Near-Infrared Light Curve of Comet 9P/Tempel 1 during Deep Impact

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Abstract

On UT 2005 July 4 we observed Comet 9P/Tempel 1 during its encounter with the Deep Impact flyby spacecraft and impactor. Using the SpeX near-infrared spectrograph mounted on NASA's Infrared Telescope Facility, we obtained 0.8-to-2.5 μm flux-calibrated spectral light curves of the comet for 12 minutes before and 14 minutes after impact. Our cadence was just 1.1 seconds. The light curve shows constant flux before the impact and an overall brightening trend after the impact, but not at a constant rate. Within a 0.8-arcsec radius circular aperture, the comet rapidly brightened by 0.63 mag at 1.2 μm in the first minute. Thereafter, brightening was more modest, averaging about 0.091 mag/min at 1.2 μm, although apparently not quite constant. In addition we see a bluing in the spectrum over the post-impact period of about 0.07 mag in $J-H$ and 0.35 mag in $J-K$. The majority of this bluing happened in the first minute, and the dust only marginally blued after that, in stark contrast to the continued brightening. The photometric behavior in the light curve is due to a combination of crater formation effects, expansion of the ejecta cloud, and evolution of liberated dust grains. The bluing is likely due to an icy component on those grains, and the icy grains would have had to have a devolatilization timescale longer than 14 minutes (unless they were shielded by the optical depth of the cloud). The bluing could also have been caused by the decrease in the "typical" size of the dust grains after impact. Ejecta dominated by submicron grains, as inferred from other observations, would have stronger scattering at shorter wavelengths than the much larger grains observed before impact.

Keywords: Comets, Tempel 1 – Infrared Observations

1. Introduction

NASA's Deep Impact spacecraft encountered comet 9P/Tempel 1 (hereafter T1) on UT 2005 July 4 (A'Hearn *et al.* 2005a,b). A 370-kg impactor was delivered to the surface at 10.2 km/s, resulting in the creation of a crater, ejecting a large amount of cometary material, and possibly briefly starting a new active region on the comet's surface. As part of a world-wide campaign to observe the comet before, during, and after this impact (Meech *et al.* 2005a,b), one of our scientific goals was to understand the overall photometric behavior of the comet. This gives us clues about the formation of the crater and the evolution of cometary activity coming from the impact site. This is important because the spacecraft itself could not easily (if at all) observe the crater; the optical depth of the ejecta was too high and obscured the impact site. Therefore an analysis of the photometric behavior of the comet after the impact is necessary if we are to understand some of the fundamental properties of the post-impact events, e.g. the duration of crater formation, the total amount of mass excavated, and the lag time for outgassing to commence. These findings could be used to constrain the mechanical and thermal properties of the nucleus better than the Deep Impact experiment could alone.

On the day of impact, we observed the comet at NASA's Infrared Telescope Facility (IRTF) using the SpeX instrument. In §2 we describe the observations and their reduction. In §3 we discuss the analysis of the data. In §4 we discuss the implications of our work.

2. Observations and Reduction

The SpeX instrument (Rayner *et al.* 2003) is a versatile near-infrared spectrograph and imager in use at IRTF atop Mauna Kea, Hawaii. We observed T1 on UT 2005 July 4 when the comet was 1.5062 AU from the Sun, 0.8940-0.8941 AU from Earth, and at a phase angle of 40.94°. Sky conditions were cloudless, photometric, and dry. Seeing in K-band was about

1 arcsec.

The data were taken with SpeX in "movie mode" utilizing a $15''$ long by $0.8''$ wide slit. We used the high-throughput prism mode, with which we obtained spectral coverage from 0.77 μm to 2.55 μm all at once at an approximate spectral resolution of 94. The slit was aligned with the parallactic angle at the start of the dataset, and that angle did not change significantly over the course of these observations. The first T1 data frame was taken at 05:40:06.9 UT and useful integrations continued for 25 minutes and 40 seconds until 06:05:46.7 UT. Exposures were just 1.0 second long and our time series cadence was 1.107 to 1.109 seconds for most of the interval. There was a gap of 97.5 seconds during the pre-impact minutes where no data were obtained due to a software crash, but in the end our observations accumulated 1274 spectra. The comet's airmass in this interval ranged from 1.16 to 1.20. Since our exposures were so short, the comet appeared as a point-source. A series of 270 sky exposures were also taken near the comet at an airmass of 1.15, just before the start of the T1 data. The data were spectrally and flux calibrated with the A0V star HD 116960, which has apparent magnitude $m_V = 8.00$. The star was observed while it was at 1.01 airmasses and only 21.6° from the comet. We corrected the comet data for telluric absorption using the method by Vacca *et al.* (2003).

The spectra were reduced with the IRTF's Spextool package version 3.2 (Cushing *et al.* 2004). All data were flat-fielded and sky subtracted. Sky background in the $15''$ slit was fit with a constant background and removed to eliminate any residual sky. Both comet and standard star were extracted in the slit with a circular aperture of radius $0.8''$ (i.e. with diameter equal to two slit widths). This radius corresponds to 519 km at the comet. The comet was typically centered in the slit, although we moved the extraction aperture to account for small drifts in the guiding ($\approx 0.1''$).

