



STS107 Image Analysis Team

Luminosity Working Group

STS-107 Debris Characterization Using Re-entry Imaging

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CAIB Report:

Volume 3, Appendix E.2, Section 6



What happens when a spacecraft enters the atmosphere?



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- Hypersonic encounter: air compressed in front of vehicle
 - vehicle velocity exceeds molecular speed
- Compressed air forms hot shock layer
 - enthalpy: joules of kinetic energy per kg air, $v^2/2$
- Hot shock layer heats vehicle surface
 - convective and radiative energy transfer
- Vehicle surface responds to heating
 - Conducts heat into vehicle
 - Radiates heat into space
 - **Ablates via chemical and phase changes**
- **Thermal protection system design goal:** manage surface heating to protect vehicle structure and payload





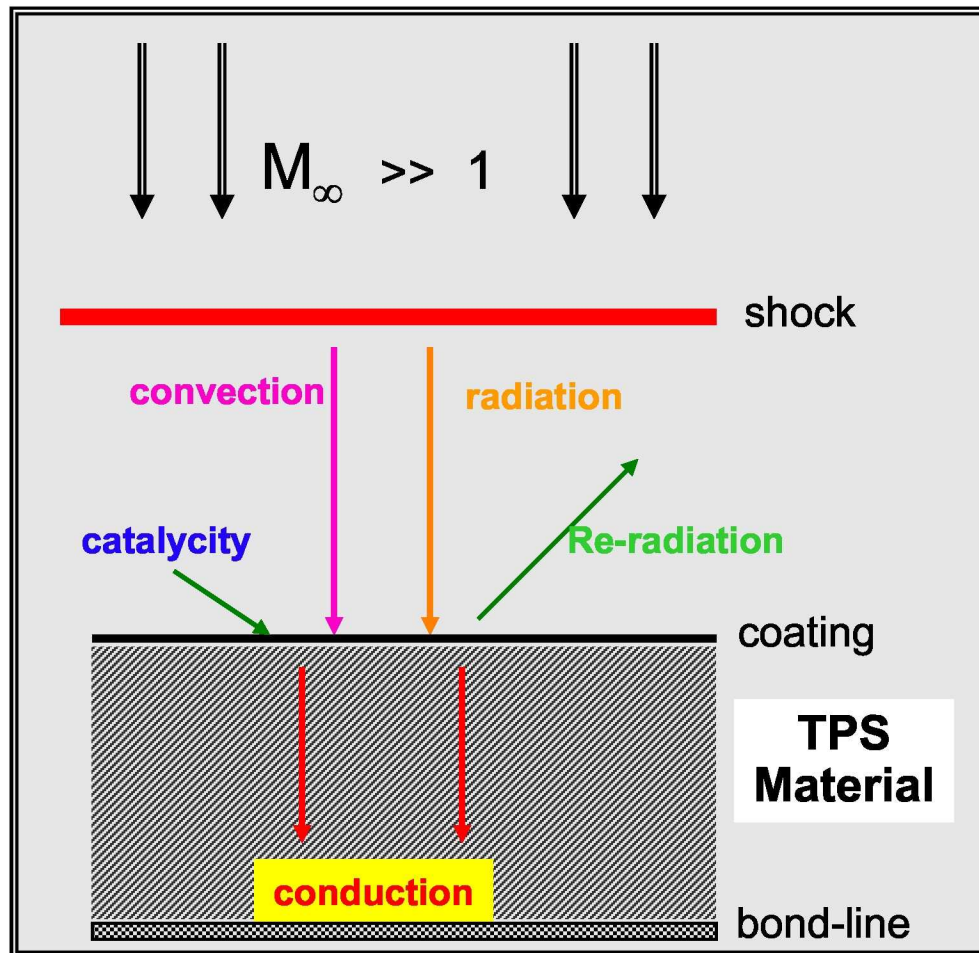
Reusable Thermal Protection Systems



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Reusable TPS systems are designed to reduce heat conduction at the bond-line to vehicle acceptable levels. Typical characteristics of a desirable TPS include low mass, high emissivity, low catalycity, and low thermal diffusivity.



High emissivity coatings $\uparrow$ $q_{\text{re-radiation}}$

$$q_{\text{re-radiation}} = \epsilon_w \sigma T_w^4$$

where ϵ_w is emissivity

Coatings with low catalytic efficiency reduce the release of chemical energy near the surface, thereby reducing the heat-flux at the wall.

Conduction within the TPS material depends on material properties: *thermal diffusivity* (K), *density* (ρ), *thermal conductivity* (k) and *specific heat* (C_p)

$$\text{thermal diffusivity, } K = \frac{k}{\rho C_p}$$

No phase transition or reactivity



What happens if the TPS fails?



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**Test 142 Run 17
Bare Aluminum
Arc Jet HSV: 14x**

**NASA-ARC/AS
Columbia LWG**



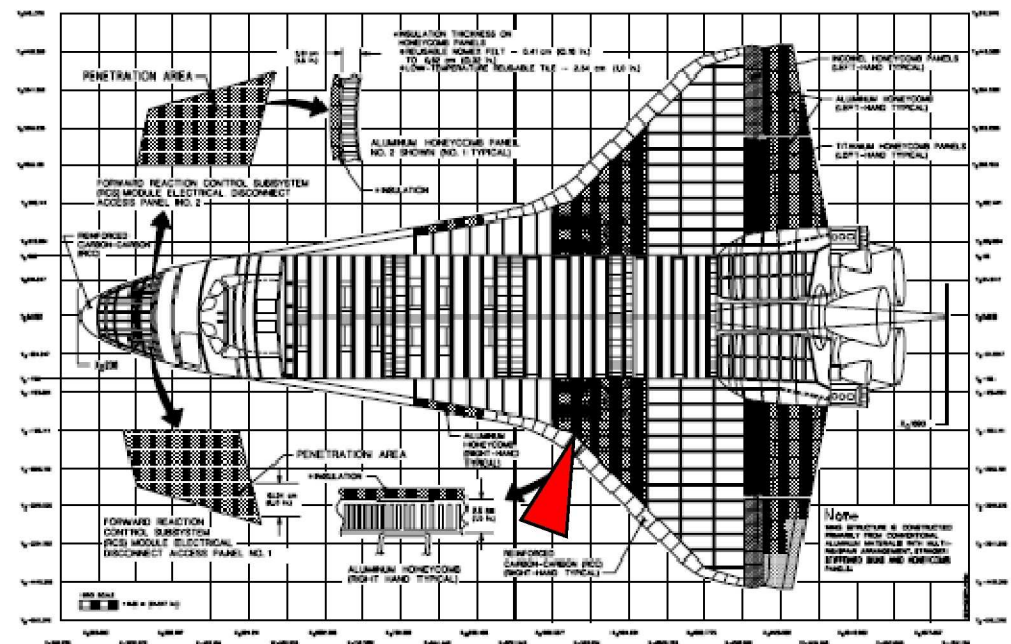
Columbia, STS-107



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- Space Shuttle Columbia, STS-107
 - Broke apart during entry
- Initial cause unknown
 - Vehicle at peak entry heating
 - Limited off-nominal data, no “smoking gun”
 - Only peak heating data: amateur observers



- Late reconstruction: damage to Wing Leading Edge
 - WLE struck by foam debris on launch
 - Hole in TPS allowed hot gases into wing structure
 - Wing structure melted, wing separated, loss of control

Peak heating:

Mach ~20

Shock layer temp: ~4300 K, 7300 F

Boundary layer thickness: ~10 cm

Surface temp: ~1800 K, 2800 F



At the time of the accident...

