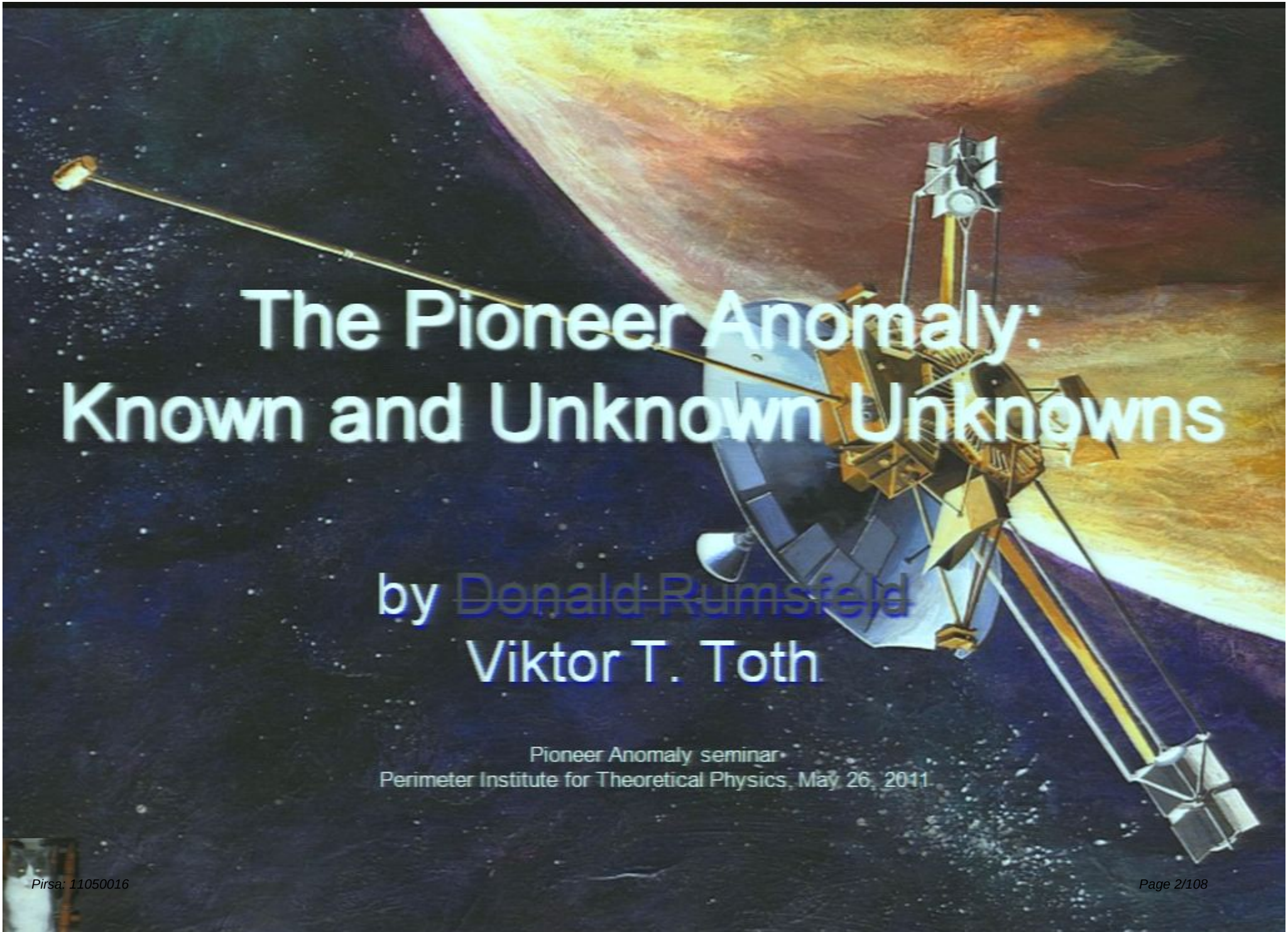
Title: The Pioneer Anomaly: Known and Unknown Unknowns

Date: May 26, 2011 01:00 PM

URL: http://pirsa.org/11050016

Abstract: TBA


The Pioneer Anomaly:
Known and Unknown Unknowns
by Donald Rumsfeld
Viktor T. Toth
Pioneer Anomaly seminar
Perimeter Institute for Theoretical Physics, May 26, 2011

The Pioneer 10/11 missions

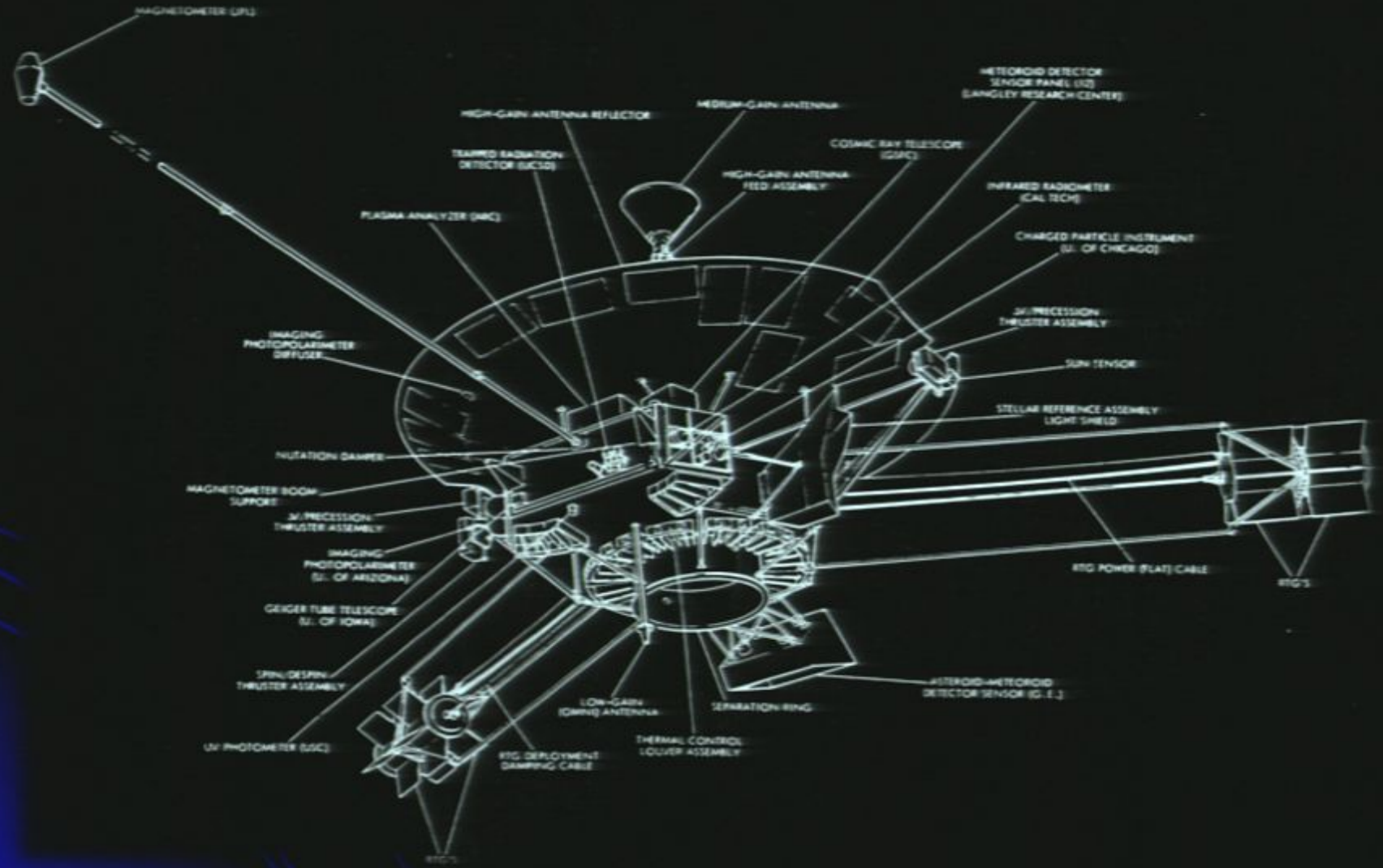
- Launched in 1972 and 1973
- First to explore beyond Mars
- First to visit Jupiter and Saturn
- Planned duration: 600-900 days




