Lecture 13.0: 

The Pioneer Anomaly: 
Effect, New Data and New Investigation

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Курс Лекций: «Современные Проблемы Астрономии»
dля студентов Государственного Астрономического Института им. П.К. Штернберга
11 февраля — 26 мая 2008
Triumph of Mathematical Astronomy in 19th Century

1845: the search for Planet-X:
- Anomaly in the Uranus’ orbit → Neptune
- Anomalous motion of Mercury → Vulcan

Discovery of Neptune: 1845

Anomalous precession of Mercury’s perihelion:
- 43 arcsec/cy can not be explained by Newton’s gravity

Before publishing GR, in 1915, Einstein computed the expected perihelion precession of Mercury
- When he got out 43 arcsec/cy – a new era just began!!

In one year 1845, LeVerrier both confirmed the Newton’s theory (Neptune) & cast doubt on it (Mercury’s’ anomaly).
The First Test of General Theory of Relativity

Gravitational Deflection of Light: Solar Eclipse 1919

Possible outcomes in 1919:
- Deflection = 0;
- Newton = 0.87 arcsec;
- Einstein = 2 x Newton = 1.75 arcsec

Eddington’s telegram to Einstein, 1919
Einstein and Eddington, Cambridge, 1930
General Relativity Works at Larger Scales: Gravitational Deflection of Light
Solar system is a laboratory with unique tools:
- planetary probes, LLR, ISS, dedicated missions, etc.

**Most frequently accessed region**

\[
\frac{GM_{\oplus}}{c^2 R_{\oplus}} \sim 10^{-9}
\]

**Strongest gravity potential**

\[
\frac{GM_{\text{Sun}}}{c^2 R_{\text{Sun}}} \sim 10^{-6}
\]

Planetary exploration offers great opportunities for precision tests of gravity.
38 Years of Solar System Gravity Tests

Techniques for Gravity Tests:

**Radar Ranging:**
- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Pioneers, Cassini, Mars Global Surveyor, Mars Orbiter, etc.
- VLBI, GPS, etc.

**Laser:**
- SLR, LLR, interplanetary, etc.

Dedicated Gravity Missions:
- LLR (1969 - on-going!!)
- GP-A, '76; LAGEOS, '76,'92; GP-B, '07; LISA, 2017 (?)

New Engineering Discipline – Applied General Relativity:
- Daily life: GPS, geodesy, time transfer;
- Precision measurements: deep-space navigation & astrometry (SIM, GAIA,....).

A factor of 100 in 38 years is impressive, but is not enough for the near future!
...There are Three Dark Clouds over General Relativity...:

Dark Energy, Dark Matter, and
The Pioneer Anomaly

Prof. Dr. Jürgen Ehlers

MPI für Gravitationsphysik (Albert-Einstein-Inst.), Golm bei Potsdam,
Physics Colloquium at the University of Bremen
February 10, 2005
Dark Energy is the dominant constituent of the Universe
Dark Matter is next

95% of the Universe is in Dark Energy and Dark matter ... for which we have no understanding!!!
The Pioneer Anomaly:  
Effect, New Data and New Investigation

Slava G. Turyshev

with special thanks to

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Jet Propulsion Laboratory, California Institute of Technology

Craig Markwardt  Viktor Toth  Louis Scheffer  Siu-Chan Lee  Daniel S. Lok
Goddard Space Flight Center  Ottawa, Canada  Cadence Systems  Applied Science Laboratories
The Pioneer Anomaly: Summary

- Anomalous acceleration of Pioneers 10 and 11:
  \[ a_P = (8.74 \pm 1.33) \times 10^{-10} \text{ m/s}^2 \]
  - A constant acceleration of both Pioneers \textit{towards} the Sun
  - \textbf{No mechanism} or \textbf{theory} that unambiguously explains the anomaly
  - Most likely cause is on-board systematics, yet to be demonstrated

- The Pioneer anomaly, taken at its face value:
  - Pioneers conducted the largest-scale-ever gravitational experiment in the solar system… that failed to confirm Newton’s gravity…
  - The Pioneer anomaly constitutes a departure from the Newton’s $1/r^2$ gravity law in regions farther than 25 AU from the Sun….

Possible Origin of the “Dark Force”?

