# Fireflies and caterpillars: the morphology and statistics of micrometeorite events on TESS

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## Abstract

Since the start of operations, full frame images have occasionally exhibited transient optical flashes best characterized as bright, trailing arcs that extend across one or more cameras. These are best observed by differencing consecutive full frames, where the stationary background is substantially reduced to reveal faint trails. These optical transients have since been called "fireflies", referring to the simultaneous appearance of dozens across the field of all camera frames, and in the next set completely disappearing. A few appear segmented, due to cosmic ray mitigation processing (CRM), and are called caterpillars. Here we present a model that lays the basis for these events – that micrometeorite impacts on the spacecraft give rise to spall and debris, which are illuminated by sunlight before being pushed away by solar pressure. The different types of arcs and blobs are explained by the origin and trajectory of the debris across the shaded and sunlit portions of the camera field of view. Numerical simulations and comparison with the fireflies provide estimates of the micrometeorite characteristics and impact location. Simulation of CRM processing also verifies the caterpillar structure, and provides visual time resolution to 20s. A summary of micrometeorite occurrences over the year will also be presented.

## Fireflies

- Raw images occasionally display faint, barely detectable flashes
- Differencing consecutive FFIs brings out transient images
- Come in different shapes, usually long arcs extending across cameras
- These transient flashes are called "fireflies", or "caterpillars" for segmented trails

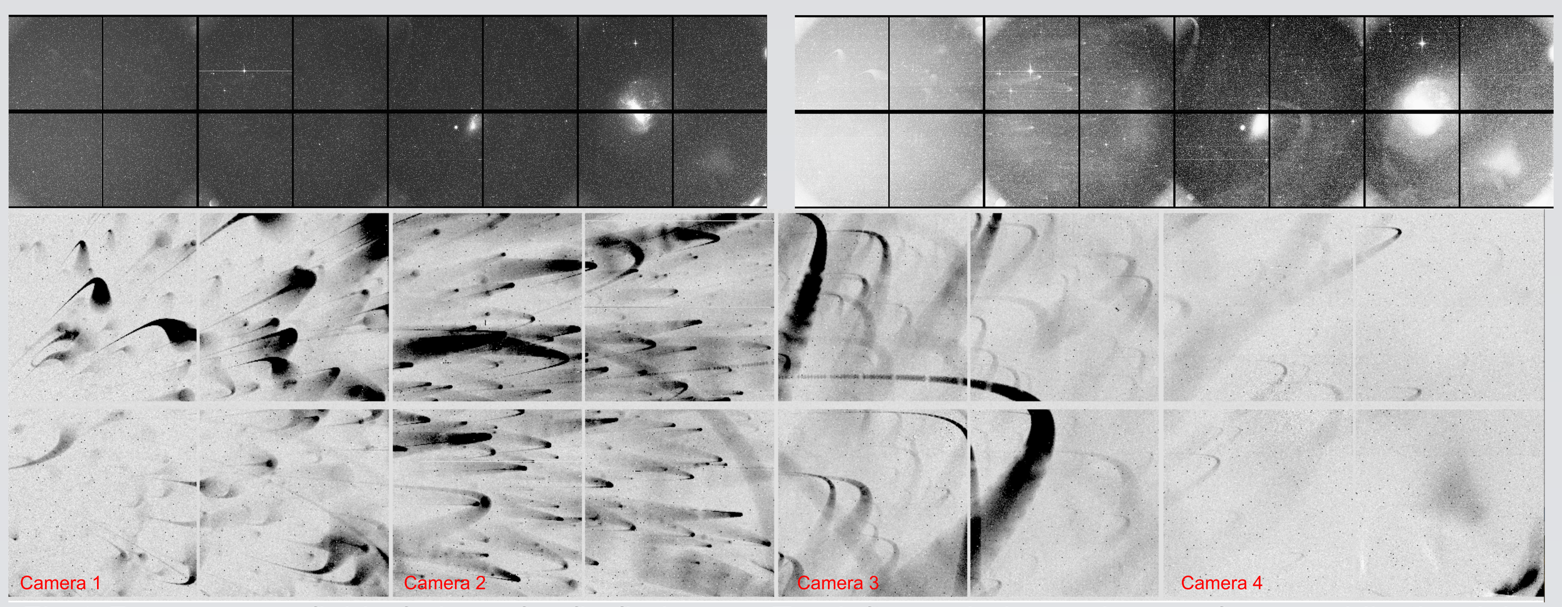


*Fig.1 Four camera field of view of a firefly image. Top left panel shows the raw frame, while the right panel partially exposes the fireflies in histogram mode. Bottom panel shows the trails fully exposed by taking difference frames of the FFIs immediately preceding this set*

