STS-107 Debris Characterization Using Re-entry Imaging

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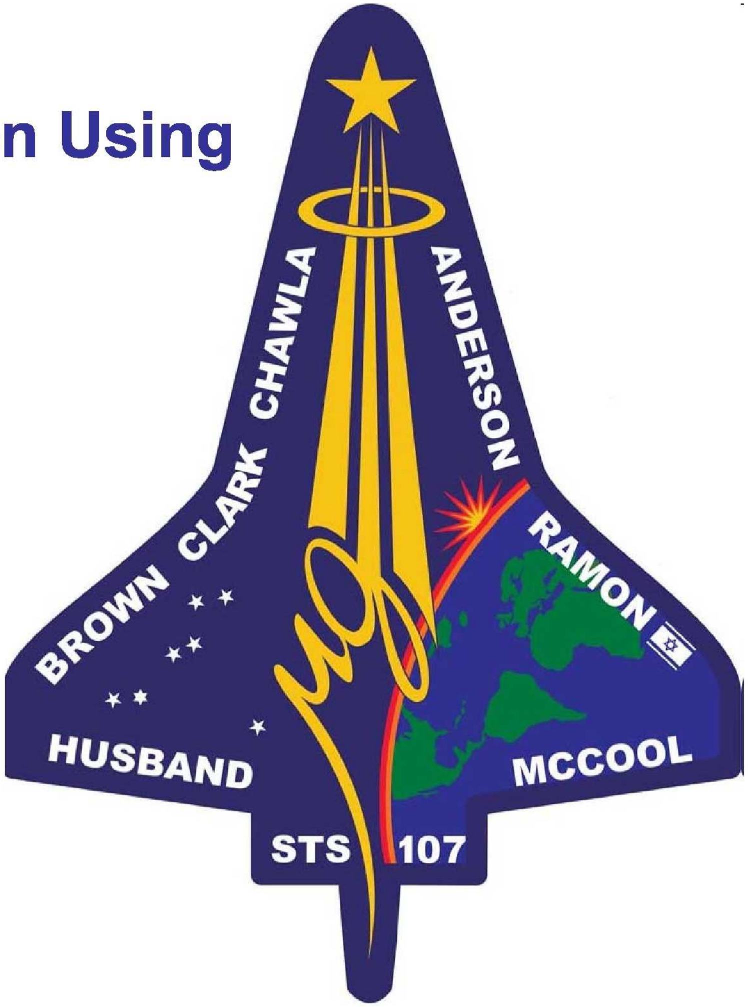
January 15, 2009



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Special thanks:
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CAIB Report:
Volume 3, Appendix E.2, Section 6

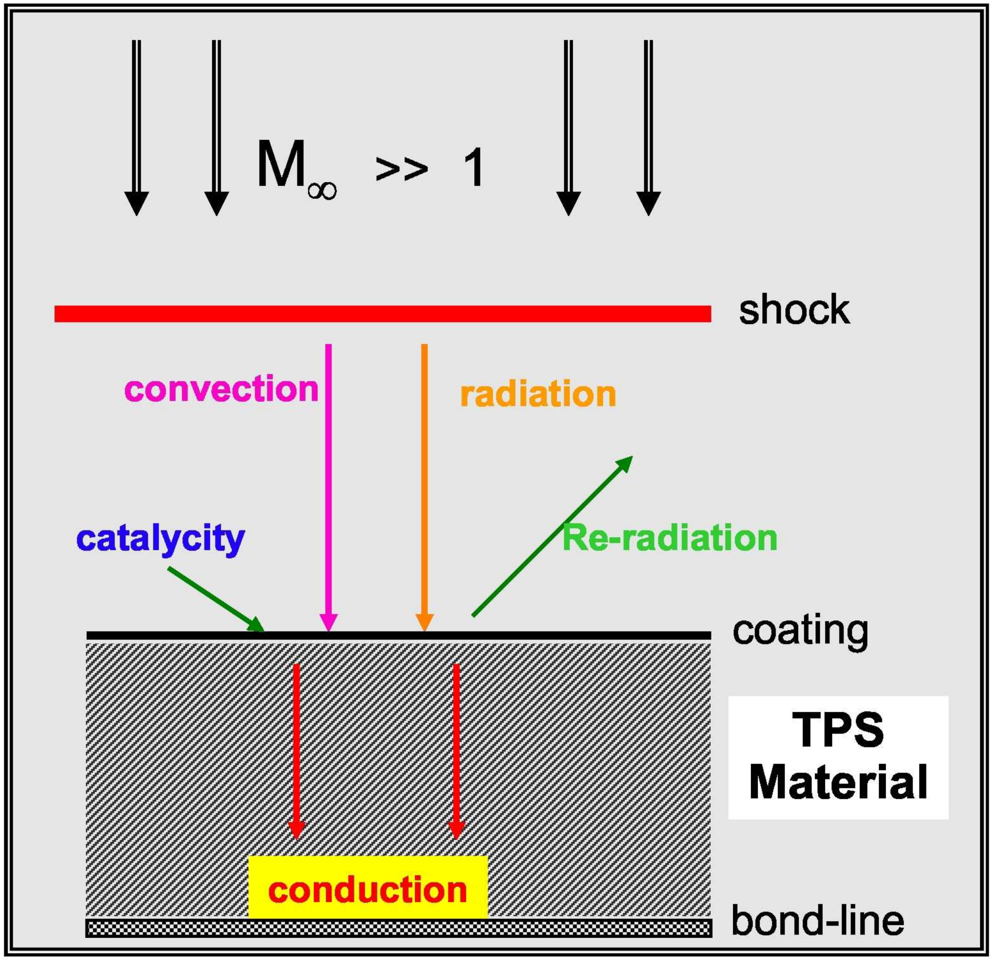
What happens when a spacecraft enters the atmosphere?

- 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

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 ⇑ $q_{re\text{-}radiation}$

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

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* (Cp)

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

No phase transition or reactivity

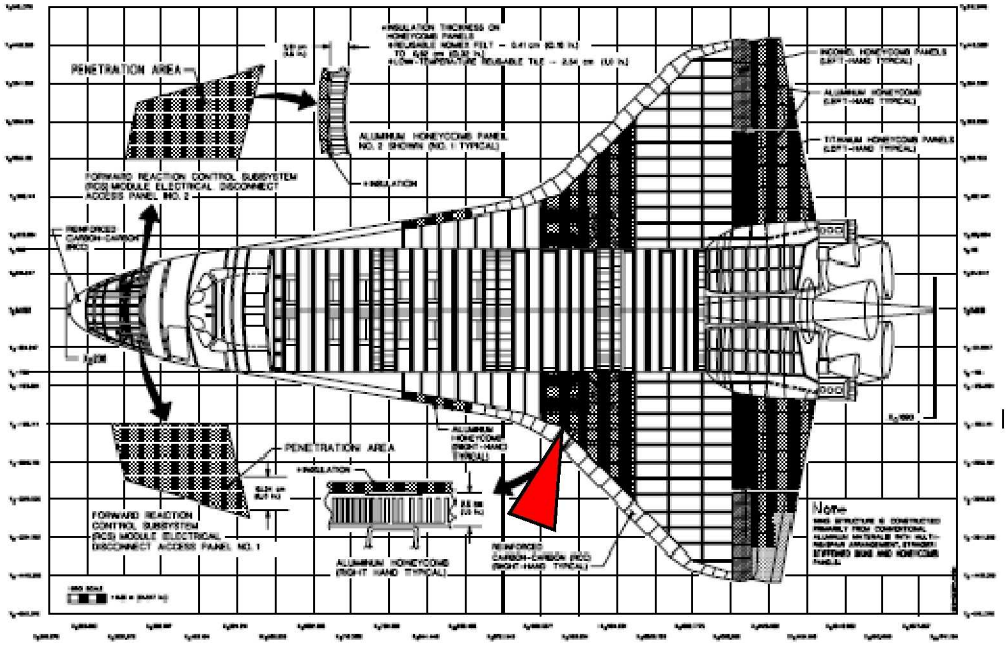
What happens if the TPS fails?

