Deep Impact: The Mission and Results

Rick Grammier
and
The Deep Impact Team

Programmatic Context

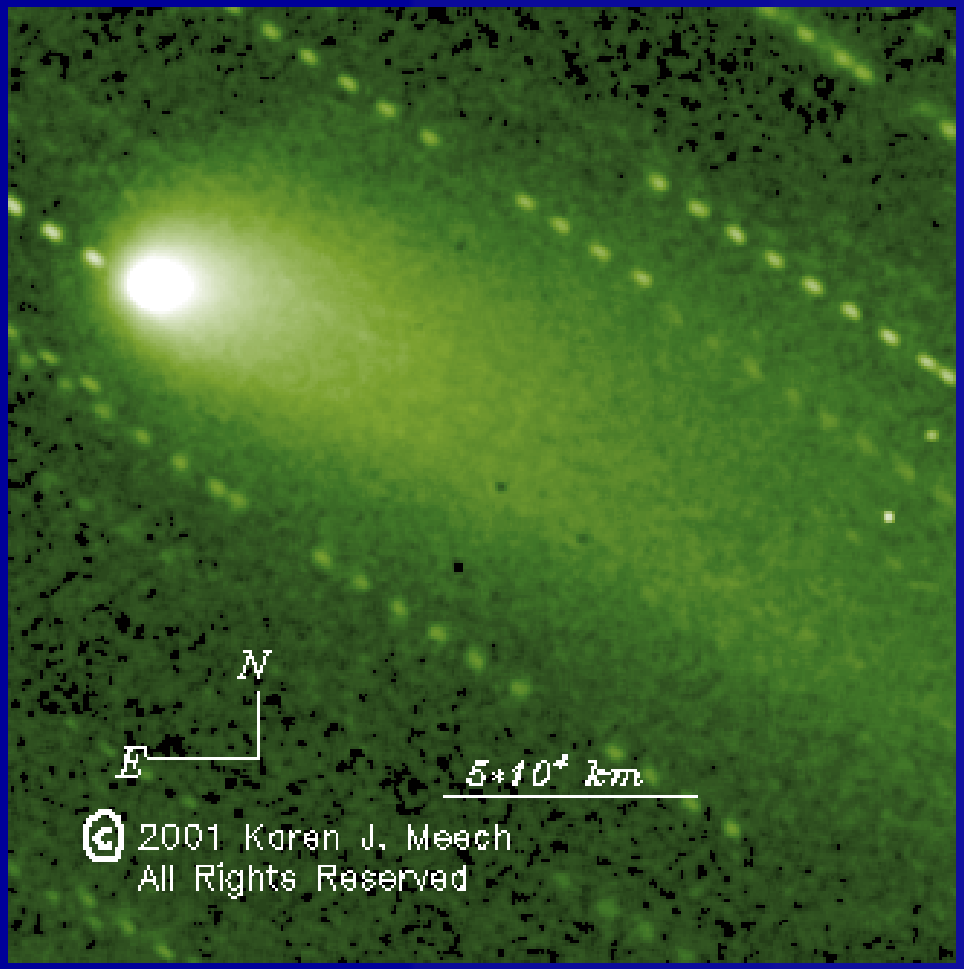
- NASA's Discovery Program
  - Low cost missions
  - Competed, science driven, PI-led missions
  - Short development schedules
- Deep Impact
  - Five years to sell it, 1995-2000
    - Proposals to Discovery Program in 1996 and 1998
    - Down-select proposal in 1999
    - Selection 1999 and confirmation (PDR) in May 2000
  - Five years to build it and fly it, 2000-2005
    - Launch 12 Jan 2005
    - Impact 4 July 2005

Scientific Objectives

- Primary Scientific Theme
  - Understand the differences between interior and surface
  - Determine basic cometary properties
  - Search for pristine material below surface
- Secondary Scientific Theme
  - Distinguish extinction from dormancy
- Additional Science Addressed
  - Address terrestrial hazard from cometary impacts
  - Search for heterogeneity at scale of cometesimals
  - Calibration of cratering record

Although science was the goal and the context for the proposal, the results are important for exploration, planetary defense, and extraterrestrial resources

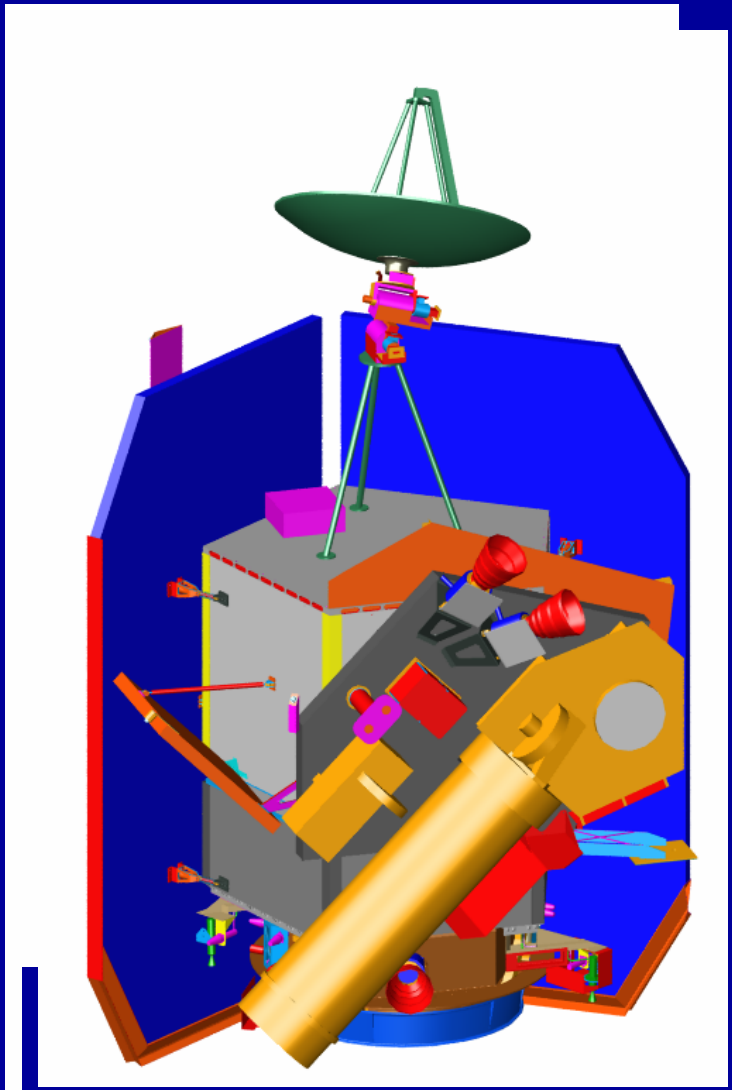
Our Target: Comet Tempel 1



- Discovered on April 3, 1867, by Ernst Tempel
- Orbits the Sun every 5.5 years, so it's a frequent flier
- About 5 km (3.0 mi) across and muffin-shaped
- Rotates on its axis fairly slowly

