

Early Recovery of Comet 55P/Tempel-Tuttle

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Abstract.

We present recovery observations of 55P/Tempel Tuttle using the Keck II telescope. At recovery, the comet was at $r = 4.5$ AU, with $m_R = 22.6$, and there was no indication of coma or activity. Pre- and post-recovery observations from 6 observing runs (1994-1997 June) will be presented. From these measurements we estimate that the nucleus radius is $r_N = 1.9$ km with a nucleus elongation greater than 1.5. As of 6/97 ($r = 3.5$ AU), the comet had not yet turned on.

Key words: Comets, Recovery, CCD Mosaic

rate of meteors is relatively stable at around 15 hr^{-1} .

Meteor streams provide us with an independent observation of comet dust from which we have inferred information on the physical nature of the dust *e.g.* the chemical properties (spectroscopy) and density (Hajduk and Hajduková, 1990; McIntosh, 1991). The particles in the stream depend on the irregular mass loss from the parent, which in turn depends on the nucleus properties. Wu and Williams (1996) predict that the 1998 / 1999 Leonid storm will be unimpressive, however, Yeomans *et al.* (1996) suggest that there is the possibility of a significant display during both years.

1. Introduction

Comet 55P/Tempel-Tuttle, discovered independently on 19 December 1865 and 5 January 1866, is the parent of the Leonid meteor stream, however much more information is known about the stream than about the parent body. The Leonid stream has produced some of the greatest meteor storms in history, most notably the storms in 1833 (with meteor rates up to $50,000 \text{ hr}^{-1}$) and 1966 (with rates up to $150,000 \text{ hr}^{-1}$; Milon, 1967). In fact, the Leonid showers have been documented back to 902 A.D. Unlike some comets, radiation pressure and planetary perturbations dominate the evolution of the dust, rather than the ejection processes. This has led to an uneven distribution of material in the orbit – where the material trails behind the comet and outside the orbit of the comet. The period of comet 55P/Tempel-Tuttle is 33.25 years, however, because the distribution of the dust from the parent comet is not uniformly distributed, significant Leonid showers are only possible when the Earth trails the comet and passes just outside of the comet's descending node (Yeomans, 1981; Yeomans *et al.*, 1996). During non-storm years, the

Comet 55P/Tempel-Tuttle is a Halley-family comet, *i.e.* it has migrated inwards from the Oort cloud via planetary perturbations. Unlike the observable short-period comets originating from the Kuiper belt, the Halley-family comets are probably less evolved than the Jupiter-family comets. Unfortunately virtually nothing is known about the parent comet. Astrometric data exist for the comet from the 1699, 1865-66 and 1965 apparitions, and from a 2000 year backward orbital integration Yeomans *et al.* (1996) believe that they may have identified observations of the comet by the Japanese in 1234 and the Chinese in 1035. Although the second comet spectrum ever taken was made in 1866, there were no observations of the comet's physical behavior made – even at the 1965 apparition, so there is no information about the dust production. The comet will be making its closest approach to Earth in 132 years (Yeomans *et al.*, 1996), passing within $\Delta = 0.36$ AU. This is the first apparition where modern detectors have been available to watch the development of the activity in the comet. The goal of the present program was to make an early observational recovery of the comet so that both nucleus observations and the development of the activity and measurement of the dust production could be made. In addition to this program to characterize the nucleus, an extensive International Leonids watch is being planned

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for the 1998 / 1999 apparition, with the beginnings of the increase in shower rates first being observed in 1994 and 1995 (Janniskens, 1996).