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

NASA-ARC/AS
Columbia LWG

Columbia, STS-107

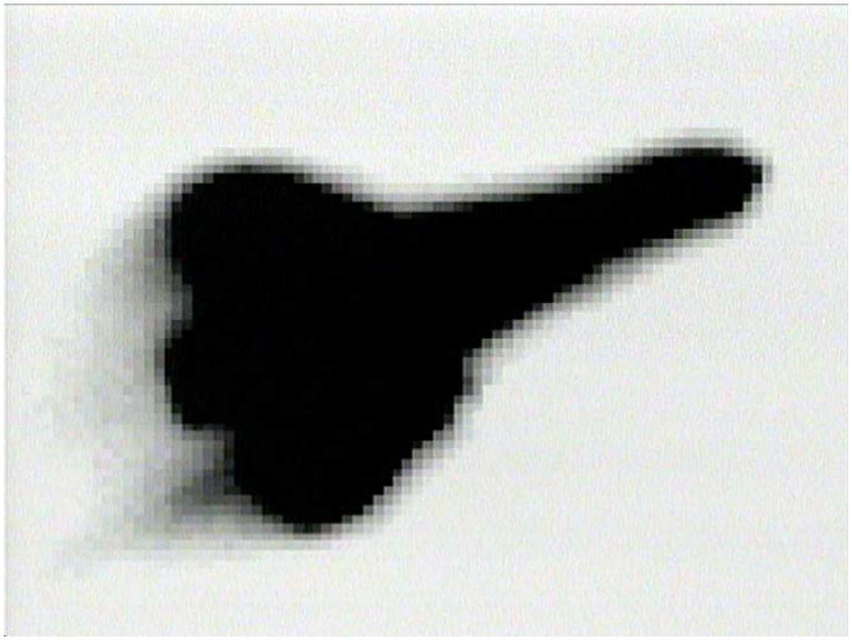
- Space Shuttle Columbia, STS-107
  - Broke apart during entry
- Initial cause unknown
  - Vehicle at peak entry heating
  - Limited off-nominal data, no “smoking gun”
  - Only peak heating data: amateur observers



- 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…

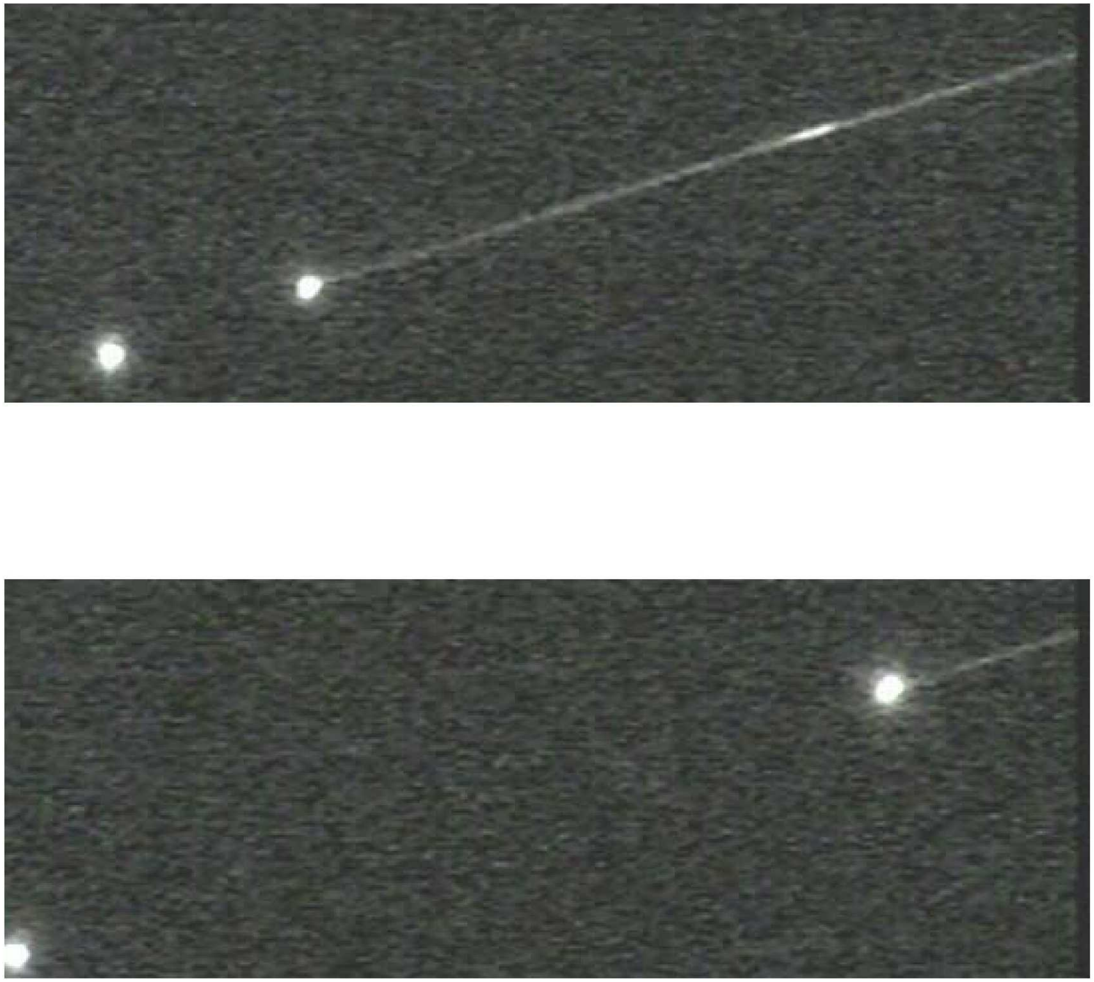


What happened?

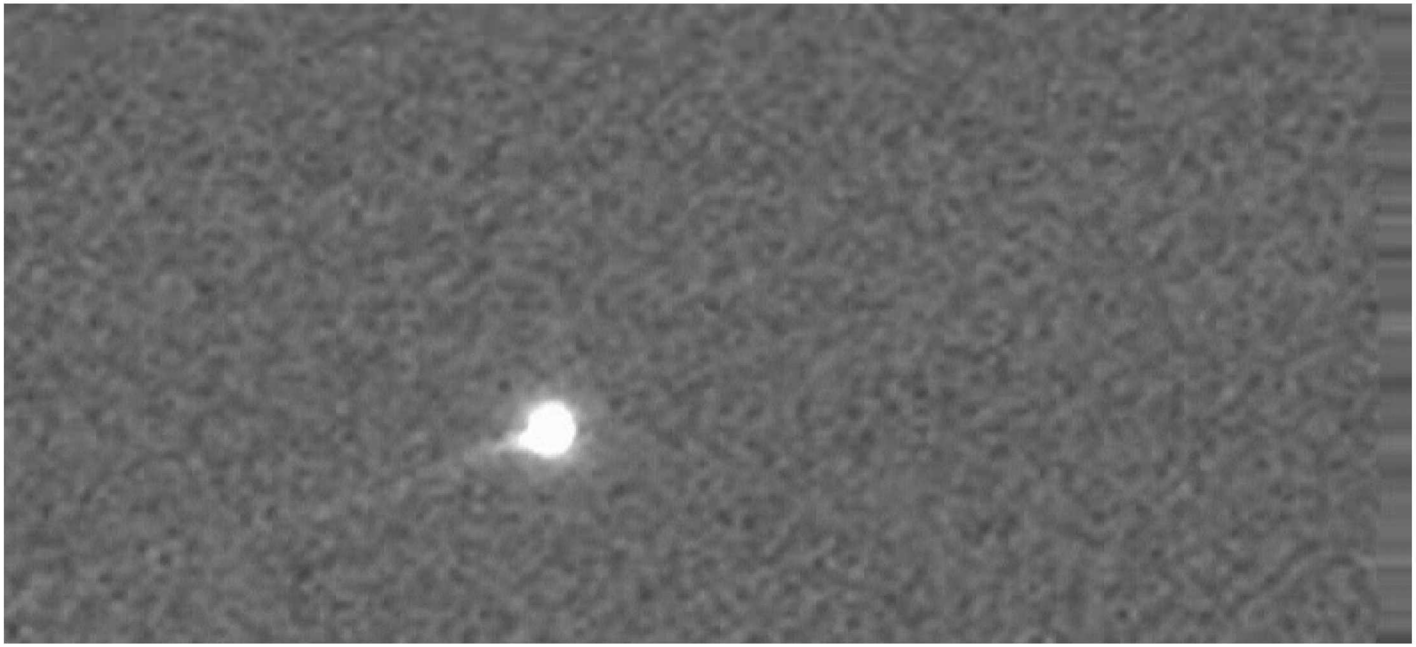
- Only record: amateur video
- No existing model of observed events
  - Unclear what a "normal" entry looks like
- Can we learn anything from these videos?