- \textbf{New Physics} [many proposals exist, some interesting]
- \textbf{We focus on Conventional Physics, as the cause:}
  - Gas leaks, drag force, \textit{thermal recoil force}, etc…
The Pioneer 10/11 spacecraft

<table>
<thead>
<tr>
<th>Agency: NASA</th>
<th>Pioneer 10</th>
<th>Pioneer 11</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Launch</strong></td>
<td>2 March 1972</td>
<td>5 April 1973</td>
</tr>
<tr>
<td><strong>Last data point received</strong></td>
<td>27 Apr 2002 distance ~80.2 AU</td>
<td>1 Oct 1990 distance ~30 AU</td>
</tr>
</tbody>
</table>

**Parameters for Pioneer 10 (Pioneer 11 – identical)**

- **Total spacecraft mass**
  - SNAP-19 RTG: mass/distance 259 kg
  - High Gain Antenna, diameter 13.6 kg / 3 m
  - Attitude control: spin-stabilized 2.74 m
  - ~4.28 rpm

- **Communication system**
  - S-band, up-link 2110 MHz
  - S-band, down-link 2292 MHz
  - Data available Doppler (λ ~ 13 cm)
  - Spacecraft transmits continuously @ 8 W

The Pioneers are still the most precisely navigated deep-space vehicles:

- Spin-stabilization and design permitted acceleration sensitivity ~10^{-10} m/s^2, unlike a Voyager-type 3-axis stabilization that were almost 50 times worse;
- Precision celestial mechanics – a primary objective of the Pioneers’ extended missions – search for gravitational waves, Planet X, trans-Neptunian objects, etc.
THE STUDY OF THE PIONEER ANOMALY

Pioneer 10 Launch: 2 March 1972

Pioneer 10 Launch: 2 March 1972
**Pioneers 10 and 11: Main Missions (before 1979)**

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**THE STUDY OF THE PIONEER ANOMALY**

**Pioneer 10**

**Pioneer 11**

Trajectories of Pioneer 10 & 11 during the main mission phase
Last signal from Pioneer 10 was received on 23 January 2003 (82.1 AU from the Sun)

Pioneer 10 last contacted in March 2006: no signal received

Pioneer 10 on 13 Apr 2008:
- Distance from the Sun: 95.03 AU
- Position, SE (lat., lon.): (3.0º, 78.2º)
- Heliocentric velocity: 12.04 km/s
- Distance from Earth: 16.01 Gkm
- Round-Trip Light Time: 26hr 16min

Trajectories of Pioneers and Voyagers
The study of the Pioneer anomaly

History: Detection of the Effect and Earlier Studies

- 1979: search for unmodeled accelerations w/ Pioneers began:
  - Motivation: Planet X; initiated when Pioneer 10 was at 20 AU;
  - Solar-radiation pressure away from the Sun became $< 5 \times 10^{-10} \text{ m/s}^2$

- 1980: navigational anomaly first detected at JPL:
  - The biggest systematic error in the acceleration residuals –
    a constant bias of $(8 \pm 3) \times 10^{-10} \text{ m/s}^2$ directed towards the Sun

- Initial JPL-ODP analysis in 1990-95:
  - $(8.09 \pm 0.20) \times 10^{-10} \text{ m/s}^2$ for Pioneer 10
  - $(8.56 \pm 0.15) \times 10^{-10} \text{ m/s}^2$ for Pioneer 11
  - NO magnitude variation with distance over a range of 40 to 70 AU
  - The error is from a batch-sequential & filter-smoothing algorithm

- An Error in JPL's ODP? – Numerous internal checks at JPL
- NASA Grant to The Aerospace Corporation: 1996-1998

Data used for the analysis conducted during 1996-1998:

- Pioneer 10: 11.5 years; distance = 40–70.5 AU ⇒ 20,055 data points
- Pioneer 11: 3.75 years; distance = 22.4–31.7 AU ⇒ 19,198 data points
THE STUDY OF THE PIONEER ANOMALY

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An Error in JPL's ODP?
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NASA Grant to The Aerospace Corporation: 1996-1998
To verify the “onset” of the anomaly...

Modeling of Spacecraft Motion

- Relativistic eq.m. for celestial bodies are correct to \((v/c)^4\):
  - Relativistic gravitational accelerations (EIH model) include: Sun, Moon, 9 planets are point masses in isotropic, PPN, N-body metric;
  - Newtonian gravity from large asteroids; terrestrial, lunar figure effects; Earth tides; lunar physical librations.

- Relativistic models for light propagation are correct to \((v/c)^2\)

- Model accounts for many sources of non-grav. forces, including:
  - Solar radiation and wind pressure; the interplanetary media;
  - Attitude-control propulsive maneuvers and propellant (gas) leakage from the propulsion system;
  - Torques produced by above mentioned forces;
  - DSN antennae contributions to the spacecraft radio tracking data.