2. Observations

During a program of very distant comet observations at the Keck II Telescope on 4 March 1997 we targeted 55P/Tempel-Tuttle for recovery (in part because the weather conditions were too poor to try for the really faint targets at $m_R \approx 28$ -29). The comet was easily visible in a 900 sec integration. Unfortunately we had only one night allocated to this program and were unable to confirm the recovery. At the time of recovery the comet did not display any evidence of coma or activity. For an inactive comet, the identification of the object is not unambiguous without 2 nights of data. (In an active comet, the morphology clearly distinguishes the comet from possible distant asteroids in the field). It is also not possible to unambiguously identify a comet by position and rates alone without a second night of data to verify the orbit (Marsden, 1981; 1994; 1996a,b; 1997; Bowell *et al.*, 1989). Because we had only obtained 1 night of data for the recovery, we put out an urgent request for followup observations. Observations were made on 7 March 1997 using the NTT telescope and the comet was reported as recovered (Hainaut *et al.*, 1997; Martin *et al.*, 1997). Subsequent to the recovery observations, we analyzed data obtained prior to 1997, and were able to identify several pre-recovery images of the comet. Table 1 lists the observation circumstances for each of the observing runs.

Notes: ¹ Geocentric and Heliocentric distances [AU] of observation; ² Solar elongation [deg]; ³ Phase Angle [deg] of observations; ⁴ Telescope: ESO NTT: 3.54m New Technology Telescope, European Southern Observatory, La Silla, Chile ESO 2.2: 2.2m ESO/Max Planck Institut, ESO, La Silla, Chile UH 2.2: 2.2m University of Hawaii'i, Mauna Kea, Hawaii'i Keck II: 10m Keck-II, W.M. Keck Foundation, Mauna Kea, Hawaii'i Palomar 5m Hale Telescope, Palomar Observatory, California; ⁵ Observer: CD: Catherine Delabodde HB: Hermann Boehnhardt JB: James Bauer KM: Karen J. Meech OH: Olivier R. Hainaut PW: Paul Weisnann RW: Richard M. West; ⁶ Exposure time [seconds]; ⁷ Sky brightness [mag arcsec⁻²]; ⁸ Seeing [arcsec]; and ⁹ comments: 1: not photometric; 2: independent calibration.

2.1. 1994 May 10-11; $r = 10.8 AU$ (NTT)

The pre-recovery orbital elements used for these observations were unfortunately off by about $70''$ with respect to the position computed using the post-recovery elements, which is more than half the field-of-view of the S&SI camera. Thanks to the large offsets applied to the telescope for the image dithering, the actual position has been imaged on one of the individual frames. However, the limiting magnitude of that frame is only $m_R = 25$, which is not

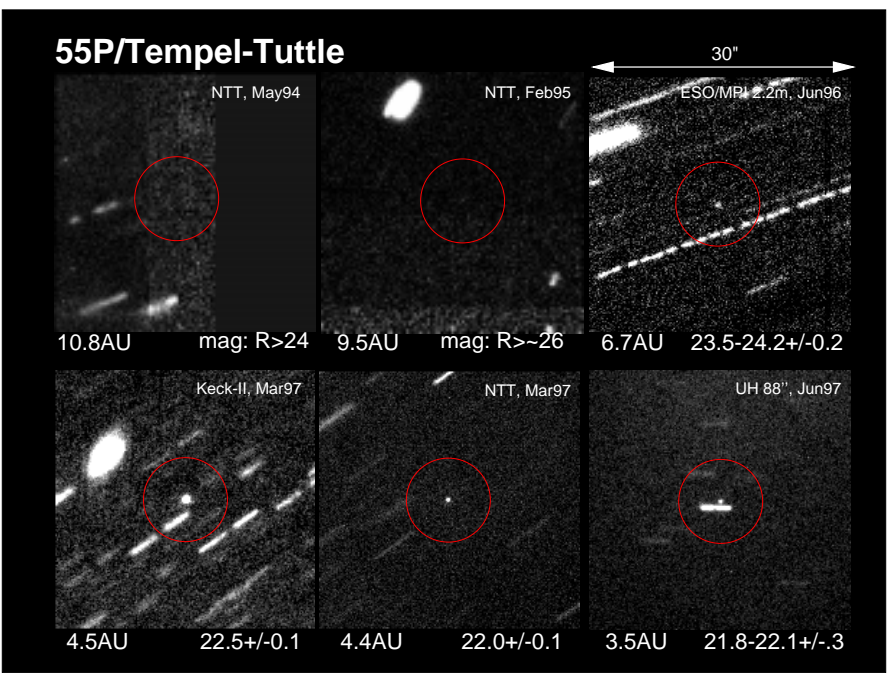


Fig. 1. Composite images of comet 55P/Tempel Tuttle from 1994 May through 1997 June.