3. Analysis

3.1. Photometric Behavior

The 1274 spectra are calibrated on an absolute flux scale, so we can convert the spectra into "effective" JHK magnitudes by convolving with a filter passband. We use the "Mauna Kea" JHK filter set passbands and zeropoints described by Tokunaga and Vacca (2005). For the conversion we applied this formula:

$$m_i = -2.5 \log \left(\frac{1}{z_i} \frac{\int S_i(\lambda) R_i(\lambda) d\lambda}{\int R_i(\lambda) d\lambda} \right), \quad (1)$$

where m_i is the magnitude in the i-th filter that has zeropoint z_i, R is the filter passband function, and S is the observed spectrum.

The results are shown in Fig. 1, presented for each band in three different ways: as all 1274 points (top panel, grey points), after application of a 10-second running average (top panel, dark curves), and after taking the average within discrete, non-overlapping 10-second intervals (bottom panel). (Averaging was done in flux space, not magnitude space.) The time axis has been shifted so that time $t = 0$ at impact, which we take to have happened at UT 05:52:02 on Earth (A'Hearn et al. 2005b, Wellnitz et al. 2005). On that scale the data extend from $t = -00{:}11{:}55$ to $t = +00{:}13{:}45$. **Fig. 1**

Before impact, the comet's magnitude within the aperture was $m_J = 14.739 \pm 0.023$, $m_H = 14.266 \pm 0.010$, and $m_K = 13.859 \pm 0.043$. In all three representations in Fig. 1, it is clear that the comet brightened considerably after impact in all three passbands: by $t = 1$ min, the comet was about 0.63 ± 0.04 mag brighter in J band, 0.52 ± 0.02 mag brighter in H band, and 0.38 ± 0.11 mag brighter in K band. The figure also shows that the comet did not sustain this rate of increase for very long, instead changing to a more modest brightening rate for the remainder of the dataset.

After $t = 1$ min, the rate of brightening changes dramatically, proceeding thereafter to only about 0.09 mag/min. By the end of the dataset, near $t = 14$ min, the comet is about 1.82 ± 0.02 mag brighter in J band, 1.75 ± 0.02 mag brighter in H mag, and 1.46 ± 0.05 mag brighter in K band compared to the pre-impact flux.

We note that the brightening after $t = 1$ min does not have a constant rate. We show this in Fig. 2, which has a close-up of the post-impact portion of Fig. 1a but includes error bars. We argue as follows: In both the J- and H-band light curves, we found the best-fitting line for three intervals: 1 min $< t <$ 4 min, 4 min $< t <$ 8 min, and $t > 9$ min. These fits are shown in the plots with the heavy dark lines. Notice how the slopes are different and that the extrapolation of one best-fit line to the other intervals does not match the data. This analysis indicates that the comet's brightening rate went through several stages. In J band, the brightening averaged -0.63 ± 0.04 mag/min in the first minute, -0.14 ± 0.03 mag/min over t =1 to 4 min, and -0.066 ± 0.017 mag/min over t =4 to 8 min, but then steepened somewhat to -0.082 ± 0.010 mag/min for $t > 9$ min. The average slope for $t > 1$ min is about 0.091 mag/min. In H band, the brightening averaged -0.52 ± 0.02 mag/min in the first minute, -0.15 ± 0.03 mag/min over t =1 to 4 min, and -0.068 ± 0.018 mag/min over t =4 to 8 min, but then steepened somewhat to -0.078 ± 0.010 mag/min for $t > 9$ min. The average slope for $t > 1$ min is about 0.095 mag/min. **Fig. 2**

3.2. Lack of Impact Flash

Though we had second-scale temporal resolution, we were unable to unambiguously detect a flash from the impact itself. This is not surprising considering the aperture scale.

A close-up of the unbinned light curve in Fig. 1a near impact is shown in Fig. 3. While the J-band photometry suggests a brightening within a few seconds after impact, this behavior is not replicated in the other wavelengths. Indeed there is a glaring lack of any significant brightening in the H band in those first few seconds. While rebinning of the light curve (Fig. 1a) may introduce light curve peaks near the time of impact, we believe these are artifacts since we cannot identify such peaks in the original dataset itself. **Fig. 3**

It is possible that the reason we see a jump in J-band but not in the others is because the temperature of the flash during those few seconds was sufficiently high to give a significant contribution at J but not in H or K. However the difference in cross section between this vaporized material and the rest of the pre-impact coma within the 519-km wide slit suggests that this is unlikely.

