Naturally Occurring Outbursts at Comet Tempel 1

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The Deep Impact Mission

- Deep Impact encountered comet Tempel 1 on July 4th 2005
- The flyby spacecraft carried 2 visible imagers (HRI-Vis & MRI) and 1 infrared spectrometer (HRI-IR)
- The impactor spacecraft carried 1 visible imager (ITS)
- The impactor had a mass of 372 kg and collided with Tempel 1 at 10.3 km/s (A'Hearn et al., 2005)
- This collision delivered 19 GJ of kinetic energy, the equivalent of 4.5 tons of TNT (A'Hearn et al., 2005)
- Data was collected both pre and post-impact

Fig. 1: The Deep Impact spacecraft

Deep Impact's Infrared Spectrometer

- HRI-IR operates between wavelengths of 1.05 and 4.85 microns, a region where H_2O, CO_2, CO, and organic molecules have emission lines
- Has a minimum spectral resolving power (λ/Δλ) of 200
- Is a long-slit spectrometer, so each frame has a spatial dimension (512 pixels, unbinned) and a wavelength dimension(1024 pixels, unbinned)
- Binned pixels have a FOV of 10^{-10} steradians
- The middle third of the slit is covered by an anti-saturation filter (ASF) to prevent the nucleus from saturating the detector
- Scans were used to gain a second spatial dimension
- Note that for these data the pixels are twice as large in the scan direction as they are in the slit direction due to the imaging mode, BINFF

Data

Scan ID	UT Time on 2 Jul 2005 (H:M:S)	Time relative to Outburst	Abbreviation
8600000	06:00:22.153	-2.5 hours	7_2_0
8600001	07:54:32.105	-0.5 hours	7_2_1 (Pre-Outburst)
8600002	10:00:22.057	+1.5 hours	7_2_2 (Post-Outburst)
8600003	12:05:12.110	+3.5 hours	7_2_3

Each scan consists of 50 8-second frames and was acquired in unbinned full frame mode. The comet is located inside the ASF for these data.

Data Calibration

- Data are decompressed, if needed
- Linearity coefficients are applied
- A dark frame is scaled to fit the scan, then is subtracted from the data
- A flat-field is divided out to correct for pixel to pixel variations in sensitivity
- Our flat-field also corrects for the transmission profile of the ASF
- Data are converted to radiance units and a wavelength value was assigned to each pixel

Creating a Viable Dark

- A dark made from the last 5 frames of the scan being calibrated was determined to be inadequate
    - These darks did not allow for a proper analysis of the long wavelength end of the spectrum and the dark created for scan 8600002 introduced artifacts into the data
- A dark was created by averaging the last 5 frames from scans 7_2_0, 7_2_1, and 7_2_3
    - Outliers beyond ± 2.5 σ were excluded from the mean
- An optimal scaling factor was determined by minimizing the average χ^2 of the best continua that could be fit to the data, though discretion was used