very constraining for a comet at 10 AU. The image presented in Fig. 1 shows the composites of all the available frames, centered on the expected positions of the comet, using the new elements.

2.2. 1995 February 3-4; $r = 9.5 AU$ (NTT)

As for the 1994 observations, the ephemerides computed using the prerecovery elements were off by almost $60''$. Fortunately, the images obtained during the second night show the expected position for the comet close to the edge XXXX. A 2.8σ object about $3''$ from the expected position is visible on the composite XXX sec image. It is too faint to be visible in the single frames, or even in partial composites. While the object may well be the comet, the 2.8σ level does not ensure a high enough statistical significance (the probability for the candidate to be a noise feature is XXX%), therefore, we cannot consider it as a detection; the 3σ limiting magnitude is reported as upper limit for the brightness in Table 3.

Table 1. Observing Circumstances

UT Date	Δ^1	r^1	Elong ²	Phase ³	Tel ⁴	Obs ⁵	Exp ⁶	Sky ⁷	Seeing ⁸	Notes ⁹
1994 May 12	9.84	10.82	166.2	1.27	ESO NTT	OH	6000	21.4	1.1	
1995 Feb 04	9.41	9.50	92.5	5.95	NTT	RW	4000	21.0	0.7	
1996 May 12	5.85	6.74	149.5	4.37	ESO 2.2m	HB	5360	xx.x	x.x	
1996 Jun XX	x.xx	x.xx	xxx.x	x.xx	Palomar 5m	PW	xxxx	xx.x	x.x	
1997 Mar 04	3.65	4.45	139.5	8.32	Keck II	KM,OH,JB	1800	20.5	x.x	
1997 Mar 07	3.60	4.43	142.6	7.83	ESO NTT	PM	900	20.4	x.x	
1997 Apr 15	3.14	4.08	155.0	5.97	UH 2.2m	OH,KM	2850	xx.x	x.x	
1997 Jun 17	3.48	3.48	81.7	16.79	UH 2.2m	OH,CD	1200	19.0	x.x	

2.3. 1996 May 12; $r = 6.7$ AU (ESO/MPI 2.2m)

While the comet is not visible on most of the single frames, it appears on some of them, and is clearly visible on a composite made from half of the collection of single frames. Because of its faintness, the comet was not immediately identified when the images were taken.

2.4. 1996 June XX; $r = 6.XX$ AU (Palomar 5m)

Do you really think his data is any good? Will it really add anything to the paper? I am not keen on including it for the following reasons: (1) first, he is not a good observer - does not really know what he is doing, and I feel strongly about not putting in data that I am not confident about into the paper (2) secondly, this may set a precedent of collaboration whereby he will expect further interaction and this may help establish his right to the UH telescopes - in the sense that the TAC may insist on collaborations (as they did with Belton in the past).

2.5. 1997 March ; $r = 4.5$ AU

March 4, Keck-II — Images were obtained with the LRIS imaging spectrometer from the remote observing room in Waimea. Several hours during the first half of the night were lost because of a coolant leak from the detector. After repairs, we were just coming on line again when thick clouds appeared. We quickly changed our program to look at bright objects and targeted 55P/Tempel-Tuttle. We obtained 7 images of the comet - 4 of which are very bad because of clouds (very poor S/N, poor image quality). The 3 remaining ones were fortunately obtained through gaps between clouds and are the deepest of all the Tempel-Tuttle images available.