3.3. Color Behavior

Having extracted JHK magnitudes, we can derive the comet's near-infrared color as a function of time. The $J-H$ and $J-K$ colors are shown in Fig. 4. We find that the pre-impact color within the aperture was $J-H = 0.473 \pm 0.025$ and $J-K = 0.880 \pm 0.049$. The comet was redder than the Sun by about 0.16 mag in $J-H$ and 0.51 mag in $J-K$ (Campins et al. 1985). It is clear from the plot that the comet blued by a few tenths of a magnitude in the first minutes after impact. Average of the colors from late in the dataset ($t > 10$ min) were $J-H = 0.407 \pm 0.022$ and $J-K = 0.527 \pm 0.027$. This means that $J-H$ blued by about 0.07 mag, and $J-K$ blued by a full 0.35 mag, approaching solar colors.

It is important to note that most of this change occurred soon after impact, with relatively less continued bluing after $t = 1$ min. Bluing is also seen in infrared observations by Knight et al. (2006) and in visible wavelengths by Hodapp et al. (private communication). **Fig. 4**

We fit a line to the $J - K$ data points in Fig. 4 beyond $t = 1$ min (excluding 3σ outliers). The fit used 676 colors and their error bars. We find that the slope of the trend is -0.012 ± 0.007 mag/min, a difference from a flat slope that is marginally significant at the 1.7σ level.

Lastly, we note that the color curve and the light curve behave differently after $t = 1$ min. While the comet continues to brighten by more than a full magnitude, the color changes almost none at all. This is a significant finding that should help us determine the cause of the photometric behavior. An acceptable scenario should explain how more cross section can be placed into the field of view without changing the comet's overall color very much.

4. Discussion

4.1. Behavior at the Impact Site

The impact, the formation of the crater, the expansion of the (probably icy) dust in the ejecta cloud, and the start of cometary outgassing from the impact site could all have determined the shape of the light curve in Fig. 1. Unfortunately, spacecraft imaging was unable to directly observe the area near the crater after impact. Therefore, we must use the photometric properties of the ejecta to give us insight into what was happening on the comet's surface.

It is likely that the cause of the rapid brightening in the light curve's first minute post-impact is due to material being thrown into space as a direct result of the impact itself and the crater's formation. While we do not yet know how long it took for the crater to form, the minute-long sharp rise in brightness suggests that it took at least one minute. Exactly what stage of formation the crater reached by $t = 1$ min requires more detailed modeling, although we note that Schultz et al. (2005) argue for a crater formation time of about three to six minutes, i.e. longer than the rapid brightening phase of the light curve.

Note that most of the material excavated by the impact remained within the slit during our observations, and so light curve features could not have been caused by slit losses until (at worst) very late in the dataset. A projected dust speed of about 0.15 to 0.20 km/s has been reported by several groups (A'Hearn et al. 2005b, Meech et al. 2005b, Keller et al. 2005, Sugita et al. 2005, Jehin et al. 2006, Schleicher et al. 2006). While the true speed is likely faster, we are here concerned with the projected motion on the plane of the sky. Thus, at fastest, the material travels one-half the slit width – $0.4''$, or 259 km – in over 21 minutes. While this simple calculation ignores PSF effects, it is clear that certainly the light curve features within the first ∼10 minutes post-impact could not have been caused by material leaving the slit.

Spacecraft imaging does show a "puff" of material rapidly moving away from the impact site at about 4 km/s. While this material probably did leave the slit within the first few minutes, it has a relatively small mass compared to the rest of the ejecta. Therefore its departure probably could not have caused the abrupt change in light curve slope.

Having established that slit losses are not a significant problem, it is useful to draw attention to the kind of light curve we did *not* see. We did not see a gradual brightening from the pre-impact level with a slow brightening rate over the course of all fourteen minutes. Nor did we see a very rapid brightening for just a few seconds, followed by a slower continued brightening. Had either of these scenarios occurred, it might be easier to assign physical phenomena to the light curve features. What we did see was a scenario intermediate to these two, where there is rapid brightening for a long time compared to the impactor penetration time scale, and a fairly abrupt and clear end to that brightening rate.

After $t = 1$ min, the explanation of the light curve behavior is somewhat murky. The comet is still brightening, but not as rapidly, and we see some variations in the brightening slope (Fig. 2). One factor that may be controlling the light curve at this point is the optical depth of the ejecta. A'Hearn et al. (2005b) report that at least some of the impact ejecta as seen by the Deep Impact spacecraft was optically thick even at $t = 13$ min, when the optical depth was still 2 to 3. Some of the brightening both before and after $t = 1$ min could then simply be from our ability to see more cross section of the expanding, thick cloud of ejecta. (I.e., surface area is increasing so luminosity is increasing.) A related effect could be the physical blocking of the impact site from our view by the optically-thick ejecta once it has expanded to a sufficient size. In that case, new material injected into space from the still-forming crater would not contribute as much to the comet's brightness, thus decreasing the brightening rate.

All this is dependent however on just how much of the ejecta remained optically thick. The spacecraft imaging is most sensitive to the core of the ejecta, whereas after a few minutes an appreciable fraction of the ejecta would presumably have been beyond the spacecraft's field of view (given the dust's speed), and could have become optically thin. Indeed it is possible that the change in brightening rate is due to the ejecta's transition from optically think to optically thin.