- Orbit determination procedure, includes:
  - Models of precession, nutation, sidereal rotation, polar motion, tidal effects, and tectonic plates drift;
  - Model values of the tidal deceleration, non-uniformity of rotation, polar motion, Love numbers, and Chandler wobble are obtained observationally via LLR, SLR and VLBI (from ICRF).
The two-way Doppler anomaly to first order in \((v/c)\) simply is:

\[
\begin{align*}
f_{\text{obs}}(t) - f_{\text{model}}(t) &= -f_0 \frac{2a_P t}{c} \\
f_{\text{model}} &= f_0 \left[ 1 - \frac{2v_{\text{model}}(t)}{c} \right] \\
v_{\text{obs}}(t) - v_{\text{model}}(t) &= -2a_P t
\end{align*}
\]

The two-way Doppler residuals (observed Doppler velocity minus modeled Doppler velocity) for Pioneer 10 vs time [1 Hz is equivalent to 65 mm/s velocity].
Adding only one more parameter to the model – a constant radial acceleration – led to residuals distribution ~ zero Doppler velocity with a systematic variation ~3.0 mm/s. Quality of the fit is determined by ratio of residuals to the downlink carrier frequency, $\nu_0 \approx 2.29 \text{ GHz}$. 

Doppler residuals as a function of time of the best fit model.
# Sources of Systematic Error: External

<table>
<thead>
<tr>
<th>Error budget constituents</th>
<th>Bias $10^{-10}$ m/s$^2$</th>
<th>Uncertainty $10^{-10}$ m/s$^2$</th>
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<tbody>
<tr>
<td>1 Sources of external systematic error:</td>
<td></td>
<td></td>
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<tr>
<td>⇒ Solar radiation pressure</td>
<td>± 0.001</td>
<td></td>
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<tr>
<td>⇒ From the mass uncertainty</td>
<td>+0.03</td>
<td>± 0.01</td>
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<tr>
<td>⇒ Solar wind contribution</td>
<td>± &lt; 10$^{-5}$</td>
<td></td>
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<tr>
<td>⇒ Effects of the solar corona</td>
<td>± 0.02</td>
<td></td>
</tr>
<tr>
<td>⇒ Electro-magnetic Lorentz forces</td>
<td>± &lt; 10$^{-4}$</td>
<td></td>
</tr>
<tr>
<td>⇒ Influence of the Kuiper belt’s gravity</td>
<td>± 0.03</td>
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<tr>
<td>⇒ Influence of the Earth orientation</td>
<td>± 0.001</td>
<td></td>
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<tr>
<td>⇒ DSN Antennae: mechanical/phase stability</td>
<td>± &lt; 0.001</td>
<td></td>
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<tr>
<td>⇒ Phase stability and clocks</td>
<td>± &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>⇒ DSN station location</td>
<td>± &lt; 10$^{-5}$</td>
<td></td>
</tr>
<tr>
<td>⇒ Effects of troposphere and ionosphere</td>
<td>± &lt; 0.001</td>
<td></td>
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<tr>
<td>2 Computational systematics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>⇒ Numerical stability of least-squares estimation</td>
<td>± 0.02</td>
<td></td>
</tr>
<tr>
<td>⇒ Accuracy of consistency/model tests</td>
<td>± 0.13</td>
<td></td>
</tr>
<tr>
<td>⇒ Mismodeling of maneuvers</td>
<td>± 0.01</td>
<td></td>
</tr>
<tr>
<td>⇒ Mismodeling of the solar corona</td>
<td>± 0.02</td>
<td></td>
</tr>
<tr>
<td>⇒ Annual/diurnal terms</td>
<td>± 0.32</td>
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</table>

An interesting set of error sources, but not of a major concern!
A drawing of the Pioneer spacecraft
Sources of Systematic Error: On-board

<table>
<thead>
<tr>
<th>Error budget constituents</th>
<th>Bias $10^{-10}$ m/s$^2$</th>
<th>Uncertainty $10^{-10}$ m/s$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Sources of external systematic error:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>⇒ Radio beam reaction force</td>
<td>$+1.10$</td>
<td>$\pm 0.11$</td>
</tr>
<tr>
<td>⇒ Thermal/propulsion effects from RTGs:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>⇒ RTG heat reflected off the craft</td>
<td>$-0.55$</td>
<td>$\pm 0.55$</td>
</tr>
<tr>
<td>⇒ Differential emissivity of the RTGs</td>
<td></td>
<td>$\pm 0.85$</td>
</tr>
<tr>
<td>⇒ Non-isotropic radiative cooling of s/c</td>
<td></td>
<td>$\pm 0.16$</td>
</tr>
<tr>
<td>⇒ Expelled He produced within the RTGs</td>
<td>$+0.15$</td>
<td>$\pm 0.16$</td>
</tr>
<tr>
<td>⇒ Propulsive mass expulsion: gas leakage</td>
<td></td>
<td>$\pm 0.56$</td>
</tr>
<tr>
<td>⇒ Variation between s/c determinations</td>
<td>$+0.17$</td>
<td>$\pm 0.17$</td>
</tr>
</tbody>
</table>

Heat is an important source, but:
- It is NOT strong enough to explain the anomaly;
- Exponential decay or linear decrease – NOT seen

