Shower signatures on the Pegasus Spacecraft

Rhiannon Blaauw, All Points Logistics/Jacobs ESSSA Group, June 2017
The University of Western Ontario Meteor Physics Group
Objective: Examine whether the meteoroid impact detectors on Pegasus I, II, III recorded any shower signatures

Outline:
▪ Background on the Pegasus Spacecraft
▪ Review of previous analysis on the meteoroid detector data
▪ Current Analysis:
  Shower identification
  Case study of 1966 Leonids
  Radiation Pressure effects
  Case study of Geminids, Arietids, Quadrantids, Ursids
▪ Conclusions
Introduction to Pegasus:

- 3 identical satellites – all launched in 1965.
- Objective: measure meteoroid abundances in mass range $10^{-7}$ to $10^{-4}$ grams where the Apollo missions would orbit.

Naumann (1965)
Introduction to Pegasus:

- Launched on Saturn I.
- Satellites remained attached to the 2nd stage of Saturn I in space.
- Once in orbit, the satellite unfolded a series of panels.
- Each wing was 29.3 m across & 4.1 m wide – which yielded ~200 m² collecting area on each satellite.
The panels

- The meteoroid detector is a parallel-plate capacitor with a mylar layer as a dielectric.

- 208 panels, composed of 2024 aluminum – either with 0.4, 0.2 or 0.04-mm thickness.

- 8 m² were of 0.04-mm thick detectors; 17 m² of 0.2-mm thick detectors, 175 m² of 0.4-mm thick detectors

- The detectors are isolated by a resistor-diode circuit between the detector and signal lead.
From NASA press kit prior to Pegasus III

July 14, 1965: “The engineering experiment consists of 48 aluminum sub-panels of ‘coupons’ attached to Pegasus which could be quickly unhooked by an astronaut and carried back to Earth. NASA officials emphasize that no decision has been made for an astronaut to rendezvous and retrieve the panels.”
The panels

- A penetrating impact of a detector produces a momentary short of the capacitor resulting in a rapid drop in impressed voltage. (Johnson 1966)

- The energy stored in the capacitor is dumped into the shorted area, which burns away the copper-capacitor deposit and clears the detector in approximately 1 sec. (D’Aiutolo 1967)
Pegasus I, II, III:

- Pegasus I: Launched 16 Feb 1965

- Detector shorting was found to be a more frequent occurrence on Pegasus I than had been indicated from laboratory tests of the detector panels, particularly at higher temperatures. (Johnson 1966)

- “Within the first few orbits … it was noted that the rate of shorting in the 0.2 and 0.4-mm thick detectors was appreciably higher than the test loss rate… [there were] problems with attitude sensing system (though it was still usable)” (Johnson 1966)

- 0.4 and 0.2-mm data are unusable
- 0.04-mm data are fine
Pegasus I, II, III:

- Pegasus II: 25 May 1965

  “The only major subsystem failure occurred in the telemetry system. Beginning about eight days after launch. Intermittent failures of both ...channels occurred. The data loss is not sufficiently great to be alarming at this time.” (Johnson 1966)

- Pegasus III: 30 July 1965

  Fixed some issues discovered in Pegasus I and II and thus far working well (Johnson 1966)
Experiment results were returned to Earth by radio

When Pegasus was active, orbital debris was not a problem – any impact was natural

Main question: Can we detect meteor showers or is it all sporadic? Can we get an overall flux and separate shower fluxes?
Previous Analysis:

• The most complete results:
• (Naumann 1965), covers Feb-July 1965 data, published December 1965
• (Johnson 1966), covers Feb-Aug 31 1965 data, published November 1966
• (Clinton & Naumann 1966), covers Feb–Dec 1965 data, published December 1966
Data from Feb-July, 1965

Pegasus I:
Four hit indications on the 0.400 mm panels in the first 11 days before these panels became unusable.
Nine hits on 0.2-mm panels before they became unusable.
0.040 mm panels: 104 penetrations

Pegasus II: all usable, but only in orbit for a couple months at time of study.
PEGASUS II
There appeared to be increase June 6-12 – Arietids and Zeta Perseids?
‘Preliminary analysis of Pegasus I indicated that the normal to the sensor plane made angles of 50 and 65 degrees with Arietid and Zeta Perseid radiant at peak.’
Thus Pegasus I may have missed those showers.
Data from Feb – Aug 31, 1965 (two more months than Naumann’s report)