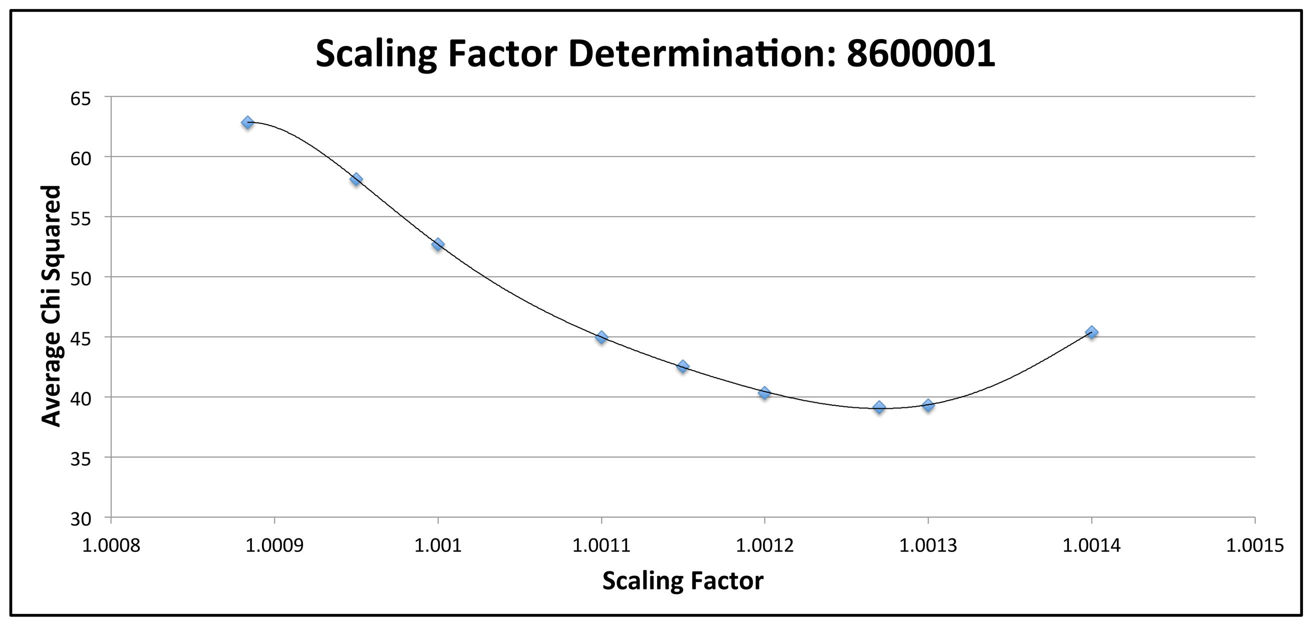

Fig. 2: Average chi squared values for the best fit continua for aperture sizes of 1*1 pixels to 29*29 pixels versus the dark scaling factor used to calibrate the data.

Research Goals

- Use HRI-IR spectra to determine if/how the composition of the coma changes due to an outburst
- Determine the spatial distribution of volatiles before and after the outburst
- Make inferences about the cause of outbursts and comets in general

Outbursts at Tempel 1

- 12 were observed by Deep Impact (A'Hearn et al., 2005, McLaughlin, private communication)
- 1 was observed by the Calar Alto observatory and Hubble Space Telescope (Lara et al., 2006, Feldman et al., 2007)
- Large outbursts eject ~10^6 kg of material (Belton et al., 2008)
- Outbursts occur at a rate of ~0.3 per day, with some rotational phases more likely to produce an outburst than others (Farnham et al., 2007)
- Outbursts are directional and vary in strength (Farnham et al., 2007)
- Only the 2 Jul 2005 outburst was large enough to be observed by HRI-IR
- These outbursts occur too frequently to be the result of impacts

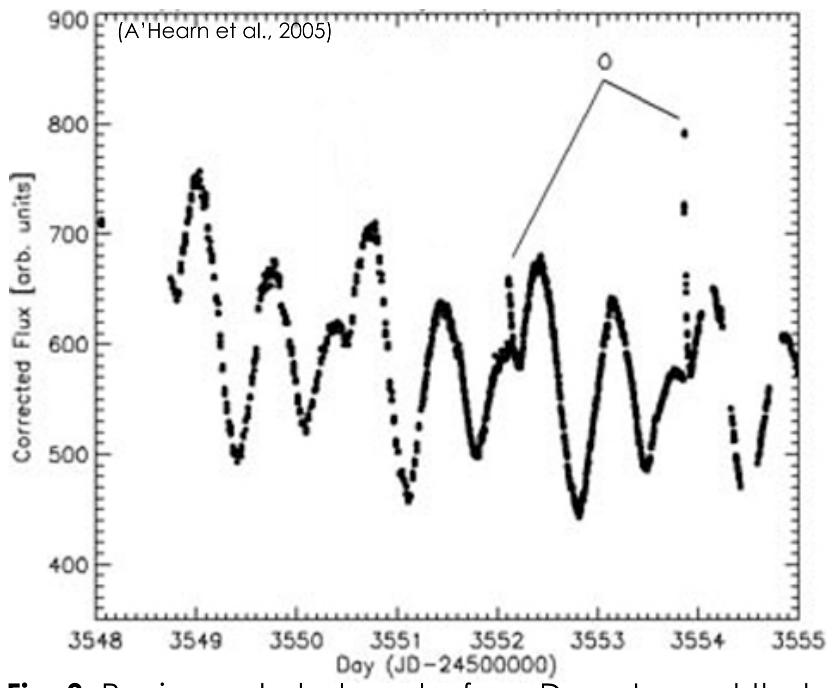

Fig. 3: Pre-impact photometry from Deep Impact that shows 2 outbursts occurring at similar rotational phases