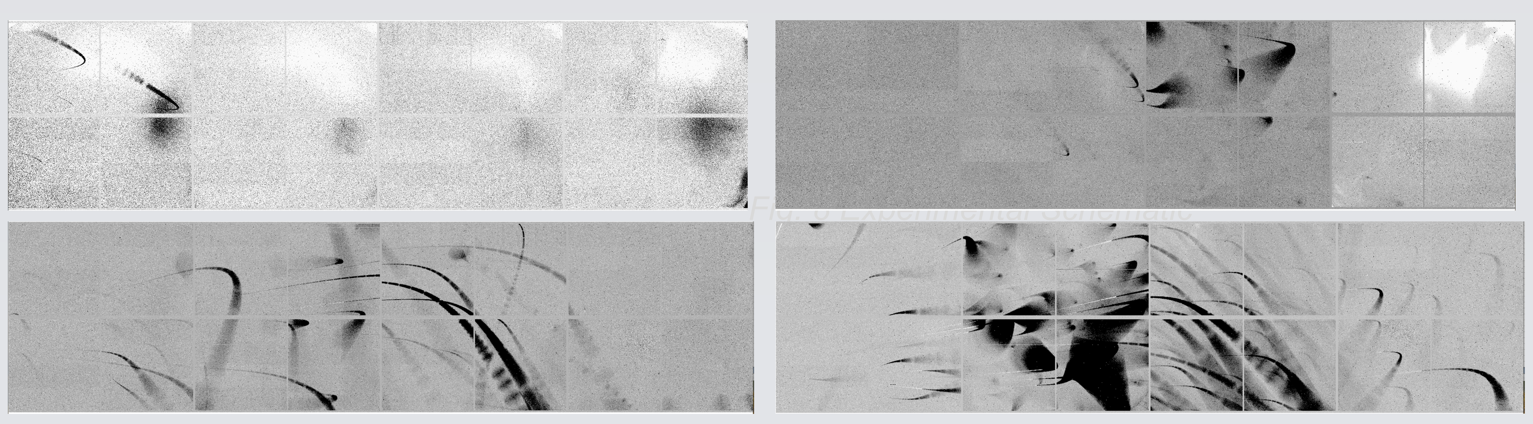

*Fig.2 Other samples showing various activity. Most typical occurrence is shown top left, where a single or a pair of trails appear in a camera. More vigorous activity is displayed in succeeding panels, leading up to the occasional "fireworks" display*

## Caterpillars

- Caterpillars come in clusters of 9 spots, separated by an interval
- Particle motion means some pixels are illuminated in only one frame
- The Cosmic Ray Mitigation (CRM) algorithm in the processor removes the outlier pixel values in every stack of 10, 2s frames
- Bright spots are intersections where a pixel is illuminated in successive frames

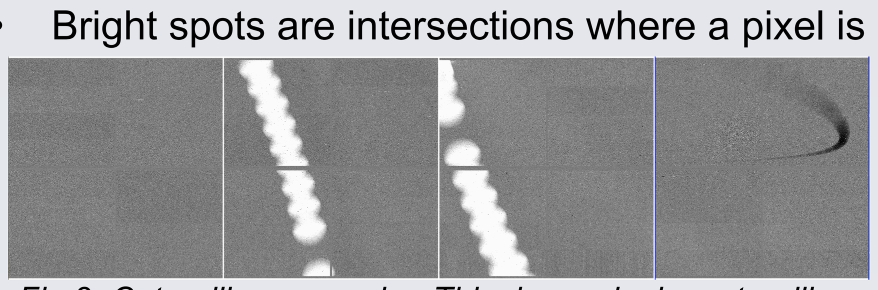

*Fig.3 Caterpillar example. This is a single caterpillar captured by cameras 2 and 3*