The Spacecraft

Let's Build Deep Impact



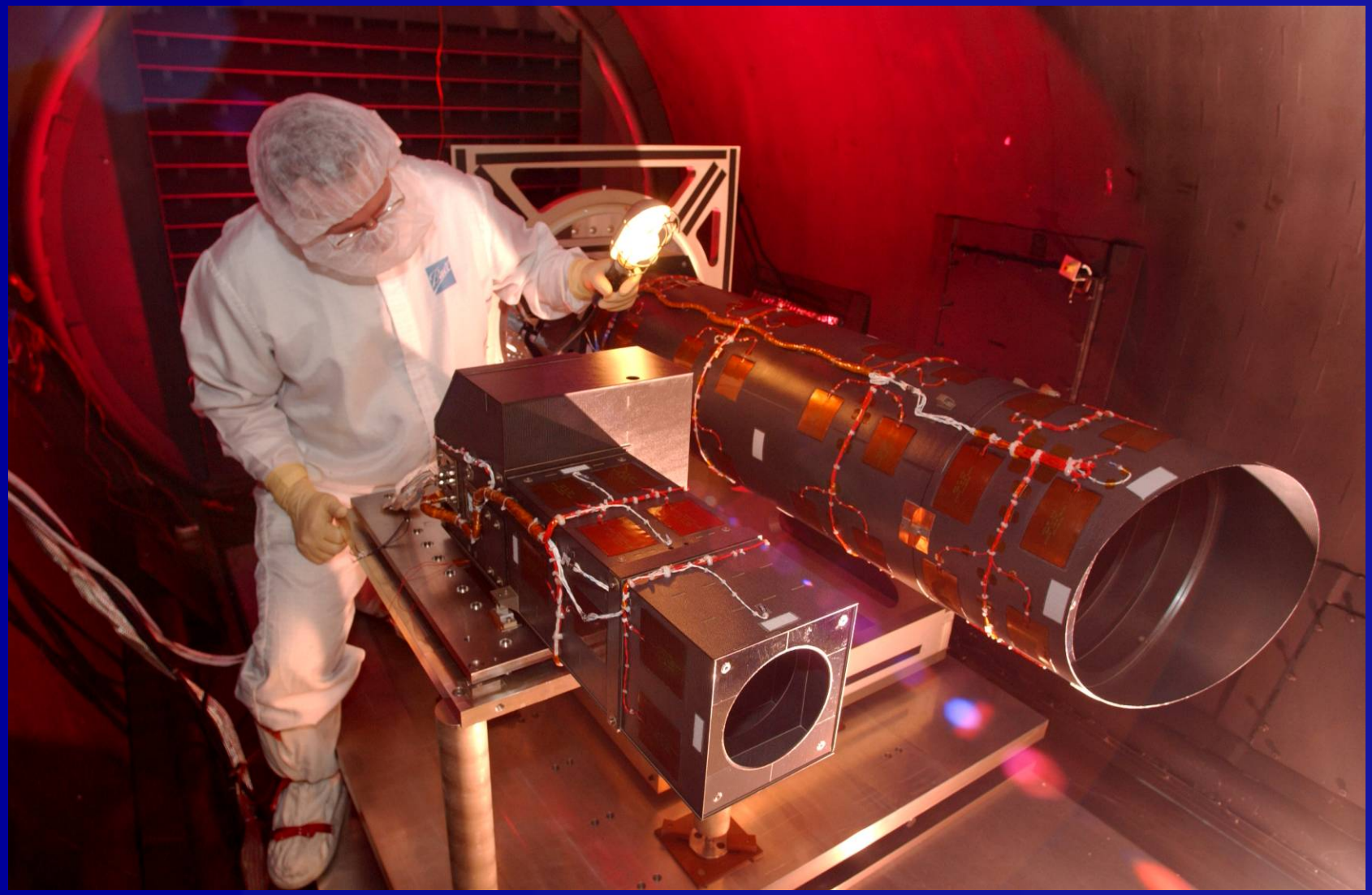
3.3 m (~11 ft) long

1.7 m (~5.5 ft) deep

2.3 m (~8 ft) wide

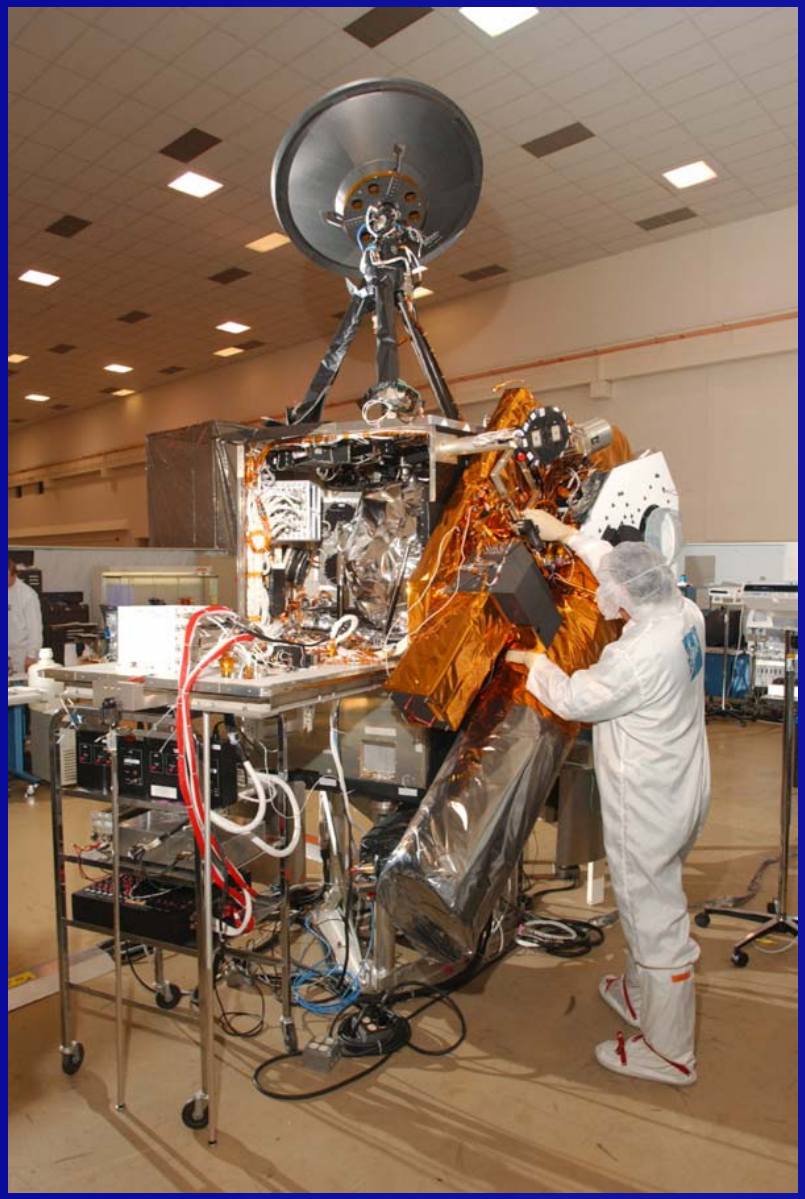
~1,000 kg (~2,000 lb)

Testing the Telescopes



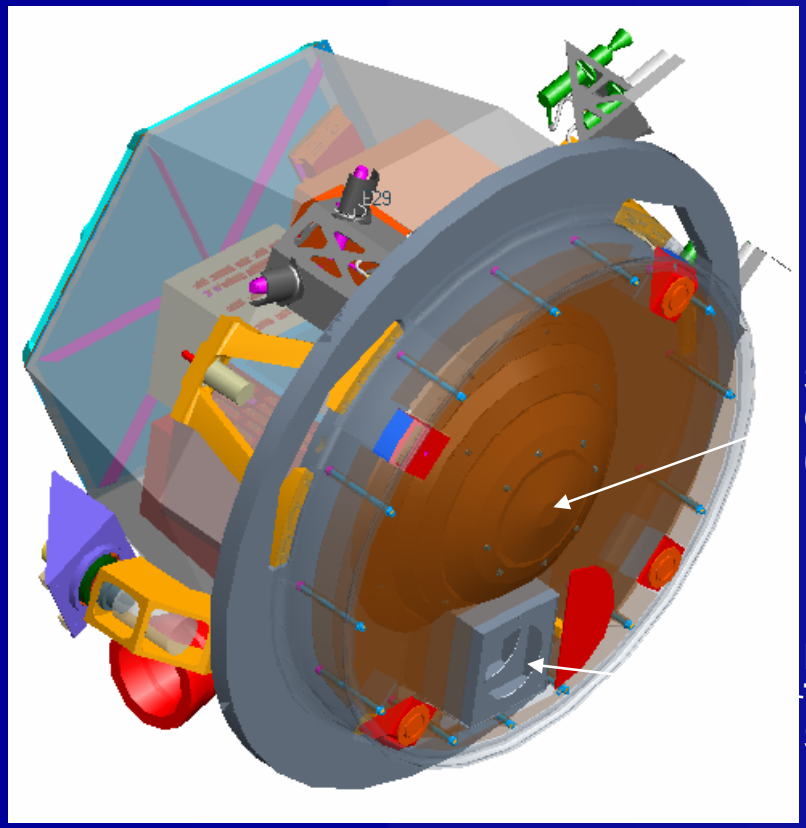
Mounting the Telescopes

Flyby Spacecraft with Instrument Platform and High-Gain Antenna



Inside the Flyby Spacecraft's Instrument Module

360 kg (~800 lb) Impactor Designed for Maximum Wallop



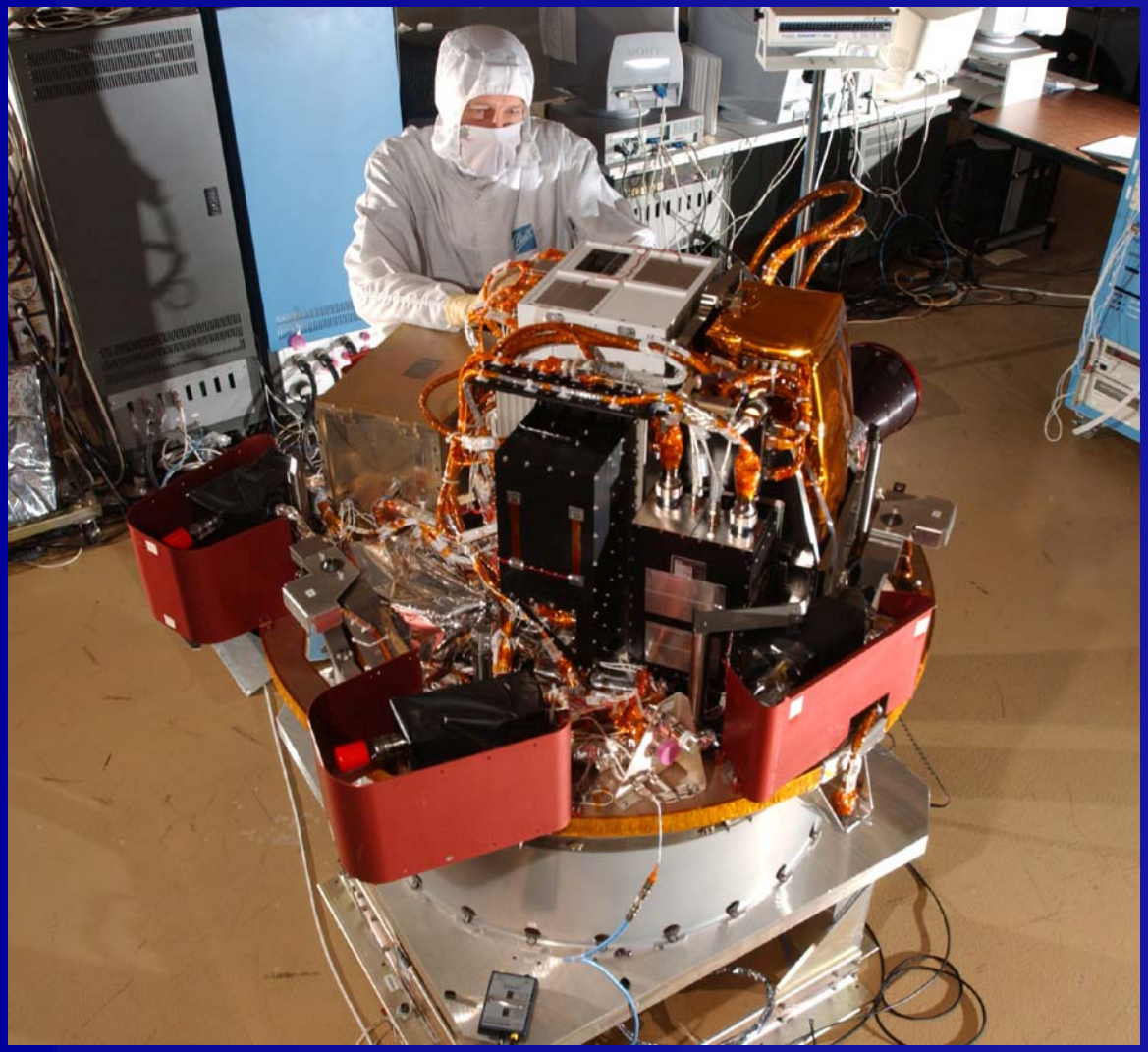
Solid Copper Cratering Mass (220 lb)