Data Reduction

- A spectrum is created by totaling spectra from different spatial coordinates
- The spectrum is fitted with a continuum, which is modeled using a smoothed solar spectrum and a Plank function (numerous solutions are tested and a chi-squared test determines the best fit)
- Once the continuum is subtracted, emission bands can be integrated over and converted to the number of molecules in the field of view

Results for Full Apertures

- Nucleus-centered square apertures (in pixel space) were created and a single continuum was fit to the totaled spectrum then the abundance of water vapor and CO_2 were plotted versus aperture size for the scans bracketing the outburst
- It is clear that the abundance of water vapor does not change as a result of the outburst
- There is an increase in the abundance of CO_2 after the outburst and the magnitude of this increase is dependent on aperture size, which is consistent with CO_2 being released during an outburst

Duplication of Results: Shells

- "Shells" were created by taking the total spectrum of a square ring of spectra
- A continuum was fit to each shell to get a well defined shape, then divided by the number of spatial pixels in the shell and normalized to each spectrum. Water vapor and CO_2 surface brightnesses were then calculated.
- A standard deviation was calculated for the water vapor and CO_2 surface brightnesses for each shell. This was taken as the error for each pixel in that shell
- These shells were used to recreate the total apertures by summing the surface brightnesses for water vapor and CO_2 from the normalized spectra

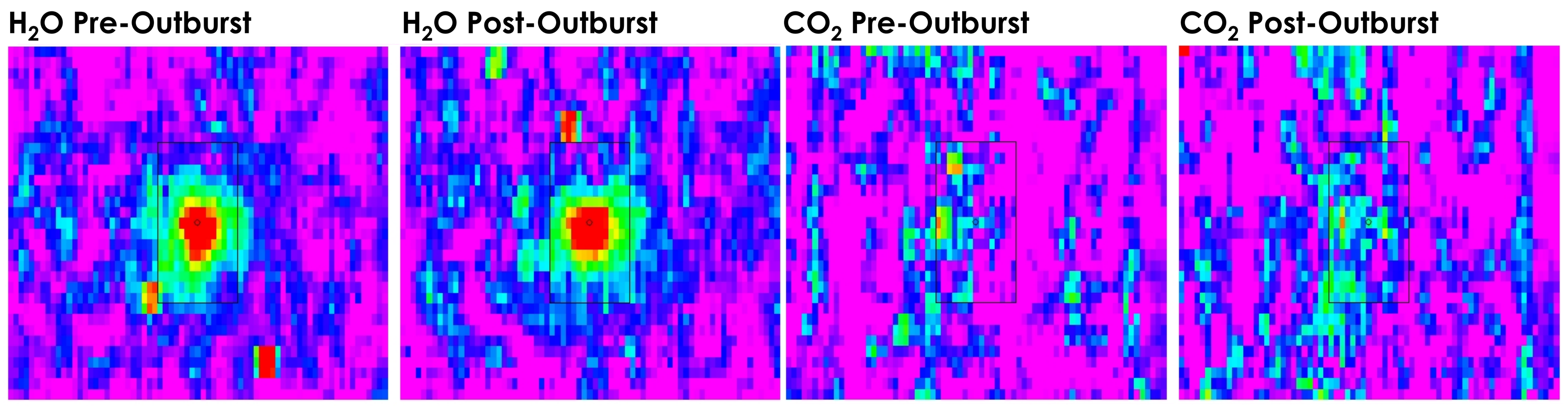

Fig. 4: Spectral maps showing, from left to right the distribution of water vapor before and after the outburst as well as CO_2 before and after the outburst. The field of view is approximately 550 km wide and high for each map. The scale is the same for all maps and the sun is located to the right. The black circle contains the nucleus and the black box is 15 pixels wide and 15 pixels high.