The activation of regular cometary outgassing from the new impact site should have manifest itself with changes in the light curve. If any outgassing started some time after impact, at best it did not last very long, based on post-impact remote observations in the subsequent days (Meech et al. 2005b, Küppers et al. 2005, Schleicher et al. 2006, Knight et al. 2006). While the optical depth of the ejecta could have initially prevented much sunlight from getting through to warm the impact site, eventually it would have thinned enough to allow this, although when this occurred is not known.

4.2. Bluing Dust

The relatively blue color of the dust after impact can be explained in two ways: through an unsublimated icy component to the liberated grains, and through a change in grain size-dependent scattering. A combination of effects is also possible. Regardless of the cause, one can roughly estimate the color of the ejecta alone, as follows. We assume that the overall color of the comet is a linear combination of the pre-impact dust with pre-impact color and the post-impact ejecta with a different, bluer color. Given the J-band magnitude changes from $t = 0$ to the end of the dataset, and the $J - K$ color changes, we estimate that the post-impact ejecta would have to have had a $J - K$ color near 0.45 ± 0.05 – almost solar color. This does assume that the ejecta color does not evolve, but it is a good first estimate. We now speculate on the dust properties below.

Reports of *in situ* observations (A'Hearn et al. 2005b), space-based remote observations (Küppers et al. 2005, Keller et al. 2005, Lisse et al. 2006), and ground-based observations (Mumma et al. 2005, Barber et al. 2006, Schleicher et al. 2006) indicate a significant amount of water was liberated after impact. The mechanical ejection of material from the impact site and crater need not have raised the ejecta's temperature to the level required for ice sublimation ($\sim$200 K). Only a relatively soft pressure (under 1 kPa) was needed to lift material off the comet against the nucleus's low gravity (A'Hearn et al. 2005b). Therefore, it is reasonable that unsublimated water ice could have been lifted off into space and survived. The reflectivity of this water ice is bluer than what would have been seen from devolatilized or non-volatile grains.

The existence of icy grains themselves can be inferred from work by e.g. Jehin et al. (2006), Schleicher et al. (2006), and Schulz et al. (2006). Filter photometry by these groups revealed that the magnitudes in passbands sensitive to gaseous daughter species took longer to reach peak brightness than did those in passbands sensitive to the dust. While photodissociation of parent species explains this phenomenon, disintegration of icy grains also can contribute. More detailed study of the apparent dissociation scalelengths would be needed to differentiate between the two effects. More promising is the finding by Schleicher et al. (2006) that the daughter-species gas column density slowly returns to pre-impact levels, suggesting that some sublimation from icy grains was occurring.

Just how long would the post-impact icy grains survive in the coma and contribute to the coma reflectance before sublimating into a gas? This depends on the radiation environment and the thermal contact with the dust (i.e. the "dirtiness" of the icy grain), as discussed by Hanner (1981) and Lien (1990). Hanner (1981) derived icy grain lifetimes at 1.0 and 2.3 AU (bracketing our observations at 1.5 AU), and for various tabulated imaginary indices of refraction, she found that a 1-μm dirty-icy grain can survive for several minutes at 1.0 AU or several hours at 2.3 AU. Lien (1990) covers a wider range of grain sizes, grain compositions, and heliocentric distances, and finds that at 1.0 AU a 1-μm dirty-icy grain can survive for several minutes even with a 10% fraction (by volume) of astronomical silicate. This all suggests that post-impact icy grains in T1's coma could last long enough to influence the color at least in the early post-impact period if they were "clean" enough. We note that in Fig. 4 the color never returns to its pre-impact level, so if icy grains are primarily responsible for the bluing, then the timescale for devolatilization of the grains is longer than 14 minutes. (This could be affected however if many icy grains are shielded from sunlight by the optical depth.)

Circumstantially corroborating this idea are the results by Sunshine et al. (2006) demonstrating the existence of ice on the surface of T1. They postulate that the surface ice was made of clean, micron-sized grains that were thermally decoupled from the surrounding surface. Such grains would have a relatively long lifetime despite being in a region where the local surface temperature is well above 200 K.

While the population of icy grains is an important consideration, a simple scattering effect could contribute to the color as well. While the grains in the coma are too large to cause pure Rayleigh scattering, grain size could have still played a role. Pre-impact mid-infrared observations by many observers (Harker et al. 2005, Wooden et al. 2005, Lisse et al. 2006) show that the pre-impact dust coma was dominated by large (supermicron) grains that showed a weak 10-μm silicate emission band. This is in great contrast to the post-impact characterization of the dust by these same groups: the ejecta was composed mainly of submicron grains, much smaller than the pre-impact ones. The near-IR wavelengths under consideration here are comparable in size to the post-impact grains themselves. The controlling parameter, $2\pi a/\lambda$, while likely well above unity pre-impact, approached unity post-impact. Thus we can expect that a decrease in the "typical" size of the grains by a factor of several can have a strong influence on the scattering efficiencies across the JHK spectrum.