Impactor Targeting Sensor

0.8 m (32 in.) long
~1 m (47 in.) diameter

Astronomer Mike A'Hearn

Inside the Impactor



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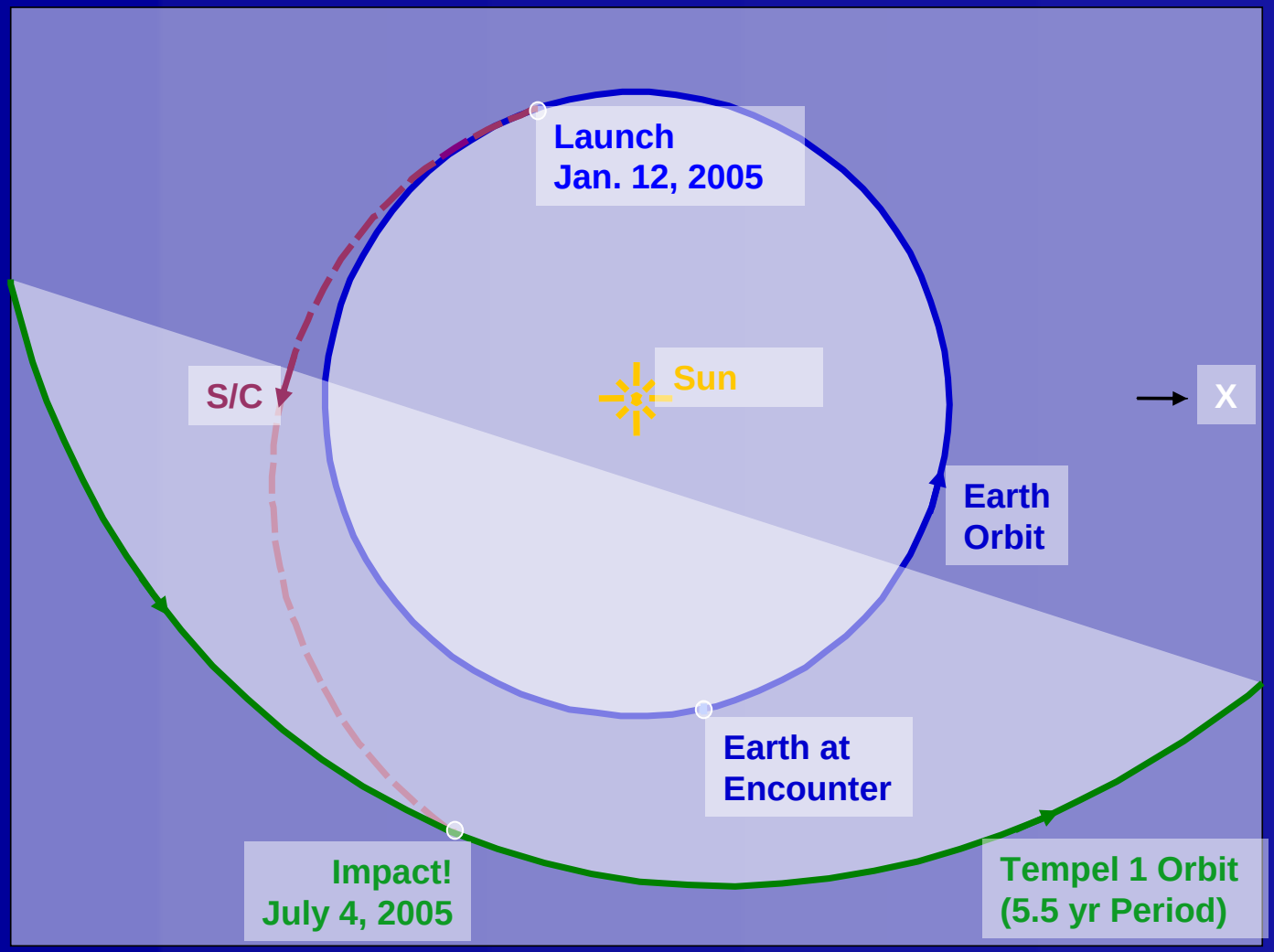
Stacking the Flyby and Impactor

