Explanatory Supplement to the IRAS Additional Observations of 9P/Tempel 1

Delivered to University of Maryland

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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. However, IRAS devoted almost 40% of its observing time to Additional Observations (AO), that is, pointed observations of selected fields of interest. Circumstances of the Tempel 1 AOs are given in Table 1. The observation labeled SOP 287, OBS 13 was made pre-perihelion, the rest were post-perihelion.

Table 1. Circumstances of the Tempel 1 Additional Observations

SOP	OBS	RHO (au)	DELTA (au)	PHASE (deg)
287	12	1.507	0.853	40.1
407	12	1.541	1.204	41.0
407	43	1.541	1.206	41.0
509	40	1.735	1.725	33.5
510	22	1.737	1.730	33.5

While construction of comet images from survey scans requires compensation for comet and spacecraft motion during the large time interval (~6000 sec.) between scans, the duration of an AO is usually less than 800 seconds. Motion compensation may not be necessary if the comet's apparent motion is sufficiently small.

Table 2. Details of the AO MACROS used for Tempel 1 Observations.

SOP	OBS	UTCS (start)	UTCS (stop)	MACRO	#S	Off "	T_{obs} sec.	T_{AO} sec.	ΔRA "	ΔDEC "
287	13	77610997	77611761	DPS52B	6	18	428	764	6.1	7.1
407	12	82793798	82794151	DPS60D	5	24	249	353	6.8	3.1
407	43	82812350	82812703	DPS60D	5	24	249	353	6.8	3.1
509	40	87233668	87234106	DPS60M	5	24	249	438	6.9	0.3
510	22	87264583	87265020	DPS60M	5	24	249	437	6.9	0.3

Notes:
1. #S is the number of scan legs in the MACRO.
2. Off is the cross-scan offset between scan legs in arcsec.
3. T_{AO} is the total duration of the AO in seconds.
4. T_{obs} is the actual time observing. The rest of the time was used to make fine attitude updates on reference stars at the beginning and at the end of the AO.
5. ΔRA and ΔDEC are the apparent motion of the comet during T_{obs} in arcsec.

Table 2 gives some details of the AO MACROS used for the Tempel 1 observations and the apparent motion of Tempel 1 during each AO. In all cases, the apparent motion of

the comet is smaller than the 15-arcsec default pixel size for HIRES processing (see description below). This pixel size is several times smaller than the best achievable HIRES resolution. The AO is completed in 0.14 of an IRAS orbit. This can produce a maximum of 1.1 arcsec parallax for a comet 1 AU away, small compared to the pixel size and best resolution. Thus, I decided that we could process the Temple 1 AOs using the HIRES program at IPAC, which assumes that the comet is fixed in inertial space during the observation.

HIRES employs the Maximum Correlation Method (MCM) (Aumann, Fowler and Melnyk, 1990) to construct resolution-enhanced coadded images of the observed fields. Details of the HIRES processing can be obtained from the IPAC/IRAS website, http://irsa.ipac.caltech.edu/IRASdocs/hires_proc.html from which are excerpted the following description: HIRES is a three-step process:

1. A program called AOCRDD is used to retrieve the raw AO data. The IRAS raw scan data are known as CRDD (Calibrated, Reconstructed Detector Data) and the full set of CRDD is stored in a FITS table format merged with the pointing information. The collection of the raw data in FITS table format is known as the Level 1 Archive.
2. A program called LAUNDR is used to clean up the CRDD.
3. A program called YORIC applies the MCM algorithm to the LAUNDR'd data. For HIRES, YORIC is iterated, progressively reconstructing a better model of the sky. In default processing YORIC is iterated 20 times.

The HIRES processing defaults were chosen to provide the best performance (highest resolution and freedom from artifacts) for the majority of targets. These were adopted for the Tempel 1 images. They are:

1. The image size is 1 degree by 1 degree.
2. The pixel size is 15".
3. All four bands (12, 25, 60 and 100μm) are processed.
4. The data are de-striped with detector baseline removal and flux bias is applied.
5. The beam sample maps use a regular grid of 10-Jansky sources on a flat background.
6. All types of ancillary maps are produced.
7. The algorithm is iterated 20 times, with maps produced at the 1st, 5th, 10th and 20th iterations.