Debris #1, #2

Debris #6/Flash 1



Debris #14

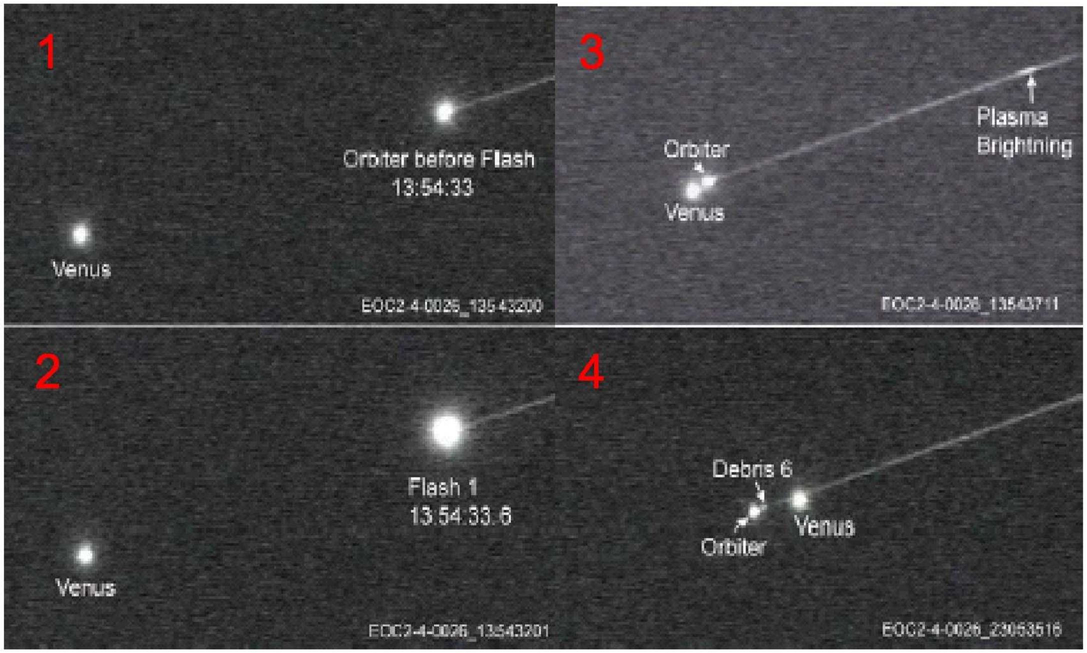


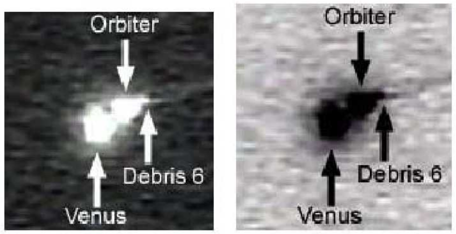
Overland track observer locations

Entry Debris Video Coverage Map (West)

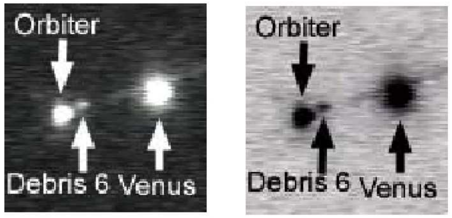
140+ videos
Several hundred stills
Many skilled observers
Several multiple coverage events

Raw image quality: poor





Debris First Observed Inverted View



Debris Event + 0.8 sec. Inverted View

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

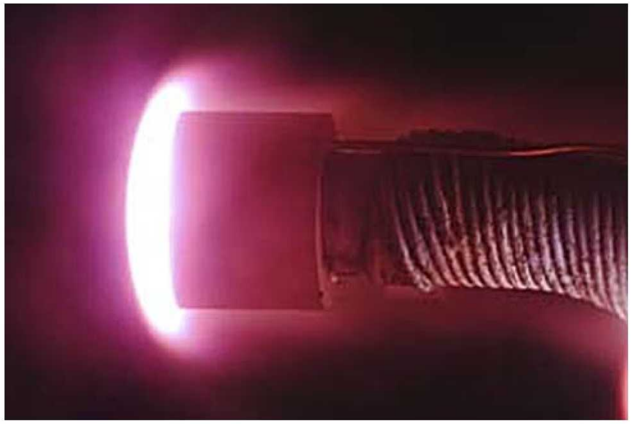
Image radiance models

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

From images: orbiter-debris separation vs time

-Orbiter velocity, acceleration known

-Constant mass

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

$$B = \frac{C_d A \rho}{2m} \qquad \frac{dv}{dt} = Bv^2 = a \qquad \boxed{\frac{dv}{v^2} = Bdt}$$

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

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

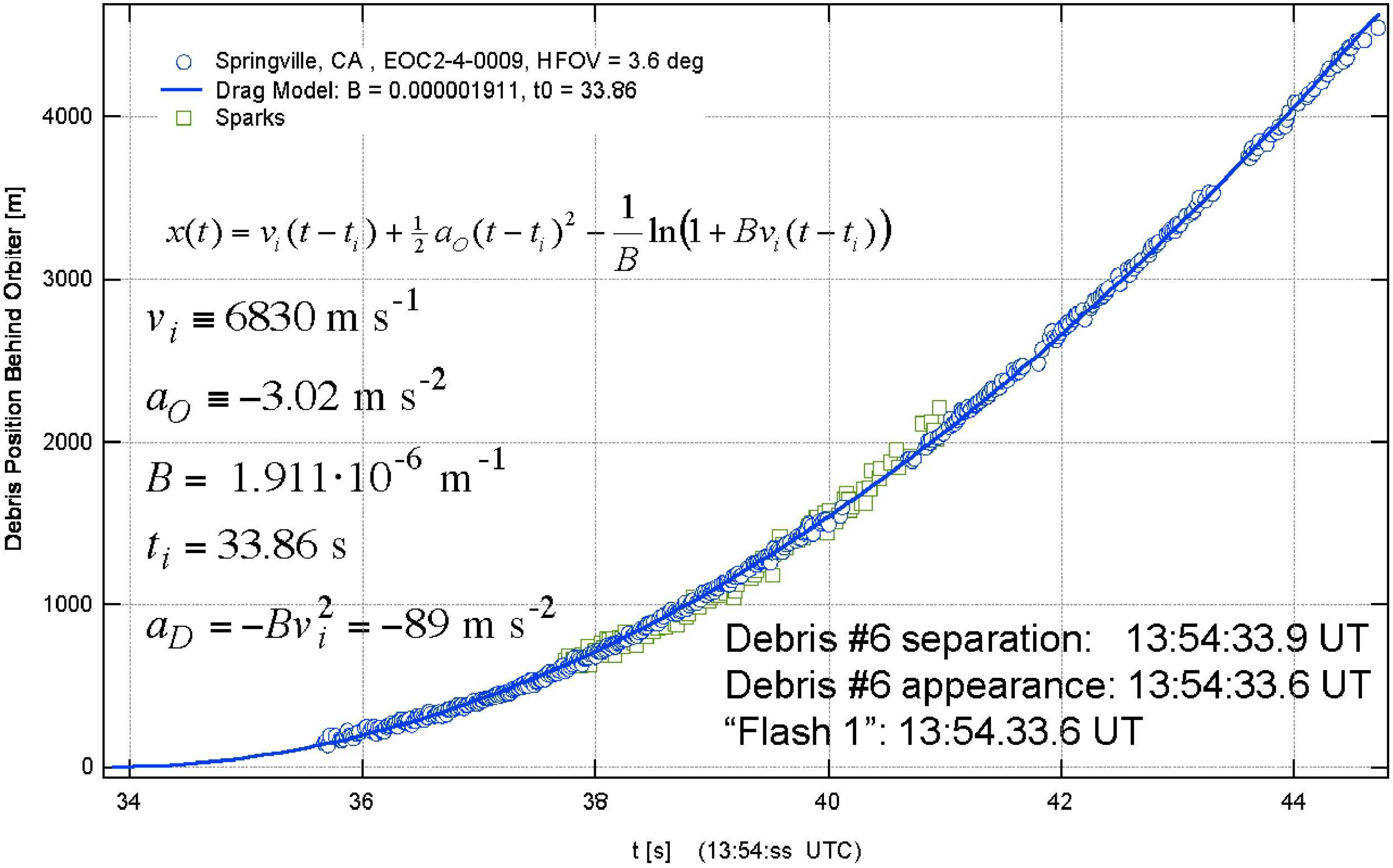
Orbiter: $x_O = x_i + vt + \dfrac{1}{2}a_O t^2$