This still leaves the question of why the color curve's plateau and the light curve's kink happened at the same time, and how the color could remain constant while the comet continues to brighten after $t = 1$ min. If the simple scenario described in the beginning of this section is valid – that is, that the dust does not evolve much over the course of the dataset – then this provides some explanation. As the rate of brightening abruptly falls at $t = 1$ min, the rate of further bluing of the coma would fall as well. The overall color of the comet will then more slowly approach an asymptotic value, and this would require that the marginally-significant tilt to the color curve in Fig. 4 be real.

However the requirement that the dust not evolve in that time may be problematic. We argued above that the sublimation time scale can be long, but this is speculative. If the icy grains are sublimating and fragmenting, however, this may provide a way to boost the cross section yet not change the color. There would be a competition between three effects: devolatilization of icy grains (which reddens the color), fragmentation of the grains as they sublimate (which blues the color via scattering effects and increases the overall brightness through increasing cross section), and input of more fresh icy grains from the impact site (which also blues and brightens). Perhaps the net result of this competition is fairly constant color for the last ∼12 minutes of the dataset. Admittedly, this requires an exquisite matching of source and sink terms that one would not expect *a priori*.

Adding to this picture however is the report by Knight et al. (2006) that the dust became even bluer after $t = 14$ min, i.e., after the end of our data set. Their light curve is built from JHK *imaging* photometry with a 3.5-arcsec radius aperture. For $t > 14$ min, the bluing increases again, much faster than it had been increasing from $1 \leq t \leq 14$ min in our dataset. Knight et al. (2006) suggest that this may be caused just by the fact that their photometry had sufficient signal-to-noise ratio only after $t = 14$ min. Nonetheless, it seems that the dust stayed bluer (and possibly continued bluing) well beyond the end of our dataset, for at least 35 minutes, as Knight et al. (2006) state. This may argue that the timescale for the icy grains to devolatilize is sufficiently long.

The numerical value of the $J-H$ and $J-K$ bluing will be a strong constraint in deciding the relative influence of grain-size dependent scattering versus icy-grain reflectivity on the color. We are disposed to believe that icy grains predominate since (as mentioned above) there is good evidence that a significant population of icy grains was in the ejecta, but such modeling is beyond the scope of this paper and will be addressed in future work.

5. Summary

We obtained 1274 near-infrared spectra of comet 9P/Tempel 1 during the 12 minutes prior and 14 minutes after the Deep Impact impactor's impact. Our cadence was 1.1 seconds. Each spectrum covers 0.77 to 2.55 μm. The spectra have been flux-calibrated using a circular aperture of radius 0.8 arcsec. We converted the flux-calibrated spectra into effective JHK photometry, and we can draw the following observational conclusions.

• 1. The comet brightened considerably after the impact, brightening by 0.63 mag in J band, 0.52 mag in H band, and 0.38 mag in K band in the first minute.

• 2. After that ($t > 1$ min), the comet brightened more modestly to the end of the dataset. By the end of the dataset that total brightness increase had been 1.82 mag in J band, 1.75 mag in H band, and 1.46 mag in K band.

• 3. After $t = 1$ min, the brightening rate was somewhat variable. In fact that brightening rate steepens somewhat for the last few minutes of the dataset compared to the middle of the light curve.

• 4. A plot of $J - H$ and $J - K$ color over time shows that the comet blued by about 0.07 mag in the former and 0.35 mag in the latter over the course of the dataset. All or nearly all of this color change occurred in the first minute after impact, coincident with rapid brightening. After that, the comet did not blue as fast as it brightened; the light curves and color curves are strongly disparate after $t = 1$ min.

These observations let us speculate about what happened on the surface of the comet in the immediate aftermath of the impact. The crater was obscured from direct observation by the optically thick ejecta.

• 1. The formation of the crater likely took at least one minute. The rapid brightening in that first minute is probably due to the lifting of material into space by the energy of the impact and the crater formation.

• 2. The abrupt change near $t = 1$ min in the rate of change in brightness and the variable brightening rate thereafter suggest that the light curve comes from a combination of one or more of the following: crater formation effects, expanding ejecta cloud, cometary outgassing, and behavior of icy grains.

• 3. The cause of the bluing is due to icy grains in the ejecta, smaller grains in the ejecta, or both. It is reasonable to expect that these bluer icy grains survive sufficiently long before sublimating, so we would not see the color return to pre-impact levels in our data. However grain-size effects could also contribute, since after impact the "typical" grain size is a factor of several closer to the wavelengths of the observations. We estimate that the $J - K$ color of the ejecta alone is around 0.45, near solar color.

• 4. As mentioned, the comet continued to brighten but almost stopped further bluing after $t = 1$ min. If the ejecta grains did not evolve, this could be explained by the comet's overall color asymptoting to the ejecta's value. If the grains do evolve, then perhaps there was a balance between competing coloring effects of fragmentation and sublimation.