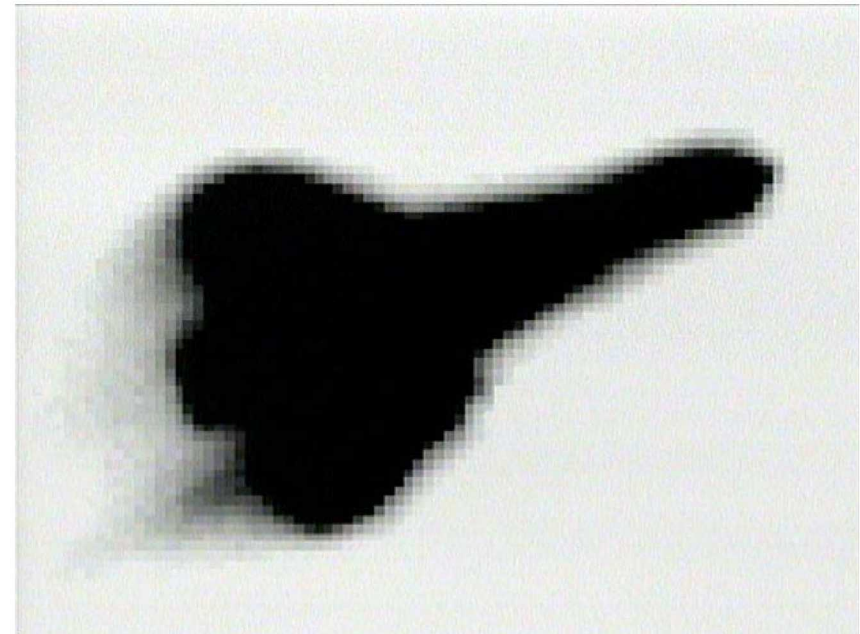


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What happened?

- Only record: amateur video
- No existing model of observed events
 - Unclear what a “normal” entry looks like
- Can we learn anything from these videos?





Debris #1, #2



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Debris #6/Flash 1



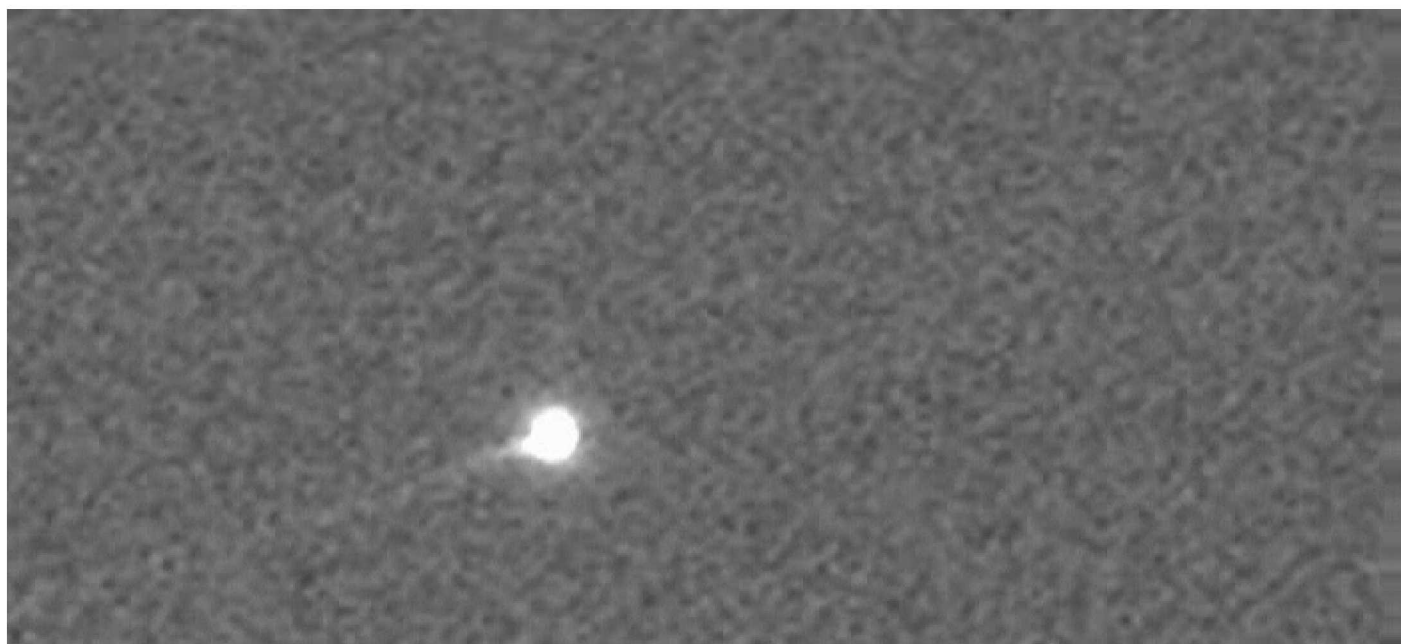
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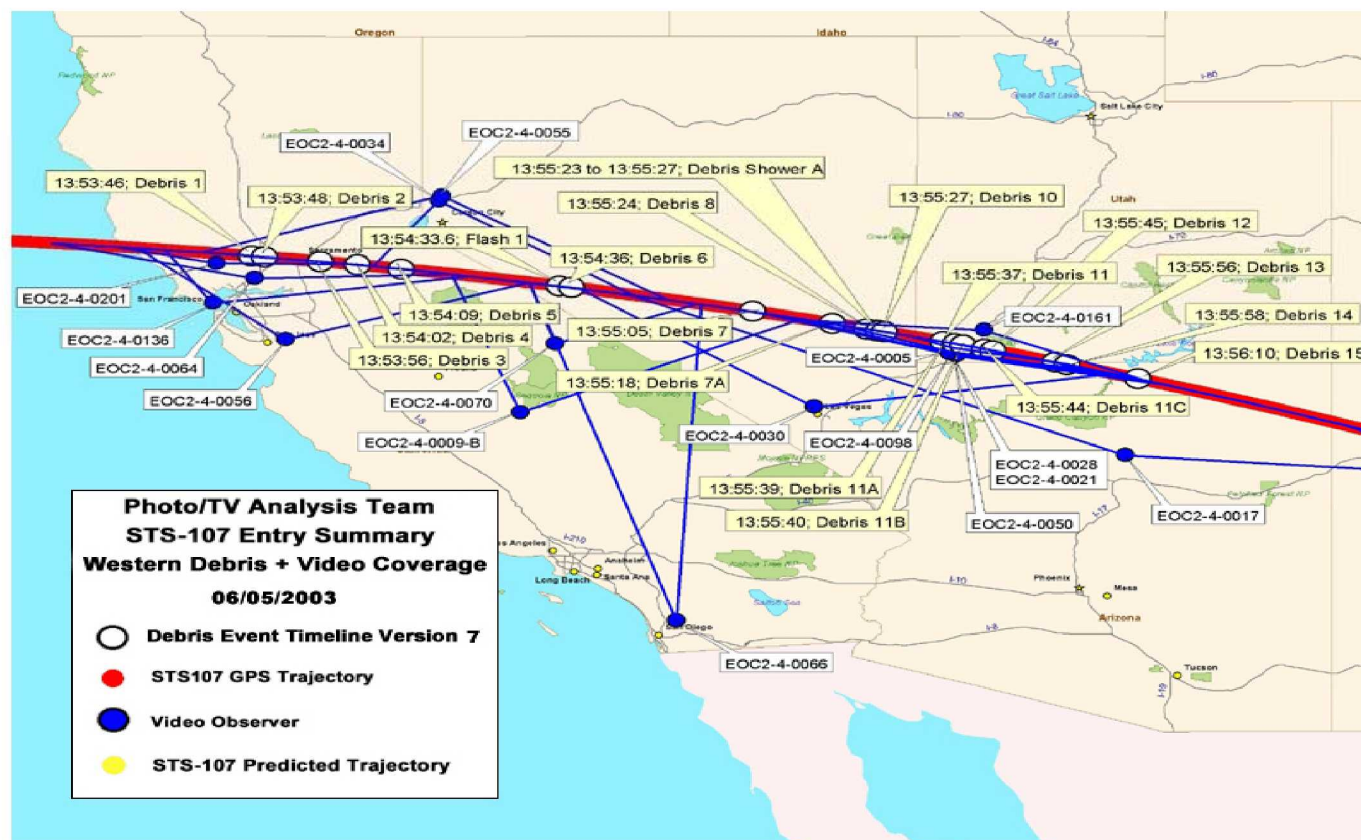
Overland track observer locations



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Entry Debris Video Coverage Map (West)



140+ videos
Several hundred stills
Many skilled observers
Several multiple coverage events