HIRES outputs several diagnostic files in addition to the surface brightness map. These ancillary maps are important to the interpretation of the HIRES results. The maps produced are:

1. surface brightness map
2. coverage map
3. photometric noise map
4. correction factor variance map
5. HIRES'd beam sample maps
6. simulator input "spike" plus background model for beam sample maps
7. detector track maps
8. beam width report for the last iteration

9. processing log file

The complete set for one AO consists of 76 images and 12 ASCII files.

HIRES accepts electronic requests for automated image reprocessing. Visit http://irsa.ipac.caltech.edu/IRASdocs/iras_data_requests.html for an electronic request form. IPAC documentation states that the last version of HIRES dates to June 1997.

File Designations and Content

The delivered data set includes radiance and noise images, processing logs, aperture photometry files, and beam profile reports. The IRAS AOs are identified by their satellite operations plan (SOP) and observation (OBS) number. The IRAS observations were made in four spectral bands centered nominally at 12μm, 25μm, 60μm, and 100μm. Images are supplied for the first (01) and 20th iteration (20). R. Walker retained the images for the 5th and 10th iterations because the images are inferior to the 20$^{th.}$ The following file names were adopted:

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

Radiance Maps (80) – sSOP_oOBS_Band_Iteration#_radiance.fit
Noise Maps (80) – sSOP_oOBS_Band_Iteration#_noise.fit

Radiance and Noise Coma Photometry Tables in /data/ao/phot/:

Radiance Phot Tables (20) – sSOP_oOBS_Band_Iteration#_radiance.tab
Noise Phot Tables (20) – sSOP_oOBS_Band_Iteration#_noise.tab

Processing logs in /calib/ao/proclogs/:

Reduction Logs for Images (20) – sSOP_oOBS_Band_log.txt
Reduction Logs for Simulations (20) – sSOP_oOBS_simul_Band.txt
Beam Width Report (20) – sSOP_oOBS_beam_Band_fwhm.txt

The numbers in parenthesis above are the number of files that you should have received. Bands b1, b2, b3, and b4 are the 12μm, 25μm, 60μm, and 100μm bands respectively.