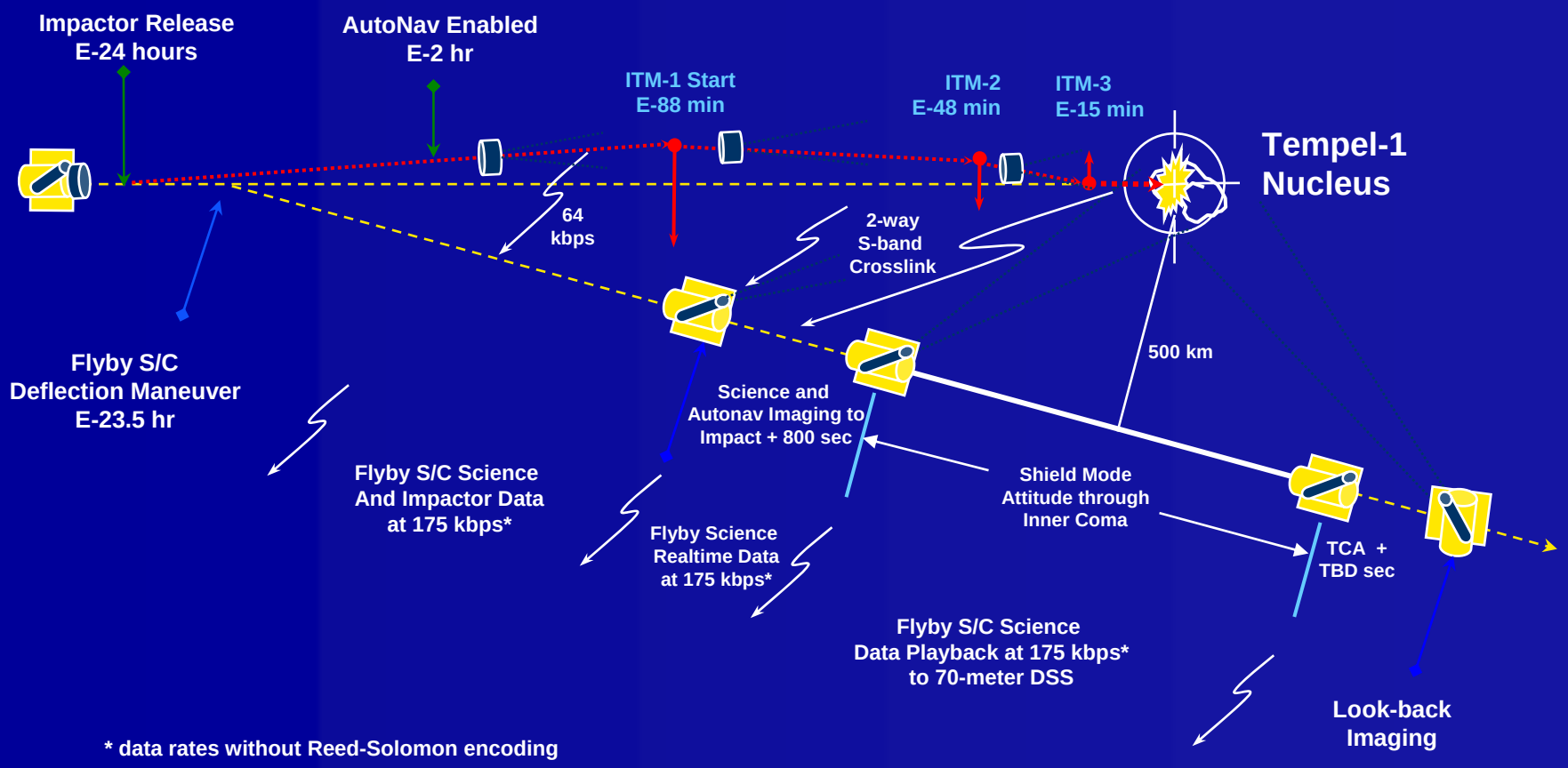
Sept. '04

The Mission

Interplanetary Trajectory

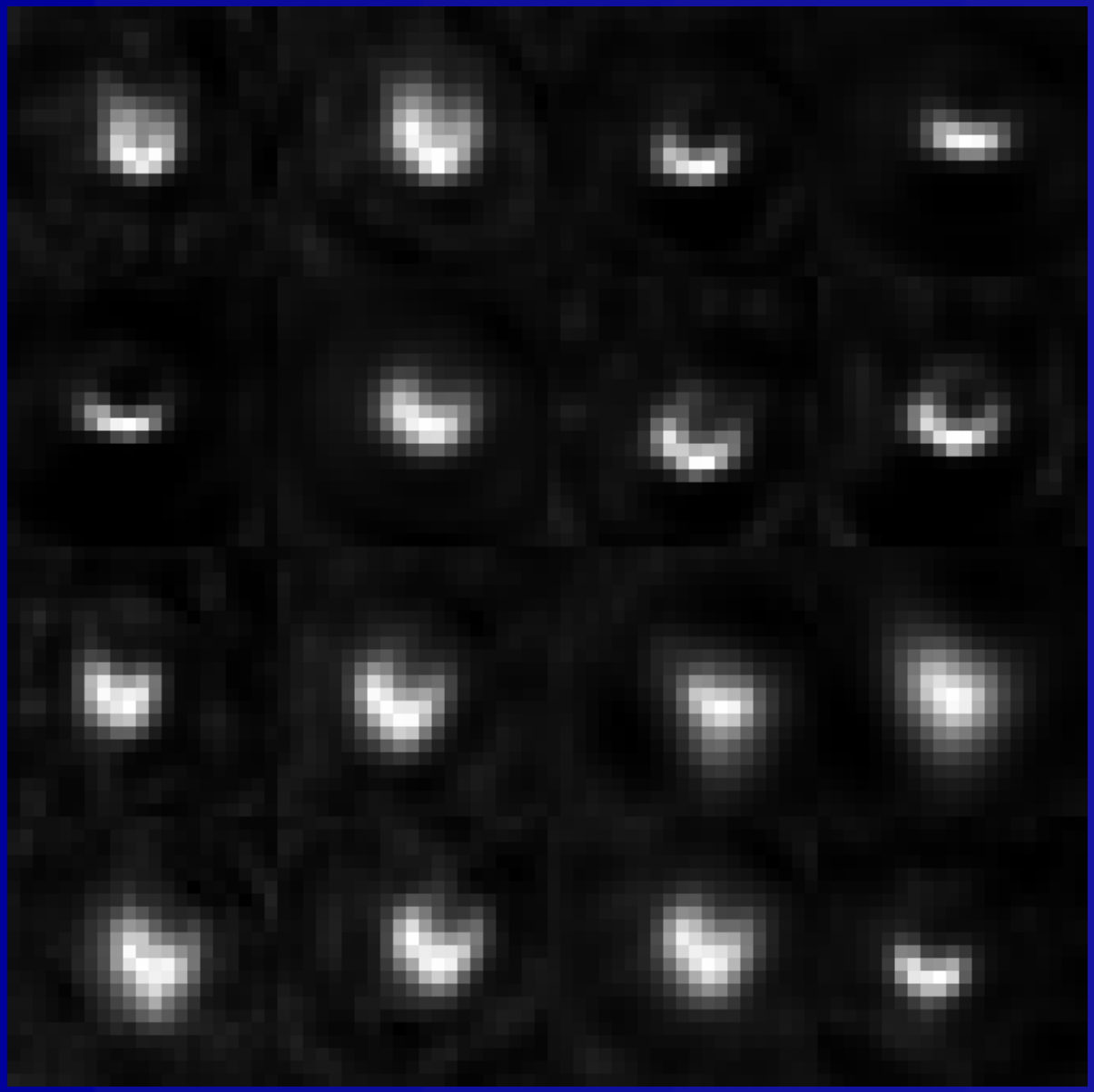


Encounter Schematic

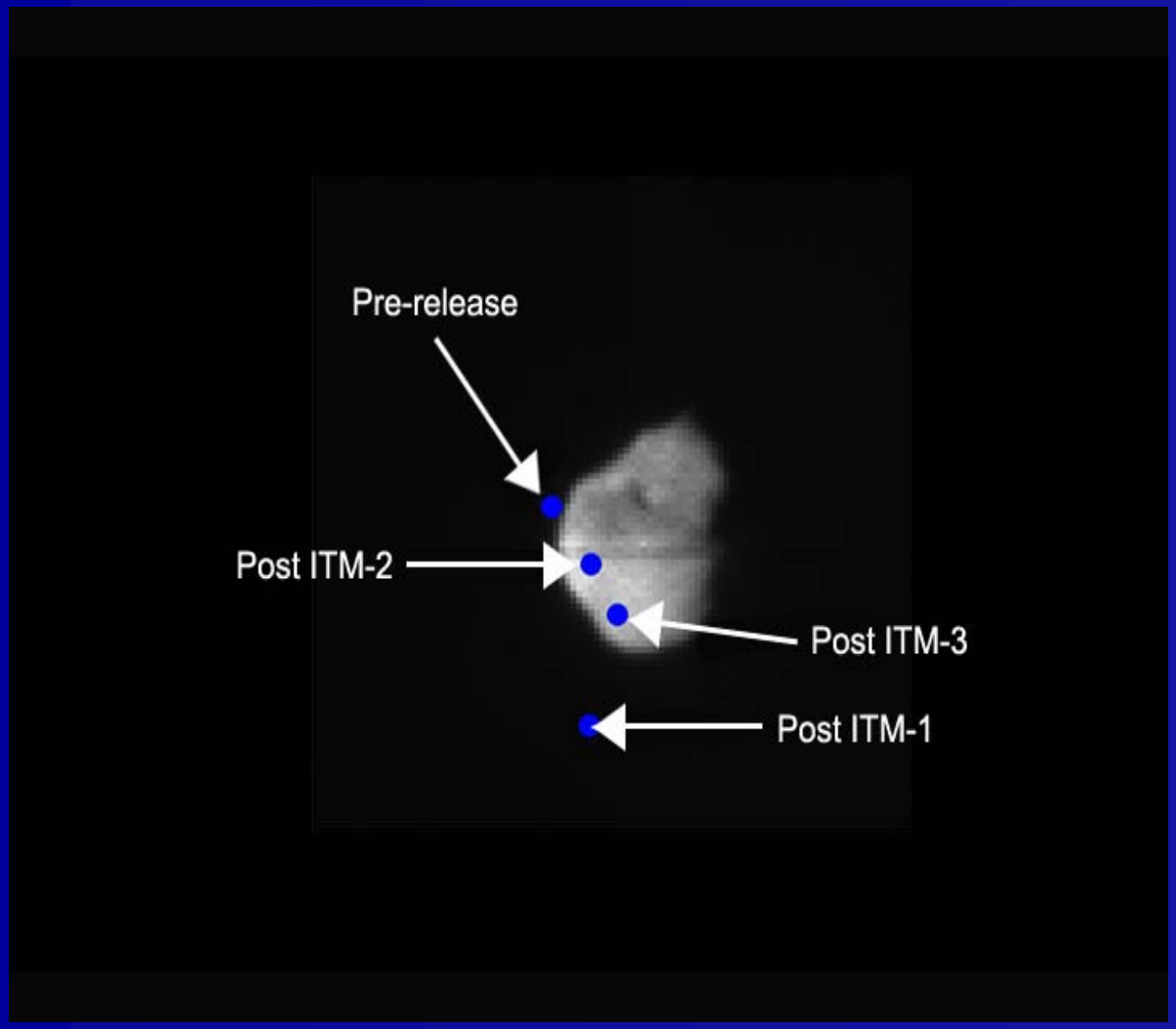


* data rates without Reed-Solomon encoding

What We Were Looking At



ANAV - Impactor Targetting Maneuvers (ITMs)



Impactor Approach

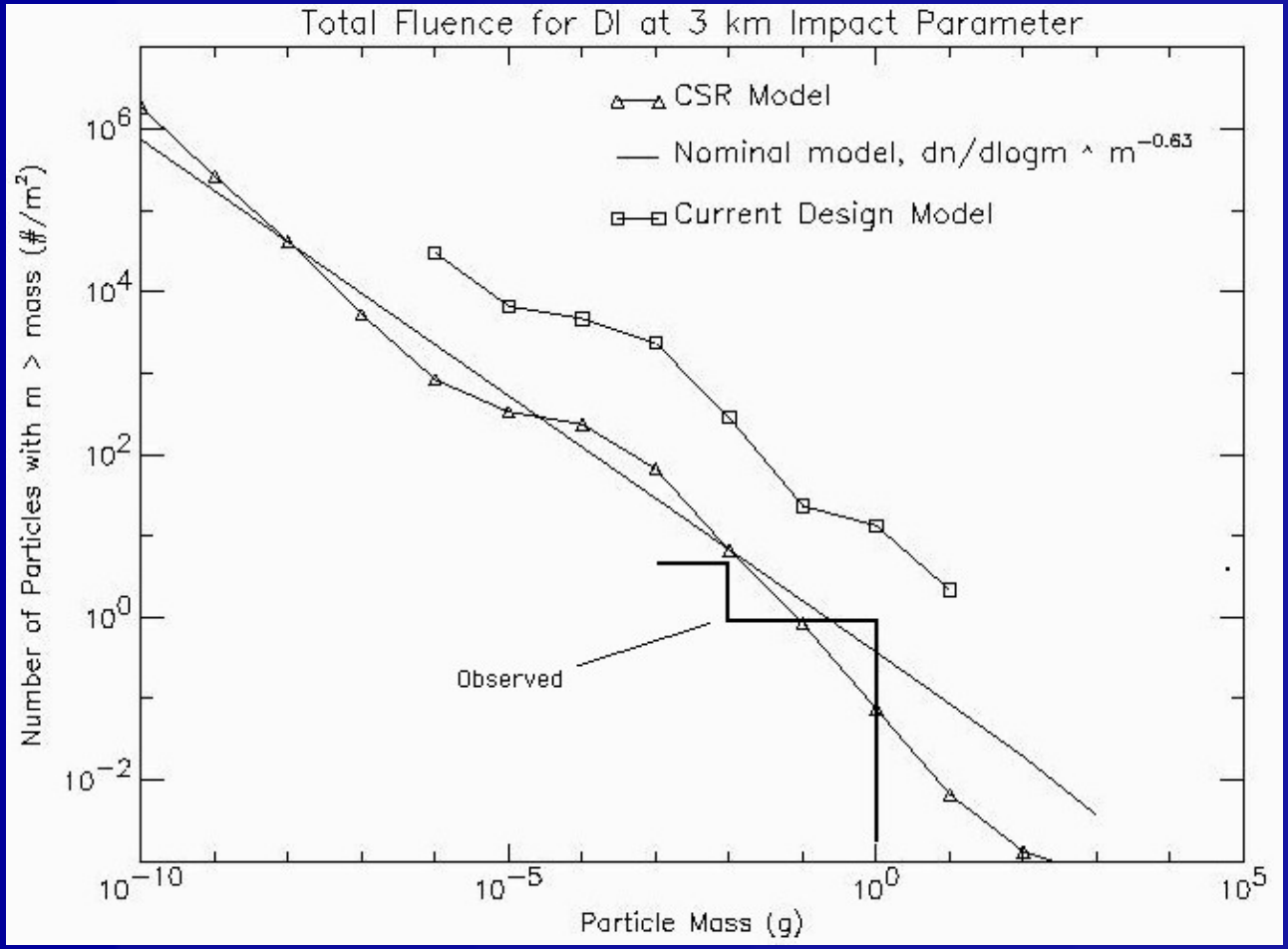
- Original movie (not registered) to show pointing jitter
- Note one big jitter early due to ITCM. Note big jitters in last 30 seconds due presumably to dust hits
- Orientation is “upside down” mirror image of “sky” to visualize landing on oblique surface (20 to 36° from horizontal) ecliptic north is roughly near the bottom

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

ITS Sequence

- ITS images - impact site indicated by arrows (now right side up - ecliptic north in upper right quadrant, sun to right)
- Sense of rotation - top is approaching
- Oblique impact - 36° from horizontal by shape model but 20 to 35° from assuming circular craters

Dust on Impactor



4 Dust hits measured by ADCS correlated with image pointing between -21 and -3 s

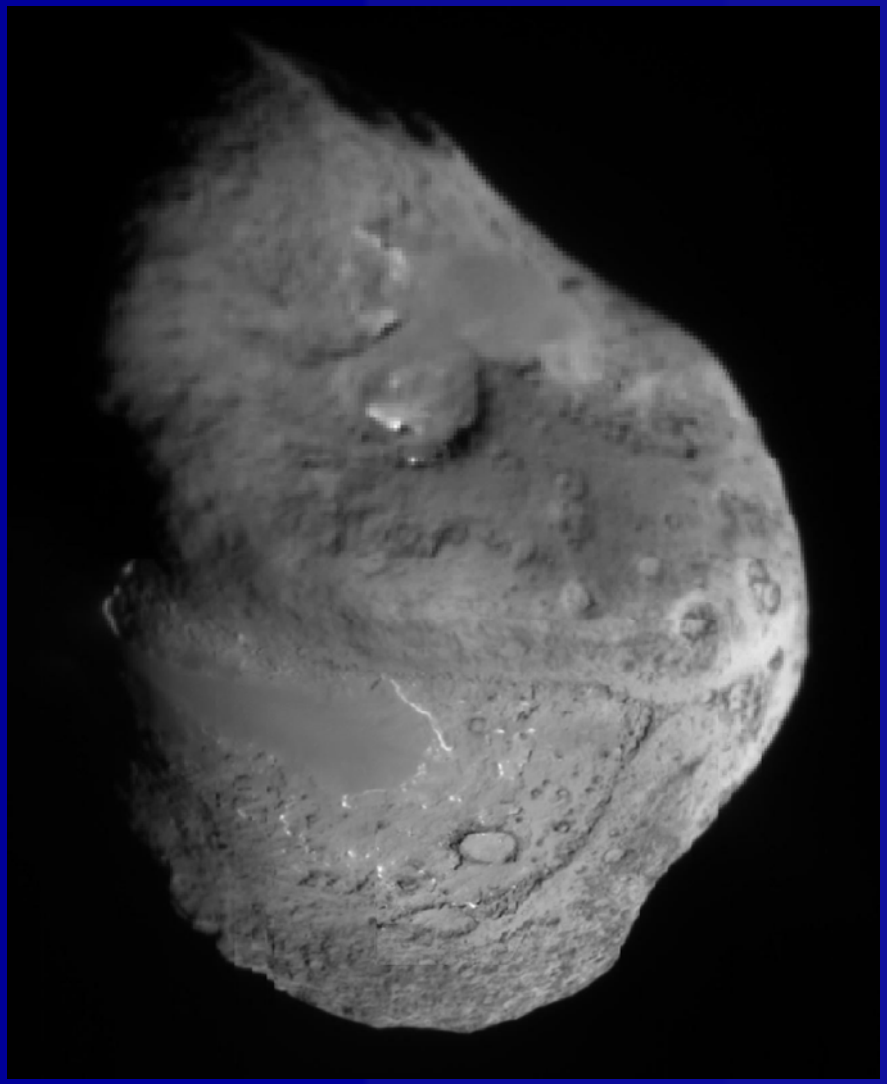
Last hit was at -3 s, after last transmitted image and had largest mass