SNAP-19 RTG

Heat chart:
- 1987 [97 W]
- ~32.8% reduction
- 1998.8 [65 W]
- 2001
Focus of the 1995-2002 Analysis

- On-board systematic & other hardware-related mechanisms:
  - Precessional attitude control maneuvers and associated “gas leaks”
  - Nominal thermal radiation due to $^{238}$Pu decay [half life 87.75 years]
  - Heat rejection mechanisms from within the spacecraft
  - Hardware problems at the DSN tracking stations

- Examples of the external effects (used GLL, ULY, and Cassini):
  - Solar radiation pressure, solar wind, interplanetary medium, dust
  - Viscous drag force due to mass distribution in the outer solar system
  - Gravity from the Kuiper belt; gravity from the Galaxy
  - Gravity from Dark Matter distributed in halo around the solar system
  - Errors in the planetary ephemeris, in the Earth’s Orientation, precession, polar motion, and nutation parameters

- Phenomenological time models:
  - Drifting clocks, quadratic time augmentation, uniform carrier frequency drift, effect due to finite speed of gravity, and many others

- All the above were rejected as explanations

Most of the systematics are time or/and space dependent!
By 2008 existence of the anomaly is confirmed by 7 codes:
- JPL’s Orbit Determination Program [various versions 1979-2008];
- The Aerospace Corporation code POEAS [during 1995-2001];
- Goddard Space Flight Center’s study in 2003 [data from NSSDC];
- Institute for Theoretical Astronomy, Norway, Oslo [2002-2008];
- Viktor Toth, Canada [2005-2008]; GAP, France [2006-2008], others.

Observed frequency drift can be interpreted as acceleration of
\[ a_P = (8.74 \pm 1.33) \times 10^{-10} \text{ m/s}^2. \]
- **Constant** acceleration of the spacecraft **towards** the Sun...
- This interpretation has become known as the Pioneer Anomaly.

Observation \( a_P \approx c H \), stimulated many suggestions…:
- Kinematical realization of local cosmological frame; momentum-
dependent gravitational coupling; modified inertia; non-uniformly-
coupled scalar field(s); Brane-worlds; higher-dimensional
gravitational models…

Primary focus of new analysis: “**the heat or not the heat?**”

Existence of the signal is confirmed, its origin is yet unknown
THE STUDY OF THE PIONEER ANOMALY

9-track Magnetic Tapes...

Somewhere in JPL...

Statistics: ~400 tapes… 90 minutes / tape
Recent Pioneer Doppler Data Recovery Effort

Data used for the Analysis (1996-1998):

- Pioneer 10: 11.5 years; distance = 40–70.5 AU ⇒ 20,055 data points
- Pioneer 11: 3.75 years; distance = 22.4–31.7 AU ⇒ 19,198 data points

Pioneer 10/11 Doppler Data available (since March 2008):

- Pioneer 10:
  - 1973-2002: ~30 years
  - Distance range: 4.56–80.2 AU
  - Jupiter encounter
  - ~150,000+ data points
  - Maneuvers, spin, initial cond.

- Pioneer 11:
  - 1974-1994: ~20 years
  - Distance range: 1.0–41.7 AU
  - Jupiter & Saturn encounters
  - ~120,000+ data points
  - Maneuvers, spin, initial cond.

- All 600+ ATDFs went through radio-metric data conditioning (2006-2008)
- The entire set of Doppler data should be available by the end of April 2008

Significant volume of the data never analyzed to study the anomaly
Critical Phases of the On-Going Investigation

Four Main Objectives:

- Analysis of the early trajectory:
  - Direction of the anomaly: origin
- Analysis of planetary encounters:
  - Should tell more about the onset of the anomaly (e.g. Pioneer 11)
- Analysis of the entire dataset:
  - Temporal evolution of the anomaly
- Focus on on-board systematics:
  - Thermal modeling using telemetry

- Towards the Sun: gravitational models?
- Towards the Earth: frequency standards?
- Along the velocity vector: drag or inertia?
- Along the spin axis: internal systematics?
Early Data: Study the Direction of the Anomaly

Trajectories of Pioneer 10 & 11 during the main mission phase
Navigational Anomalies during Earth fly-byes were observed with multiple spacecraft:
- Galileo: #1 on 10/8/1990 @ altitude of ~960 km; #2 on 12/8/1992 @ altitude of ~305 km;
- NEAR: 01/22/1998 @ altitude of ~550 km;
- Cassini: 08/19/1999 @ altitude of ~1,171 km;
- Stardust: 01/15/2001 @ altitude of ~6,000 km;
- Rosetta: 03/04/2005 @ altitude of ~1,900 km.

Are they relevant to the Pioneer anomaly?