The flux results are fairly consistent between spacecraft, even with the low number fluxes.
Johnson 1966

Pegasus II

FIGURE 30. TIME HISTORY OF CUMULATIVE HITS ON 0.04-mm PANELS (PEGASUS II)

FIGURE 31. TIME HISTORY OF CUMULATIVE HITS FOR 0.2-mm PANELS (PEGASUS II)

FIGURE 32. TIME HISTORY OF CUMULATIVE HITS FOR 0.4-mm PANELS (PEGASUS II)
Clifton & Naumann - Dec 1966

- NASA TM – data from Feb – Dec 1965
- Temporal effects were analyzed – diurnal or seasonal effects
- ‘No significant/unexpected diurnal or seasonal effect has been observed with any certainty during the months from June to December’
- ‘Pegasus II recorded high penetration rates throughout the periods of June 6-12 and Oct 2-4. The first of these coincides with the Zeta Perseids and Arietids, the second period coincides with no major showers.’
• Looked at times in 0.04-mm panel from Pegasus II and III where flux deviated by at least two-sigma.

• Six periods of high activity: Aug 19-21, Oct 6, Oct 17-21, Nov 10, Nov 15-17, and Dec 1-3. Only two of these periods relate to meteor showers.

• ‘On purely statistical grounds, you would expect some two and three sigma variations.’
• ‘Pegasus II and III continued to operate through 1967 and their data are available in the NSSDC archives and have never been analyzed.’

• Examined whether diurnal variation showed differing fluxes between sporadic sources.

• They conclude there is no seasonal effect, as well.

• Showers: Unusual activity: Pegasus III: Day 487 (May 2, 1966), Day 490 (May 5, 1966), and again on Day 514 (May 27, 1966). On Day 682 (Nov 13, 1966), 6 events were recorded in the space of 24 minutes (they attribute to 1966 Leonids outburst)
Current analysis

- The following data was retrieved from the NSSDC for each spacecraft and detector:
  - Day, year, hour, and minute of penetration
  - Satellite penetrated
  - Side penetrated
  - Panel penetrated
  - Thickness penetrated
  - Pulse verify
  - Temperature probe on each side when penetrated
  - Satellite clock time
  - Local time
  - Longitude and Latitude
  - Ecliptic longitude and ecliptic latitude
  - Right ascension and declination when penetrated
Current analysis

• NOT included was…. Attitude info! Nor is it readily available. Some clues...

• Johnson 1966: “Orientation of the spacecraft with respect to center of the earth can be determined with an accuracy of 3-5 degrees through a knowledge of sensor states.” “Attitude data was recorded every 1.25 seconds.”

• Clifton & Naumann 1966: “The rotational dynamics of Pegasus II and III is such that an analysis of the directional distribution is not yet possible.”
Current analysis

- Data from Pegasus I spanned February 17, 1965 - March 29, 1966
- Pegasus II: May 25, 1965 - October 31, 1967
- Pegasus III: July 30, 1965 - August 15, 1967

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<th>Days Active</th>
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</table>
Impacts with time

Pegasus II, 0.4-mm aluminum detector, 1965

Cumulative impacts

Date (1965)

Pegasus II, 0.4-mm aluminum detector, 1966

Cumulative impacts

Date (1966)
Impacts with time

Pegasus II, 0.04-mm aluminum detector, 1965

Pegasus II, 0.04-mm aluminum detector, 1966
Impacts with time
Shower Identification

• Began looking at times when the activity was above normal, how close to shower peaks those times were, and whether the shower radiant was visible to the spacecraft.

• To systematically look at this:
  Separated hits vs. time into periods in which there is an average of 1 hit per period
  Examined periods with at least four hits.
  Were there active showers during that time?
  Was the spacecraft visible to the aberrated radiant?

• Example:
  Pegasus I, 0.04-mm, 1965 [avg 1hit/1.33 SL]: SL 213.2 - 214.1 had four hits.
  Orionid signature? Only two of those hits were visible to the radiant.

• Shower catalog used: The showers included in the forecast, with ASGARD’s shower specs, except the ZPE’s, received from the IMO.
Shower Identification
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<th>DEC</th>
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Shower Identification

- Altogether: 115 of these periods across the three spacecraft, three detectors, and three years.
- Inconclusive! No significant periods of increase occur near shower peak. No case of heightened activity can be conclusively or even likely attributed to a shower.
- Generated a figure of merit based on flux, proximity to the peak, and elevation of radiant. This figure did not help.
- Note this exception: there were 6 hits registered within 10 hours on November 13, 1966 on Pegasus III's 0.04-mm detector, 4 days before 1966 Leonid outburst. However, the LEO radiant was not visible for two of these hits.
Case Study: 1966 Leonids!