Mission objectives

- Primary Objectives
  - Explore the asteroid belt
  - Explore beyond Mars
  - Explore Jupiter
- Secondary Objectives
  - Explore the outer solar system
  - Search for gravity waves
  - Search for “Planet X”

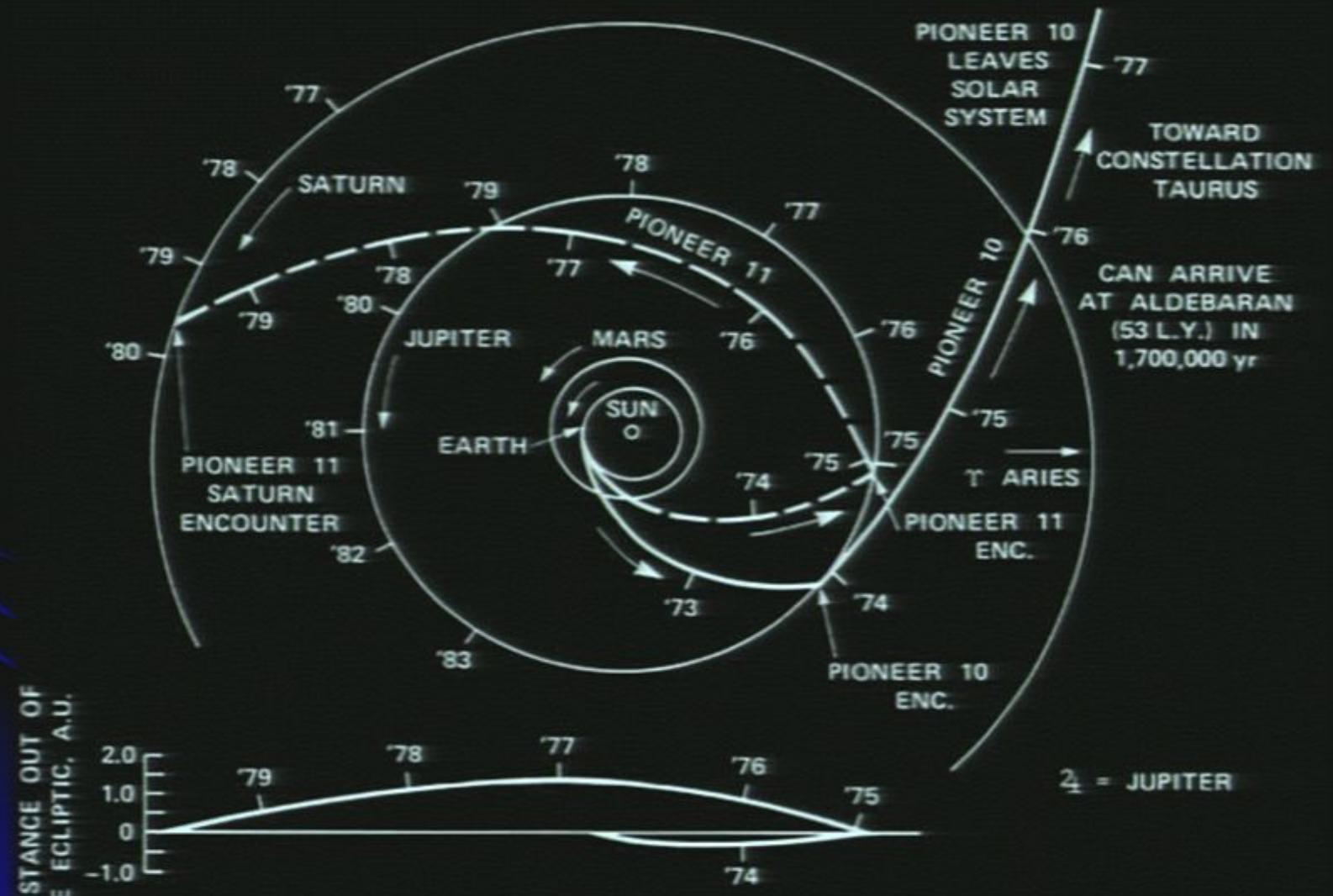
The Pioneer spacecraft



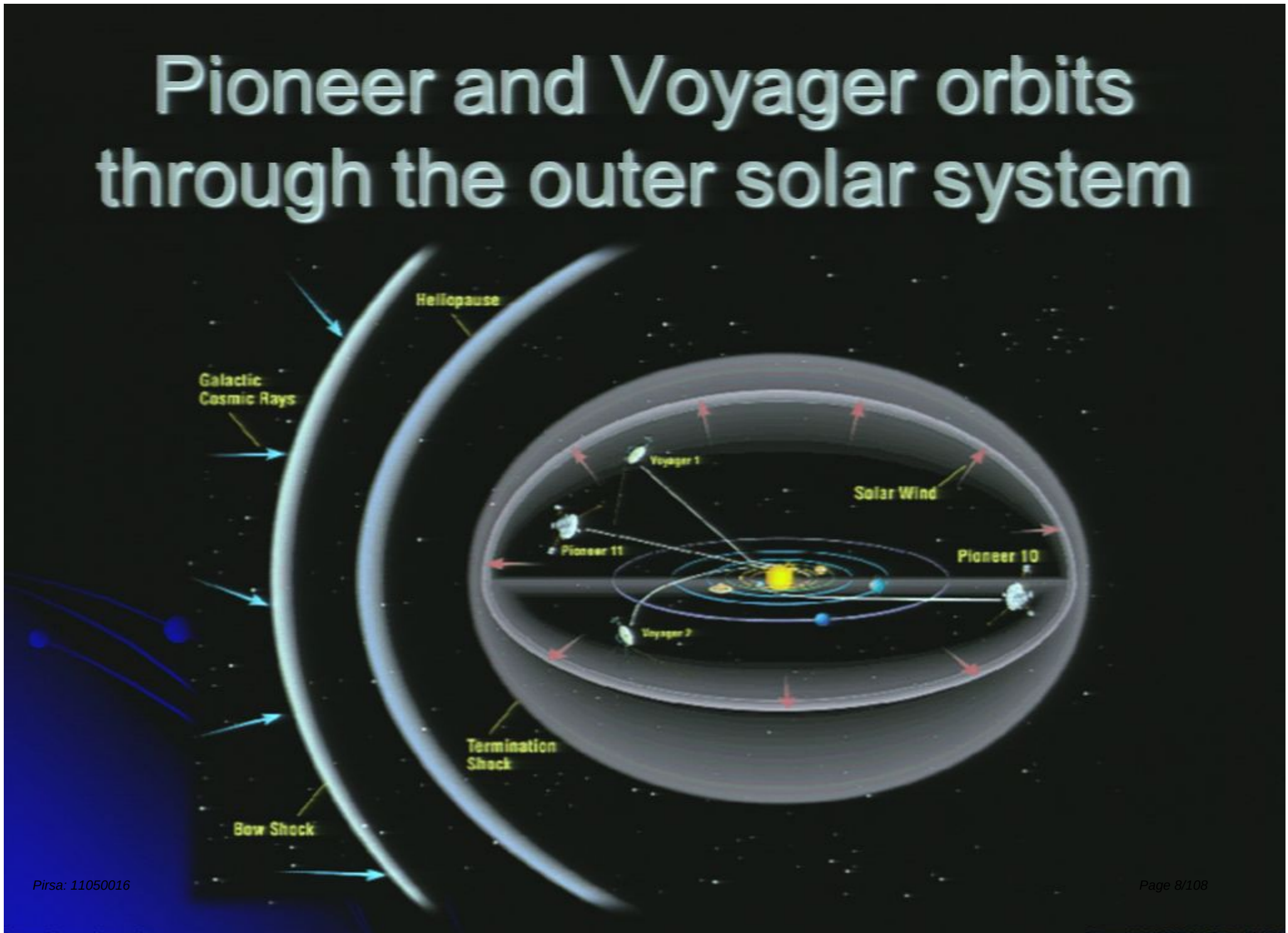
The Pioneer spacecraft

- Mass: ~250 kg
- Radioisotope Thermoelectric Generators
- Electrical Power: ~160 W (at launch)
- 11 Scientific Instruments
- 2.75 m High Gain Antenna
- Transmitter: 8 W
- Data rate: 16-2048 bps
- Spin stabilized (4.8 rpm nominal)

Pioneer orbits – early years



Pioneer and Voyager orbits through the outer solar system



Orientation maneuvers

- Few maneuvers needed for spinning spacecraft
- Few maneuvers → clean data
- Ingenious "Closed loop" CONSCAN maneuver lets the spacecraft "home in" on DSN signal
- Late in the mission, ~2 CONSCANs a year were performed

Pioneer 10 after 30 years

- Distance from Sun: ~80 AU
- Round-trip light time: ~21 hours
- Speed relative to the Sun: ~12 km/s

Pioneer 10 after 30 years

- One instrument (GTT) was still operating (power-down command sent last track, but never confirmed)
- Bus voltage ~ 26VDC instead of nominal 28VDC
- Transmitter XCO failed (probably due to cold)
- Transmitter still operating in coherent mode
- Many temperature readings “off scale” or outside calibrated ranges
- Propellant lines frozen (no maneuvers possible)

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Pioneer 10/11 are the most precisely navigated deep space craft to date.