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 20 iteration 100μm image.

```
SIMPLE  =                    T / Written by IDL:  14-Feb-2001 12:59:15.00
BITPIX  =                  -32 / IEEE single precision floating point
NAXIS   =                    2 /
NAXIS1  =                  241 / Cross-scan grid dimension
NAXIS2  =                  241 / In-scan grid dimension
BLOCKED =                    T / TAPE MAY BE BLOCKED IN MULTIPLES OF 2880
```

```
EXTEND  =                    T / TAPE MAY HAVE STANDARD FITS EXTENSIONS
OBJECT  = '9P/TEMPEL 1'        / Object imaged by YORIC
CTYPE1  = 'RA---CAR'           / Decreases in value as sample index increases
CUNIT1  = 'deg'                / RA unit
CRVAL1  =          194.0374908 / RA at origin (deg)
CRPIX1  =                121. / X-axis origin (cell)
CDELT1  =      -0.004166666884 / Pixel X-width (deg)
CROTA1  =                   0. / Twist (celest clk) angle undefined for X-axis
CTYPE2  = 'DEC--CAR'           / Increases in value as line index increases
CUNIT2  = 'deg'                / DEC unit
CRVAL2  =        -0.6277800202 / Dec at origin (deg)
CRPIX2  =                121. / Y-axis origin (cell)
CDELT2  =       0.004166666884 / Pixel Y-width (deg)
CROTA2  =                   0. / Rotates +NAXIS2 into Lat axis (angle
COMMENT                          measured positive CCW from
COMMENT                        +NAXIS2 to +Lat) (degrees)
BUNIT   = 'W/cm2/sr'           / Watts/cm2/steradian
BLANK   =          -2000000000 / Value for empty cell
BSCALE  =              1.00000 / TRUE=TAPE*BSCALE+BZERO
BZERO   =             0.000000 /
DATAMAX =        3.0684367E-10 / Watts/cm2/sr (in-band radiance) max valid phys
DATAMIN =       -6.7676536E-13 / Watts/cm2/sr (in-band radiance) min valid phys
SIGMA   =      6.800000072E-13 / Median detector noise (Watts/cm2/sr)
SIGORIG =         0.6800000072 / Median detector noise (MJy/ster)
BIAS    =                   0. / Median pixel flux subtracted
EQUINOX =                1950. / EME50
RADECSYS= 'FK4     '           /
TELESCOP= 'IRAS    '           / IRAS Satellite
INSTRUME= 'YORIC   '           / HiRes imaging program developed
COMMENT                          for IRAS data at IPAC, Pasadena, CA
DATE    = '02/15/2001'         / Date of final processing (m/d/y)
ITERNO  =                  20 / Number of iterations done
VERSION = '2.11 960805'        / Version of YORIC
COMMENT     This is a "HiRes" image generated by the Maximum Correlation Method
COMMENT     (see Aumann, Fowler, and Melnyk, Astron. J. Vol. 99, No. 5, p. 1674,
COMMENT      1990)
COMMENT     YORIC: Offset compensation was used for destriping
COMMENT     The destriping method was the same in all input observations.
FBIAS   =       1.06500002E-14 / Flux bias used (Watts/m2)
FBIASL  =       1.06500002E-14 / Flux bias from Laundr (Watts/m2)
COMMENT     Laundr flux bias is the maximum in all input observations
FMIN    =     -1.746099975E-14 / Min normalized flux (Watts/m2) in Laundr
FBPCT   =       0.009999999776 / FBIAS percentile (dec. fraction) in Laundr
DETMIN  =                    1 / Detector on which FMIN was found in Laundr
FILENAME= 's287_o13_100um_20_radiance.fit' / OUTPUT FILE NAME
INFIL01 = 'data/tmpl_s287o13s' / INPUT FILE NAME
COMMENT      SOP =        287    OBS =  13
COMMENT     Input Destripe:  Baseline removal
COMMENT    Laundr version: 1.39 951004
COMMENT    Raw data were Laundred on 11/22/ 0
COMMENT    Pass 3 CRDD were used; Level 1 Archive usage: NONE
COMMENT    Data are on the AC scale
COMMENT  AOCRDD VERSION  4.2   940603; date of run:  11/22/00
COMMENT  Jan 2003, PDS Small Bodies Node modified the header:
COMMENT    1) Removed the unused NAXIS3 = 1 keyword.
COMMENT    2) Corrected several keywords and values.
COMMENT    3) Added keyword comments for clarification.
COMMENT    4) Added observation-specific keywords at end of header.
COMMENT    5) Image size is 1 degree by 1 degree.
COMMENT    6) Pixel size is 15 arcsec by 15 arcsec.
COMETMAX=          1.69721E-11 / Watts/cm2/sr  (in-band radiance)
PIXMAXX =                  120 / x pixel number of max comet radiance
PIXMAXY =                   94 / y pixel number of max comet radiance
```

```
WAVE    =                  100 / Wavelength (microns)
MEAN_JD =          2445503.780 / Mean Julian date of combined observations
MEANDT  = '1983-06-18'         / Mean UTC date of combined obs
MEANTM  = '06:43:12.000'       / Mean UTC time of combined obs
SOP     =                  287 / Satellite operations plan number
OBSNUM  =                   13 / Observation number within SOP
RHO     =                1.507 / Sun-Comet distance (AU)
DELTA   =                0.853 / Earth-Comet distance (AU)
PHASE   =                 40.1 / Phase angle (S-T-O) (deg)
MACRO   = 'DPS52B'             / AO MACRO used
NLEGS   =                    6 / Number of scan legs by MACRO
XSCANOFF=                   18 / Cross-scan offset between scan legs (arcsec)
TOBS    =                  428 / Actual time observing (sec)
TAO     =                  764 / Total duration of AO observation (sec)
DELRA   =                  6.1 / App. motion of target during Tobs (arcsec)
DELDEC  =                  7.1 / App. motion of target during Tobs (arcsec)
UTCSTART=         2445503.7754 / UTC at start of obs (JD)
UTCSTOP =         2445503.7843 / UTC at end of obs (JD)
STARTDT = '1983-06-18'         / UTC date at start of obs
STARTTM = '06:36:37.000'       / UTC time at start of obs
STOPDT  = '1983-06-18'         / UTC date at end of obs
STOPTM  = '06:49:21.000'       / UTC time at end of obs
SCSTART =             77610997 / IRAS native time at start of obs
SCSTOP  =             77611761 / IRAS native time at end of obs
NO_SCAN =             -9999.00 / Array elements outside of scan are set to -9999
END
```

