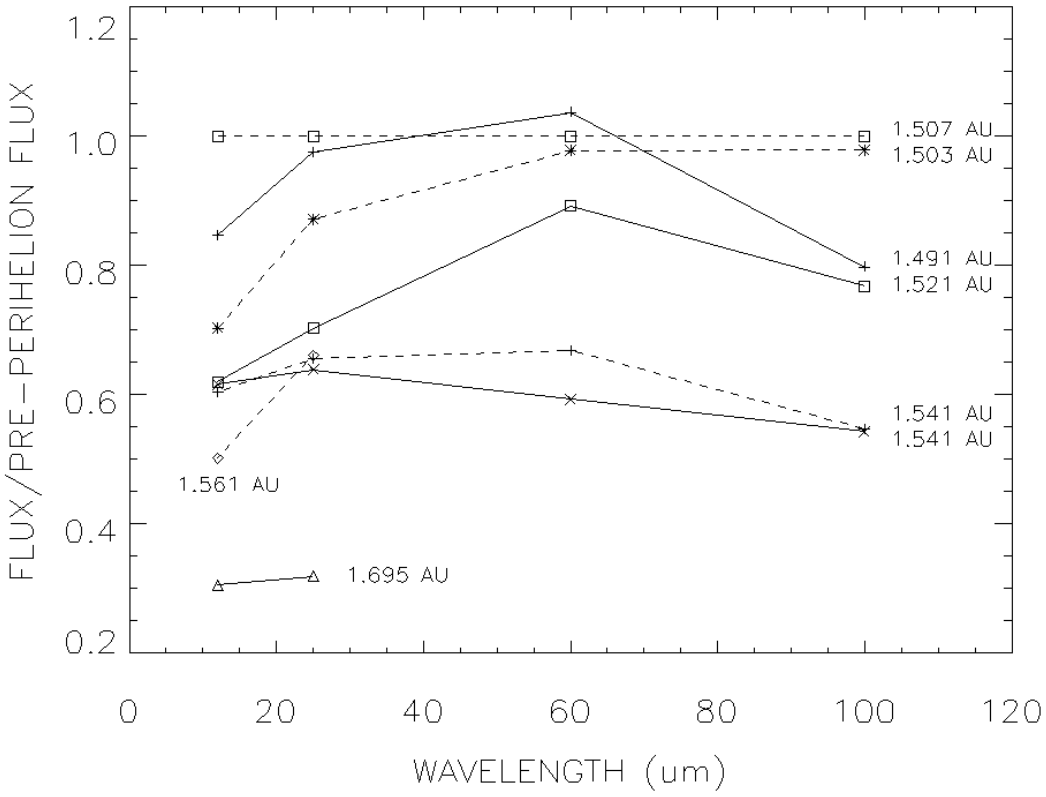

Figure 2. Tempel 1 spectrum relative to its pre-perihelion spectrum at 1.507 AU.

Figure 3 is a plot of the relative "activity" of Tempel 1 as a function of heliocentric distance. The "activity" is defined as Δ^2 x Flux (Δ), where Δ is the geocentric distance of the comet. This quantity is a measure of the dust production rate, or perhaps more properly, the resident time of dust within the beam. These data are normalized to the "activity" of the pre-perihelion observation. The heliocentric distances are labeled.

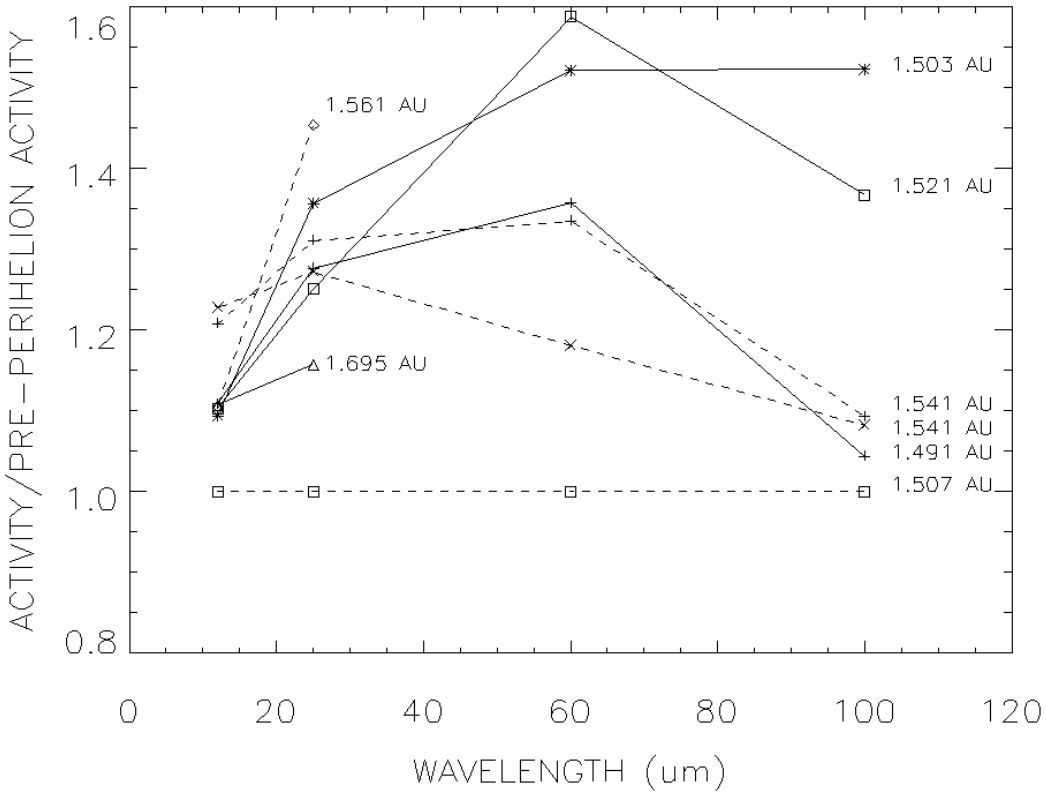

Figure 3. Activity of Tempel 1.

References

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