The Pioneer Anomaly

- Anomalous acceleration of the Pioneer 10/11 spacecraft was detected in the 1980s, confirmed by several research teams
- May be mechanical in origin, may be "new physics"
- In the past, limited stretches of data were studied; new effort under way with complete data set, including on-board telemetry.

Discovery of the Anomaly

- Search began in 1979 (for "Planet X")
- Anomaly first detected in 1980
- Initial JPL ODP analysis in 1990-95
- Aerospace Corporation confirms: 1996-98
- Another independent confirmation by Markwardt (2002)
- Also confirmed independently by Olsen (2005), Toth (2009)

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Interpreting the residual

- Frequency drift: $(5.99 \pm 0.01) \times 10^{-9}$ Hz/s (@ ~2 GHz)
- Velocity change: $(8.74 \pm 1.33) \times 10^{-10}$ m/s^2
- Clock acceleration: $(2.92 \pm 0.44) \times 10^{-18}$ s/s^2
- Velocity change (acceleration) is the "conventional" interpretation
- Effect small by engineering standards, but huge by the standards of gravity physics

Consensus as of 2006

- The Pioneer Anomaly is real
- Conventional physics *fails* to explain it
- Alternatives proposed include
  - Gravity modification (MOND, MSTG, Yukawa potential)
  - Dark matter
  - Cosmological origin
- $|a_P| \approx cH_0$: coincidence?

Background

- First "Pioneer Collaboration" meeting: ISSI, November 2005
- Presentation of newly recovered telemetry: complete thermal, electrical and operational record of the Pioneer 10 and 11 spacecraft
- Discussions with Slava Turyshev: No detailed thermal model for Pioneer!

Why is it important?

- Total thermal output: 2.5 kW
- Small anisotropy: −2.5% on one side, +2.5% on the other, sufficient to explain acceleration
- Thermal models are approximations
- The anisotropy is a difference that is almost 2 orders of magnitude smaller than the estimated quantities

ACCURACY IS ESSENTIAL!

But difficult...

- Spacecraft were built 40 years ago
- Documentation is incomplete, some saved from dumpster

BUT...

- We recovered the complete telemetry record of both craft
- Telemetry is low resolution but redundant
- Sufficient documentation exists to reconstruct thermal power and material properties

What we are trying to do...

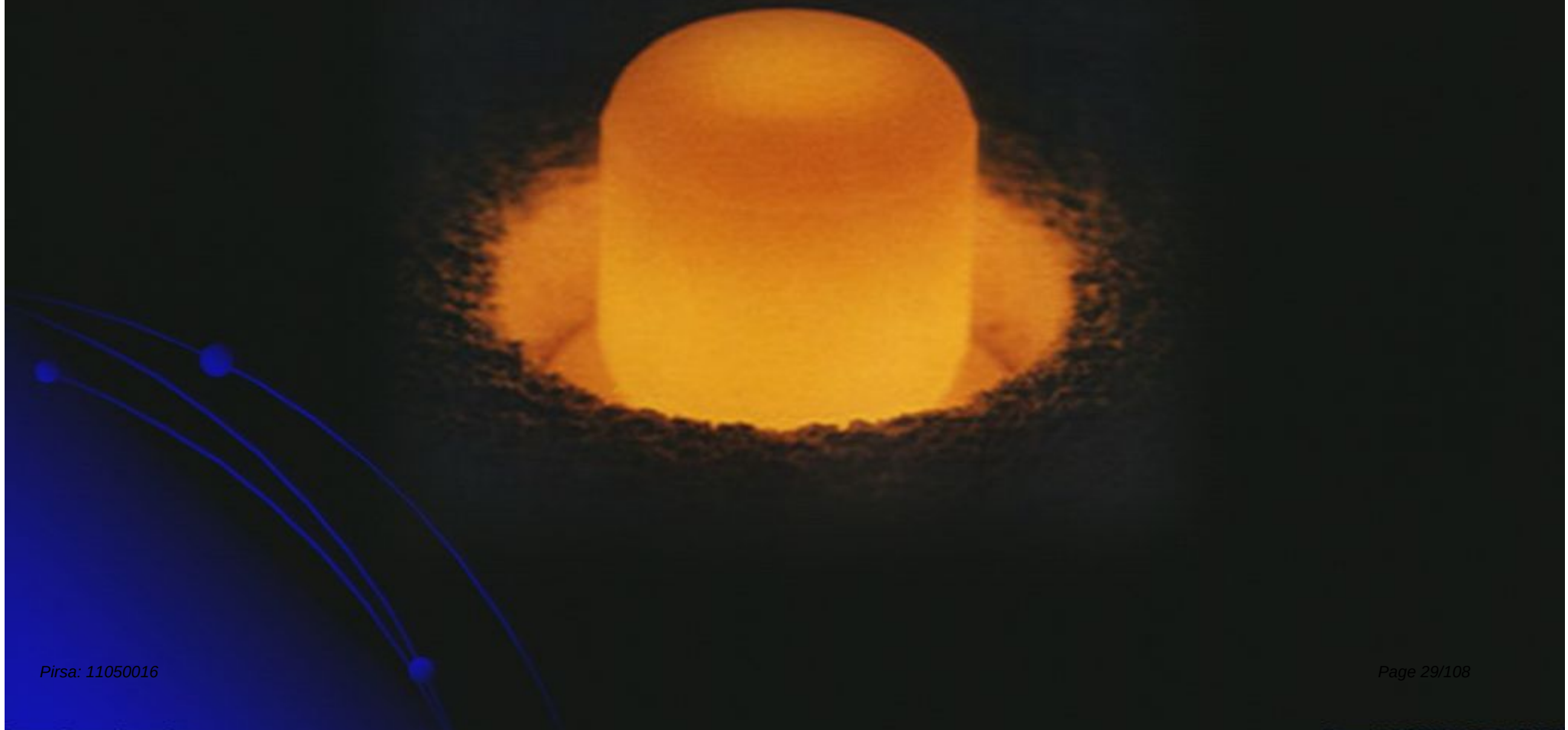
- It's not a question of either-or, but a question of how much
- Recoil force is conventional physics...

WE CANNOT IGNORE CONVENTIONAL PHYSICS!

The case for thermal recoil

- Let me establish the case for the thermal recoil force:

The case for thermal recoil



The case for thermal recoil

- Case has been made in 1998
- Case has been made by many others since...
- "Back of the envelope" models are a dime a dozen:

$$P_{1\to 2} = \iint P_1 \cos\chi_1 \cos\chi_2 \,/\, \pi r^2 \, dA_1 dA_2$$

- Doing it the right way is hard.