Expectation values of mass

3 between 1 - 10 mg, 1 (last hit) 100-1000 mg

Impactor cross-section about 1.1 m^2

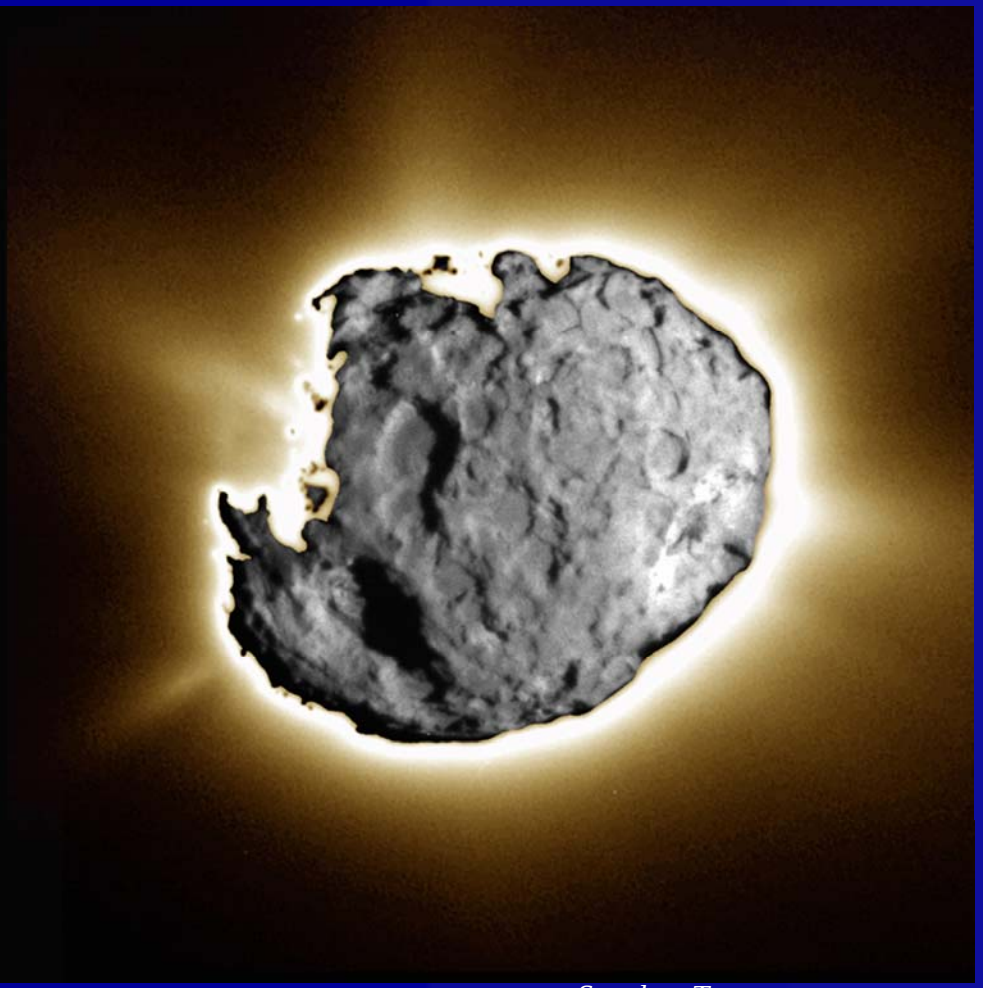
ITS Composite Image



- Note geological features
  - Large, smooth surfaces
  - Round features = craters? (size-freq plot consistent)
  - Stripped terrain (old)
  - Scarps
  - Evidence of layers
- Overall Shape
  - Effective radius 3.0±0.1 km
  - Max-min diameters 7.6 and 4.9 km but very uncertain
  - Well-mapped surface is mostly in 3 large more-or-less flat areas
- Impact site is between two craters near bottom of image.