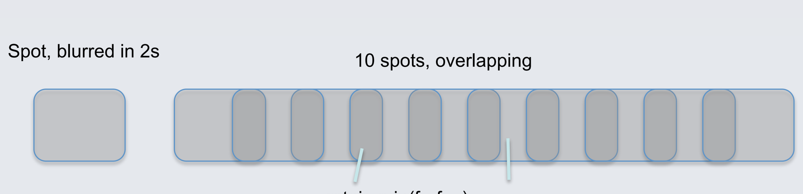


*Fig.4 How the CRM algorithm produces caterpillars*

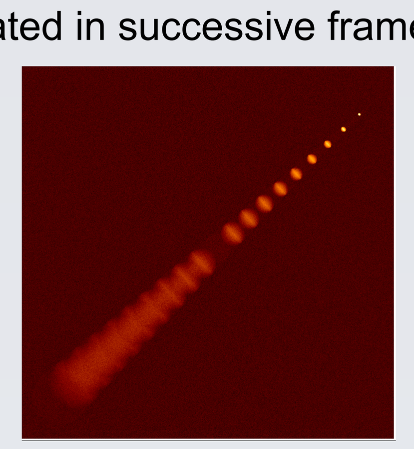

*Fig.5 CRM simulation. A particle starts from the lower right hand corner, and moves away from the camera and to the top left*

## Occurrence Rates

- In year 1 (13 sectors), 90 events have been detected (~3.5/orbit)
- Correlation with meteor showers(?)

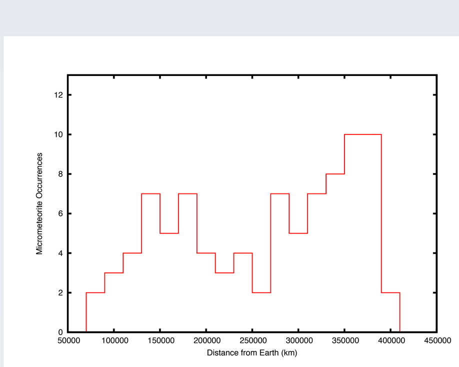

*Fig. 6 The higher rates at farther distances suggest that the source of impacts is not terrestrial*

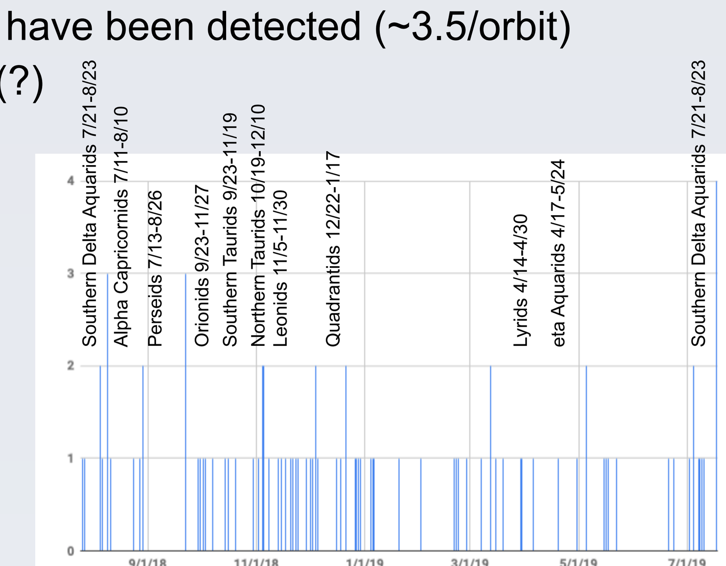


*Fig.7 Occurrences at different times of the year, along with the approximate major meteor shower dates*

## Model of firefly generation

- A micrometeorite hits the spacecraft, creating a spall cloud of debris
- Some of the particles cross into the camera field of view
- At close distances these particles are defocussed and appear large, but at large distances are point like
- Particles travel in a straight line in the shadow of the TESS, but get accelerated once exposed to direct solar light
- Trails point to a vanishing point on the left side of camera 1, corresponding to the anti solar direction