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

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

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

Relative motion plots from image separation



$$x(t) = v_i (t - t_i) + \tfrac{1}{2} a_O (t - t_i)^2 - \frac{1}{B} \ln\left(1 + B v_i (t - t_i)\right)$$

$$v_i \equiv 6830 \text{ m s}^{-1}$$

$$a_O \equiv -3.02 \text{ m s}^{-2}$$

$$B = 1.911 \cdot 10^{-6} \text{ m}^{-1}$$

$$t_i = 33.86 \text{ s}$$

$$a_D = -B v_i^2 = -89 \text{ m s}^{-2}$$

Debris #6 separation: 13:54:33.9 UT
Debris #6 appearance: 13:54:33.6 UT
“Flash 1”: 13:54.33.6 UT

Object radiance proportional to “lost” kinetic energy

Assume radiance proportional to lost kinetic energy

No consensus on detailed mechanism for light generation

Case 1: Debris mass constant (no ablation)

$$P_{rad} = -\tau_{na}\frac{d}{dt}\left(\frac{1}{2}mv^2\right) = -\tau_{na}mv\frac{dv}{dt} = -\tau_{na}mva$$

Detection efficiency τ same for debris and orbiter

$$\frac{P_D}{\frac{\partial}{\partial t}\left(\frac{1}{2}m_D\vec{v}_D^2\right)} = \frac{P_O}{\frac{\partial}{\partial t}\left(\frac{1}{2}m_O\vec{v}_O^2\right)} \qquad \boxed{\Rightarrow m_D = m_O\left(\frac{P_D}{P_O}\right)\left(\frac{a_O}{a_D}\right)}$$

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

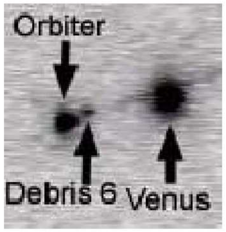
m = mass

a = deceleration

D, O: debris, orbiter

Intensity recovery, saturated images

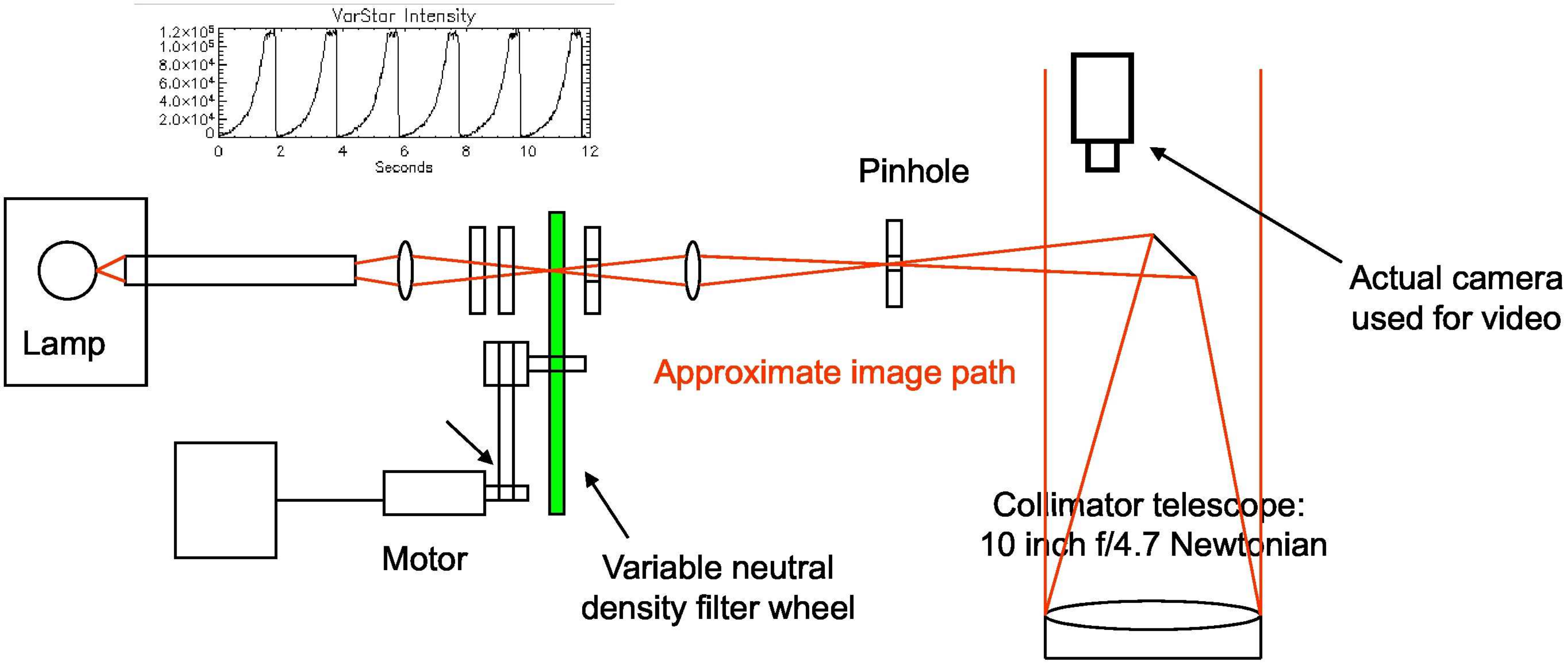
Most images saturated with extremely high contrast
-Common meteor photometry problem