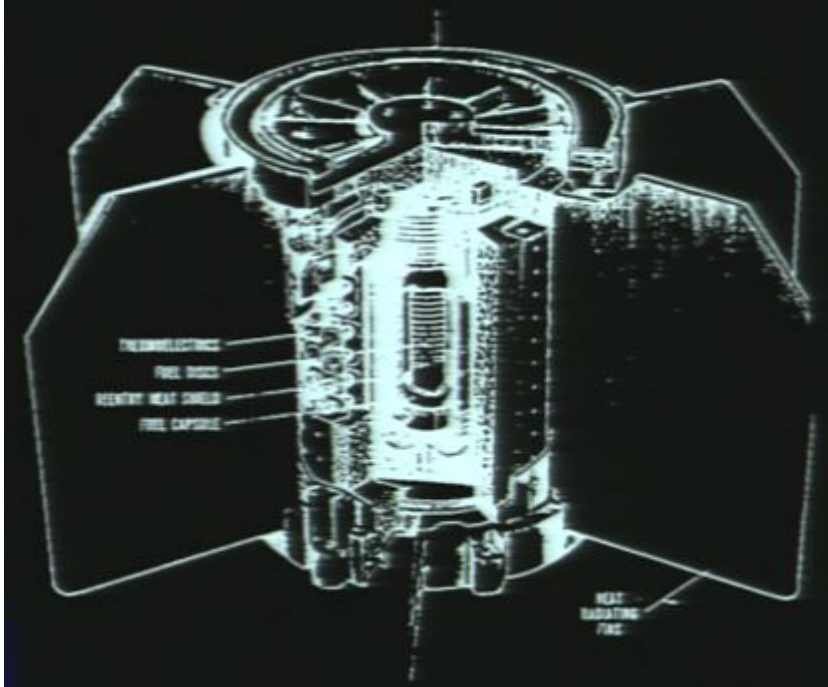
The ideas are not new...

- They have been around for some time:
  - Murphy (1999): Electrical heat accounts for much of the acceleration
  - Katz (1999): Electrical heat and reflected RTG heat account for the acceleration
  - Scheffer (2003): Combination of conventional forces (including paint degradation) explain acceleration
- Dismissed using "back-of-the-envelope" estimates

Heat sources

- Heat sources are easily enumerated:
  - RTG waste heat (~2.5 kW)
  - Electrical heat (~100 W)
  - RHUs (~10 W)
  - Propulsion system (transient)

Pioneer power source



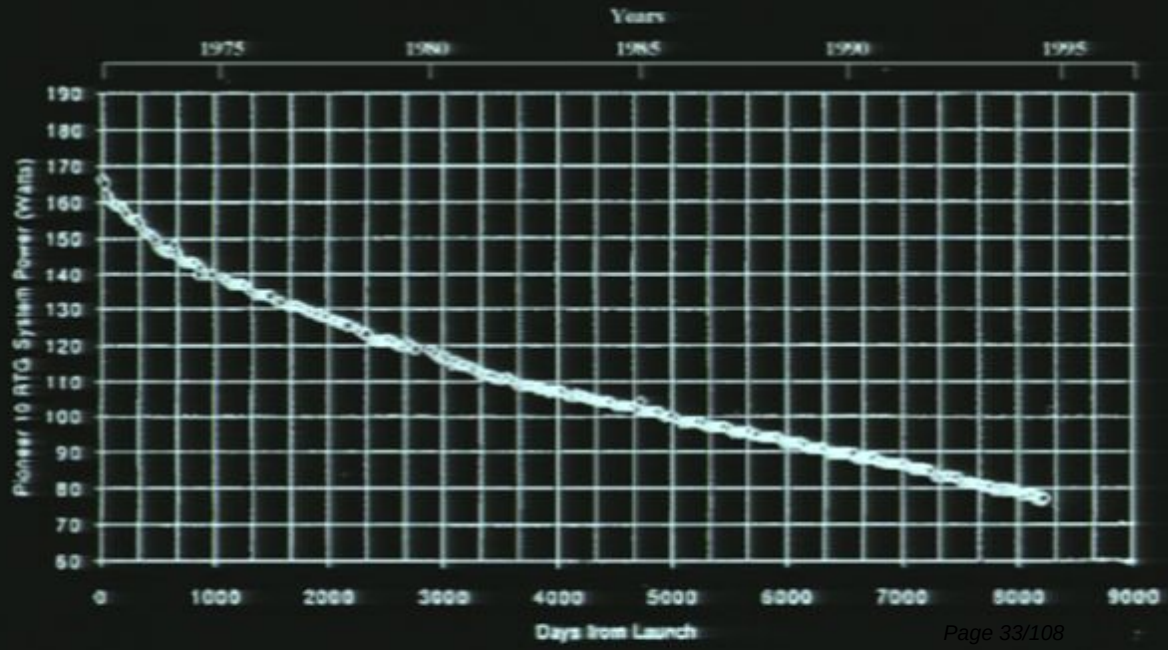
SNAP 19/PIONEER RADIOISOTOPE THERMOELECTRIC GENERATOR

RTG Thermal Power: ~650W

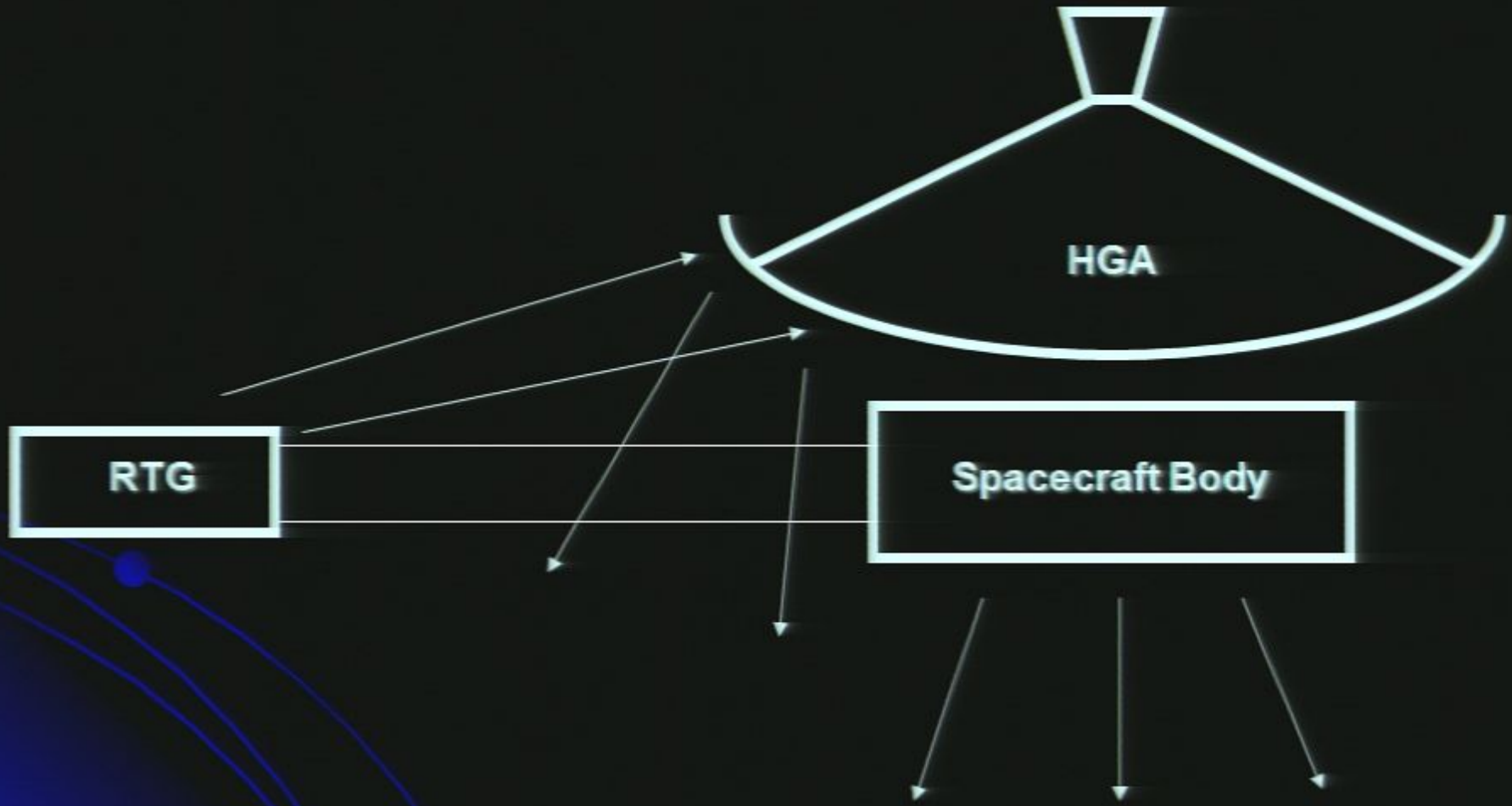
Electrical Power: ~40W

4 RTGs per spacecraft

~4.6 kg ^{238}Pu on board



Thermal recoil geometry



Significance of spin

- Thermal forces are slowly changing. Rate of change much smaller than angular velocity: $\dot{F}/F \ll \omega/\pi$
- To first order, force components perpendicular to spin axis average to zero
- Hence only spin axis component of thermal forces needs to be computed