Pioneer Project Documents (1966-2003) @ Ames:
- All Pioneer 10 and 11 Project documents (design, fabrication, testing, calibrations, quarterly reports, memoranda, etc.)
- Maneuver records, spin-rate data, significant events of the craft, etc.
- Lack of funding resulted in improper storage, near destruction

Master Data Record (MDR): 40GB spacecraft telemetry
- All housekeeping data for both Pioneer 10 & 11 – the only available data on their behavior through the missions
- Developed a C++ code to read the MDRs and distribute the data
- MDRs will be used together with the Doppler data to study on-board systematics (e.g. finite-element thermal model, etc.)

Project documents and data are saved in Ames’ Archives!
- The Pioneer anomaly saved the Pioneer Project archive!
- Late 2006 started development of a finite-element thermal model that uses the recovered telemetry to estimate recoil force

Pioneer design documents & performance data available for analysis
Each craft: ~114 parameters
Master Data Record will be critical in studying the effect of on-board systematics.
A thermal model may now be aided by the actual flight data.
Objectives of Thermal Engineering Study

Evaluate if anisotropic S/C thermal radiosity can explain the anomaly

- Radiosity includes emissive power plus reflected thermal irradiation
- Develop geometric math model (GMM) to:
  - Calculate radiative exchange among all modeled S/C surfaces
  - Calculate absorbed solar loads on S/C (although tiny at 25 AU)
- Develop thermal math model (TMM) to:
  - Calculate predicted temperatures for all modeled S/C surfaces
  - Calculate predicted heat flows for all modeled S/C surfaces
- Develop modeling method to calculate directional components of radiative heat flow
  - Focus on radiative loading parallel to S/C spin axis
- Primary objective:
  - To achieve ample model fidelity needed to either confirm or eliminate thermal emission as an explanation for the Pioneer anomaly
- Pioneer anomaly work is interesting … and like a treasure hunt
  - Modeling a 35+ year old spacecraft is challenging due to limited info

MODEL DEVELOPMENT SOURCES

- PROJECT DOCUMENTS
- S/C CONFIG DRAWING
- PHOTOS (WEB, SMITHSONIAN)
- PRIOR FLIGHT EXPERIENCE
- TRW THERMAL RETIREES
- TECHNICAL PAPERS
- GMM & TMM DEVELOPMENT
Pioneer 10 S/C Configuration

Flight S/C (Courtesy of Jim Moses, TRW Retiree)  Pioneer in the Smithsonian Air & Space Museum
THE STUDY OF THE PIONEER ANOMALY

Science Instrument Locations

CHARGED PARTICLE DETECTOR (UC)

AMD TELESCOPE (GE)

UV PHOTOMETER (USC)

MAGNETOMETER ELECTRONICS (JPL)

AMD ELECTRONICS (GE)
Science Instrument Locations

- IMAGING PHOTOPOLARIMETER (UA)
- IR RADIOMETER (CIT)
- TRAPPED RADIATION DETECTOR (UCSD)
- GEIGER TUBE TELESCOPE (UI)
- Used TSS (Thermal Synthesizer System) – one of the standard thermal industry tools
  - Calculates radiative exchange factors and environmental heat loads for all modeled surfaces.
  - Used on many JPL flight projects since the mid 1990s.
- Model S/C geometry, thermo-optical properties, sun position in TSS
  - S/C geometry simulated by utilizing geometric primitives (rectangle, cylinder, disk).
- S/W uses Monte-Carlo ray tracing
  - 2M rays per surface for calculation of radiation interchange factors.
  - 4M rays per surface for solar loading calculation.
- Pioneer 10/11 GMM runs two days to calculate radiation network and solar loads
THE STUDY OF THE PIONEER ANOMALY

Pioneer Vehicle Geometric Math Model

Pioneer 10 GMM

Test Article in Thermal Model Test
(Mix of Flight and Non-flight H/W)
Note: RTGs are Deployed in GMM, but Shown Stowed in S/C Configuration Drawing
THE STUDY OF THE PIONEER ANOMALY

Thermal Geometric Model (Closed Louvers)

- MGA
- HGA
- RTGs 3 & 4
- Light Shield
- Meteoroid Detector
- Louvers, Closed
- RTGs 1 & 2
- Launch Adaptor Ring
- Main Spacecraft
- Meteoroid Sensor
THE STUDY OF THE PIONEER ANOMALY

SNAP-19 RTG Modeling

Pioneer 10/11 GMM
Used SINDA/3D (S3D): One of the standard thermal industry tools
- S3D is a FEM thermal analyzer consists of a GUI & the SINDA-G solver
- Used on many JPL flight projects the past ten years

Pioneer spacecraft thermal mathematical model (TMM)
- Models material property values and thicknesses, power, thermal boundary conditions.
- ~3000 nodes and 2600 plate elements.
- 3.4 million radiation conductors, ~7000 linear conductors

TMM checkout process includes multiple distances and solar load cases, and RTG temperatures