March 7, NTT — While the S/N of the March 4 images did not leave any doubt about the reality of the object, its star-like appearance and the short time span covered by the Keck observations left some doubt about the identity of the object. A single, 900s image was obtained at the NTT by XXX and the NTT team, showing the object and confirming its identity. [put some details about the instrumentation and observing techniques here].

2.6. 1997 April 15,17; $r = 4.08$ AU (UH 2.2m)

Images were obtained on 1997 April 15 using the UH 2.2m telescope with the Tektronix 2048 CCD camera (scale: $0.219'' \text{ pix}^{-1}$) at the Cassegrain focus. The night started

with some high altitude clouds and high humidity, however by 8 UT the sky appeared clear, and the humidity had dropped enough to open by 10:30 UT. Although the night appeared photometric after opening, and some standards were taken, the 55P/Tempel Tuttle fields were re-calibrated on the following night. Images were also obtained on 1997 April 17, also during non-photometric conditions.

2.7. 1997 June 18; $r = 3.5$ AU (UH 2.2m)

Director's discretionary time was obtained on the UH 2.2m from 1997 June 17-19 UT for the purpose of calibrating comet data taken under non-photometric conditions. The Tektronix 2048 CCD was used with the f/31 focus giving a plate scale of $0.14''$ per binned pixel. On the first night of the run all of the previous 55P/Tempel Tuttle images were re-calibrated, and on 1997 June 18 additional images of the comet were obtained.

3. Data Reduction

All the images have been processed in a usual way: a template bias frame is created by taking the 2-dimensional median of a collection of many 0-sec exposures obtained at the beginning and end of each night. This composite bias is subtracted frame by frame from all the raw data. Additional variations of the global bias level are corrected for using the mean of the overscan region of each frame. The dark current was estimated using long, dark exposures; in all cases, it was found small enough to be neglected. Special care was taken to generate excellent detector sensitivity maps, or flat-fields, that correct all the sensitivity variations without introducing any significant amount of noise. Ideally, for each night, a series of dome flat fields and sky twilight flat fields are obtained. They are bias subtracted, then normalized to a mean level of 1, and median averaged to form a template dome flat-field and a template twilight flat-field. The long scientific exposures are themselves very valuable as flat-fields, as the sky color and detector illumination are exactly those prevailing during the observations, while the twilight and especially the dome flats are obtained with a different color of light and type of illumination. In order to use the science images as flat-fields, it is important to dither the telescope between each of the exposures, so that a given object always falls on a different part of the detector. The scientific images are normalized so that their mean sky level is equal to 1, the

brightest stars and objects of each frames are marked, and all the frames are median averaged (rejecting the marked regions, if necessary), forming a template science flat-field.

Each of the three template flat-fields has its advantages and problems: the dome flat has an excellent signal-to-noise ratio, but very poorly represents the large scale variations of sensitivity; the twilight flat has also a good signal-to-noise ratio, and better represents the large scale variations of the flat-field. These variations are perfectly measured by the science frame flat, but this flat has a very poor signal-to-noise ratio (being the average of only a few images, each one having only a few hundred to thousand counts), and is therefore useless for small scale sensitivity variations. If only one of the three templates can be used, the twilight flat is a very good compromise. When possible, however, full advantage of each of the templates can be utilized (Hainaut *et al.* 1994). To do this, we separate each of template flat into a series of frames, each containing the information from the sensitivity map for a range of spatial frequencies (pixel-to-pixel variations, small scale variations, small scale gradients to finally large scale gradients). This separation is performed using a wavelet decomposition package implemented in MIDAS. The final flat-field template is obtained by combining the frames corresponding to the frequencies that each of the templates sample the best. While the actual combination varies from situation to situation, a typical example would be:

Final Flat = 0.5 × (high frequencies from dome + high frequencies from twilight) + medium frequencies from twilight + low frequencies from science flat