Differences Among Nuclei

81P/Wild 2



Stardust Team

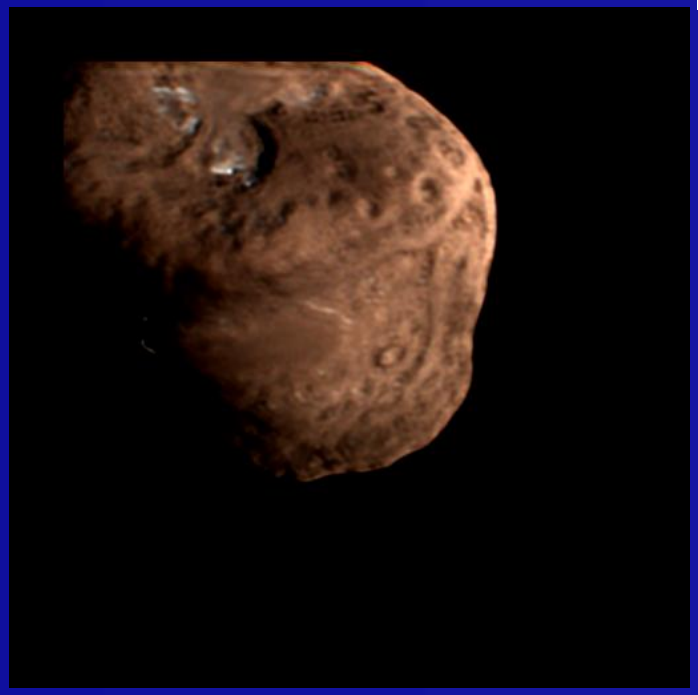
Stardust Web Site

19P/Borrelly

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

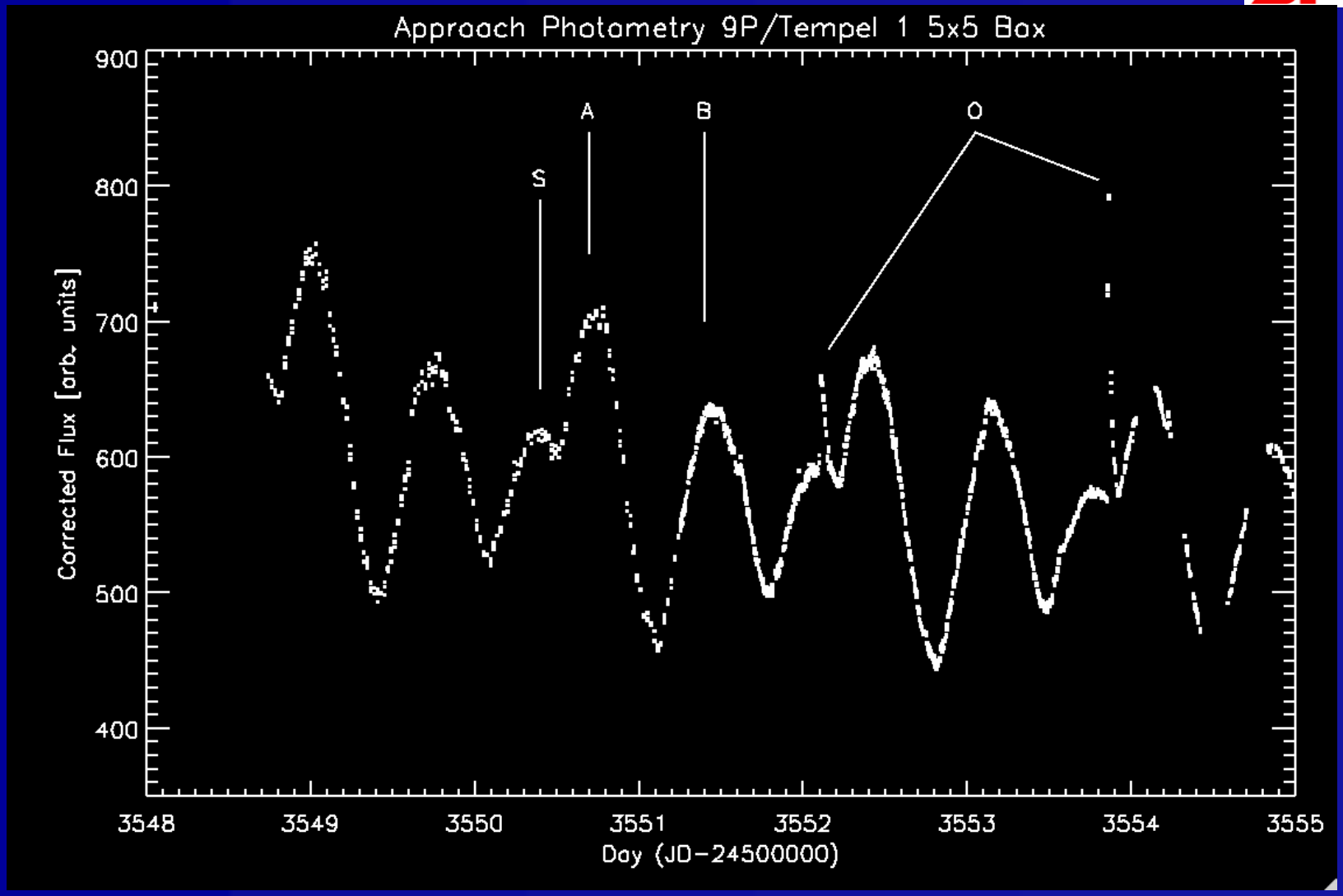
L. Soderblom

HIR Color Composite



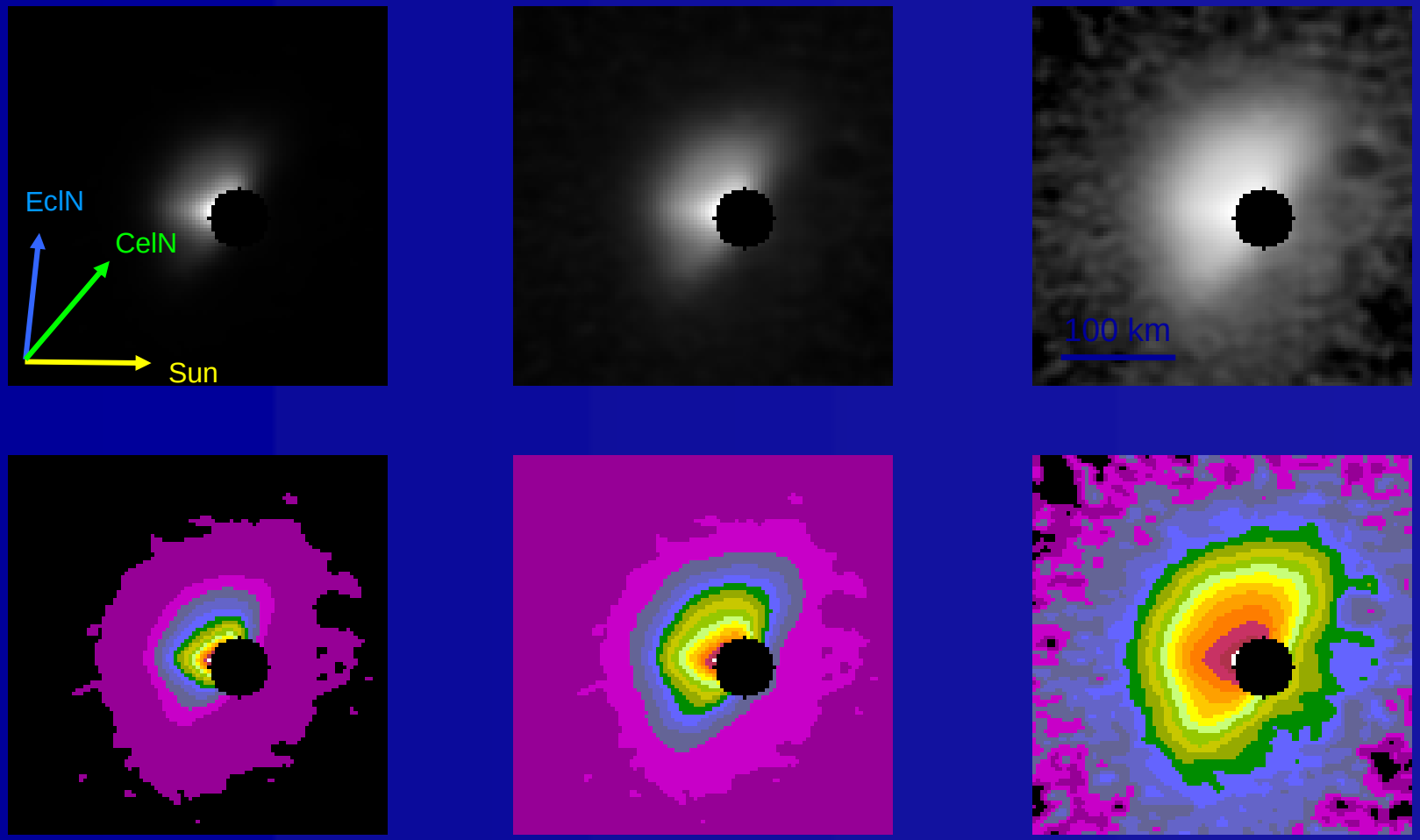
- Red, green, and blue
- Note effects of deconvolution on HRI images
- Color constant over nearly all surface except a couple of bright areas near “top” brighter in UV than most of surface.
- Brightness variations 2x
- Large smooth areas (no craters), scarps, ridges, old cratered terrain lower than high smooth terrain; large areas have low curvature. Impact craters?

Approach Photometry

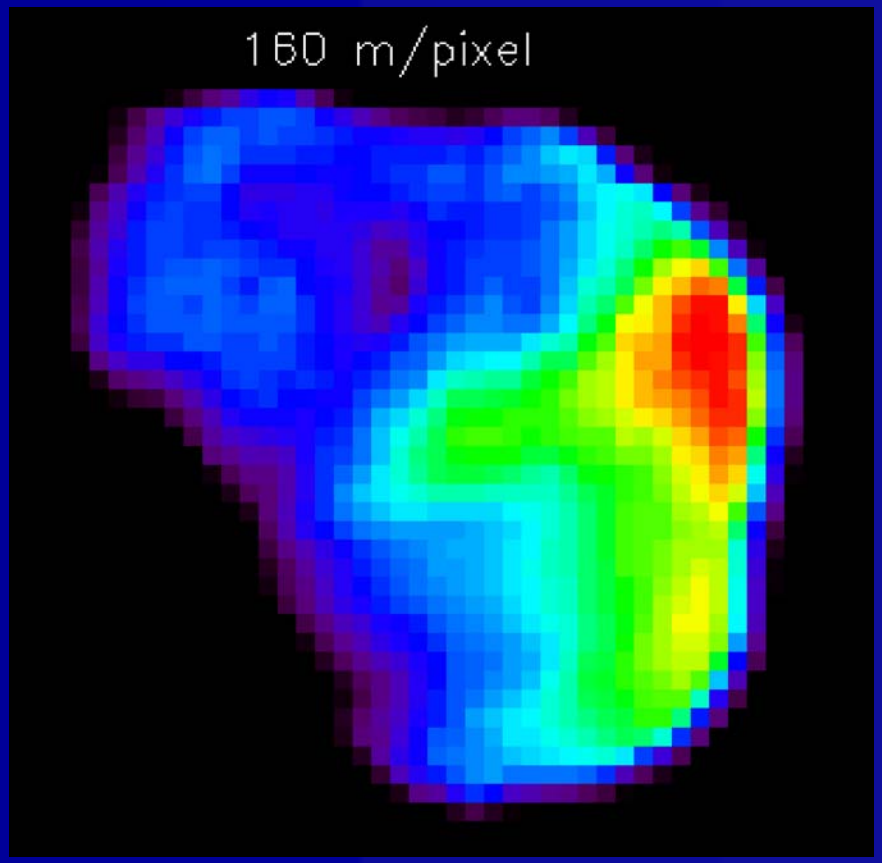


Additional details by Belton

Deconvolved Images



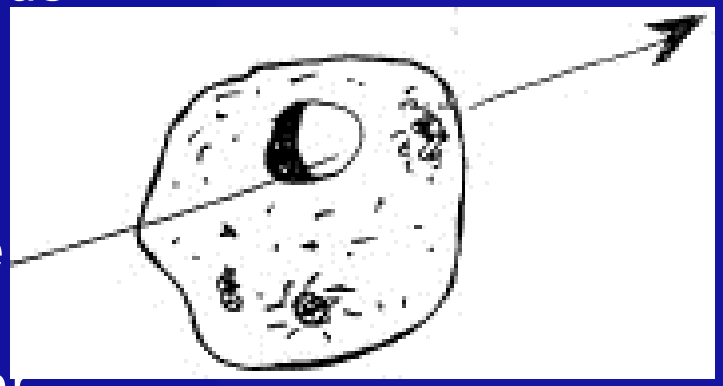
Thermal Map of Nucleus



- First real thermal map of a nucleus
- Consistent with STM
- Subsolar point: T = 365K
- Coldest measurable point: T = 225K, limited by scattering in spectrometer near terminator
- No sunlit locations as cold as sublimation temperature of H_2O ice
- Therefore ice must be below the surface but “not far” below

Possible Scenarios

- Crater formation on an intact nucleus
  - Gravity controlled crater
  - Compression controlled crater
- Split nucleus
- Crater formation on an intact nucle
  - Strength controlled crater
- Aerogel-like capture of the impactor
- Shattered nucleus
- Transit through the nucleus



D. K. Yeomans
CSR page 1-12

- Above are roughly in order of decreasing probability (as guessed by the PI)
- N.B.: K.E. of Impactor << Gravitational Binding Energy of Cometary Nucleus
- N.B.: $v^2/2$ > maximum energy per mass of any chemical explosive

MRI Movie

- Frames every 62 msec
- Initial stages of excavation only
- Small “poof” that goes rapidly to left at onset is hot, self-luminous
- Later ejecta are cold
  - Water ice survives the ejection
  - Speeds start at few x 100 m/s and drop to below escape velocity as excavation continues

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

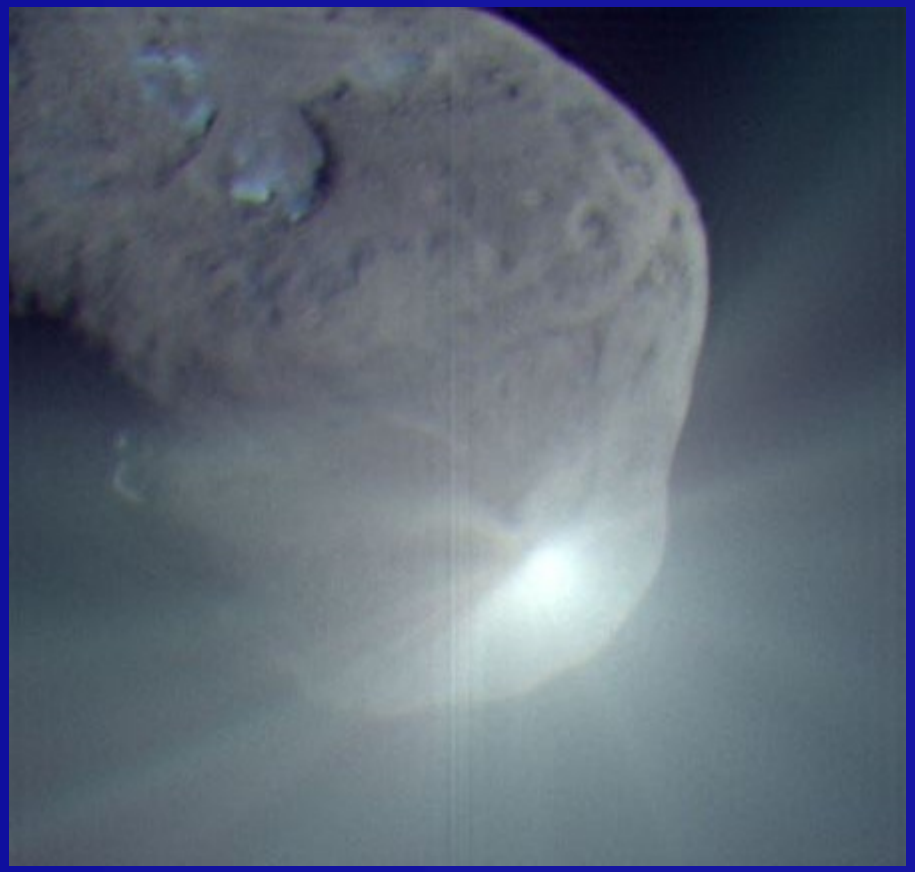
HRI Movie

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

- Much slower frame speed than with MRI
- Longer period included in movie
- “Vertical bar” immediately after impact is bleeding of the saturated CCD, not real ejecta
- Note shadow cast by optically thick ejecta