debris6_eoc2-4-0026.mpeg

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



Pinhole

Lamp

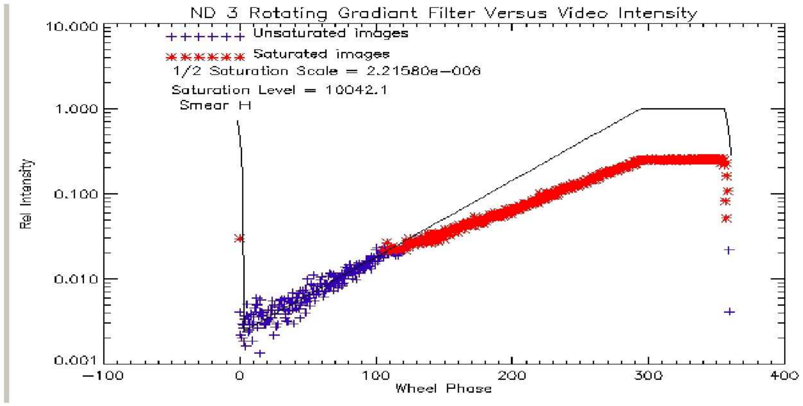
Actual camera used for video

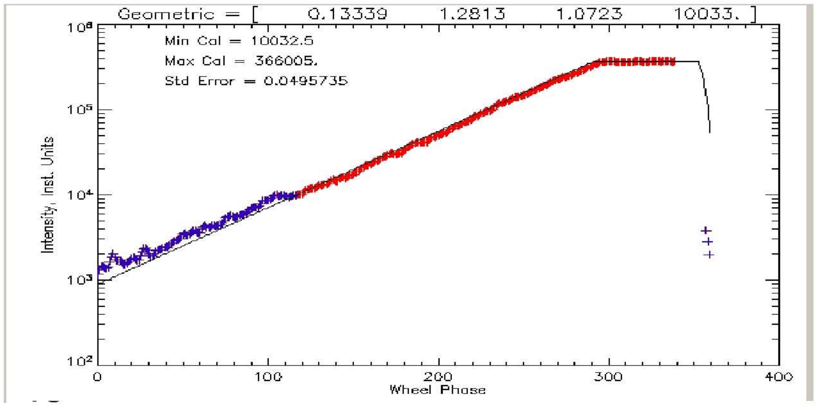
Approximate image path

Motor

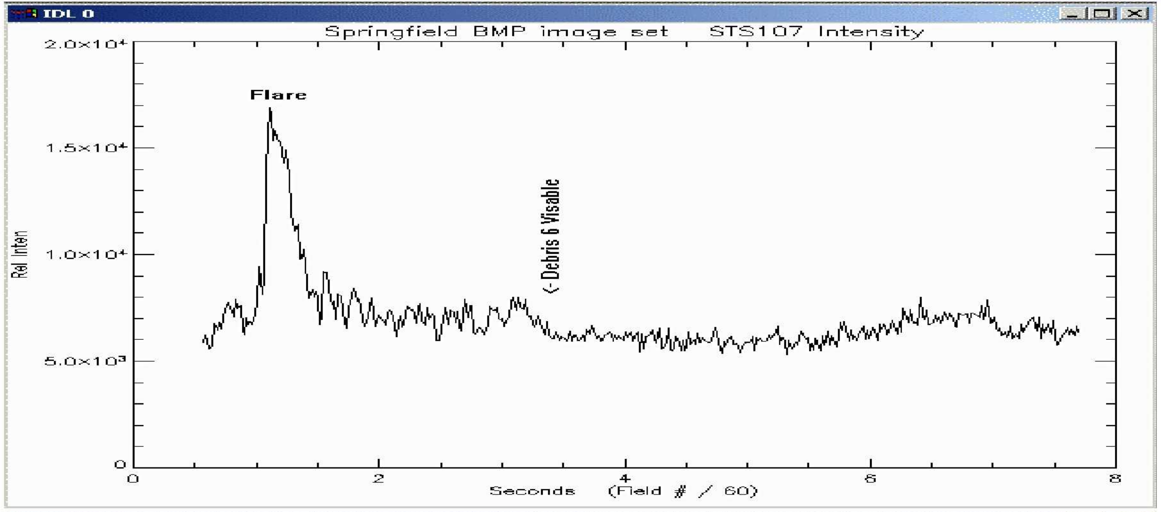
Variable neutral density filter wheel

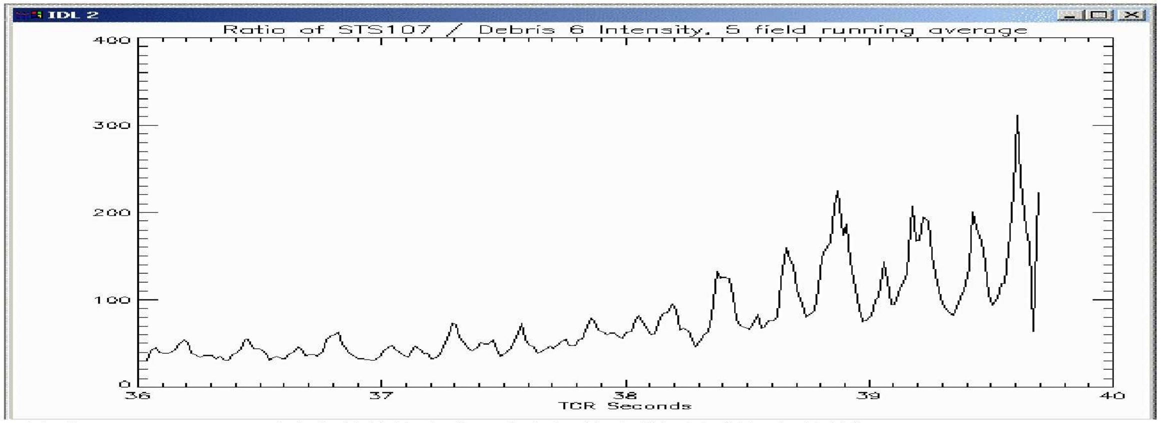
Collimator telescope: 10 inch f/4.7 Newtonian





Raw brightness ratios



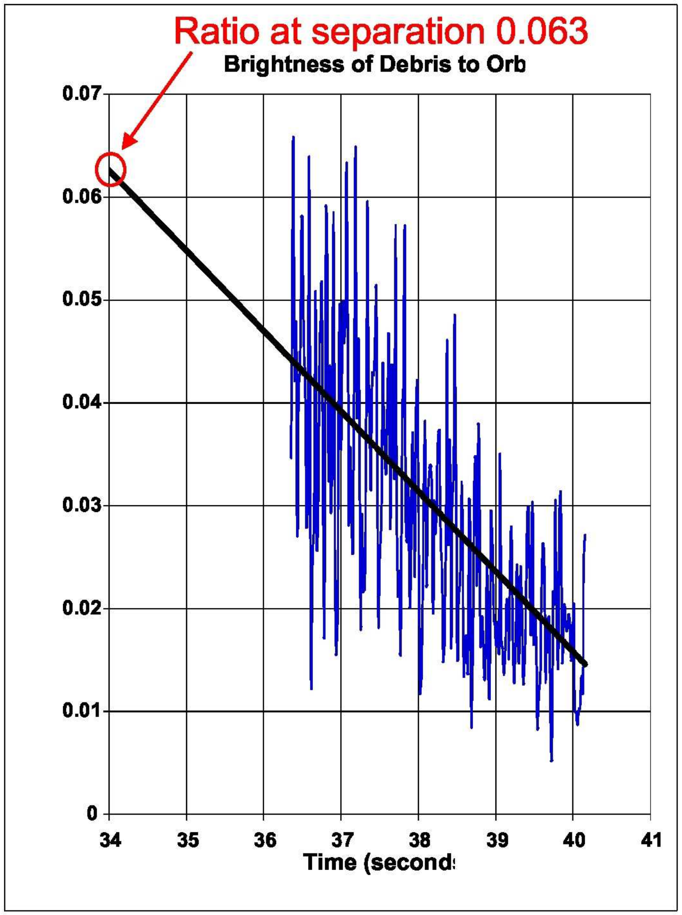


D6 mass = (106000 kg)(3.02/89)(**0.063**)

= **226 kg** (!) (Effective area $Bm_d/\rho=6\ m^2$)

-**Upper bound!**

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


Ratio at separation 0.063

Linear extrapolation to t_i

--Assumes brightness linear in v

-Scatter contains noise, atmospherics

-Tumbling?