Duplication of Results: Spectral Maps

- Spectral Maps were created by summing the spectra in a square box to get the shape of the continuum, then normalizing the average continuum to each individual spectrum in the box
- The sum of the surface brightnesses from the normalized spectra were used as the value for the central pixel of that box
- Standard deviations were calculated for each continuum that was fit and for each pixel, as each pixel would have between 1 and the box size squared different continua fit to it
- To recreate the full apertures the spectral maps were divided by the box size squared and then the surface brightnesses within each aperture were summed
- Errors were calculated using both the standard deviation from the continuum and the standard deviation of each pixel, though the latter is about an order of magnitude smaller than the former

Conclusions

- The surface brightness, and thus abundance, of water vapor is essentially identical before and after the outburst
- The CO_2 surface brightness increased significantly, by roughly 50 %, after the outburst
- Water ice, CO, and organics were not detected before or after the outburst
- The distribution of CO_2 shown in the post-outburst spectral map is consistent with the direction of the outburst determined by Farnham et al. (2007)
- CO_2 played a significant, if not the main, role in propelling the outburst

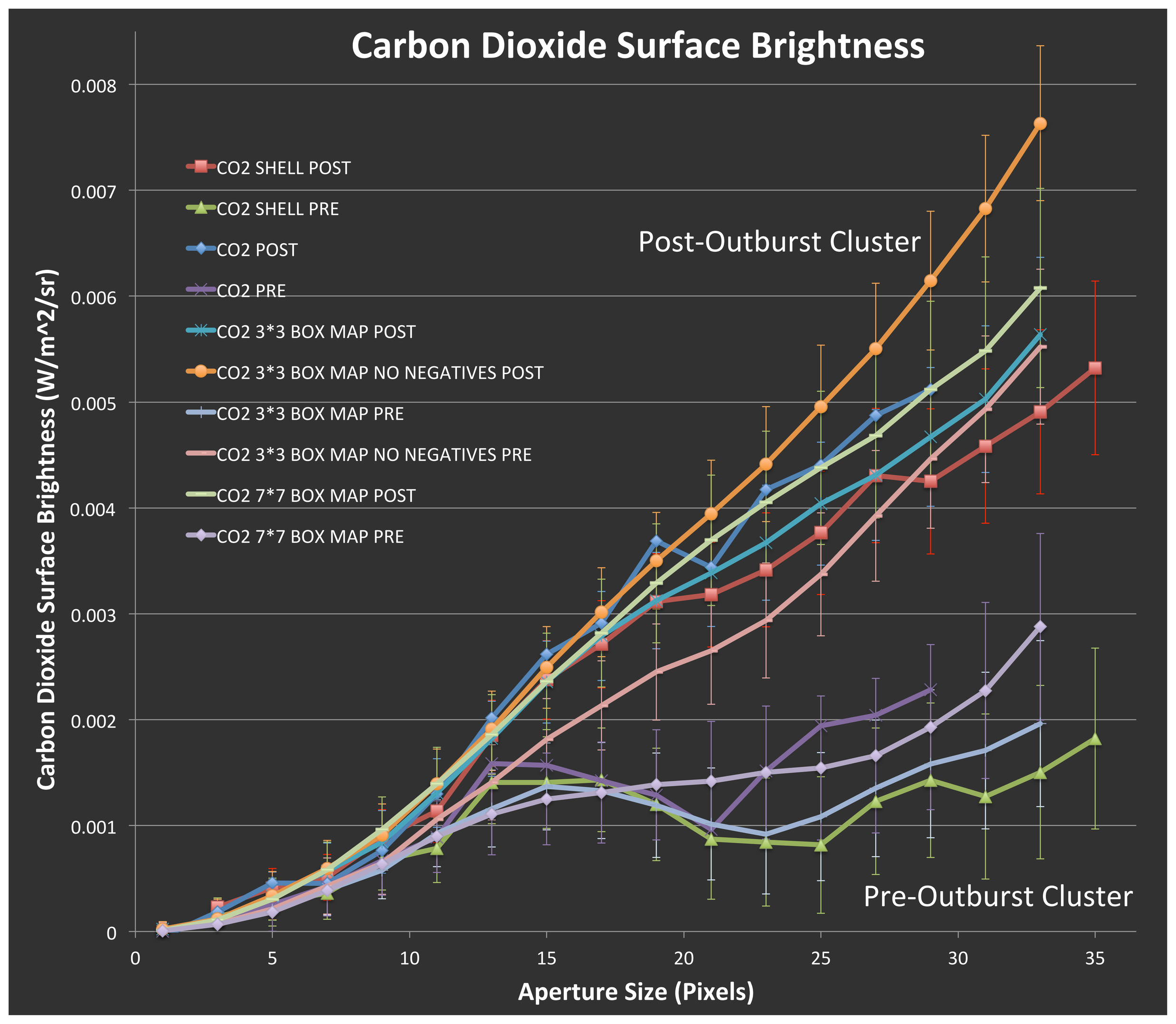

Fig. 5: Carbon dioxide surface brightness versus aperture size pre and post-outburst with 1 σ error bars that were calculated for each data set.

Error Analysis

- Error bars calculated pre and post-outburst are consistent with each other
- Changes in surface brightness are the main cause of changes in the SNR
- The CO_2 surface brightness is larger post-outburst when compared to pre-outburst for all aperture sizes, though this is more significant at larger aperture sizes
- The CO_2 surface brightness before the outburst becomes overwhelmed by noise at the 15*15 pixel aperture size, as can be seen by the surface brightness leveling off in **Figure 5**.
- The CO_2 surface brightness after the outburst does not appear to level off within a 35*35 pixel box, though an increase in the scatter between the different methods indicates that noise is becoming more significant at larger apertures, beyond roughly 19*19 pixels.

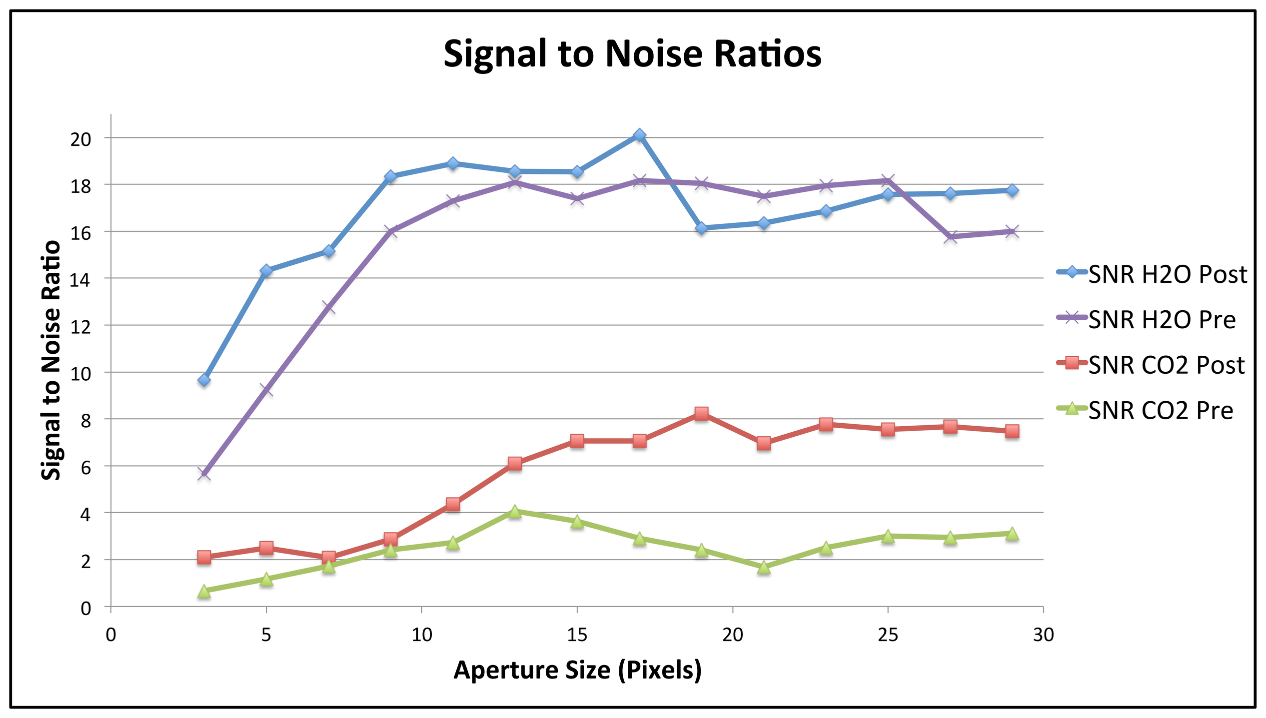

Fig. 6: Signal to noise ratio versus aperture size for water vapor and CO_2.