- The most significant meteor shower in the 20th century! And all three spacecraft were in orbit!
- Objective: predict how many impacts should have impacted each detector, based on measured activity of the 1966 Leonids.
Predicting impacts from a meteoroid stream

1. Read in Pegasus data from specific spacecraft and detector
2. Read in TLE file that corresponds to spacecraft
3. Read in Leonid ZHR profile (taken from Brown’s thesis)
4. Loop through Leonid activity in 0.001 SL increments (every 1 min, 30 sec).
5. Find Leonid ZHR closest to that time, from the ZHR profile (Peter Brown’s peak and activity near the peak + Sirko Molau’s activity before/after the peak).
6. Find the LEO radiant at that SL.
7. Find the azimuth, elevation for the Leonids, and Earth’s limb elevation.
8. Find the flux at magnitude +6.5 (Eqn 1):
9. Find the flux at 1 mg (1e-3 grams) (Eqn 2):
10. Scale flux to limiting mass of each detector (Eqn 3):
11. Take into account the radiant elevation (don’t have attitude data yet…so only using elevation), and converting flux from meteors/km²/hr to meteors/m²/minute.
12. Since each 0.001 SL equals 1.5 minutes, integrate over whole duration of Leonids to get the total # of Leonids expected.

\[ Q(m \leq 6.5) = \frac{ZHR(13.1r - 16.5)(r - 1.3)^{0.748}}{37200km^2} \]

\[ Q(M \geq 10^{-3} g) = Q(m \leq 6.5)r^{9.775} \log\left(\frac{29km/s}{v_{inf}}\right) \]

\[ (1 - s) = \frac{\log(Flux_2) - \log(Flux_1)}{\log(Mass_2) - \log(Mass_1)} \]
Case Study: 1966 Leonids!

- Worst case scenario: High ZHR and high population index!
- Used Brown’s (PhD thesis) 1966 Leonid activity curve with ZHR of 115,000.
- Used IMO visual activity curve and IMO video fluxes (via Sirko Molau) to find activity leading up to/after the peak.
- Leonid population indices varied from 1.8 up to 2.8. Frequently they are 2.3-2.5. Found results using 2.8 (worse case scenario) and 2.3, for comparison.
- The impact prediction takes into account that the 0.4-mm AL detectors covered 175 m$^2$, 0.2-mm detectors covered 17 m$^2$, and 0.04-mm covered 8 m$^2$.
- Prediction done for each spacecraft as their orbits were unique. This particularly matters in such a short and extreme outburst.
- Found impact predictions during entire active period of shower (128-140 SL), and for 12 hours around the peak (235.0-235.5 SL).
Case Study: 1966 Leonids!

Predicted Leonid impacts per square meter on Pegasus I, $r=2.3, 2.8$

- $r=2.8$
- $r=2.3$
Case Study: 1966 Leonids!

Results! Impacts predicted on each detector.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Limiting Mass (g)</th>
<th>Peg I (entire shower)</th>
<th>Peg I (12-h peak)</th>
<th>Peg II (peak)</th>
<th>Peg III (peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>r=2.8</td>
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<tr>
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<td>1.35</td>
<td>1.26</td>
<td>2.88</td>
<td>2.16</td>
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</table>

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<thead>
<tr>
<th>Detector</th>
<th>Limiting Mass (g)</th>
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<th>Peg I (12-h peak)</th>
<th>Peg II (peak)</th>
<th>Peg III (peak)</th>
</tr>
</thead>
<tbody>
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<td>1.47</td>
<td>3.29</td>
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<td>0.30</td>
<td>0.29</td>
<td>0.63</td>
<td>0.48</td>
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</tbody>
</table>

If population index was high, we don’t see these # of impacts… why? Radiation Pressure?
Radiation Pressure

- At what mass limit does radiation pressure start to remove meteoroids from the stream?
- \( \beta \) is the radiation force over the gravitational force, and is a function of the orbit of the particles. \( \rho \) is the bulk density of a particle, and \( s \) is the particle radius.
- When \( \beta \geq (1-e)/2 \), the particle ejected from a comet can become unbound.
- For example, 55P/Tempel-Tuttle (parent body of the Leonids), has a density of 0.806 g/cc and an eccentricity of 0.9055.
- Particles can become unbound from 55P’s orbit if they are \( \leq 1.1e^{-8} \) grams.
- This can be broken down into a refined calculation of \( \beta \) for leading ejecta and trailing ejecta. Leading: \( 2.18e^{-8} \) grams, trailing: \( 5.91e^{-9} \) grams.
Thus for many showers, extrapolating ZHR or flux to these size ranges is not realistic, as radiation pressure would have removed particles.