Linear behavior

- The two significant non-transient heat sources are electrical and RTG:

$$F \approx c^{-1} \Sigma q_i P_i \qquad (P_i = P_{\text{rtg}}, P_{\text{elec}})$$

- No significant trapped heat relative to the rate of change in temperatures (no latency)
- No significant variability in the emission/absorption spectrum of materials at spacecraft temperatures
- Physical configuration of spacecraft and mass constant during deep space cruise
- Temperatures are high enough
  - it can be shown that the necessary condition is $T^3 \gg k/\sigma\epsilon l$, where k is the conductance, ϵ is the emittance, l is the scale or thickness of the material, and σ is the Stefan-Boltzmann constant

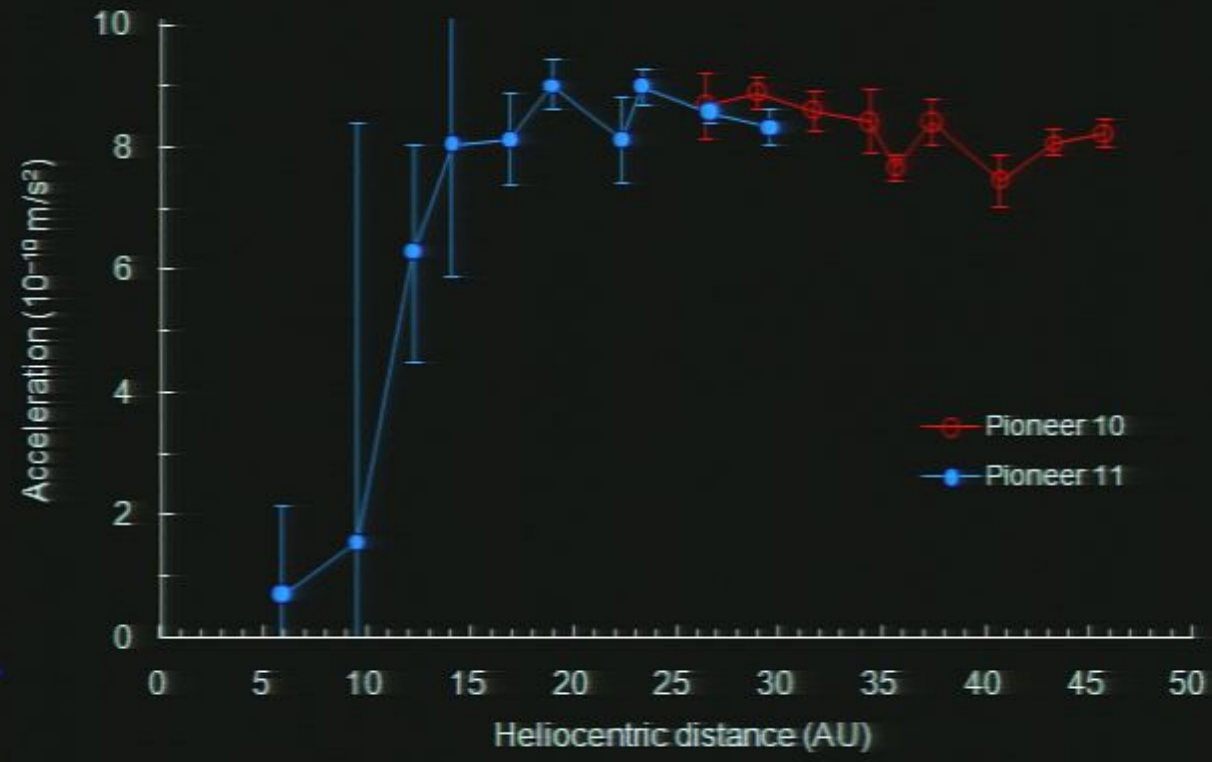
Constancy and direction

- Isn't the acceleration a) constant, b) sunward?
- Short answer: No
- Long(er) answer: Acceleration is not the observable.
- Long answer: ...

The Pioneer Anomaly is NOT

$$a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$$

The Pioneer Anomaly is NOT



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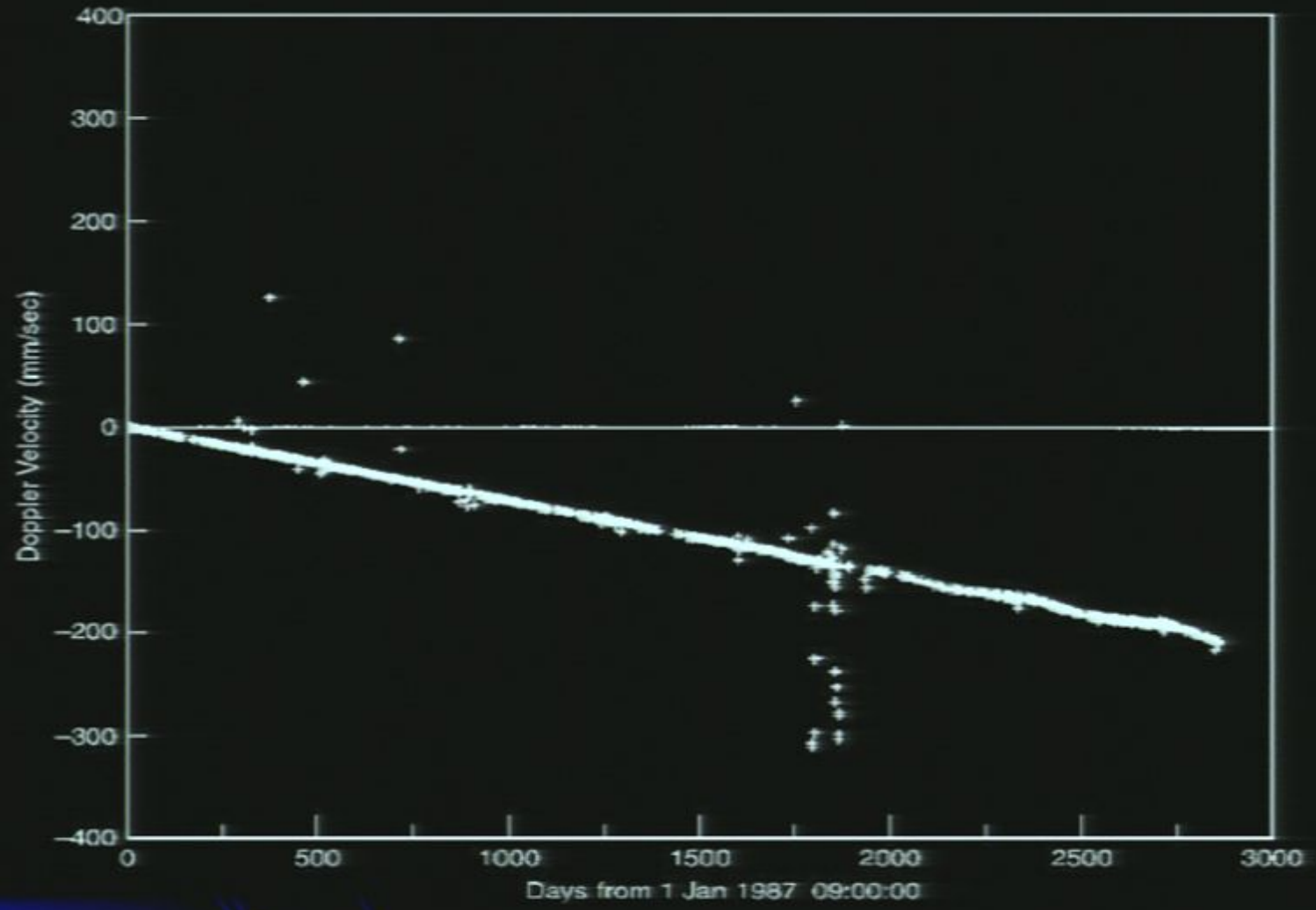