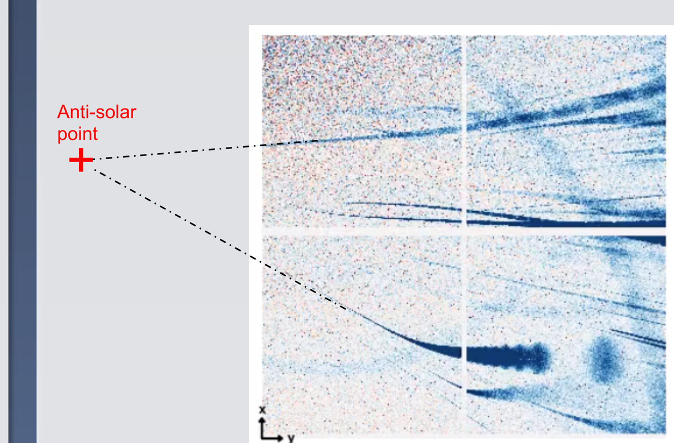


*Fig. 8 Trails in camera 1 converging to the anti-solar point to the left of this image*

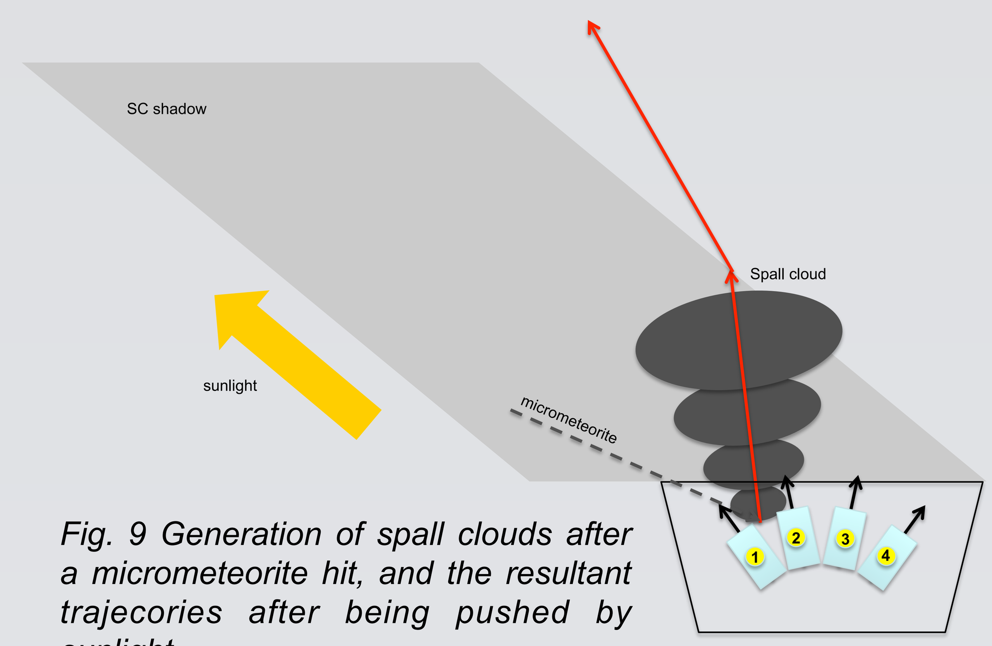


*Fig. 9 Generation of spall clouds after a micrometeorite hit, and the resultant trajecories after being pushed by sunlight*

## Spallation and Solar pressure

- A perfectly reflecting particle will be accelerated by radiation pressure of 9 $\mu$N/m$^2$
- Assume a cross-sectional area ($\pi d^2/4$) of a particle of diameter $d$, with density~ 1.42 g/cm$^3$ (polyimide)
- acceleration = F/m = 0.0135 /(d($\mu$m) $\rho$(g/cm$^3$)) m/s$^2$
- A particle 1$\mu$m in diameter can get accelerated 0.01m/s$^2$, enough to move ~15km in 30 minutes
- How bright is it? Assume solar flux 5.2x10$^{17}$ ph/s/cm$^2$, a 1 $\mu$m particle can scatter ~1000ph/frame at 100m