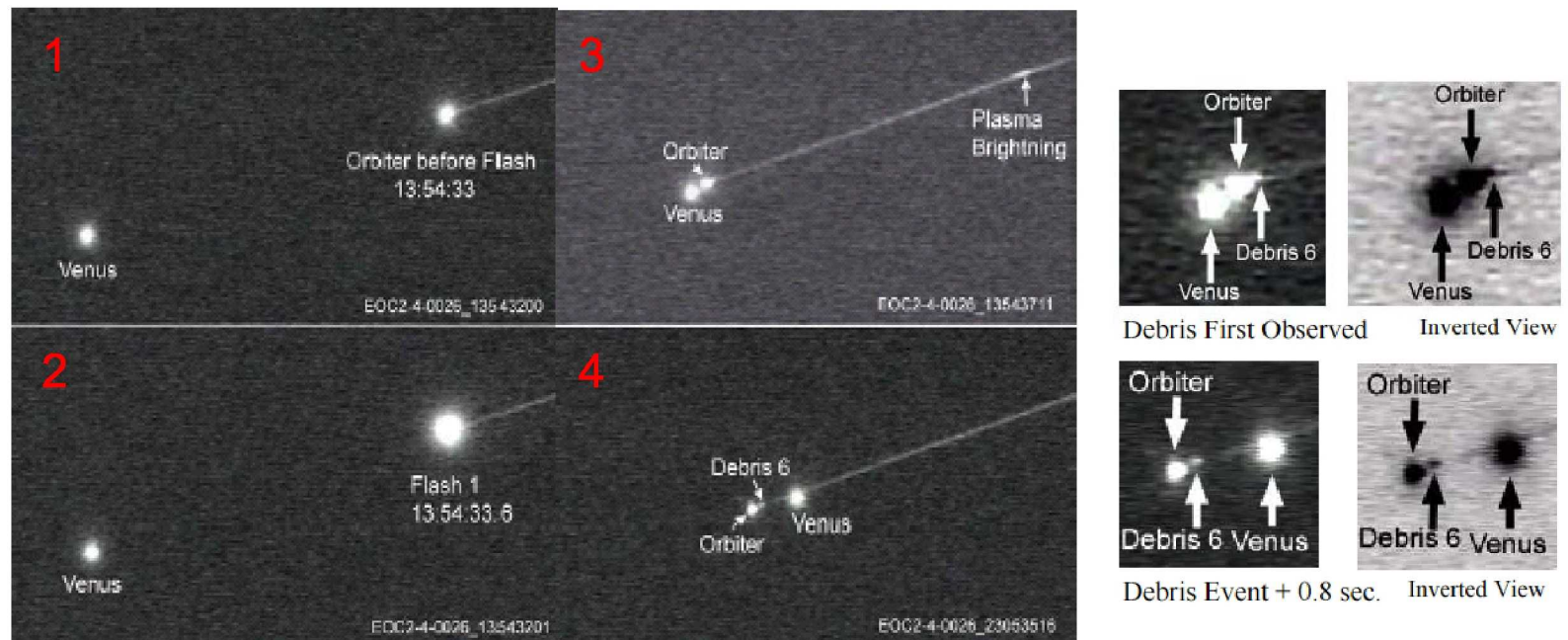


Raw image quality: poor



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Debris event 6: Images from Sparks, Nevada; southeast view

Information content:

- Timing: relative and absolute
- Debris relative motion
- Relative brightness: orbiter, debris, wake
- Color channels (very little info)

Challenges:

- Variable FOV
- Automatic gain
- Saturation
- Focus
- Jiggle



Image radiance models



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Three cases for interpreting debris images:

1. Radiance proportional to “lost” kinetic energy as debris decelerates;

- Non-ablating
- Mechanism unknown
- Upper bound

$$\frac{d}{dt}(KE) = \frac{d}{dt}\left(\frac{1}{2}mv^2\right) = mva$$

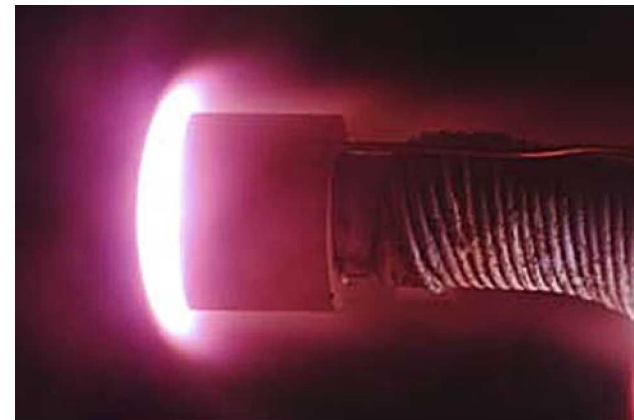
2. Radiance proportional to lost kinetic energy; moderate ablation

- Constant debris area
- Ablation as non-radiative loss mechanism

3. Radiance from shock phenomena as

4. “equivalent disk”

- Flat disk, maximum area to mass
- Non-ablating
- Lower bound



Basic approach:

- 1) Determine debris motion from separation analysis; orbiter trajectory known
- 2) Reference debris radiance to orbiter radiance; orbiter brightness “known”
- 3) Need to extract **debris acceleration** and **debris:orbiter brightness ratio**



Derivation of equations of debris motion



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From images: orbiter-debris separation vs time

- Orbiter velocity, acceleration known
- Constant mass

Derive debris acceleration from drag equation: $F_d = \frac{C_d A \rho v^2}{2} = m \cdot a$

$$B = \frac{C_d A \rho}{2m} \quad \frac{dv}{dt} = Bv^2 = a$$

$$\frac{dv}{v^2} = Bdt$$

Integrate for v: $v = \frac{v_i}{1 + Btv_i}$

Integrate for x: $x = x_i + \frac{1}{B} \ln(1 + Btv_i)$

Orbiter: $x_O = x_i + vt + \frac{1}{2} a_O t^2$

Differentiate for a: $a = -\frac{B(v_i)^2}{(1 + Btv_i)^2} = -Bv^2$

Debris position relative to orbiter: plot Δx vs t to find B and t_0

$$\Rightarrow \Delta x_d = v_i(t - t_0) + (1/2)a_o(t - t_0)^2 - \frac{1}{B} \ln[1 + B(t - t_0)v_i]$$

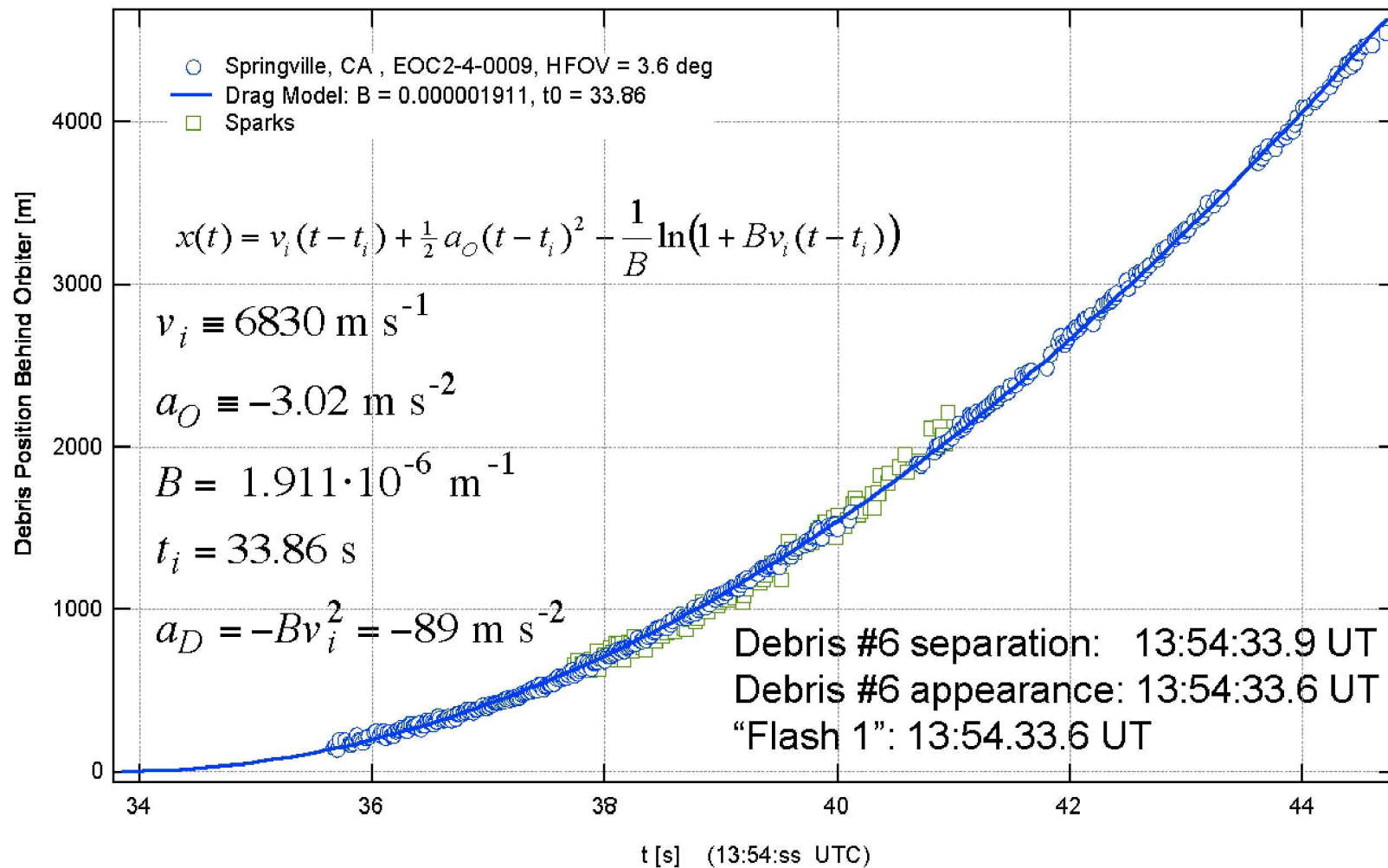


Relative motion plots from image separation



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Object radiance proportional to “lost” kinetic energy