The image is 241 x 241 pixels (NAXIS1 x NAXIS2). The coordinate system is equatorial (RA,DEC (B1950)). The comet is not centered in the image. The pixel size is 15 x 15 arcsec. The maximum radiance of the comet (COMETMAX) occurs at PIXMAXX and PIXMAXY. MEAN JD is the Julian date at the mid-time of the AO. You will also 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.

The maps are 1 degree by 1 degree, but the IRAS scan is only ~30 arcminutes wide and therefore does not fill the image area. The array elements that lie outside of the scanned area a have the value –9999.00, identified by the FITS keyword NO SCAN = -9999.00. .

Note that the original value for SIGMA was in units of mega Jansky per steradian. This value was converted to the in-band radiance by multiplying the original SIGMA value in the FITS header by (13.48, 5.16, 2.58, and 1.00) x 10^{-12} for the 12, 25, 60, and 100μm bands respectively. The original SIGMA value is retained in the SIGORIG keyword.

Although the images are binned into 15 arcsecond pixels, the actual resolution within the image is dependent on (among other things) the number of iterations.

HIGHRES creates a grid of 10 Jansky point sources spaced throughout the image field and then processes these sources as if they were scanned by the AO. The beam width reports give the full width at half maximum of the best fitting gaussian to the resulting profiles. These can be used as an estimate of the resolution as a function of position within the field.

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 photometry files delivered to PDS-SBN in 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. This is given in Table 3 for the AO data and Table 4 for the survey data.

Table 3. 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	?	"

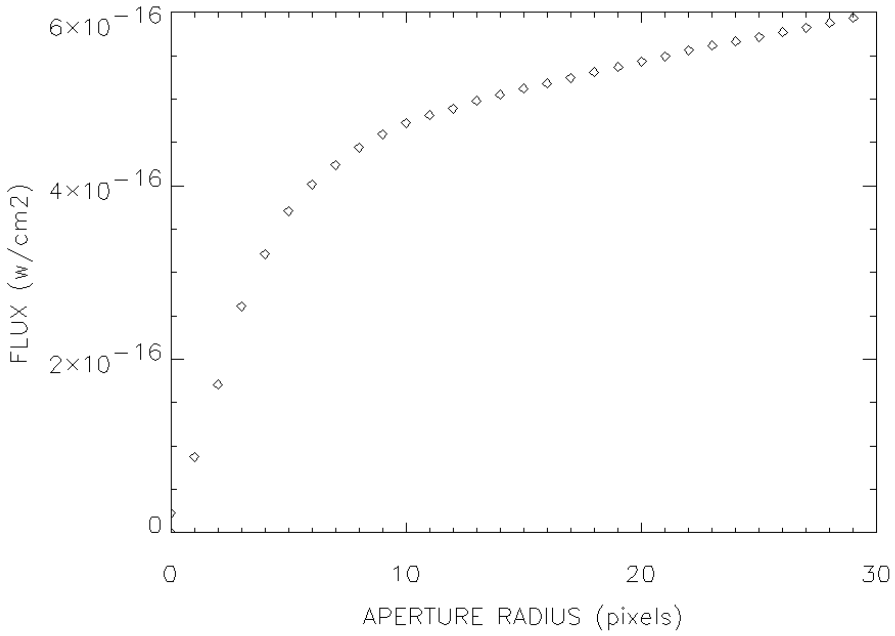

Figure 1a. Aperture photometry of the 12 μm survey radiance image #339 with median background subtraction as delivered on December 29, 2000.