TMM boundary conditions include space + S/C surfaces using flight telemetry
- Used telemetry for 4 RTG fin roots, 6 panels (equipment/science compartments), & various science instruments.
RTG fin root temperature telemetry is used as boundary condition nodes in the TMM (RTGs 1 & 3 are inboard, RTGs 2 & 4 are outboard RTGs)
RTG Fin 3 Flt Temp = 142.8°C
RTG Fin 3 Prediction = 142.4°C

RTG Fin 1 Flt Temp = 141.2°C
RTG Fin 1 Prediction = 140.8°C

RTG Fin 4 Flt Temp = 136.2°C
RTG Fin 4 Prediction = 136.2°C

RTG Fin 2 Flt Temp = 136.2°C
RTG Fin 2 Prediction = 136.0°C

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)
Panel Temperature Telemetry Locations

S/C Bottom View, -Z Side

Equipment Compartment

Instrument Compartment
PIONEER 10 S/C: PLATFORM TEMPERATURES

TMM predicted panel temperatures compared to this thermal telemetry at 25 AU
E.C. is Equipment Compartment, I.C. is Instrument Compartment
## THE STUDY OF THE PIONEER ANOMALY

### Modeled Surface Properties

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</thead>
<tbody>
<tr>
<td>Electronics Boxes</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>ε* of MLI on Electronics Box</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.03</td>
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<td>0.03</td>
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<tr>
<td>MLI on Electronics Box</td>
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<td>--</td>
<td>--</td>
<td>0.17</td>
<td>0.70</td>
<td></td>
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<tr>
<td>Exterior Electronic Box (Battery and DSU)</td>
<td>silver backed Teflon</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.17</td>
<td>0.65</td>
</tr>
<tr>
<td>Equipment Compartment, Interior</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Science Compartment, Interior</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>S/C panel (h=0.0183 W/in²-K)</td>
<td>--</td>
<td>Al honeycomb</td>
<td>0.25</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
<td>0.59</td>
</tr>
<tr>
<td>S/C surface below louvers</td>
<td>second surface mirrors (5 MIL AgFEP?)</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.09</td>
<td>0.81</td>
</tr>
<tr>
<td>Outer SC Body (panel that divides the two hexagonal S/C Bodies)</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>ε* of MLI on SC</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MLI (+Y,-X, -Y,X Side Panel, &amp; Side Facing Aft) on S/C</td>
<td>2 mil alum Kapton</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.46</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>MLI (+X,-X, +Y,X, -Y,X &amp; +Z Side Panels) on S/C</td>
<td>2 mil alum Mylar</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.20</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>Louvers (facing both sides)</td>
<td>bare</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.17</td>
<td>0.04</td>
</tr>
<tr>
<td>Shunt Radiator</td>
<td>white paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.24</td>
<td>0.84</td>
</tr>
<tr>
<td>ε* of MLI behind Shunt Radiator</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Shield (Exterior)</td>
<td>bare</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.17</td>
<td>0.04</td>
</tr>
<tr>
<td>Light Shield (Interior)</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.95</td>
<td>0.84</td>
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## Modeled Surface Properties (Cont’d)

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Launch Support Ring (Exterior)</td>
<td>bare</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.24</td>
<td>0.10</td>
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<tr>
<td>Launch Support Ring (Interior)</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.95</td>
<td>0.84</td>
</tr>
<tr>
<td>Meteoroid Detector (Inside Facing)</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.95</td>
<td>0.84</td>
</tr>
<tr>
<td>e* of MLI on Meteoroid Detector</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MLI on Meteoroid Detector</td>
<td>2 mil Alum Mylar</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.17</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>Meteoroid Sensors (facing space)</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td></td>
<td>0.36</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Meteoroid Sensors (facing HGA)</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.98</td>
<td>0.90</td>
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<tr>
<td>HGA (facing Earth)</td>
<td>DC92-007 white paint, 1% specularity</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.50</td>
<td>0.84</td>
</tr>
<tr>
<td>HGA Honeycomb (h=0.0183 W/in$^2$-K )</td>
<td>--</td>
<td>Al honeycomb</td>
<td>0.25&quot;</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HGA (facing S/C)</td>
<td>bare</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.17</td>
<td>0.04</td>
</tr>
<tr>
<td>MGA (Exterior)</td>
<td>white paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.50</td>
<td>0.84</td>
</tr>
<tr>
<td>MGA (Interior)</td>
<td>black paint</td>
<td>Al 6061</td>
<td>0.1</td>
<td>169.0</td>
<td>2770</td>
<td>961.2</td>
<td>--</td>
<td>0.95</td>
<td>0.84</td>
</tr>
<tr>
<td>RTG Body</td>
<td>white paint HM31A-F Mg Alloy</td>
<td>0.16</td>
<td>104.6</td>
<td>1800</td>
<td>1047.6</td>
<td>--</td>
<td>0.50</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>RTG Fin (from root fin to mid fin)</td>
<td>white paint HM21A-T8 Mg Alloy</td>
<td>0.1</td>
<td>136.6</td>
<td>1800</td>
<td>1047.6</td>
<td>--</td>
<td>0.50</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>RTG Fin (from mid fin to fin tip)</td>
<td>white paint HM21A-T8 Mg Alloy</td>
<td>0.1</td>
<td>136.6</td>
<td>1800</td>
<td>1047.6</td>
<td>--</td>
<td>0.50</td>
<td>0.82</td>
<td></td>
</tr>
</tbody>
</table>
Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)
Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)
THE STUDY OF THE PIONEER ANOMALY