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Figure Captions

Fig. 1. The light curve from our spectra, converted into JHK photometry and presented three different ways. The aperture size is a 0.8-arcsec radius circle. (a) Grey points in this plot show the results from each of the 1274 individual spectra. The three bands have been offset from each other for clarity; note the y-axis scales on both the left and right sides of the plot. The error bars have been left off for clarity also. Dashed horizontal lines indicate the pre-impact magnitudes. The medians of these points' 1σ uncertainties are: 0.15 mag pre-impact and 0.10 mag post-impact in J-band, 0.14 mag pre-impact and 0.07 mag post-impact in H-band, and 0.22 mag pre-impact and 0.10 mag post-impact in K-band. Dark lines in this plot show the 10-second running average, which does a better job of delineating the photometric trends. (b) Points in this plot show the average in discrete, non-overlapping 10-second intervals. Offsets and y-axis scales are the same as in (a). The photometric trends are again easier to see.

Fig. 2. Part of the light curve shown in Fig. 1a, but without the running average. (a) J-band light curve; (b) H-band light curve. Error bars on the magnitudes are as shown. For both light curves, a line was fit to the data over three intervals, 1 min $< t <$ 4 min, 4 min $< t <$ 8 min, and $t > 9$ min. The best fitting lines are drawn as heavy black lines. The extensions of those lines are drawn as thinner black lines. Notice how the slope for one interval does not work for the other intervals. This suggests that the brightening evolved through different stages, perhaps as different processes waxed and waned.

Fig. 3. A close-up of the original data in Fig. 1a, centered on the one minute around impact. Horizontal solid lines indicate the comet's pre-impact brightness. No flash from

the impact was unambiguously detected. Note that in J band there is a suggestion of a flash a few seconds after the nominal impact time, but this is not corroborated by the other wavelengths. The brightness in K band is somewhat (though not significantly) higher, while in H band there is no hint of it.

Fig. 4. Plot of the $J - H$ (top) and $J - K$ (bottom) color of the comet within the $0.8''$ aperture as a function of time. In the first minute after impact, the comet noticeably blues. Solid horizontal lines pre-impact indicate the pre-impact colors. Solid horizontal lines post-impact indicate the colors at the end of the dataset. In $J - H$, the difference between the two is 0.07 mag; in $J - K$, it is 0.35 mag. For $J - H$, there is no indication of bluing after the first minute. For $J - K$, there is some suggestion of continued bluing but fitting a slope to the post-impact color (tilted solid line) yields a slope that deviates from flat at only the 1.7σ level. In comparison to Fig. 1, there is very little further bluing after $t = 1$ min despite the continued brightening.