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Assume radiance proportional to lost kinetic energy

No consensus on detailed mechanism for light generation

Case 1: Debris mass constant (no ablation)

$$P_{rad} = -\tau n a \frac{d}{dt} \left(\frac{1}{2} m v^2 \right) = -\tau n a m v \frac{dv}{dt} = -\tau n a m v a$$

Detection efficiency τ same for debris and orbiter

$$\frac{P_D}{\frac{\partial}{\partial t} \left(\frac{1}{2} m_D \bar{v}_D^2 \right)} = \frac{P_O}{\frac{\partial}{\partial t} \left(\frac{1}{2} m_O \bar{v}_O^2 \right)}$$

$$\Rightarrow m_D = m_O \left(\frac{P_D}{P_O} \right) \left(\frac{a_O}{a_D} \right)$$

mass=constant
vectors colinear
 $v_D = v_O$ at separation

Solve for debris mass, with estimated:

- Orbiter mass, deceleration
- Debris deceleration at separation
- Brightness ratio** P_D/P_O

P = optical power

m = mass

a = deceleration

D, O: debris, orbiter



Intensity recovery, saturated images

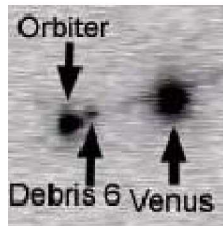


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Most images saturated with extremely high contrast

-Common meteor photometry problem



NASA purchased actual cameras

MSFC developed “synthetic star” calibration technique

-Record synthetic star values with identical cameras and tapes

-Extrapolate pixel values to saturated intensity levels

-Derive quantitative brightness ratios

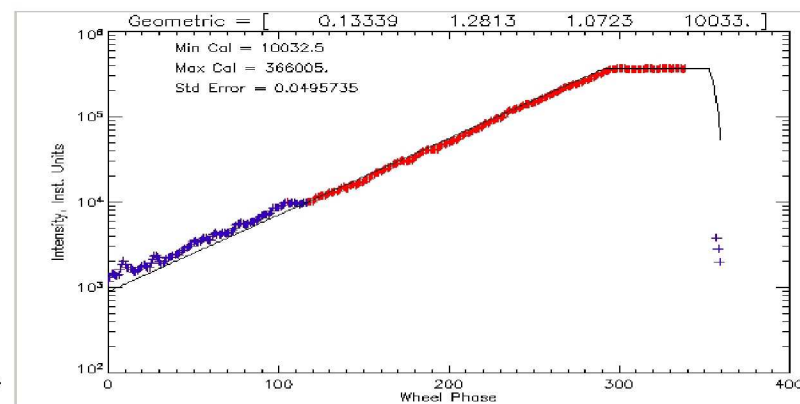
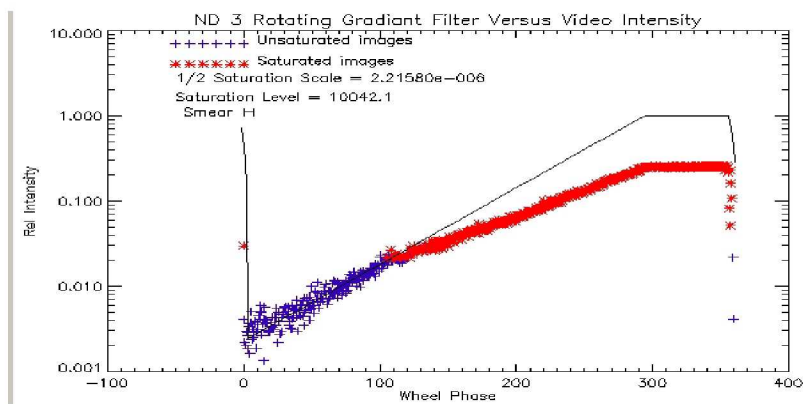
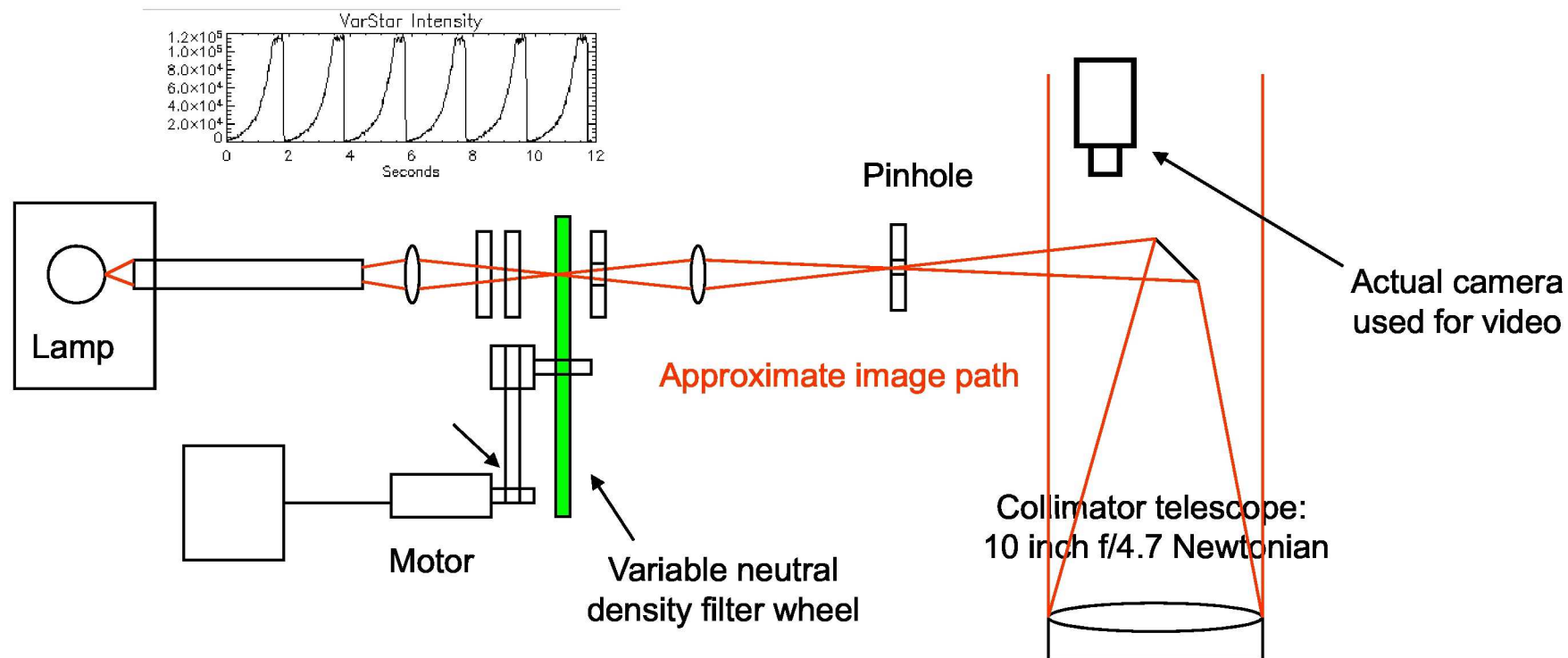