Percent Change

- The percent change in water vapor is negligible and within the error bars
- CO_2 is consistently more abundant after the outburst
- The increase in CO_2 post-outburst is consistently ~50 % within the 15*15 pixel aperture
- If negative surface brightnesses are neglected, the percent increase in CO_2 remains relatively constant

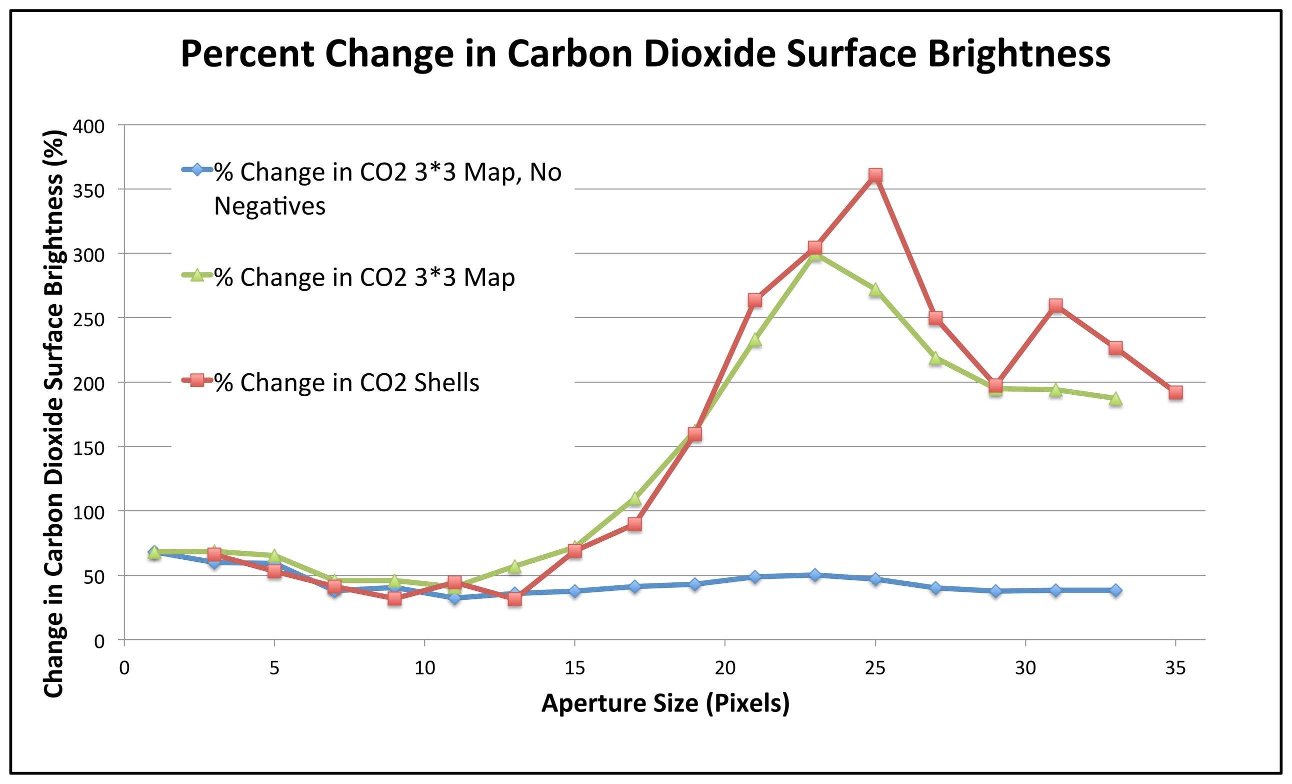

Fig. 7: Percent change in CO_2 surface brightness versus aperture size.