Moderately ablating debris

Case 2: debris ablating

-Mass ablation linear with time

-Effective debris area constant (moderate ablation)

-Ablated mass KE is fractionally radiated

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

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

Radiation power:

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

Assume all efficiencies τ equal:

Intensity ratio:

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

Initial debris mass:

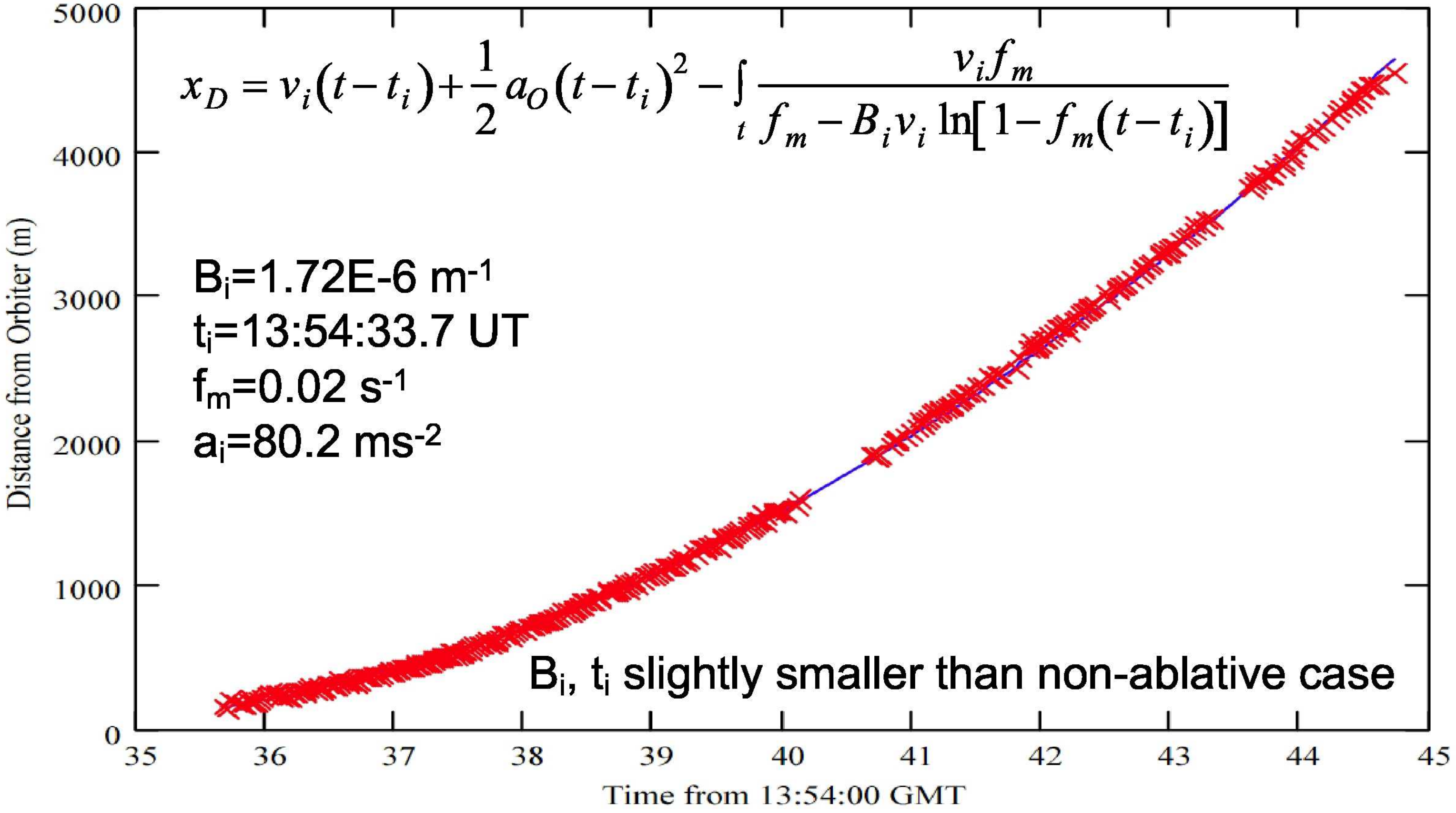
$$\Rightarrow m_i = \left(\frac{P_D}{P_O}\right)\frac{m_O v_O a_O}{v_D a_D\left[1 - f_m(t - t_i)\right] + \frac{1}{2} v_D^{\,2} f_m}$$

From equations of motion:

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

Relative motion analysis, ablating debris

Fit relative motion curve for B_0, t_0, f_m



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

B_i=1.72E-6 m^{-1}
t_i=13:54:33.7 UT
f_m=0.02 s^{-1}
a_i=80.2 ms^{-2}

B_i, t_i slightly smaller than non-ablative case

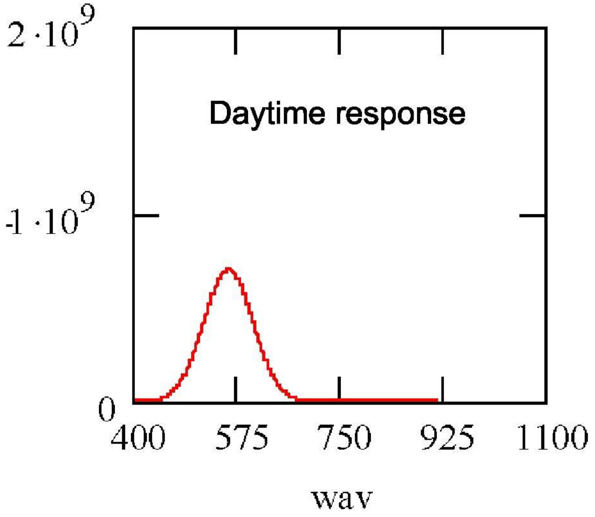
Using lower bound intensity ratio P_D/P_O=0.04, D6 mass **86.5 kg**
-CAIB–reported value

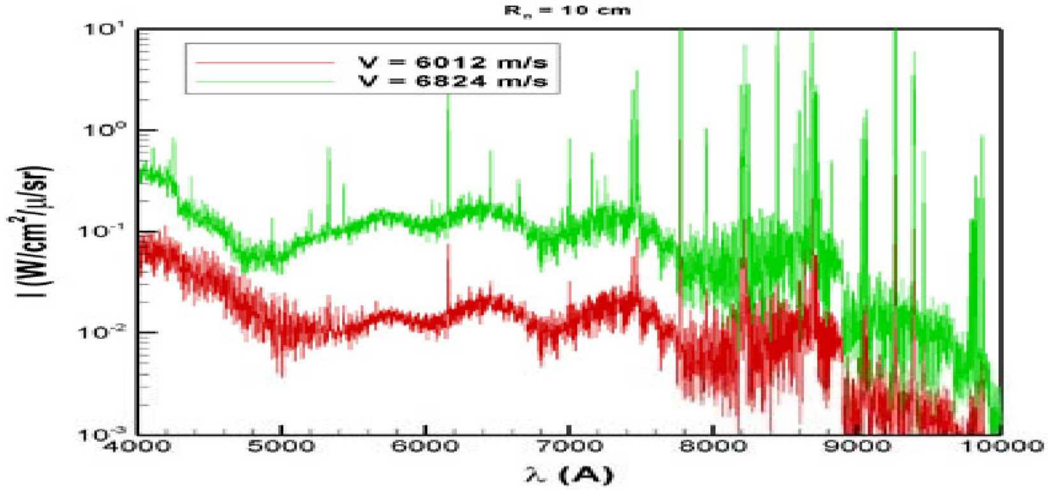
Debris entry shock radiation

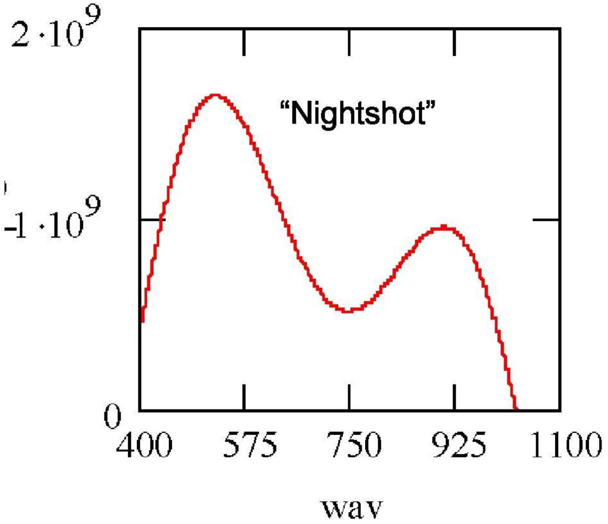
Debris undergoing hypersonic ballistic entry; substantial shock component to total signal