Calibrate pixel value vs “star” intensity



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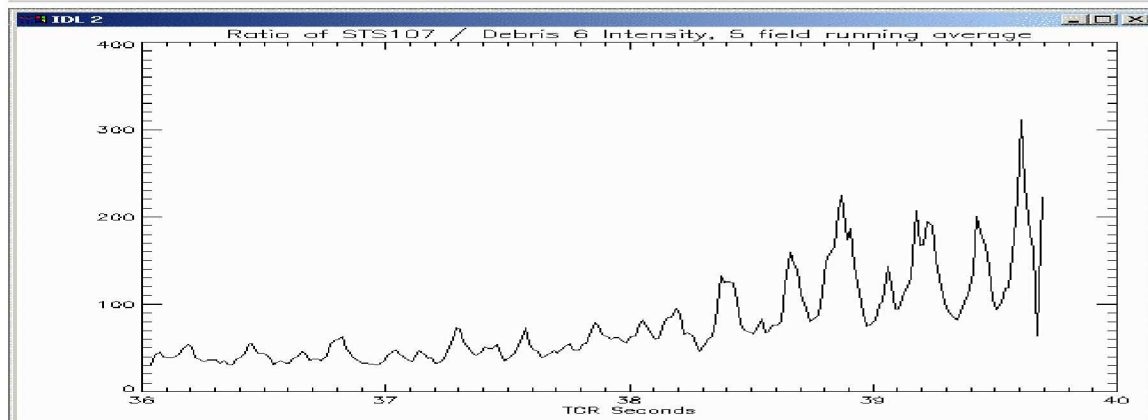
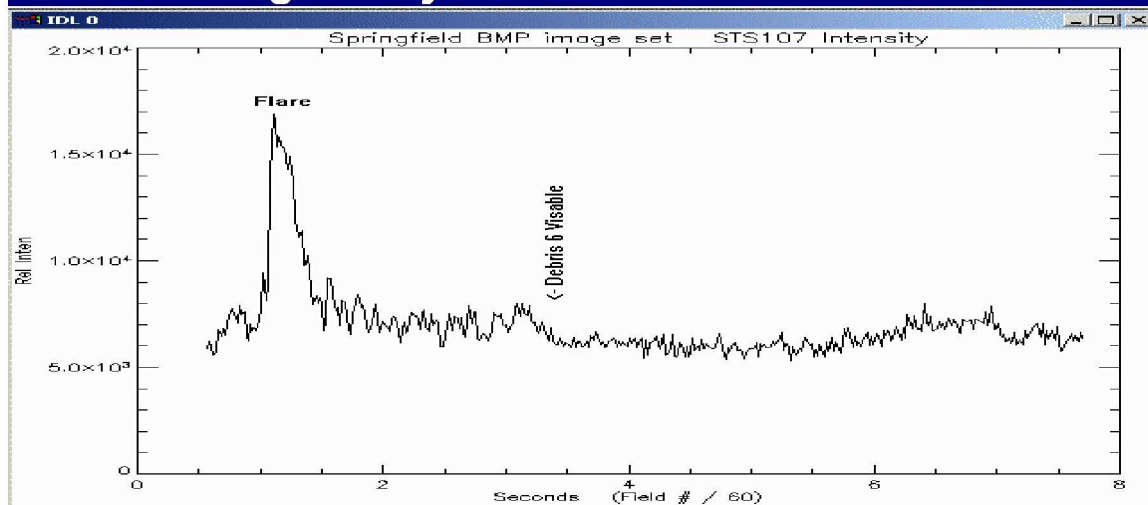


Raw brightness ratios



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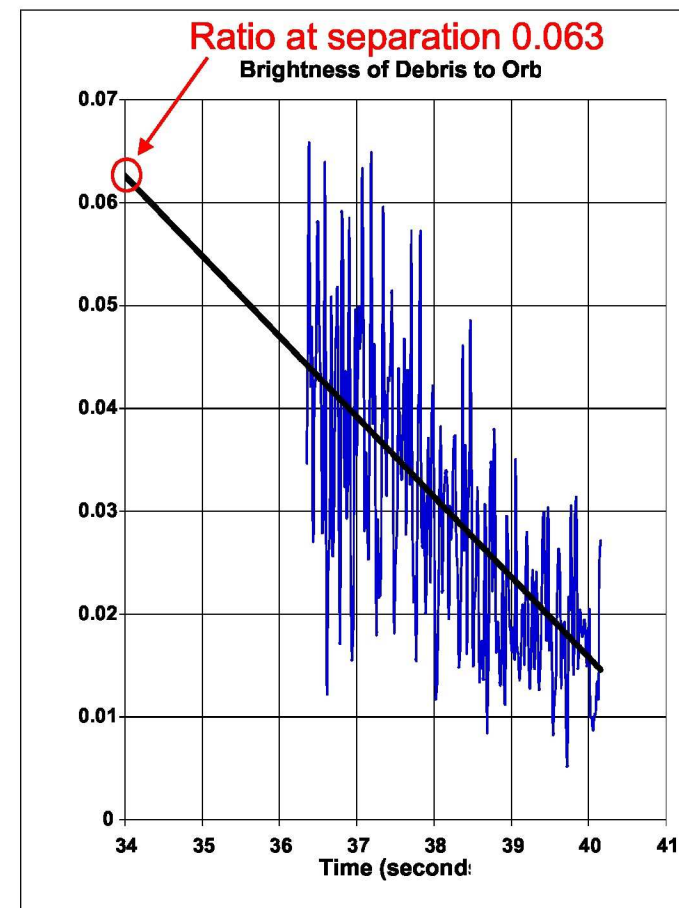


$$\begin{aligned} \text{D6 mass} &= (106000 \text{ kg})(3.02/89)(0.063) \\ &= 226 \text{ kg (!)} \quad (\text{Effective area } B_{m_d}/\rho = 6 \text{ m}^2) \end{aligned}$$

-Upper bound!

-An uncomfortably large (but un-refuted) debris mass

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Linear extrapolation to t_i

--Assumes brightness linear in v

-Scatter contains noise, atmospheric

-Tumbling?



Moderately ablating debris



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Case 2: debris ablating

- Mass ablation linear with time
- Effective debris area constant (moderate ablation)
- Ablated mass KE is fractionally radiated

$$m = m_i [1 - f_m(t - t_i)]$$

$$B = \frac{C_d A \rho}{2m} \Rightarrow B = \frac{B_i}{[1 - f_m(t - t_i)]}$$

Radiation power:
$$P_{rad} = \tau_{na} m v a - \frac{1}{2} \tau_a \frac{dm}{dt} v^2 = m_i \left[\tau_{na} v a [1 - f_m(t - t_i)] + \frac{1}{2} \tau_a v^2 f_m(t - t_i) \right]$$

Assume all efficiencies τ equal:

Intensity ratio:
$$\Rightarrow \frac{P_D}{P_O} = \frac{m_i \left[\tau_{na} v_D a_D [1 - f_m(t - t_i)] + \frac{1}{2} \tau_a v_D^2 f_m \right]}{\tau_{na} m_O v_O a_O}$$

Initial debris mass:
$$\Rightarrow m_i = \left(\frac{P_D}{P_O} \right) \frac{m_O v_O a_O}{v_D a_D [1 - f_m(t - t_i)] + \frac{1}{2} v_D^2 f_m}$$

From equations of motion:

$$v_f = \frac{v_i f_m}{f_m - B_i v_i \ln[1 - f_m(t - t_i)]} \Rightarrow x_D = v_i(t - t_i) + \frac{1}{2} a_O(t - t_i)^2 - \int_t \frac{v_i f_m}{f_m - B_i v_i \ln[1 - f_m(t - t_i)]}$$