Deconvolved HRI Image

- IR + green + violet
- Forced to average gray
- Note very localized “bluish” areas
- Note curvature of ejecta in up-range direction
  - Consistent with lab experiments
- Note smoothness of ejecta in radial direction
  - Primarily small particles
  - Rays from initial conditions (first fraction of a second) of impact

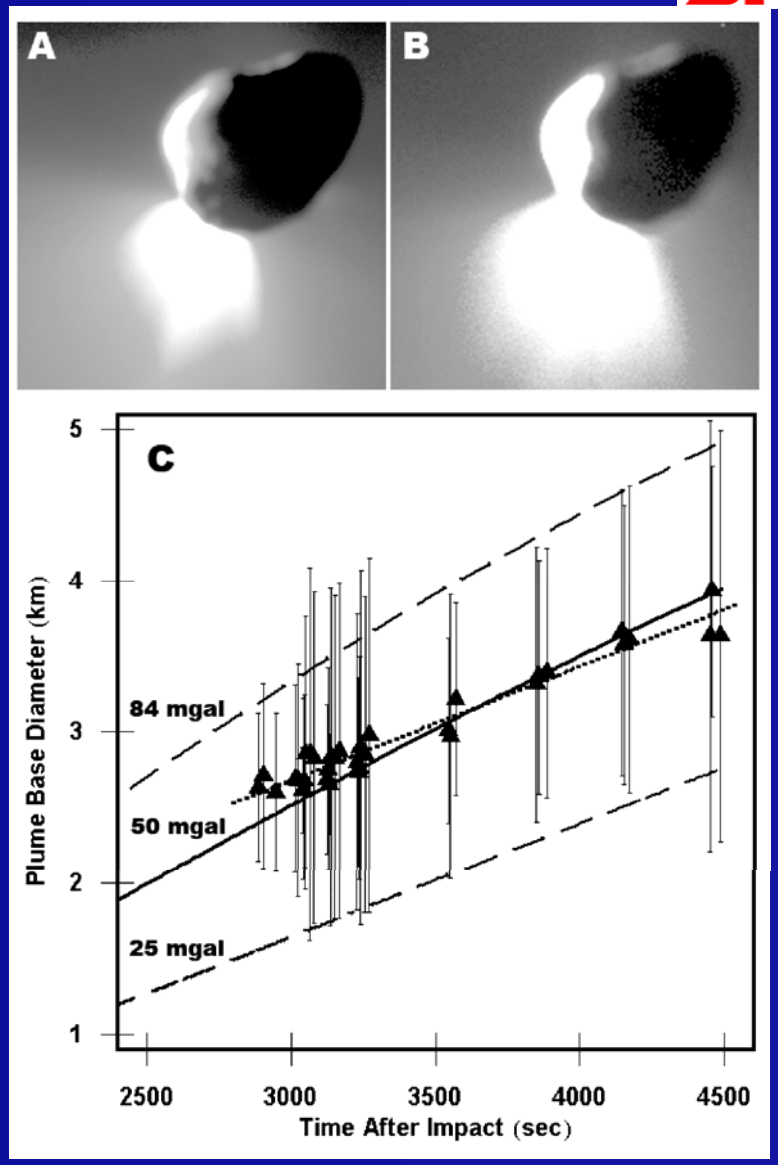


Nature of Impact

- Oblique impact (20-36° from horizontal)
- Self-luminous vapor plume (low mass)
  - formed within first 0.5 seconds and decoupled from bulk of ejecta
  - Plume speeds downrange range from 5km/sec to 8km/sec (depending on projection)
- Bulk of ejecta
  - likely followed power-law decay of increasing ejected mass with decreasing velocity
  - Likely predominantly particles << 10 μm
  - Total ejected mass for gravity-scaled cratering ~ 1-2 $\times 10^7$ kg - consistent with observed dust depending on model
- Plume remains connected to surface for hours
  - Gravity-controlled crater
  - Strength < 65 Pa on scales of 1m to 100m

Fallback of Ejecta Yields g

- Assuming ballistic trajectories and gravity scaling!!!
- Measure width of base of plume
- Yields local gravity about 50 mgal (.05 cm/s^2) at impact site
- Shape model yields mass, 7e13 kg, assuming uniform density. 50% error bars, not dominated by volume, will be reduced.
- Density = 0.6 g/cc
- If bulk material density is 2 (average of ice and rock), porosity is 70% averaged over entire nucleus!

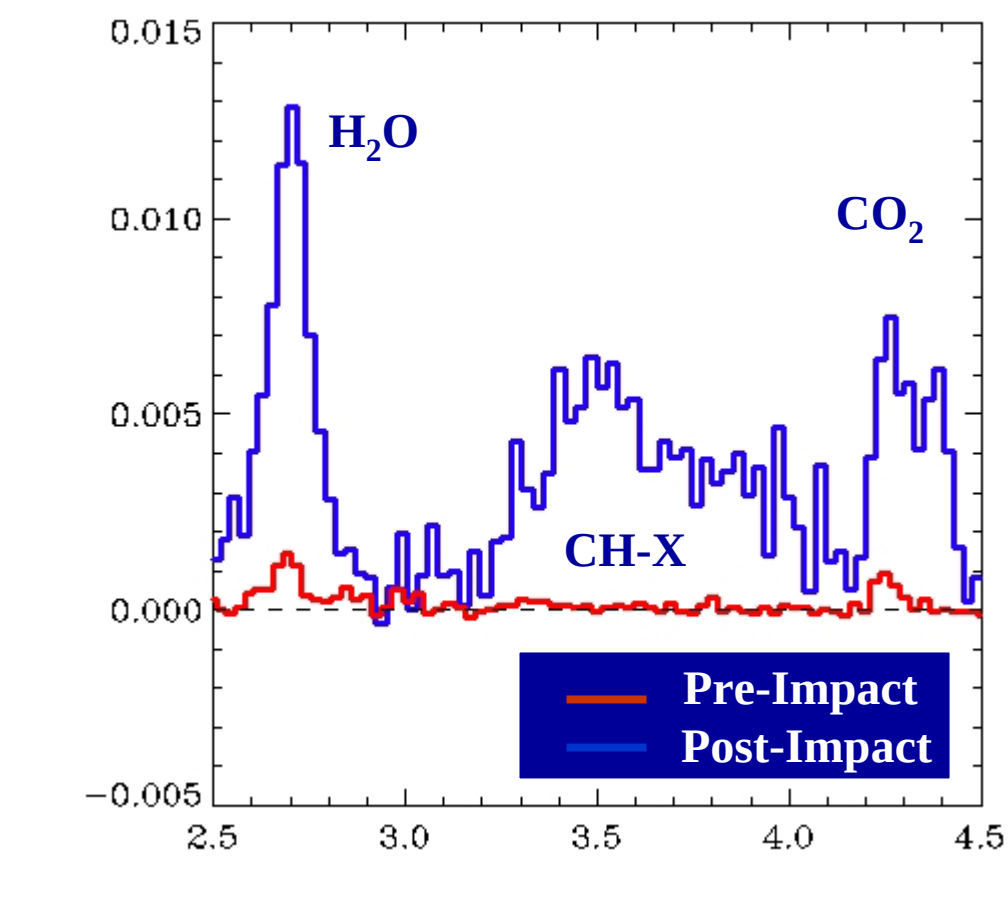


Nature of Ejecta

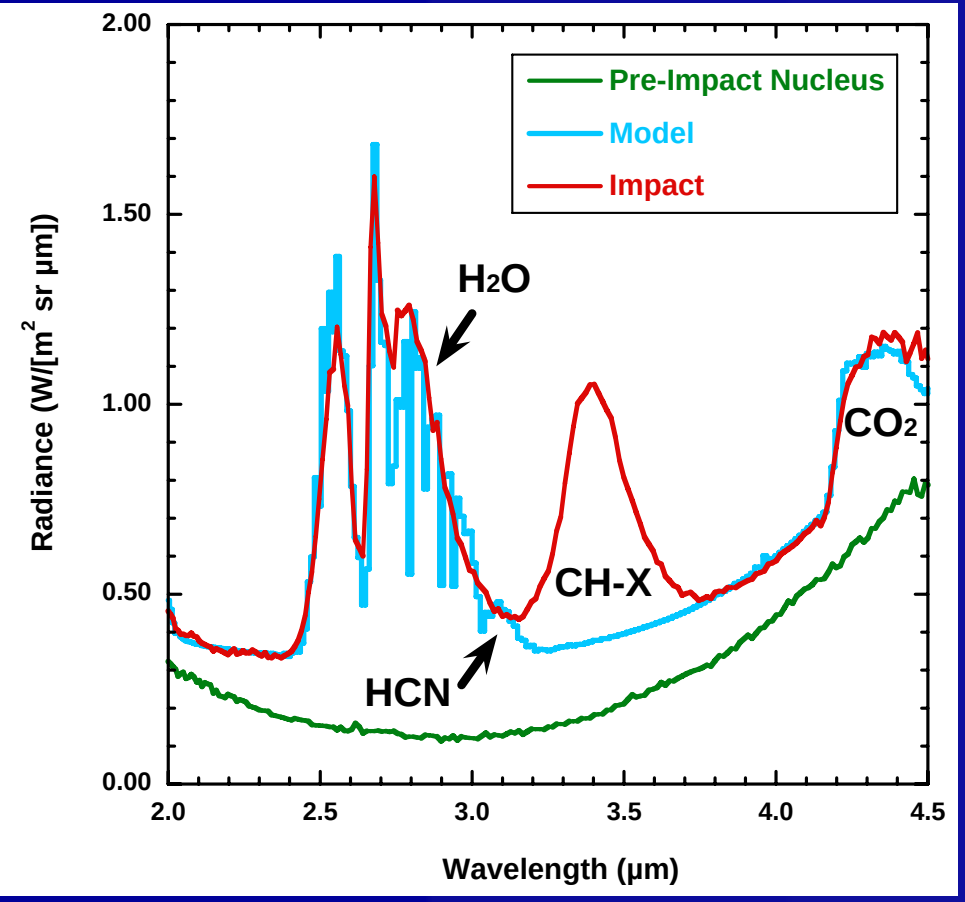
- Total ejecta from scaling laws - 1-2x10^7 kg
- Total volatiles (Keller H_2O, Feldman CO) - 5x10^6 kg, but with Schleicher's H_2O, 15x10^6 kg
- Dust/Ice ratio ~1 per Schleicher, ~3 per Keller
- Particle size - mostly < 10 μm
  - Superheat
  - Mass per cross-section
  - Radiation pressure model (Schleicher)
    - But see possible contrary view by Keller
  - Strong mid-IR emission features (Lisse *et al.*)
  - Implies pre-existing 1μm grains or very weak aggregates thereof to depths of tens of meters
- Particle composition
  - Mix of silicates and volatile solids
    - Ice detected *in situ* in ejecta
  - Additional refractories seen with Spitzer (carbonates?)
- Gaseous Ejecta - see following slides