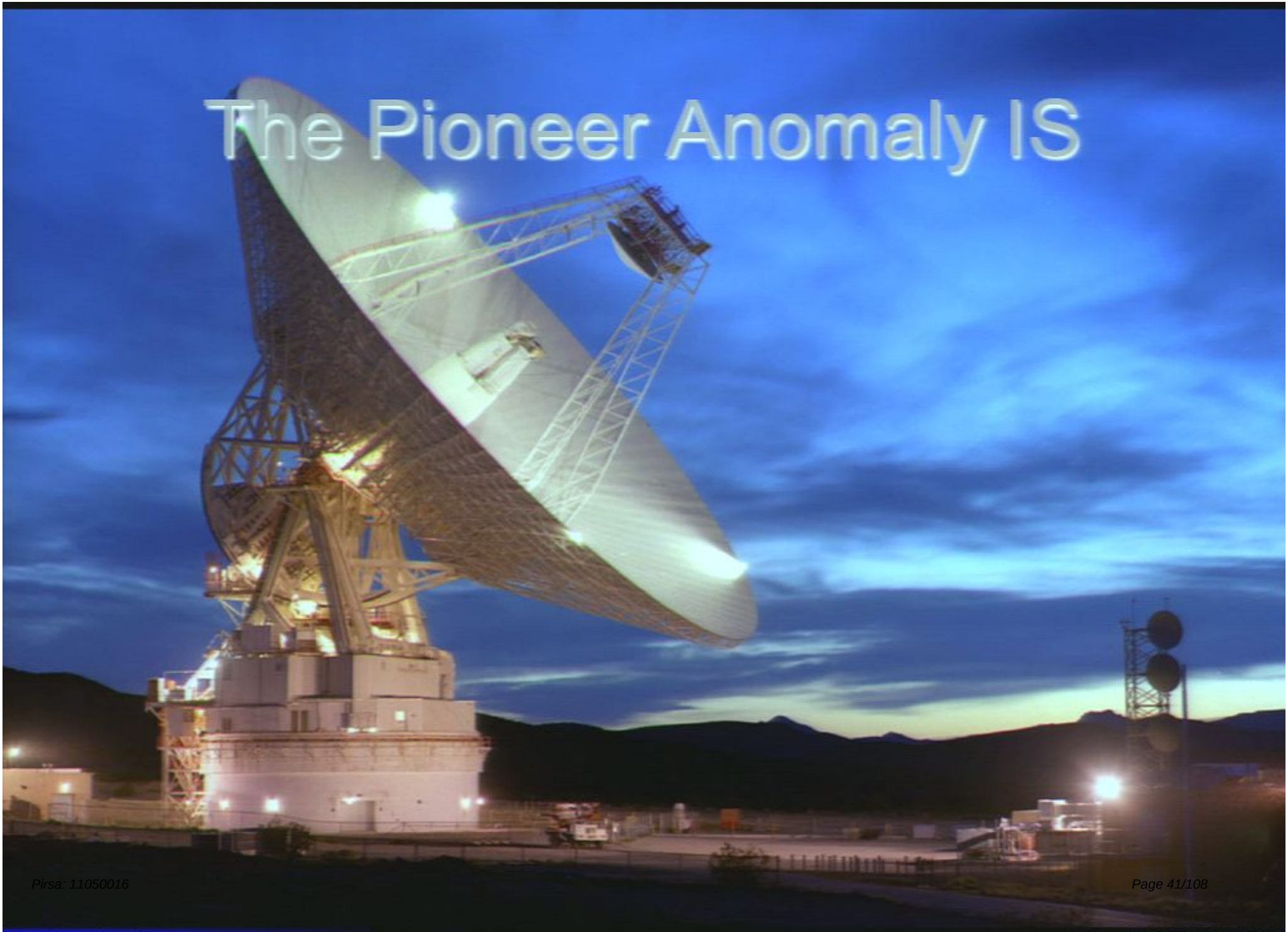
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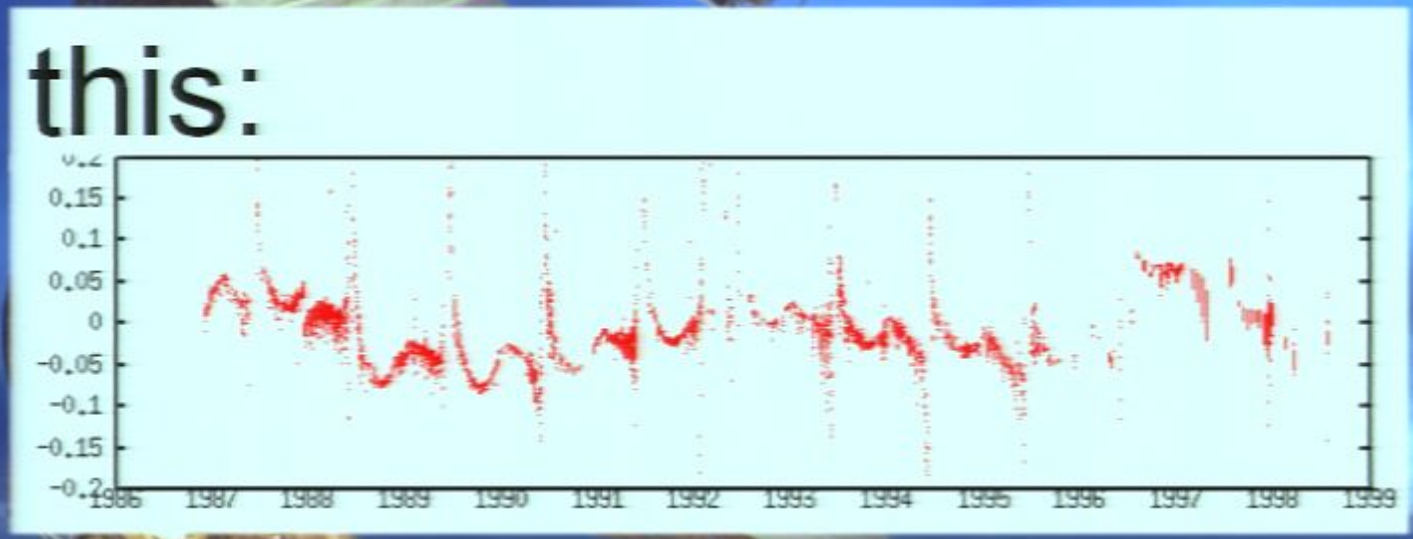

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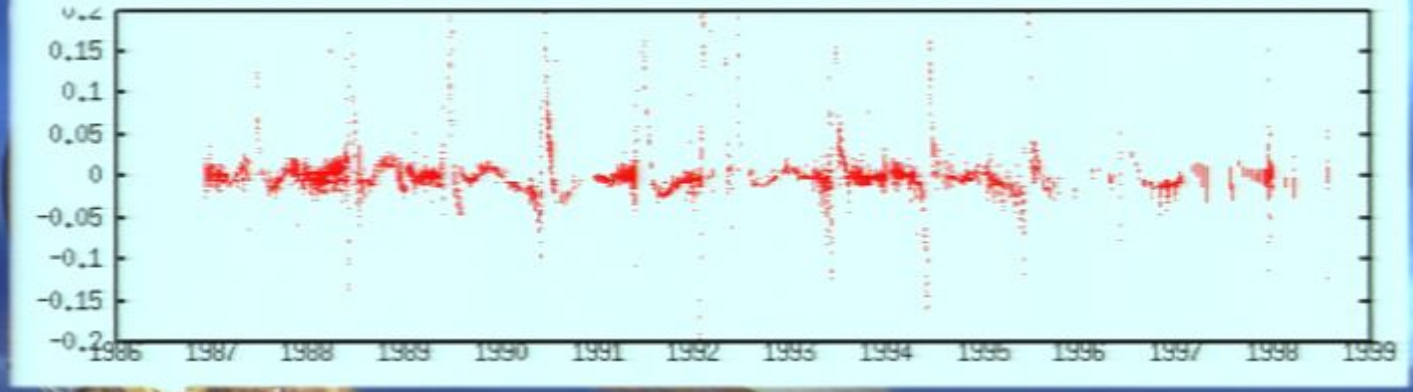