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

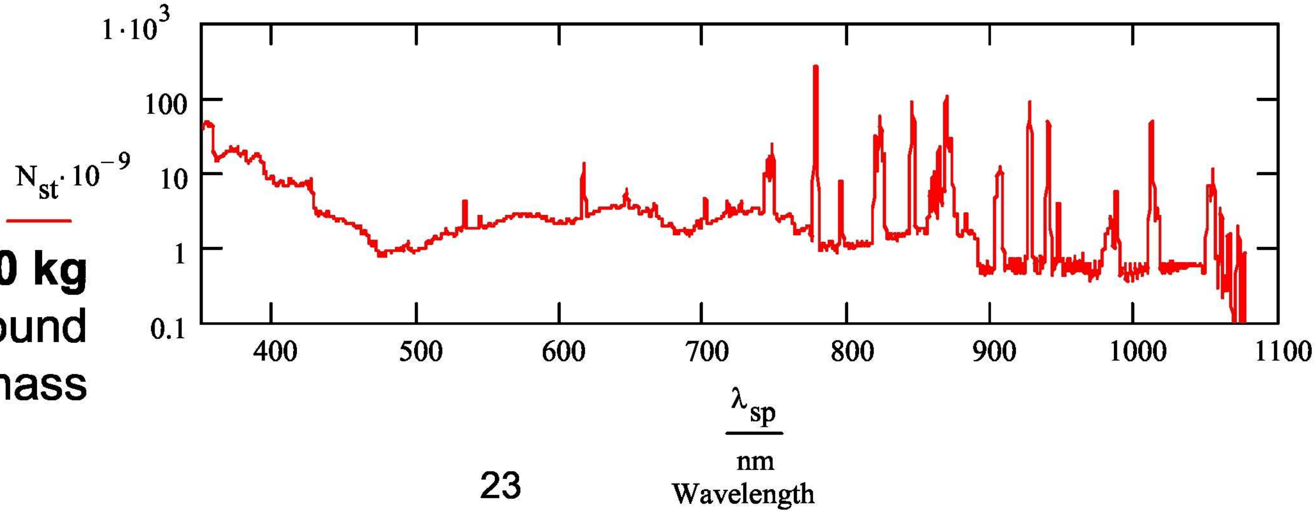
Case 3: Non-ablating debris-disk

-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

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:

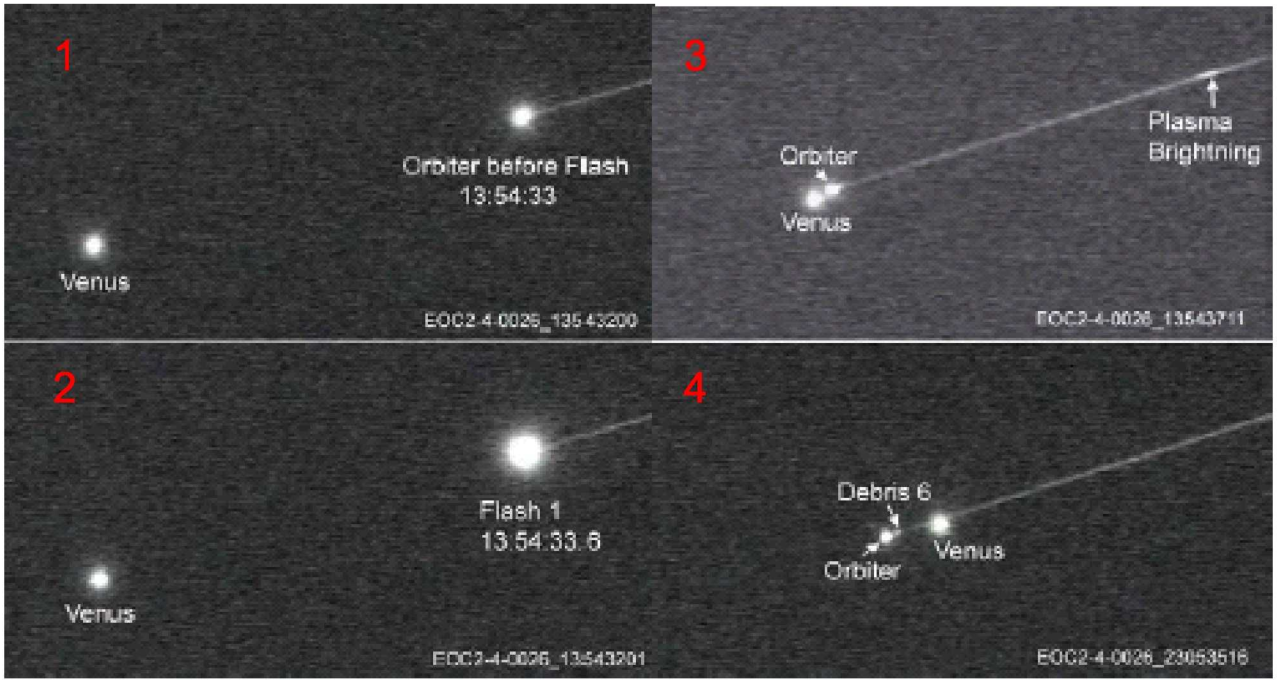
-Debris shapes, composition, orientation, etc., etc., unknown

-Spectral characteristics not explicitly modeled

-Observer point of view not compensated

-Assumes debris and orbiter share luminosity mechanism

Debris #6 “Flash #1”



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

Hypothesis: flash caused by ejection of friable debris

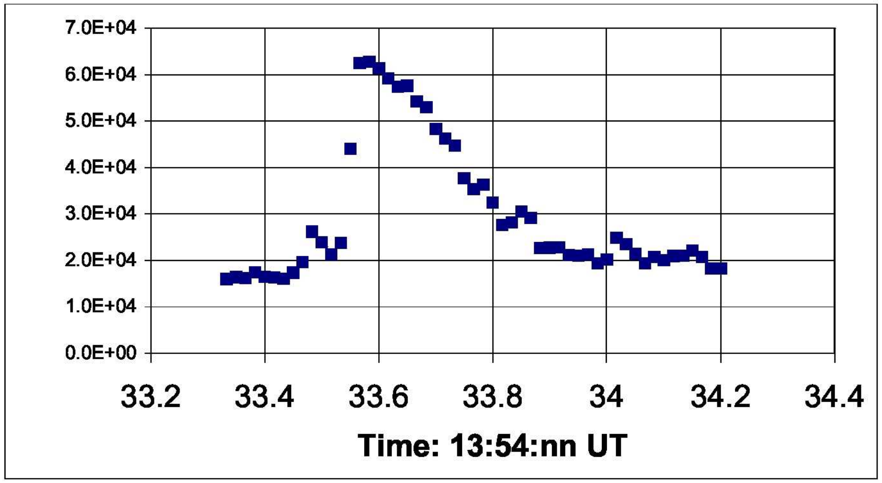
-Possibly loosened by D6 emission

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 $(14m)^2$; 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