## Numerical Simulations

- Use a simple model of a particle being accelerated by a constant force once it crosses a shadow boundary
  - ballistic (straight line) trajectory in the shadow
  - accelerated towards the anti-sun direction past the shadow
- Initial boundary conditions are particle starting position and velocity, and acceleration (related to particle size, shape, and composition)
- Particle image is blurred at close distances, with a blur radius approximated by thin-lens equivalent
- Model the cameras as image focal planes rotated and shifted in the SC body frame
- Track and project particle trajectories onto these camera frames

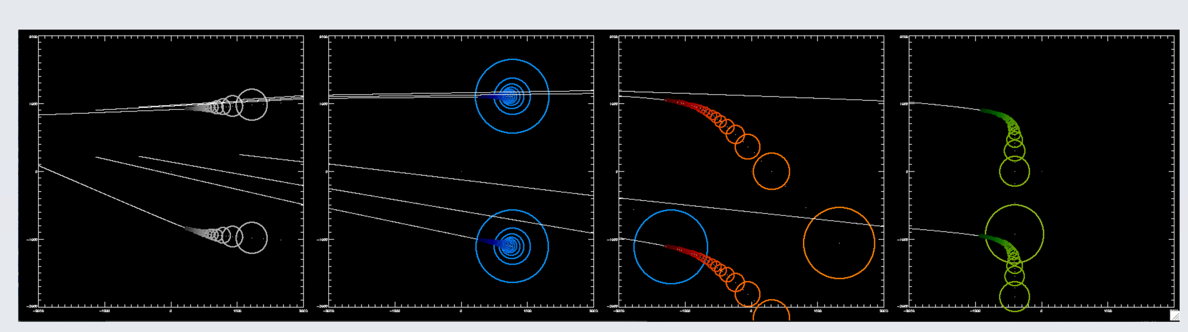

*Fig. 10 Spall trajectories. Circles show the defocussing due to the proximity to the cameras. The bend occurs when these particles cross into the sunlight*

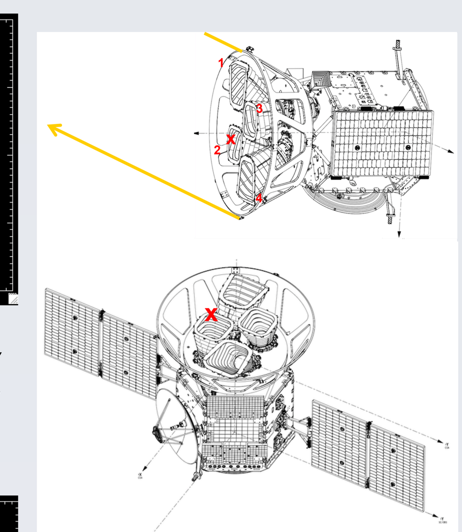

*Fig. 11 Spacecraft orientation with respect to the sun and and spall origin for the simulation in Fig.11.*

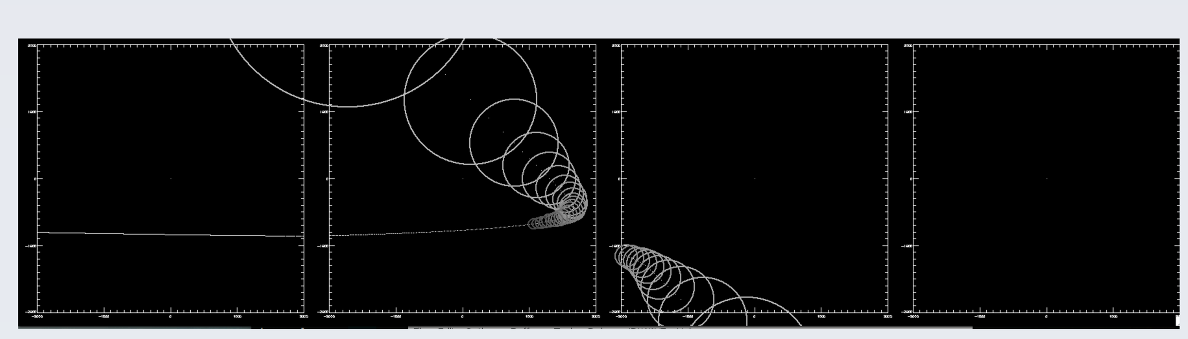

*Fig.12 Single events can look like two events as a particle traverses the Camera 2/3 y-axis*

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