Spectra off Southern Limb

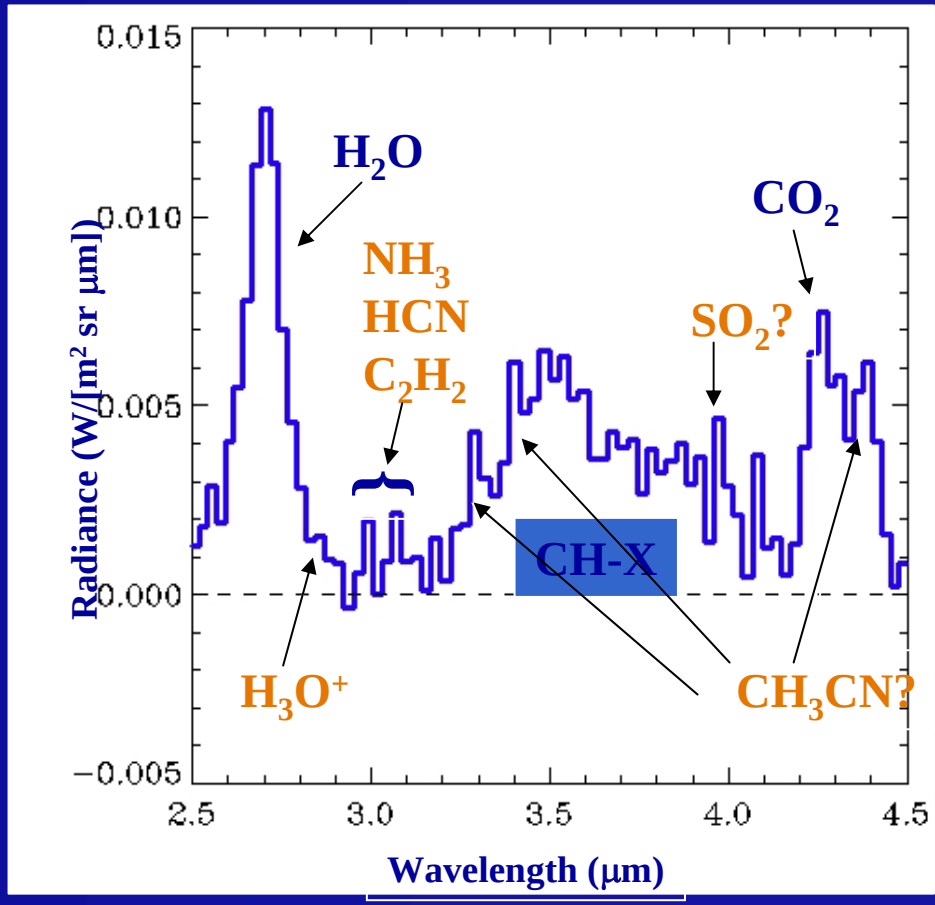
- Post-impact spectrum obviously different from pre-impact spectrum
- Initial ejecta are hot but after few seconds ejecta leave nucleus cool
- At end of observations, composition seems to be asymptotic suggesting we excavated “deep enough”!
- CO (4.7 μm) and minerals in reflection (1.05 to 2 μm) waiting on improved reduction of spectra at ends
- Most species have optically thick lines so that column densities are not easy to determine



Volatile Composition



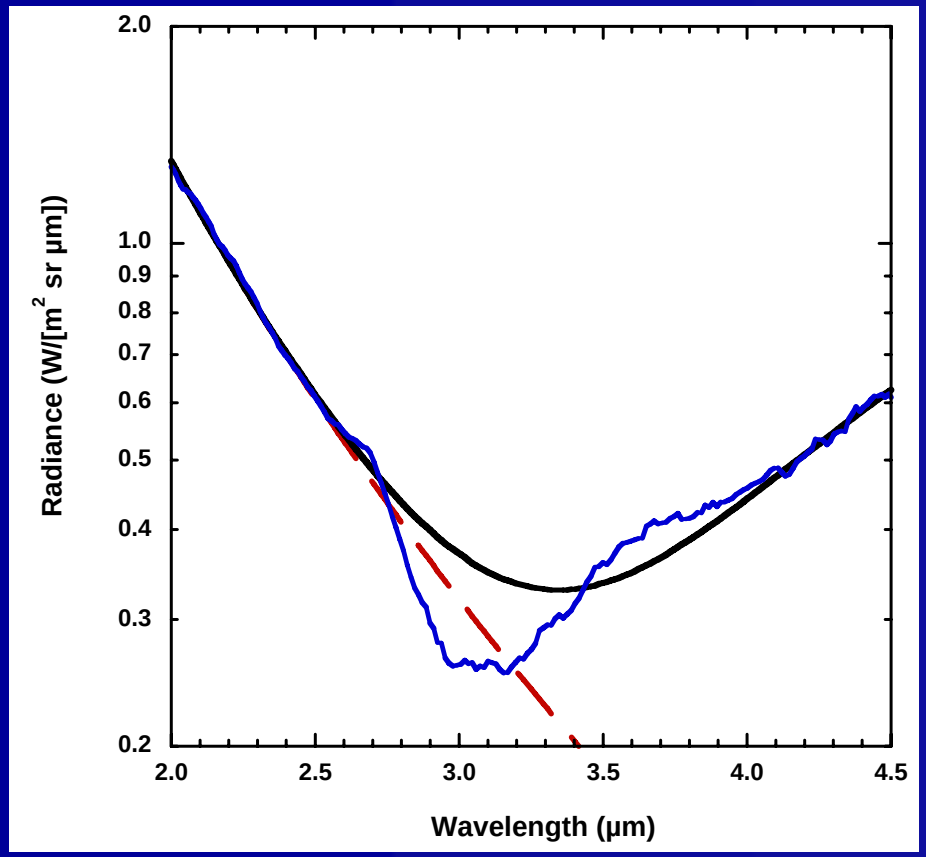
First 0.2 sec

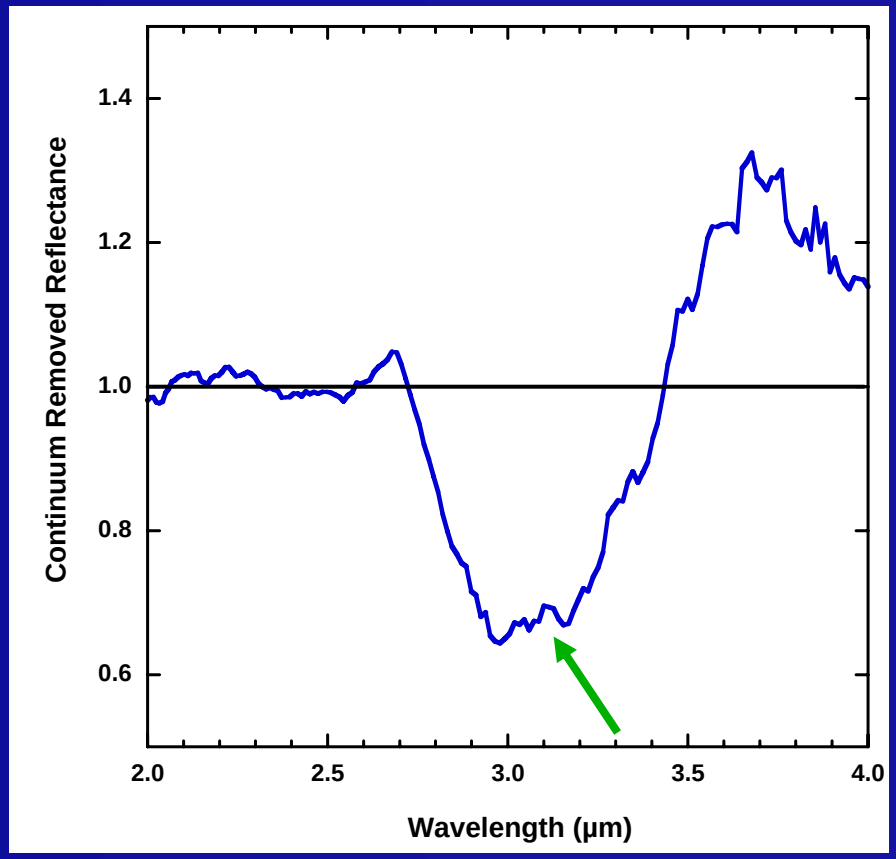


I+4 min

Details in talk by Sunshine

Average Early Ejecta





3 µm Absorption

- Present even without correcting for thermal component
- Consistent with microscopic crystalline H_2O ice particles

- Near-Surface Water Ice
- Ejecta are cold, thus unprocessed!!

Results thus far

- Nuclei are different!!!
  - Probably impact craters
  - Distinct layers not understood
  - Negligible thermal inertia
  - Outbursts are common
- Oblique Impact
- Gravity controlled crater
  - Strength negligible compared to very low gravity
  - Bulk nucleus mostly porous
  - Crater diameter - TBD but probably $10^{2.0\pm0.3}$ m
- Ejecta
  - Microscopic particles of ice and “dirt”
  - Large increase in organics relative to water vapor (ice not quantified yet)
  - Tentative identifications of several species including CH_3CN, SO_2, C_2H_2 in addition to firm identification of H_2O, CO_2 and HCN.
  - Abundances depend on radiative transfer in optically thick lines

Summary

- Deep Impact accomplished or exceeded all of its primary mission goals
- The DI spacecraft performed their mission in a completely nominal manner
- The observation campaign provided enormous data on the behavior and characteristics of Tempel 1
- There is no reason to believe that Tempel 1 is not typical of the rest of the Jupiter family comets
- Lots of organic material below the surface
  - Still need to determine the molecular composition
  - Still need to determine whether organics are polymerized or in a “useful” form or whatever
- Heterogeneity -
  - Obvious topographic regimes: are they same structure?
  - Differences among comets: are they similar in structure?