What showers are NOT unbound that we can use as a check?

Showers that CAN be extrapolated: LEO (to 0.4 and 0.2-mm), GEM, QUA, URS (to 0.4 and 0.2-mm), ARI (to 0.4-mm)
More Case Studies - Geminids

- Radiation pressure does not take particles away until $3.28 \times 10^{-10}$ grams, which is below the limiting mass of all detectors.
- Activity profile from IMO visual activity and IMO video network fluxes.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Detector} & \text{Limiting Mass (g)} & \text{Peg I} & \text{Peg II} & \text{Peg III} \\
\hline
0.04-\text{mm} & 1.5e-9 & 2.71 & 2.19 & 1.55 \\
0.2-\text{mm} & 6.9e-8 & 0.13 & 0.10 & 0.07 \\
0.4-\text{mm} & 2.9e-7 & 0.31 & 0.25 & 0.18 \\
\hline
\end{array}
\]

- $s=2.0$, $r=2.6$

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Detector} & \text{Limiting Mass (g)} & \text{Peg I} & \text{Peg II} & \text{Peg III} \\
\hline
0.04-\text{mm} & 1.5e-9 & 0.016 & 0.013 & 0.009 \\
0.2-\text{mm} & 6.9e-8 & 0.002 & 0.002 & 0.001 \\
0.4-\text{mm} & 2.9e-7 & 0.009 & 0.008 & 0.005 \\
\hline
\end{array}
\]

- $s=1.69$, $r=1.95$
More Case Studies - Arietids

- Activity from CMOR Arietid Decadal Survey Paper by Bruzzone et al. (2015)
- 0.2 and 0.04-mm detectors are affected by radiation pressure, we can examine results of 0.4-mm detectors.
- Arietids are long-duration (45 SLs!), and have significant flux for most of that time, thus integrated impact probabilities over duration of shower may be significant.
- $s=2.0, r=2.7$

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</tr>
</thead>
<tbody>
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</tbody>
</table>
More Case Studies – QUA, URS

QUA:
• Radiation pressure does not remove particles unless they are smaller than 7.2e-12 grams.
• All detectors should be unaffected by radiation pressure.
• Activity from IMO Video fluxes + IMO visual
• s=1.81, r=2.1

URS:
• Radiation pressure does not remove particles unless they are smaller than 1.6e-9 grams.
• All detectors should be unaffected by radiation pressure.
• Activity from IMO Video fluxes + IMO visual
• s=2.2, r=3.0

<table>
<thead>
<tr>
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<th>Peg III</th>
</tr>
</thead>
<tbody>
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<td>0.005</td>
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<td>1.7e-9</td>
<td>1.63</td>
<td>1.67</td>
<td>1.99</td>
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<tr>
<td>0.2-mm</td>
<td>7.8e-8</td>
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<td>3.2e-7</td>
<td>0.06</td>
<td>0.07</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Conclusions:

- Pegasus Spacecraft = huge collecting area.
- No obvious shower signatures – even for 1966 Leonids.
- Projected impacts would indicate there should be heightened activity during some major showers.
- After considering radiation pressure affects, there are only a few possible showers and a few detectors that are not affected by radiation pressure and we can examine projected impacts by scaling the flux: Geminids, Arietids, Quadrantids, Ursids.
- For those showers & detectors not affected by radiation pressure, the flux is too low to be noticeable from background flux.
- No confirmed or even probable showers seen in Pegasus data.
Backup Slides
Pegasus II, 0.4-mm
Pegasus II, 0.4-mm
Pegasus II, 0.04-mm
Pegasus II, 0.04-mm
Pegasus III, 0.4-mm
Pegasus III, 0.4-mm
Pegasus III, 0.2-mm
Pegasus III, 0.04-mm
Pegasus III, 0.04-mm