Photometric Calibration — The images presented in this paper were obtained over a long time period, using different detectors and telescopes; moreover, some of the observing runs were not photometric. Therefore, we preferred to recalibrate all the data. During the June 1997 run, all the fields (except Palomar’s) were re-imaged using the UH2.2m telescope, through the R and I filters. During this run, we also obtained images of a large number photometric standard fields (Landolt, 1992) at different airmasses, ensuring a complete calibration of the system used, including the atmospheric extinction and the color terms of the photometric transformation. The magnitude of the comet (or the limiting magnitudes) during the other runs were determined from relative photometry using all the stars visible in the original and June 1997 images. The magnitude of the comet was obtained using a color R-I = 0.35 for the color transformation; this color was selected as the mean of a well measured sample of cometary nuclei (Meech, 1997). Note that the change introduced by the use of another value would be much smaller than the other errors.

Astrometric Calibration — The position of the comet was calibrated using the position of field stars as measured on the Digital Sky Survey. At least 5 or 6 stars

were used in the transformations; the RMS residuals of the transformation are 0.1–0.4'' depending on several factors, including the number and brightness of the stars, and their trailing in the original images. All the frames were registered with respect to each other using several stars visible in each image. The registered frames were then calibrated astrometrically, and the expected position of the comet was obtained using its equatorial position computed for the epoch of the mid-exposure and the astrometric transformation. The frames were also co-added after registration on the expected position of the comet. The resulting composites show the stars as long trails, and the comet as a point source. It should be noted that the trails are not necessarily straight lines, since the ephemerides used for the dithering took into account the variations of the comet’s proper motion caused by the earth’s rotation. Below is a table of the astrometry for 55P/Tempel-Tuttle.

4. Discussion

4.1. Absolute Magnitude and Nuclear Diameter

Assuming that the comet does not display any cometary activity, its brightness should strictly follow an inverse square law which can be expressed as

$$m(r, \Delta, \alpha) = m_{1,1,0} + 5 \log(r\Delta) + 0.04\alpha$$

where $m_{1,1,0}$ is the magnitude normalized to $r = \Delta = 1$ AU and the phase angle $\alpha = 0$. This may of course be modulated by brightness variations due to the rotation of the comet. In Table 3 we present the photometry for all of the runs (average m_R magnitudes), and in addition have presented the $m_{1,1,0}$ values calculated from the data. Within the errors, the data do not deviate from the inverse square law, thus we interpret this to mean that the comet was not active, even at $r = 3.5$ AU. The m_R magnitude reduced to $\Delta = r$ is plotted in Fig. 2.

The weighted mean value of $m_{1,1,0}$ may be used to compute the radius of 55P/Tempel-Tuttle (Russell, 1916):

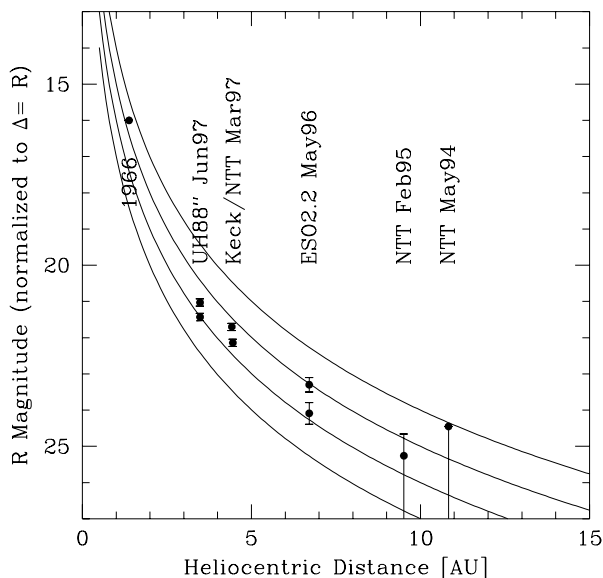
$$p_v R_N^2 = 2.235 \times 10^{22} r^2 \Delta^2 10^{0.4(m_\odot - m_R)}$$

where $p_v = 0.04$ is assumed for the geometric albedo and $m_\odot = -27.10$ is the red solar magnitude. The radii derived from this equation are shown in Table 3. Although a small nucleus, this is consistent with what is being found for other comet nuclei (Meech, 1997). A comparison of the nuclei sizes is shown in Fig. 3.