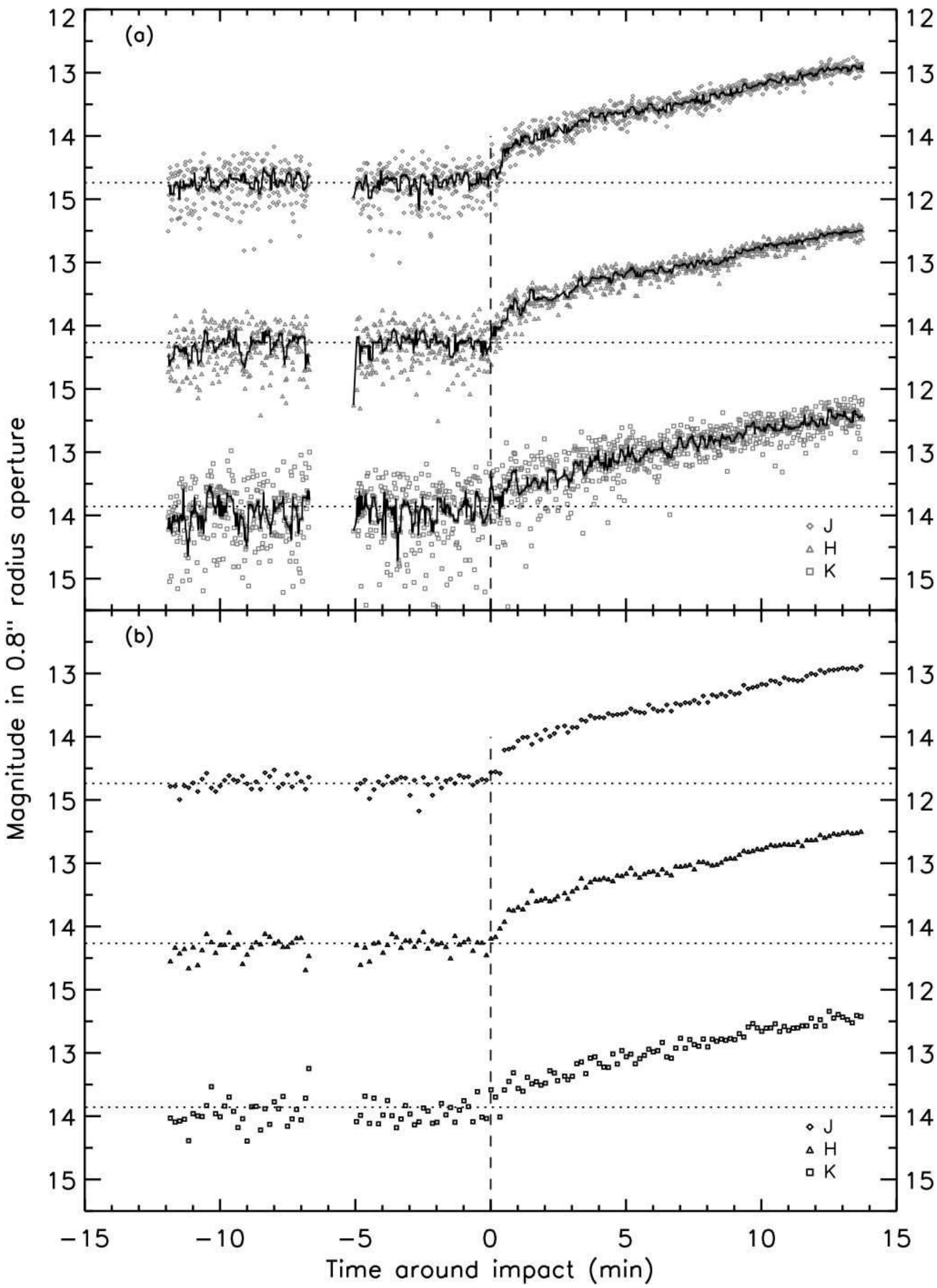

Figure 1, Fernández et al., IRTF Observes Deep Impact

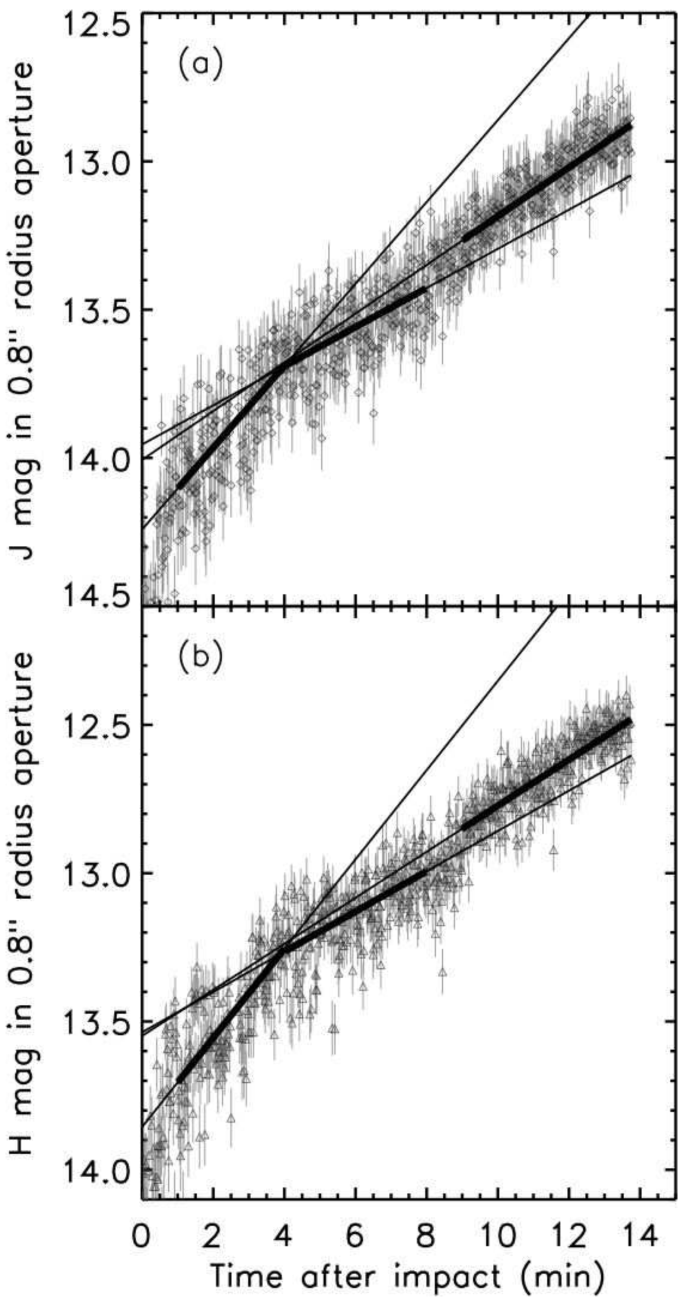

Figure 2, Fernández et al., IRTF Observes Deep Impact