Predicted Temps - Exterior Compartment Surfaces

S/C Top View, +Z Side

S/C Bottom View, -Z Side

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)
THE STUDY OF THE PIONEER ANOMALY

Measured Versus Predicted Compartment Temps

Platform 5 Flt Temp = 0.2C  Platform 5 Prediction = 1.7C
Platform 6 Flt Temp = -2.9C  Platform 6 Prediction = -1.9C
Platform 4 Flt Temp = 7.5C  Platform 4 Prediction = 7.3C
Platform 3 Flt Temp = 0.2C  Platform 3 Prediction = -0.2C
Platform 2 Flt Temp = 3.2C  Platform 2 Prediction = 3.2C
Platform 1 Flt Temp = 11.9C  Platform 1 Prediction = 8.6C

EQUIPMENT AND INSTRUMENT COMPARTMENTS

Note: Ignore Temp Scale 2nd Sig Digit (S/W Artifact)
THE STUDY OF THE PIONEER ANOMALY

Predicted Temps - Spacecraft MLI

S/C Top View, +Z Side

S/C Bottom View, -Z Side

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)
Predicted Temps - HGA Temperatures

Note: Disregard Second Significant Digit to Right of Decimal on Temperature Scale (Software Artifact)
Spacecraft emits in all directions, but only the component parallel to the spin axis is relevant.
Control Volume in Geometric Math Model

- S/C is Located at the Center of a Large Control Volume
- DCV = 40L, L is the Radial Distance Between the S/C centerline and the RTG
- Directional Radiative Heat Flow is Evaluated at 5° polar angle intervals (5° Wide Latitude Bands)
Net thermal emission in the direction of the Z-axis:

\[ Q_z = \int_{A} \overrightarrow{q} \cdot d\overrightarrow{A}_z + \overrightarrow{S} \cdot \overrightarrow{e}_z \]

\[ = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} \varepsilon_i A_i \sigma T_i^4 B_{i,jk} \cos \theta_j + \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} (1 - \alpha_i) A_i B_{i,jk} \frac{S_{1AU}}{R_{AU}^2} \cos \theta_j \]

- \( S_{1AU} \) is the solar constant at 1 AU
- \( R_{AU} \) is the distance in AU of the spacecraft from the sun
- Subscripts \( j,k \) refer to the element located at \((\theta_j, \phi_k)\) on the spherical control volume

Net directional emission = 0 for an isothermal, isotropic emitter when external sources are absent (i.e., uniform S/C temp & e)
Anisotropic Thermal Emission from Pioneer 10 s/c

S/C +Z Axis

\[ Q(\theta) \text{ [W]} \]

\[ Q_{\text{IR(\text{polar})}} \]

\[ Q_{\text{isotropic (example)}} \]

\[ \theta = 0^\circ \]

\[ \theta = 90^\circ \]

\[ \theta = 180^\circ \]

S/C -Z Axis
THE STUDY OF THE PIONEER ANOMALY

TMM and Post-Processing Results

- Total thermal emission from spacecraft is 2233 W
  - RTG thermal power: 2580 W (3/2/72 launch), 2050 W (2001)
  - 2398 W estimated for 7/81 date
  - Modeled emission is ~ 7% lower than estimated RTG power

- Net thermal emission in the –Z axis direction is 17 W
  - S/C mass in the 229 kg to 256 kg range for acceleration calculation
  - Depends upon propellant consumption

- -Z net thermal emission results in +Z axis reactive force
  - Predicted $a_{P10\ s/c}$ in the $3.2 \times 10^{-10}$ m/s$^2$ to $2.4 \times 10^{-10}$ m/s$^2$ range
  - $a_{S/C+\ Z\ axis} = Q_{-Z\ axis}/(m_{s/c} \cdot c)$, $a_{S/C}$ follows Newton’s 3rd law
  - Observed $a_{P10\ s/c} = 8.74 \times 10^{-10}$ m/s$^2$

- Preliminary results encouraging:
  - Anisotropic emission can explain 28% to 36% of the anomaly at 25 AU
Examples of Parametric Thermal Cases

- Various modeled properties
  - Calculate P10 anisotropic thermal emission at 25 AU