The amplitude of any observed lightcurve caused by rotation of the nucleus may be used to obtain a minimum axis ratio for the comet. None of the runs had sufficient time base coverage to constrain the rotation; however, on several runs (1996 May, 1997 March and 1997 June)

Table 2. Comet 55P/Tempel-Tuttle Astrometry

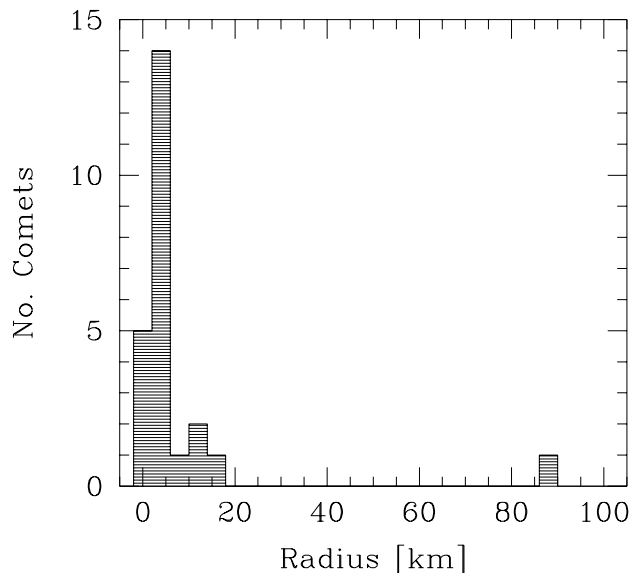
UT Date	$\alpha_{(J2000)}$	$\delta_{(J2000)}$	Obsty
1996 05 12.09294	13 38 41.72	+00 16 22.2	808
1996 05 12.13955	13 38 39.77	+00 16 33.2	808
1996 05 12.11580	13 38 40.79	+00 16 27.5	808
1997 03 07.31080	13 40 40.80	+05 10 45.3	809
1997 03 04.62838	13 43 12.63	+04 43 37.7	568
1997 03 04.63700	13 43 12.31	+04 43 41.7	568
1997 03 04.64876	13 43 11.57	+04 43 49.0	568
1997 03 04.65752	13 43 11.07	+04 43 54.4	568
1997 06 18.30963	11 36 32.60	+17 21 54.0	568
1997 06 18.31785	11 36 32.37	+17 21 53.2	568

**Fig. 2.** Lightcurve of 55P/Tempel-Tuttle normalized to $\Delta=r$. Pre-recovery upper limits are shown for the 1994 and 1995 NTT data. The data are consistent with no activity from a 1.9 km radius nucleus.

more than 1 image was taken, and in all cases the difference between the magnitudes obtained from the images was greater than the errors (*i.e.* significant). We assume that the differences are due to rotational modulation. The largest change in brightness occurred during the 1996 May run. We assume that the bare nucleus can be modeled as a tri-axial ellipsoid with axis dimensions $a > b > c$. If the comet is rotating along the shortest axis, then the area of the nucleus projected on the plane of the sky would vary from πac to πbc (if the aspect angle is 90° ; or πab for an aspect angle of 0°). The measured lower limit to the amplitude of the light curve can be interpreted as a lower limit for the $a : b$ ratio:

$$\epsilon = b : a \leq 10^{-0.4\Delta m}$$

where here Δm is the full range of the light curve in magnitudes. Using this equation, we obtain a lower limit to the axis ratio for the comet of $\epsilon = 1.5$.