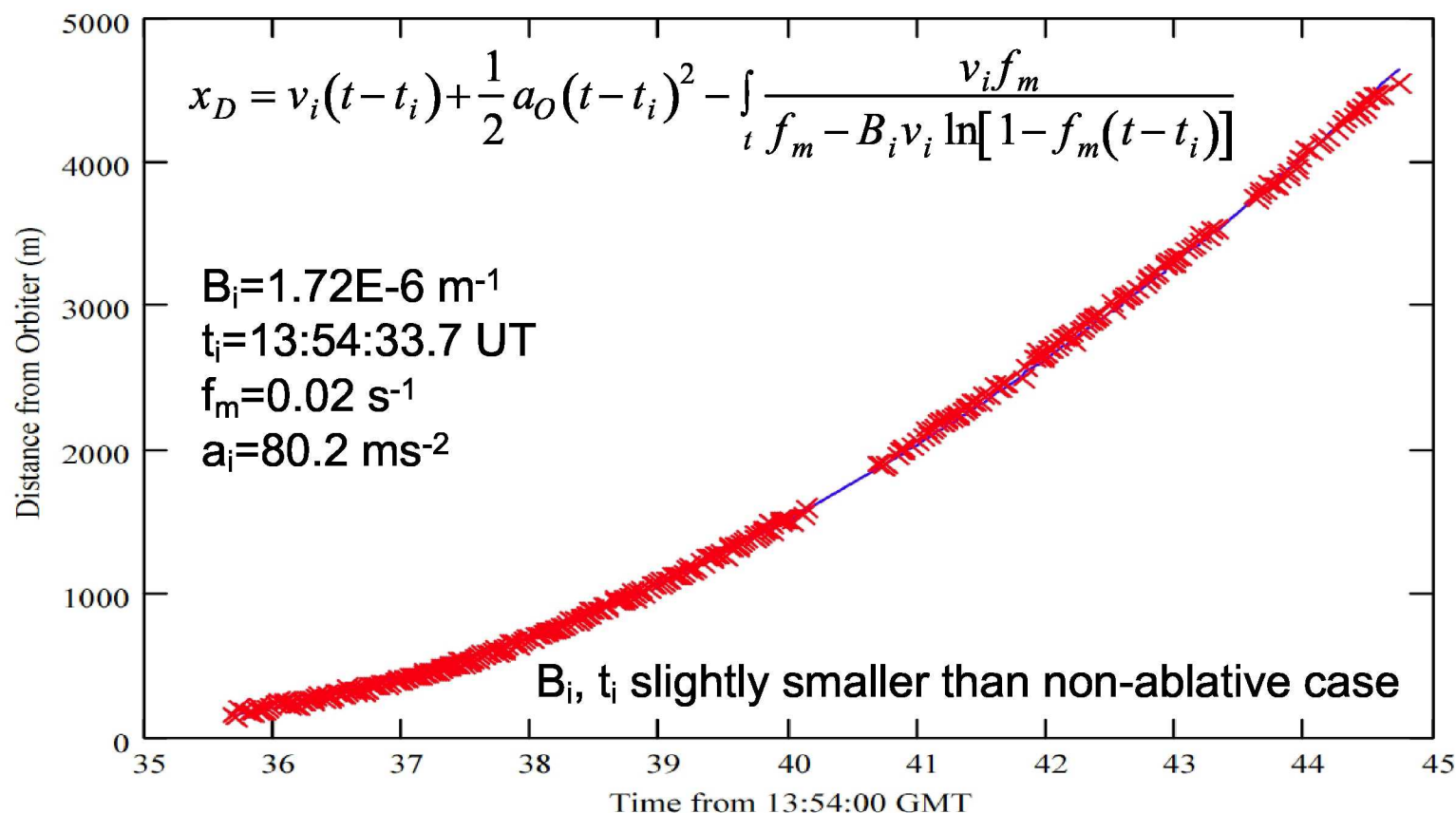
Relative motion analysis, ablating debris



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Fit relative motion curve for B_0 , t_0 , f_m



Using lower bound intensity ratio $P_D/P_O = 0.04$, D6 mass **86.5 kg**
-CAIB-reported value



Debris entry shock radiation



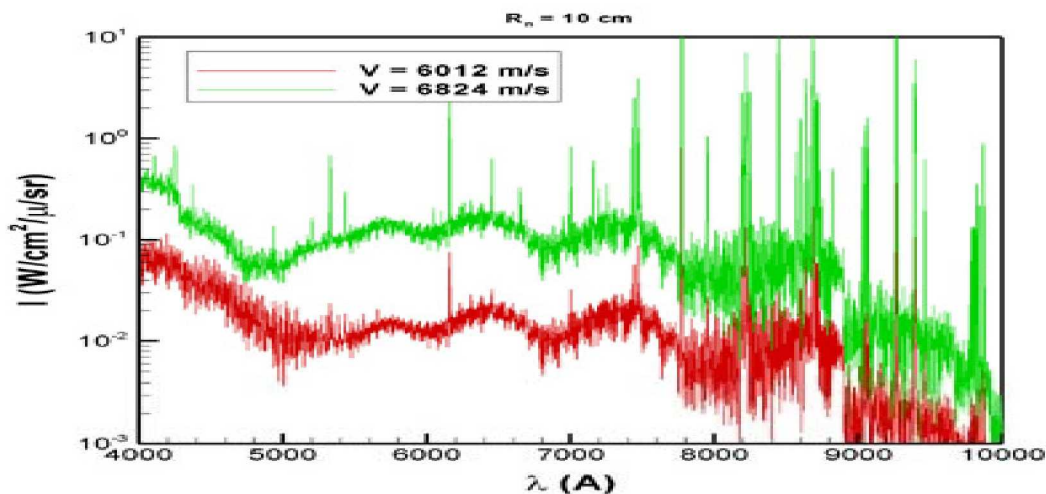
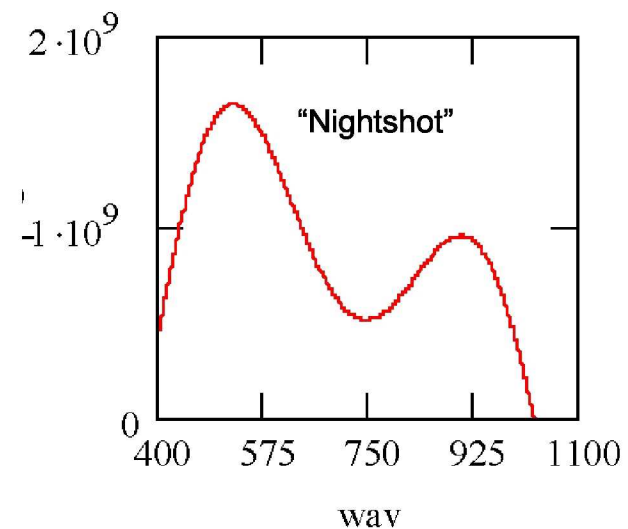
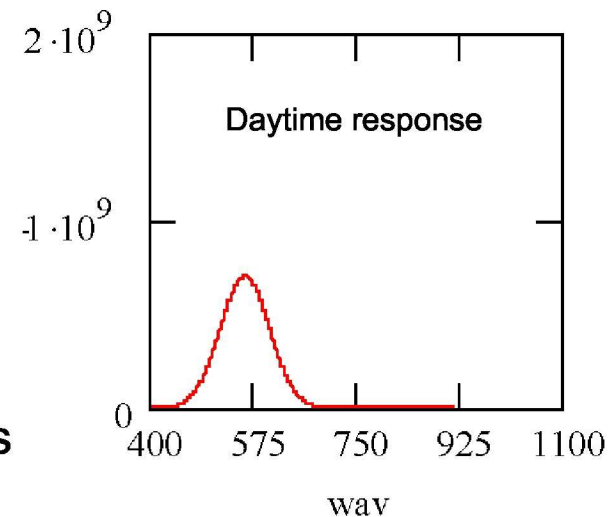
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**Debris undergoing hypersonic ballistic entry;
substantial shock component to total signal**

Simulate camera response for different shock intensities:

- Integrate simulated orbiter spectra through camera response functions
- Compare integrated intensities to observed debris signal; scale by area





Sphere-equivalent disk luminosity



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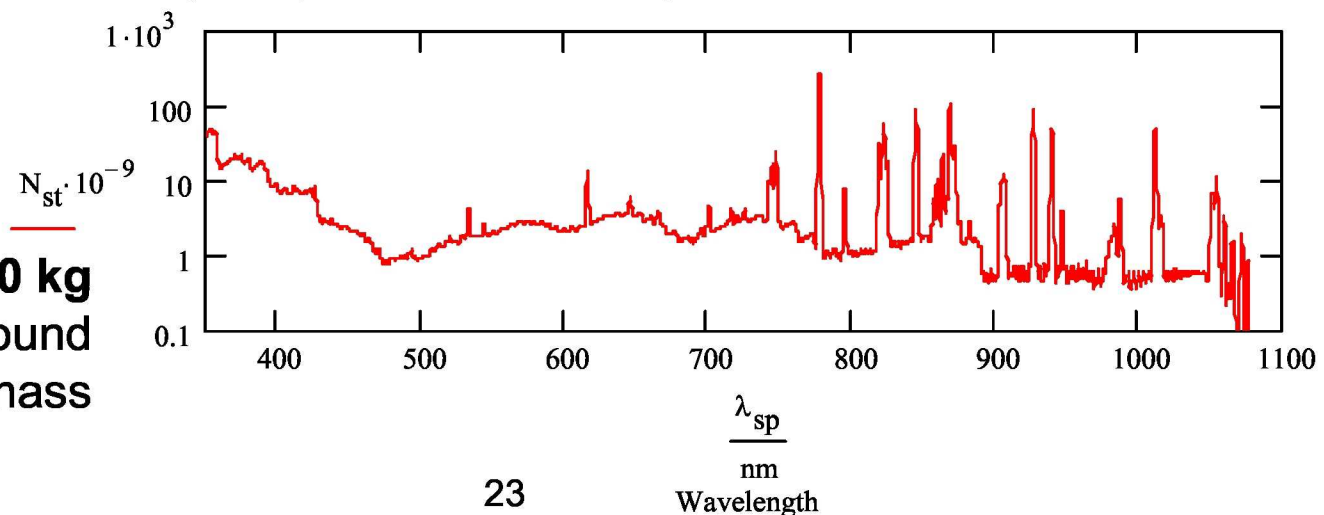
Case 3: Non-ablating debris-disk