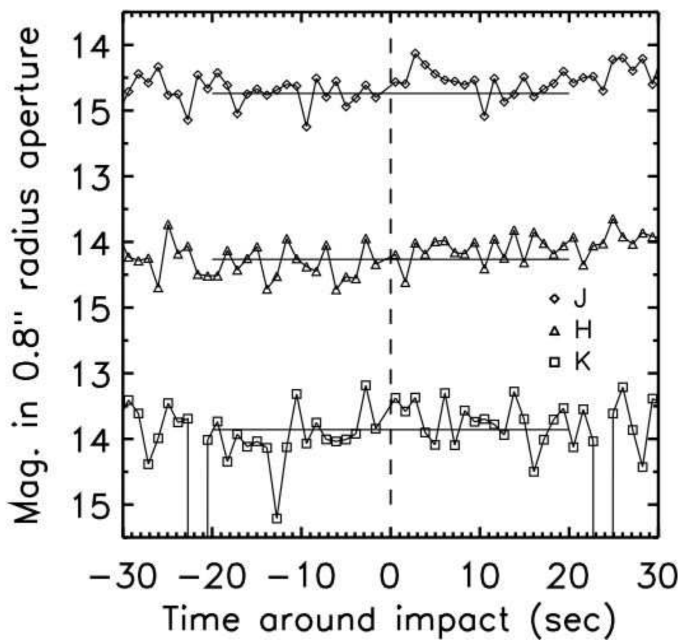

Figure 3, Fernández et al., IRTF Observes Deep Impact

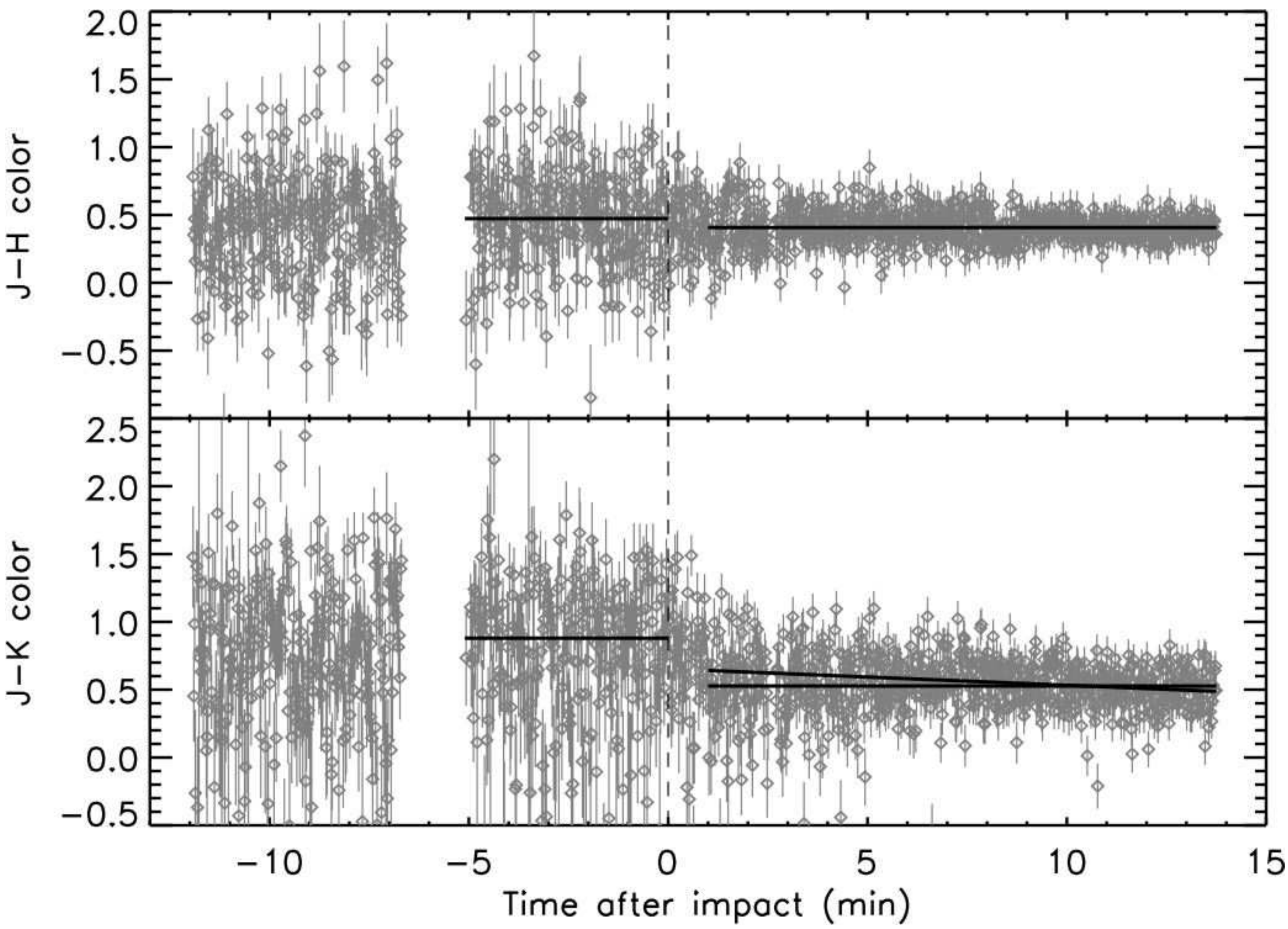

Figure 4, Fernández et al., IRTF Observes Deep Impact