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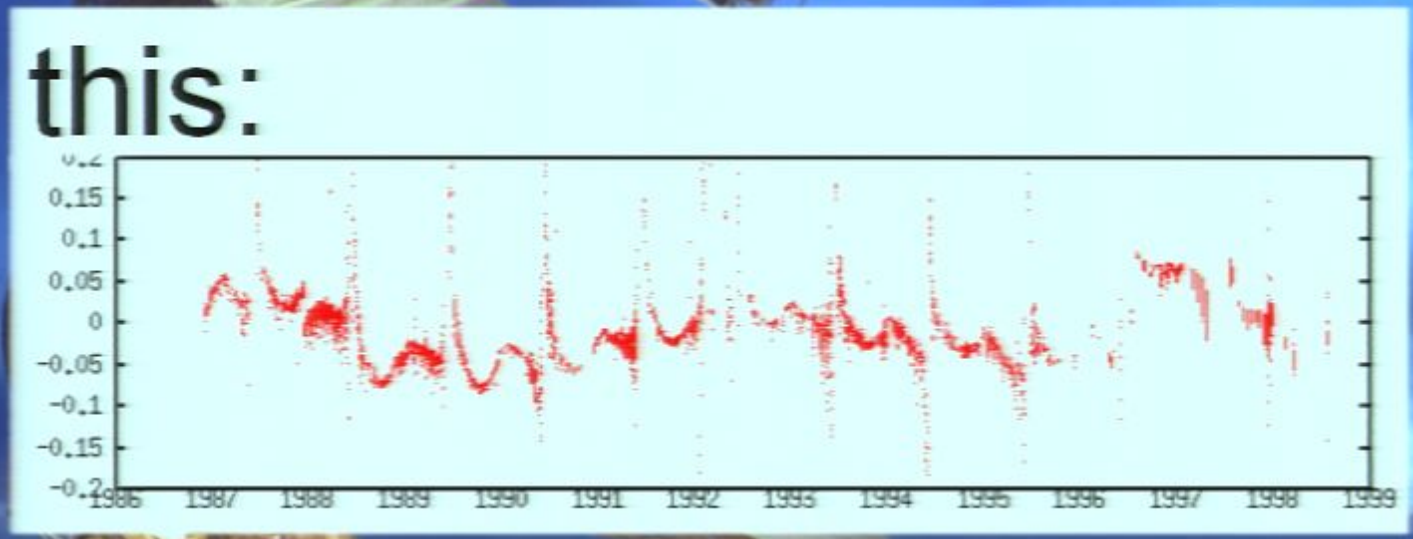

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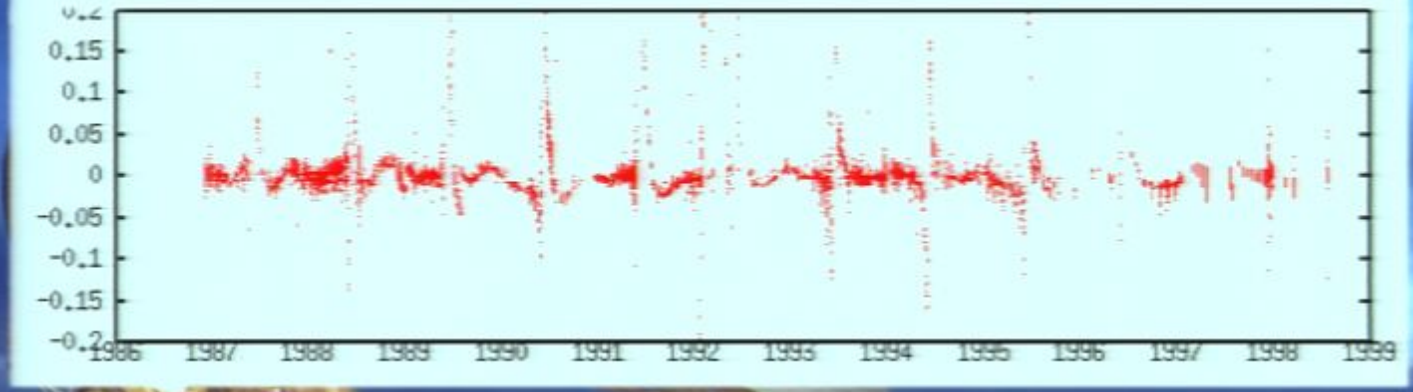

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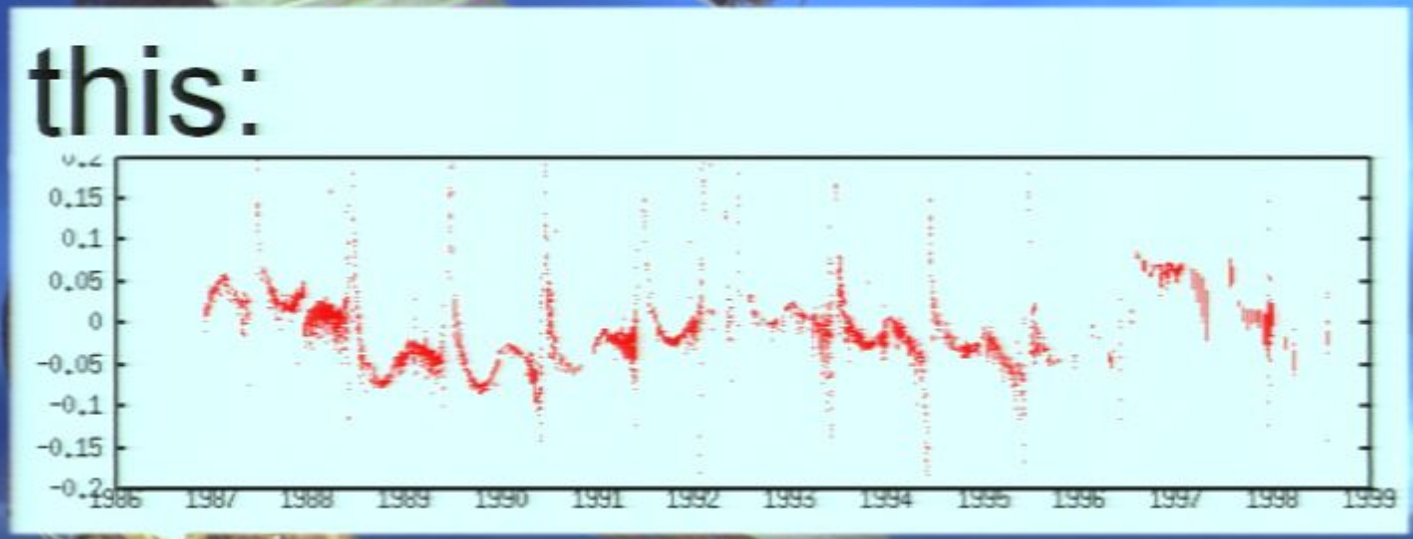

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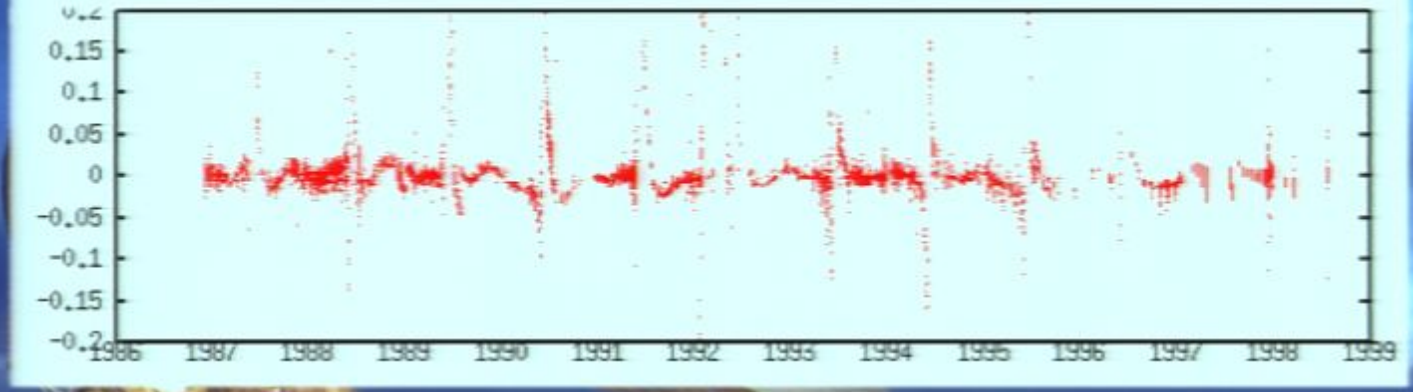