-use CFD to compare bow shock intensity radiated by sphere-disk equivalents

Procedure:

- 1) Model intact orbiter as $R=1$ m sphere (nosecap)
- 2) Compute average radiance (NEQAIR) over the hemisphere surface
- 3) Calculate signal generated by camera for sphere
- 4) Calculate area of flat disk necessary for same signal
- 5) Scale disk area by debris/orbiter luminosity ratio
- 6) Use scaled area and measured debris deceleration to calculate mass

Stagnation point radiance, $R=1.0$ m sphere



Debris #6 mass: **6.0 kg**
-Thin disk, lower bound
-Largest area per mass



“Official” Mass Estimates



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CAIB: Volume 3, Appendix E.2, Section 6

Debris Event and Observer Location	Intensity Ratio at Time of Separation (Debris/Orbiter)	Upper Bound Non-Ablative Mass Estimate, kg (lb)	Moderate Ablative Mass Estimate		Lower Bound Non-Ablative Mass Estimate*, kg (lb)
			Ablation Rate	Mass kg (lb)	
Debris 6					
Springville, CA	0.04 - 0.063	144 – 225 (316 – 495)	2% / sec	86.5 (190)	4.68 – 7.37 (10.3 – 16.2)
Debris 14**					
St. George, UT	0.135	250 (550)	9% / sec	55 (121)	7.7 (17)
Debris 1					
Fairfield, CA	0.0016 – 0.0026	1 – 3 (2 – 7)	27% / sec	0.2 (0.44)	0.057 – 0.092 (0.12 – 0.2)
Debris 2					
Fairfield, CA	0.0027	2 - 4 (4 - 8)	27 % / sec	0.3 (0.66)	0.11 (0.24)

Caveats:

- Debris shapes, composition, orientation, etc., etc., unknown
- Spectral characteristics not explicitly modeled
- Observer point of view not compensated
- Assumes debris and orbiter share luminosity mechanism

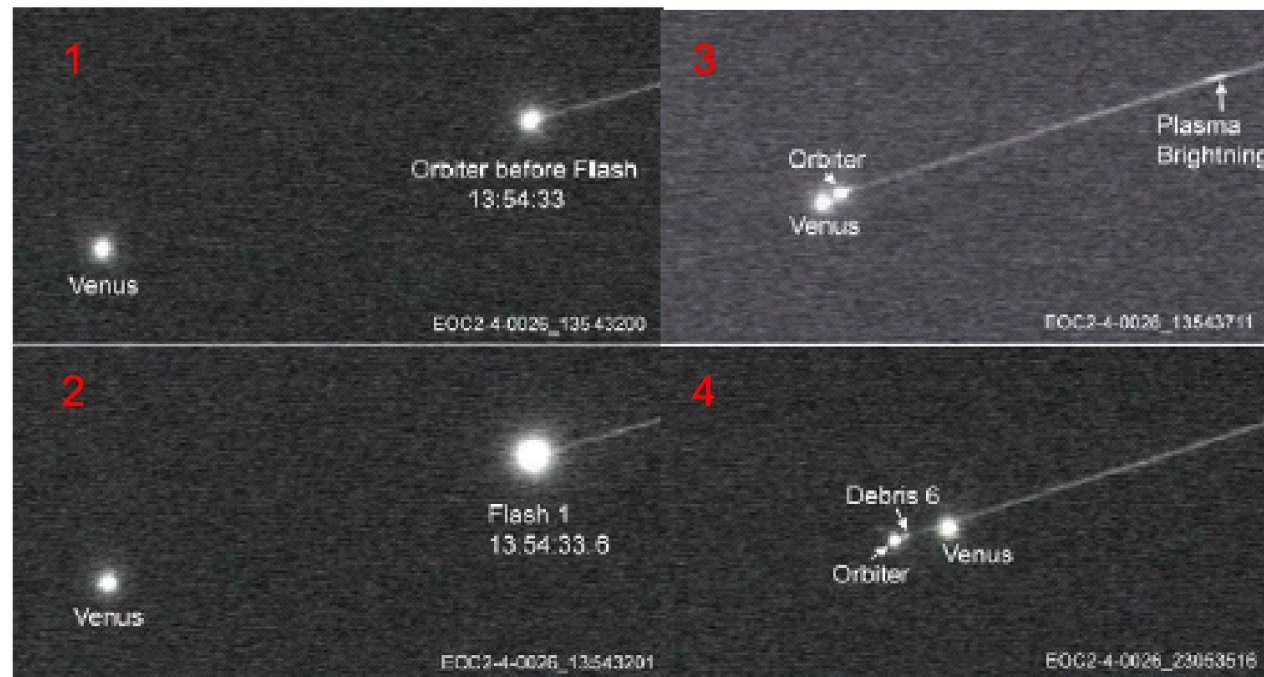


Debris #6 “Flash #1”



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Not unique-several flashes during entry

- Coincident with D6 separation
- Not RCS firing, liquid ejection, tires, aluminum
- Absolute intensity available for Venus



Flash Origin: Loose Debris Luminosity



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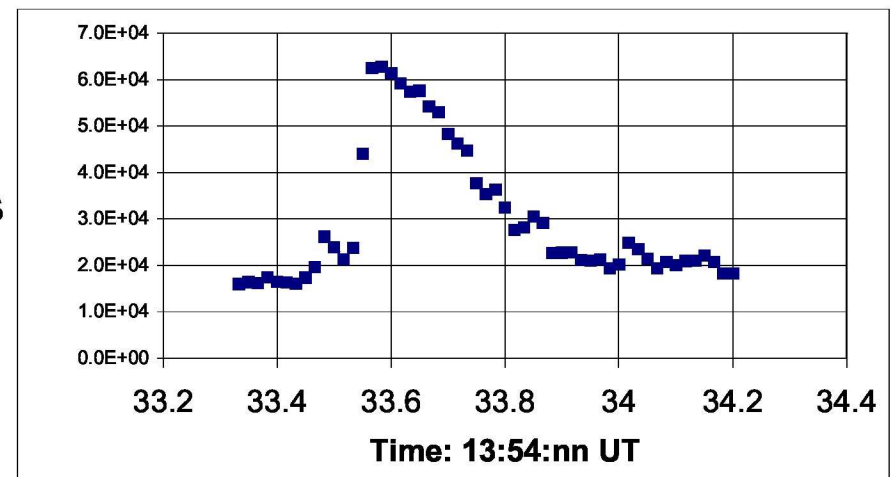
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Hypothesis: flash caused by ejection of friable debris

-Possibly loosened by D6 emission

Case 1: Non-ablating debris

- Same luminosity physics as large debris
- Object breaks apart, glows, stalls in <0.5 s
- Mass ~ 75 kg; A_e $(14\text{m})^2$; 0.4 kg/m 2



Case 2: Fully (>95%) ablating

- Use meteor models and absolute flash magnitude (rel Venus)
- Object breaks apart, particles ablate, glow, disappear
- Model as $R=2$ mm spheres, $d=1$ g/cm 3 , $n=1.6E6$
- Mass ~ 45 kg, sphere area 16 m 2 ; ~ 3 kg/m 2



Arc jet testing: simulate entry conditions



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Hypersonic, arc-heated wind tunnel; 25 MJ/kg; $T \sim 1800$ K