<table>
<thead>
<tr>
<th>CASE</th>
<th>DESCRIPTION</th>
<th>LOUVER BLADES</th>
<th>NOMINAL DEGRADED α/ε PROP</th>
<th>EXTREME DEGRADED α/ε PROP</th>
<th>ESH EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASLINE</td>
<td>BEST LOUVER ε\text{EFF}, NOMINAL DEGRADED WHITE PAINT</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>NO</td>
</tr>
<tr>
<td>4B</td>
<td>REALISTIC LOUVER ε\text{EFF}, ESH EFFECT</td>
<td>ε\text{EFF} = 0.13</td>
<td>X</td>
<td>X</td>
<td>YES</td>
</tr>
<tr>
<td>4C</td>
<td>DUST-COVERED RTGs, α = ε = 1</td>
<td>ε\text{EFF} = 0.13</td>
<td>X</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>4D</td>
<td>OPEN FAULT ALL LOUVERS, ESH EFFECT</td>
<td>ε\text{EFF} = 0.74</td>
<td>X</td>
<td>YES</td>
<td></td>
</tr>
</tbody>
</table>

ESH EFFECT = EQUIVALENT SUN HOUR EFFECT WHICH MEANS DIFFERENT α/ε PROPERTIES ARE USED FOR SUNLIT AND SHADED SURFACES

<table>
<thead>
<tr>
<th>MODELED SPACECRAFT ASSEMBLY</th>
<th>BASELINE CASE NOMINAL DEGRADED α/ε PROP</th>
<th>CASE 4B &amp; 4D EXTREME DEGRADED α/ε PROP</th>
<th>CASE 4C DUSTY RTGs α/ε PROP</th>
</tr>
</thead>
<tbody>
<tr>
<td>HGA, SUNLIT SIDE</td>
<td>0.50/0.84</td>
<td>0.65/0.84</td>
<td>0.50/0.84</td>
</tr>
<tr>
<td>RTG FRAME, SUNLIT SIDE</td>
<td>0.50/0.82</td>
<td>0.65/0.84</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>RTG FRAME, SHADED SIDE</td>
<td>0.50/0.82</td>
<td>0.21/0.85</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>RTG FIN, SUNLIT SIDE</td>
<td>0.50/0.82</td>
<td>0.65/0.84</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>RTG FIN, SHADED SIDE</td>
<td>0.50/0.82</td>
<td>0.21/0.85</td>
<td>1.0/1.0</td>
</tr>
<tr>
<td>MGA EXTERNAL</td>
<td>0.50/0.84</td>
<td>0.65/0.84</td>
<td>0.50/0.84</td>
</tr>
<tr>
<td>SHUNT RADIATOR</td>
<td>0.24/0.84</td>
<td>0.21/0.85</td>
<td>0.24/0.84</td>
</tr>
</tbody>
</table>

- Temperature telemetry data are used as boundary conditions.
- Louvers are modeled with effective emittance between ε\text{eff} = 0.13 (closed) and 0.74 (open)
Planned Thermal Model Development

- More analysis to quantify anisotropic contributions from individual sources
  - Calculate percentage of 23 W that RTGs, louvers and HGA contribute
- Calculate anisotropic emission at other AU distances and off-sun angles
- Thermal sensitivity analysis
  - Vary $a_s$ and $e_{IR}$ properties for key surfaces (HGA backside, RTGs, louver OSR)
    - Apply extreme property values to bound degradation
    - Evaluate impacts on temperature, heat flow and force
  - Apply distinct $e_{IR}$ properties to sunlit & shaded RTG surfs (degradation differs)
    - Thermo-optical property degradation differs
  - Evaluate HGA backside specularity impact
  - Vary spherical control volume diameter to ensure results convergence
    - Increase angular mesh of spherical control volume
- Investigate TRW/NGST archivist lead (P10 Thermal PDR/CDR info there?)
  - Provide design and configuration details not supplied in high-level project docs
    - Materials, thicknesses, geometric details, surface finishes
  - Show this TMM to retired TRW thermal engrs (spark memories, more details?)
May 2008 the new Doppler data will be available, thus

- Primary effort – certification & analysis of the extended Doppler data
- To determine true direction of the anomaly and its behavior as a function of distance from the Sun

High fidelity Thermal Model of the Pioneers is available and evolving

- Ideal tool for future analysis
- Capable of examining all heliocentric distances and off-sun angles
- Capable of identifying anisotropic thermal contributions from individual spacecraft subsystems

Next Steps: focus on the Anomaly using all available data:

- Analysis of Pioneer 11 Doppler data (proceed with early data, then entire mission)
- The proceed with Pioneer 10…
- Combined analysis of Doppler and telemetry data

Stay tuned… the fun part of the analysis has just began!
The Pioneer Collaboration

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