**Fig. 3.** Comparison of nucleus sizes – after Meech (1997).

4.2. Cometary Activity

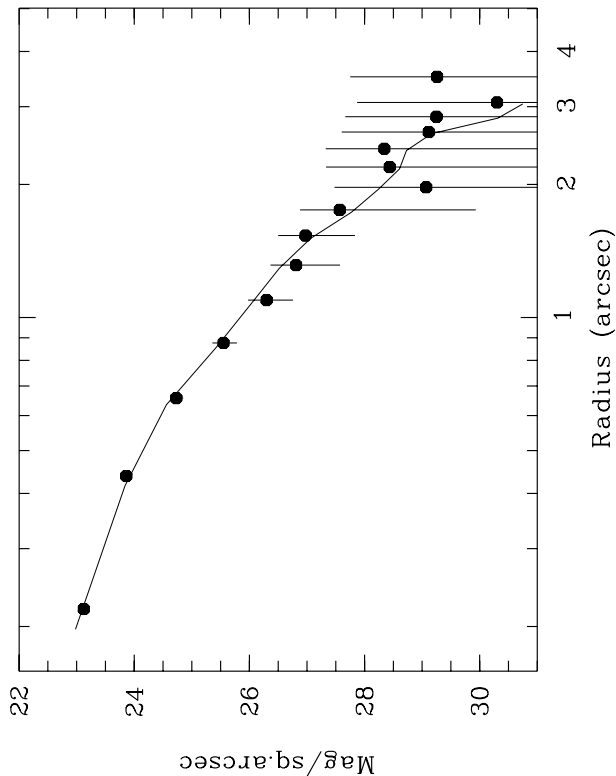
Although observations of deviations from the inverse square law on the heliocentric lightcurve is the most sensitive way to detect any cometary activity (and was the method by which activity was first detected on comet P/Halley; Meech *et al.* 1986) we computed the radial surface brightness profile of the comet compared to field stars to see if there was any evidence of an extended image indicative of coma. This was done by computing the sky subtracted total counts in concentric annuli centered on the peak pixel and using the photometric transformations to place this on an absolute scale. The profile, shown in Fig. 4, is consistent with a bare nucleus.

4.3. Future Plans

We propose to continue to observe the comet as often as possible to try to monitor the onset of the dust production. During the fall of 1997, in collaboration with M. A'Hearn and Y. Fernandez, we will be observing the comet simul-

Table 3. Comet 55P/Tempel-Tuttle Photometry

UT Date	r [AU]	m_R	$m(1,1,0)$	R_N [km]
1994 May 12	10.8	>24.5	>14.31	<4.7
1995 Feb 4	9.5	>25.5	>15.49	<2.7
1996 May 12	6.7	23.9-24.2	15.33-16.12	1.6-2.3
1996 Jun XX	x.x	xx.x	xx.xx	x.x
1997 Mar 04	4.5	22.6	16.08	1.6
1997 Mar 07	4.5	22.3	15.70	1.9
1997 Jun 17	3.5	21.7-22.1	15.61-16.01	1.7-2.0

**Fig. 4.** Radial surface brightness profile of 55P/Tempel Tuttle (filled circles) compared to a stellar profile from the 1997 March 4 Keck run.

taneously in the optical and IR in an attempt to directly measure the nucleus size and albedo. [Oli – do you want to put an observing planner (similar to the one for the Wirtanen paper) in here at this point? Do you want to put any info on when and where the Leonids might be best observed?

We would like to thank James Bauer for his help with the 1997 March Keck observations, and Catherine Delahodde for help with the 1997 June observations and the data reduction. We would especially like to thank the ESO team for being able to reschedule part of their night to obtain the followup recovery observation on 1997 March 7.

In addition, we thank Brian Marsden for updating the orbits so we could recover the comet. Support for this work was provided by NASA Grant No. NAGW 5015, and an NSF REU Supplement to Grant No. AST 92-21318.

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