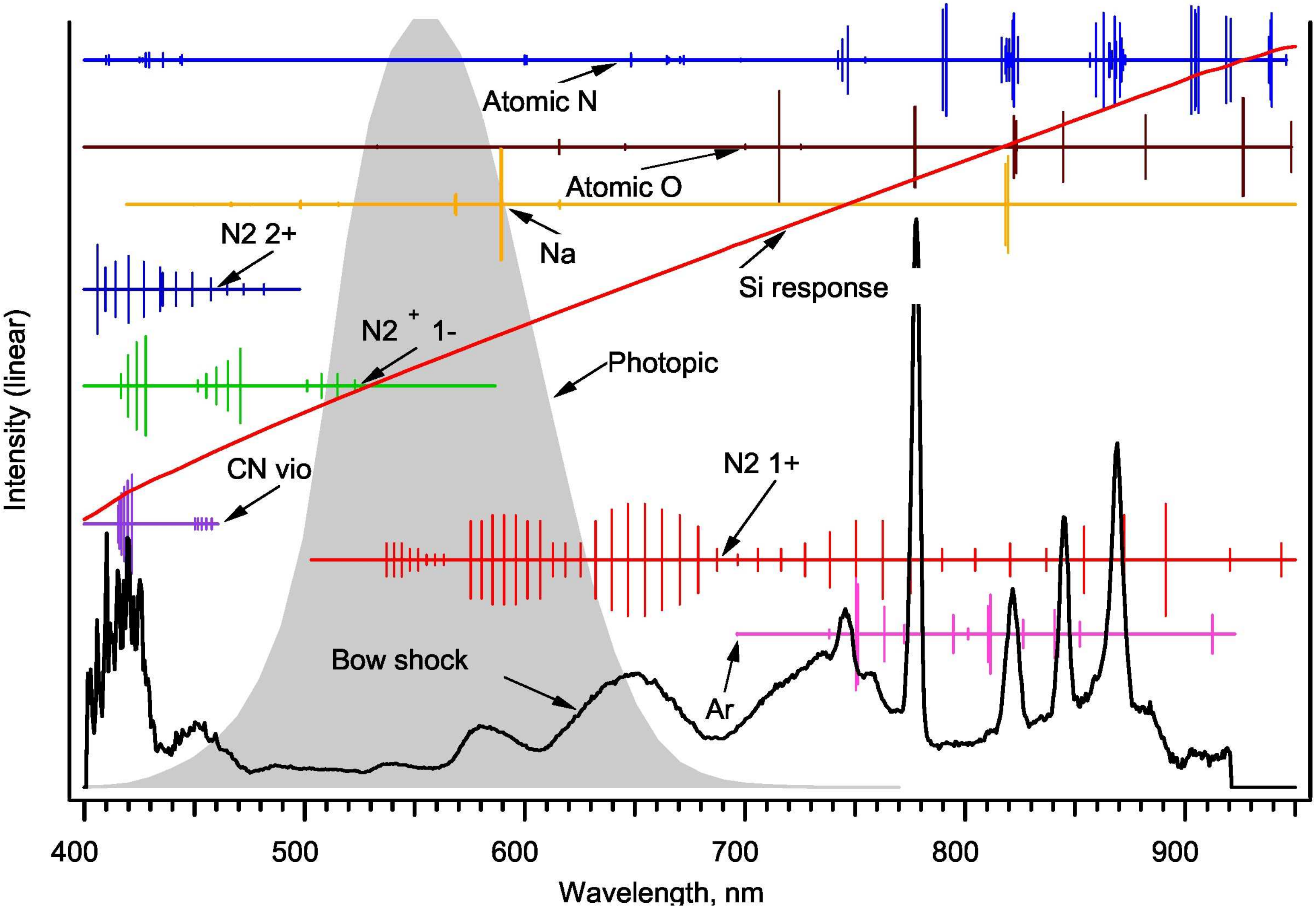
-Mass ~45 kg, sphere area 16 m^2; ~3 kg/m^2

Arc jet testing: simulate entry conditions

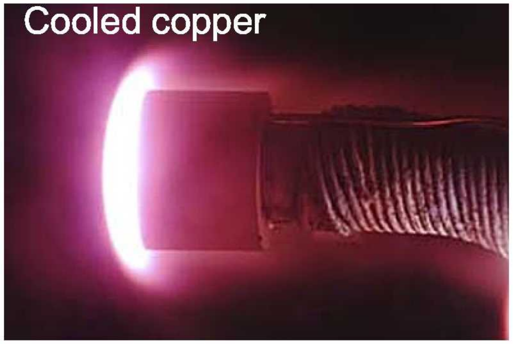
Hypersonic, arc-heated wind tunnel; 25 MJ/kg; T~1800 K

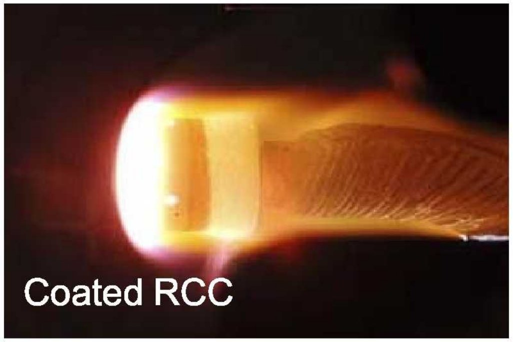
Arc jet shock spectrum: air

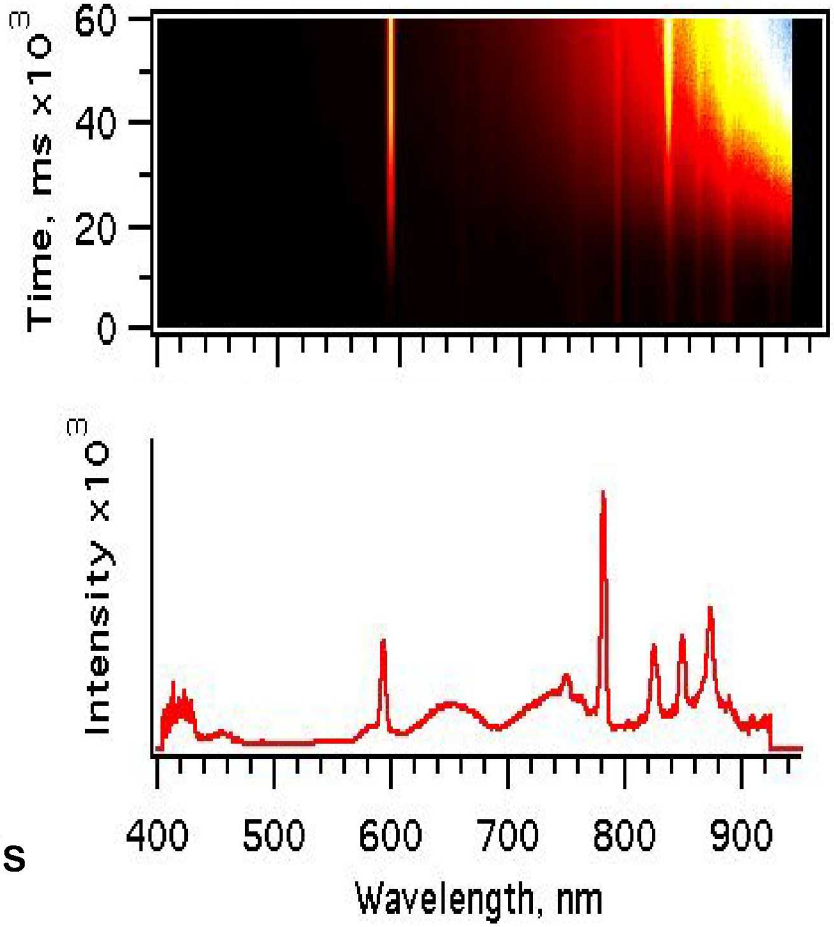
STS107 Image Analysis Team **Luminosity Working Group**



Arcjet Tests of Debris Spectral Output


Cooled copper


Coated RCC



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

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!