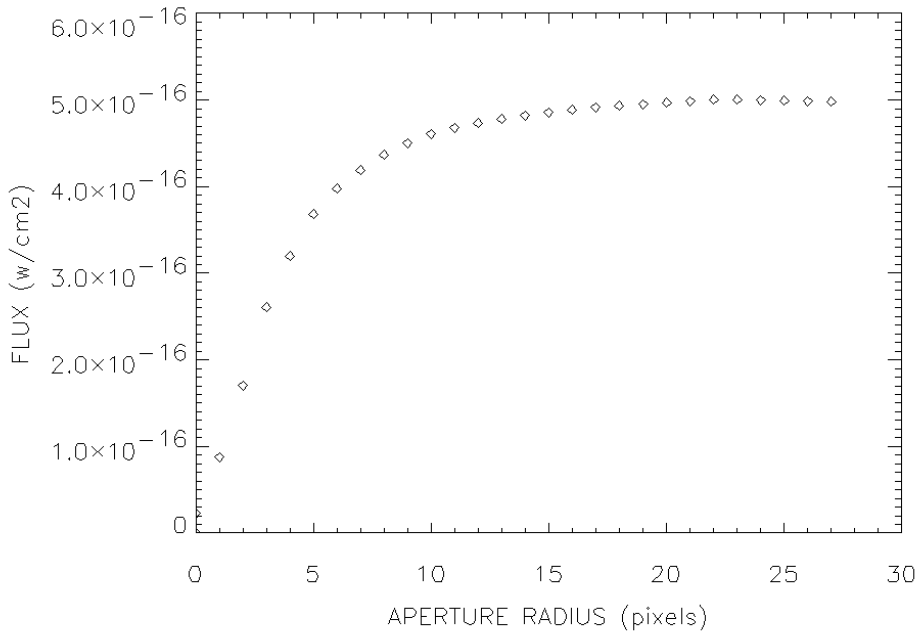

Figure 1b. Aperture photometry of the 12 μm survey radiance image #339 with iterative background subtraction (coma photometry).

Table 4. 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

The survey photometry has been redone using the new software and radiance survey "coma" photometry files have been included in the present delivery.

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-resolution 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-resolution 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 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 in Tables 3 and 4 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.

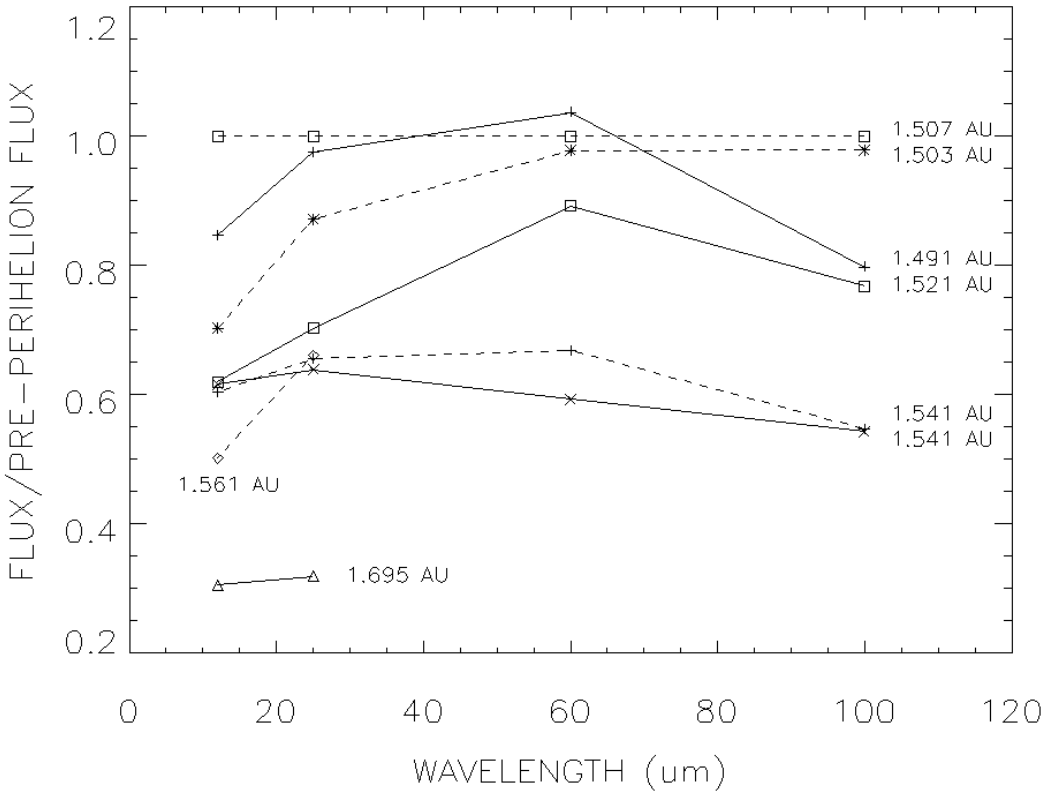

Figure 2. Tempel 1 spectrum relative to its pre-perihelion spectrum at 1.507 AU.