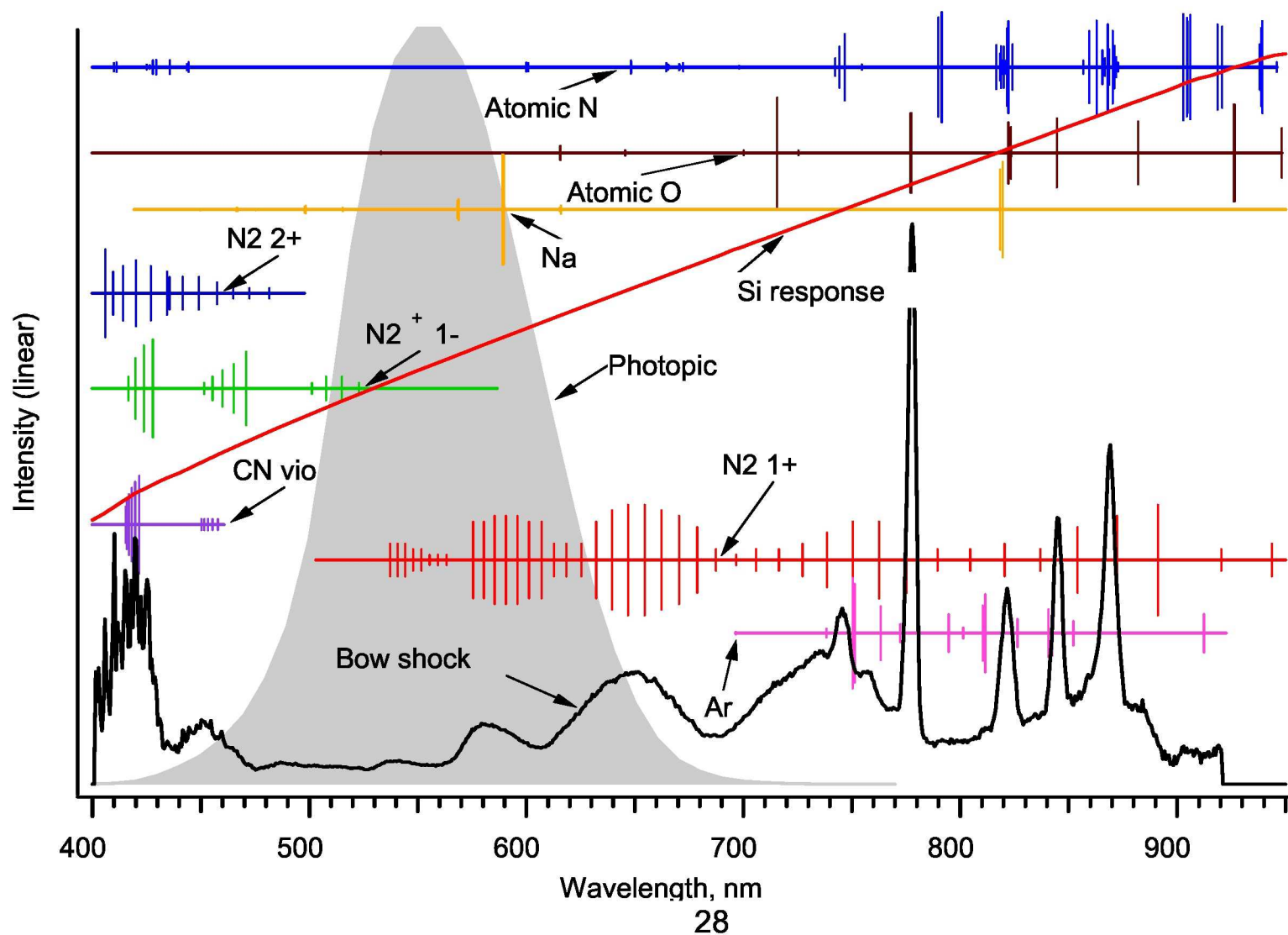


Arc jet shock spectrum: air



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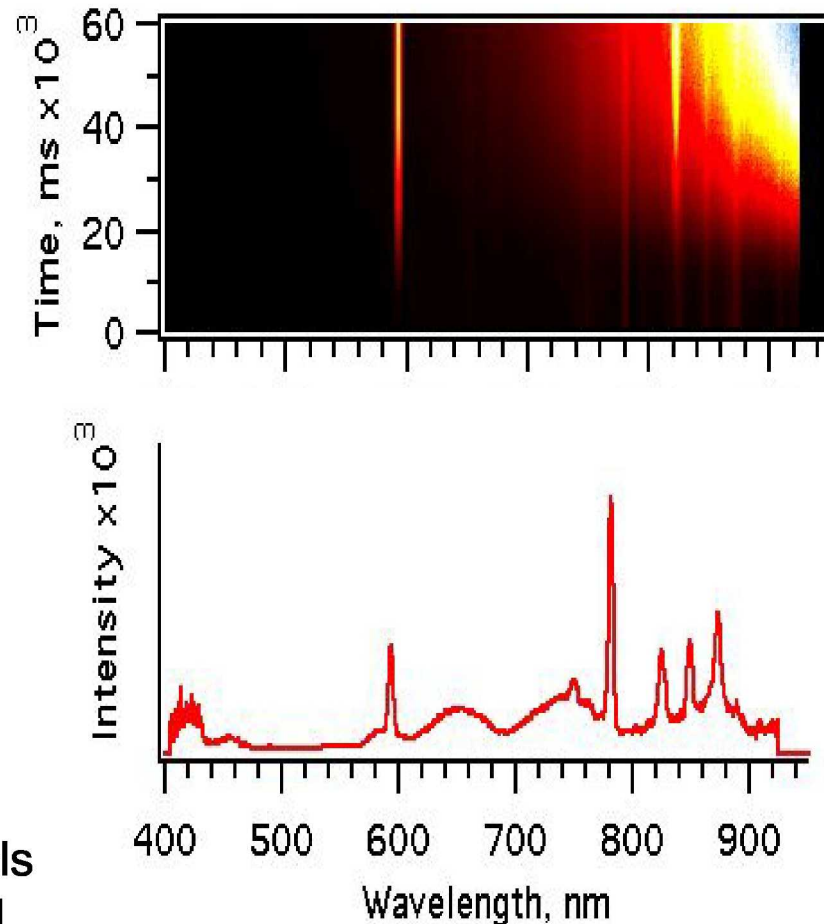
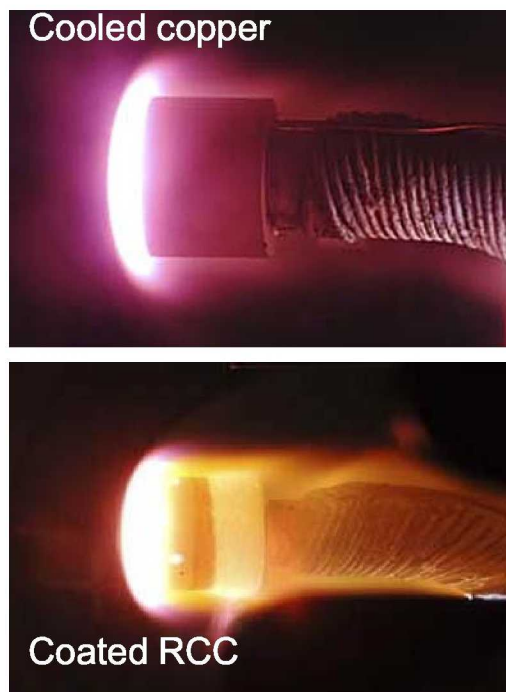


Arcjet Tests of Debris Spectral Output



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Bow shock spectral output not grossly dependent on composition

- Insufficient color info to discriminate materials
- RCC, RTV emit strong atomic sodium signal
- Aluminum doesn't burn or flash



Summary and Conclusions



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Amateur videos contain usable timing, relative motion, intensity information

- Simplistic model allows estimates of debris mass
- Debris size ranges from tile-like to huge
- Flash from dispersing material
- No aluminum “explosion”

Substantial TPS damage prior to loss of control

- Many visible events with no indication in flight control data
- Large items shed during early parts of peak heating
- Vehicle remained in control for minutes while structure was under attack

NASA needs better entry imaging/photometry/radiometry

- Imaging to monitor vehicle health from on-orbit to on-tarmac inspections
- Orbiter radiation characteristics not well-studied for forensics
- Radiation phenomena are increasingly important for larger, faster entries

Simple physical assumptions yield useful insights!