Figure 3 is a plot of the relative "activity" of Tempel 1 as a function of heliocentric distance. I have defined the "activity" 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. I have normalized these data to the "activity" of the pre-perihelion observation. The heliocentric distances are labeled.

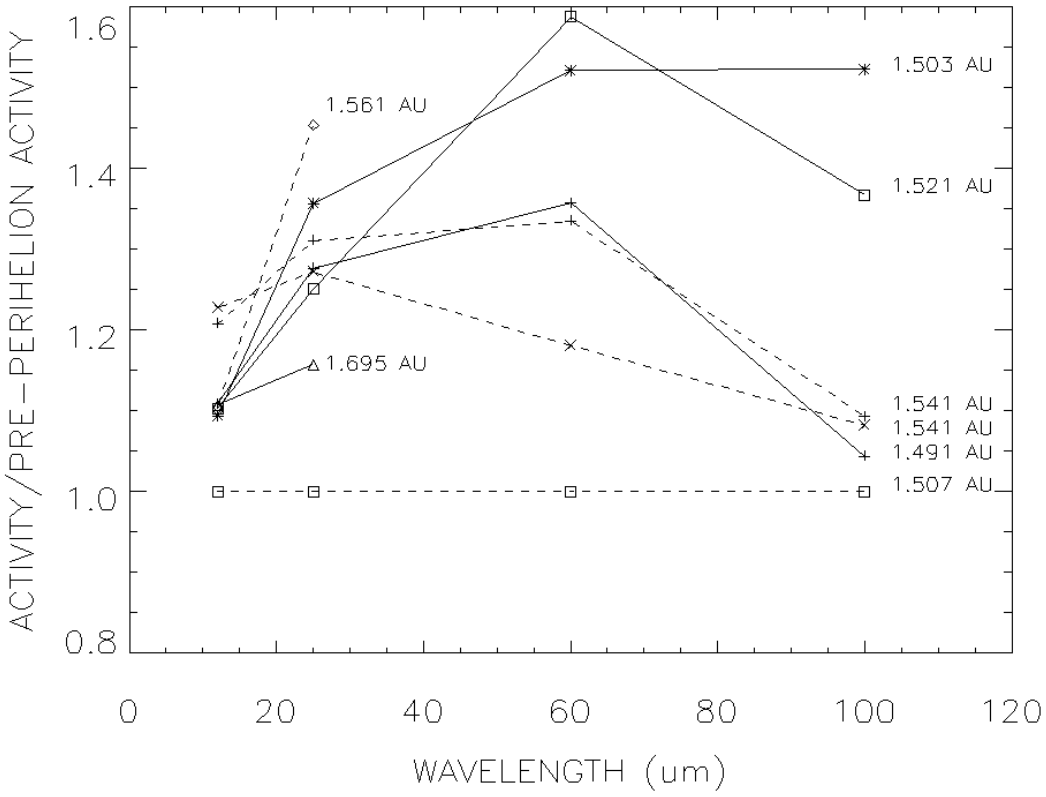

Figure 3. Activity of Tempel 1.

References

Aumann, H.H., Fowler, J.W., Melnyk, M., 1990, "A Maximum Correlation Method for Image Construction of IRAS Data", Astron. J. 99, 1674-1681

Beichman, et al, 1988, 'IRAS Catalogs, Vol 1. Explanatory Supplement'

Cohen, M., Walker, R.G., Barlow, M.J., Deacon, J.R., 1992, "Spectral Irradiance Calibration in the Infrared. I. Ground-based and IRAS Broadband Calibrations", Astron. J. vol. 104, no. 4, pp 1650-1657.