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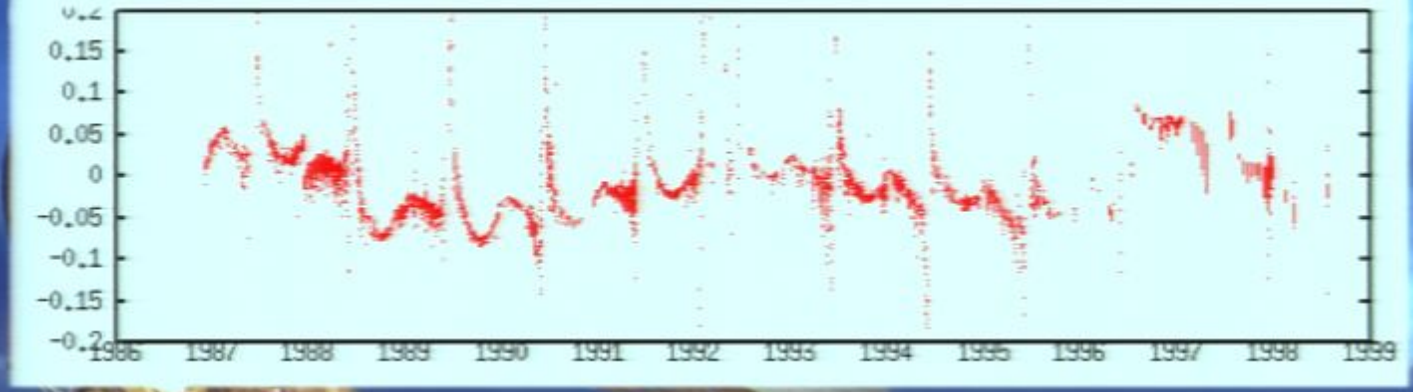

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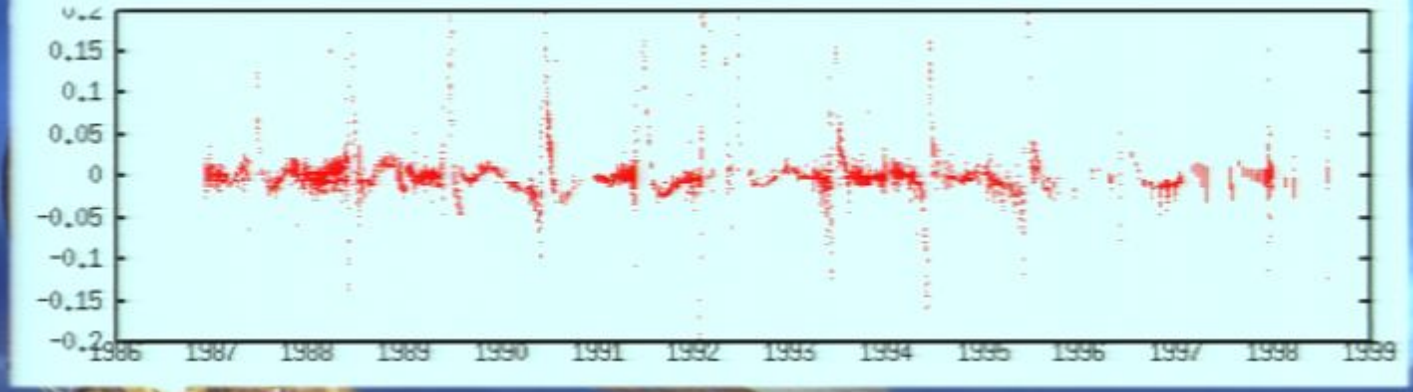


THE PIONEER ANOMALY IS OUR *INABILITY TO MODEL THE DOPPLER RESIDUAL AT THE EXPECTED LEVEL OF ACCURACY* USING ONLY KNOWN CONVENTIONAL PHYSICS.

The solution

- Navigators aren't doing fundamental physics. They fix the *navigational problem* by introducing fictitious forces.

The canonical solution

- A constant sunward acceleration ($a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$) fixes the problem. It does NOT mean that the Pioneer spacecraft necessarily experience a constant sunward acceleration.

Other solutions

- A temporally decaying acceleration fixes the problem and it is slightly better (no statistically significant difference.)
- Earthward acceleration fixes the problem.
- Earthward, temporally decaying acceleration fixes the problem.
- Other, equally valid solutions also exist.

The goodness of fit

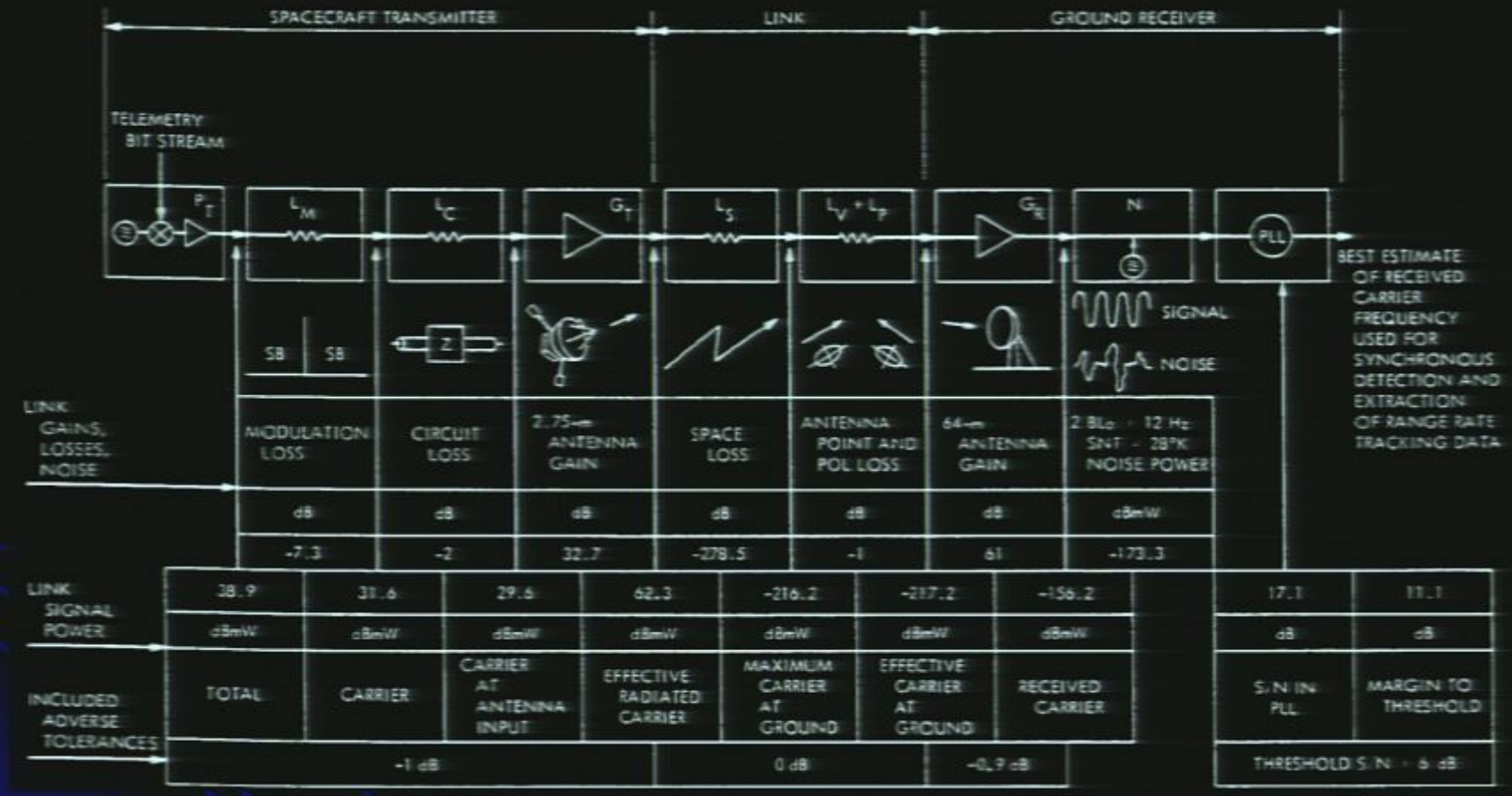
- To compare solutions, we compare residuals
- Even the best residual contains plenty of noise:
  - Mismodeling of the solar system
  - Unknowns: solar plasma, troposphere, other effects
  - Unmodeled forces: small leaks
  - Measurement noise, clock stability, etc.
  - Numerical accuracy

THE PIONEER SIGNAL IS MODELED WITH AN ERROR AS LOW AS ~2 mHz OVER 20 YEARS IN A 2.29 GHz RADIO SIGNAL!

Accuracy

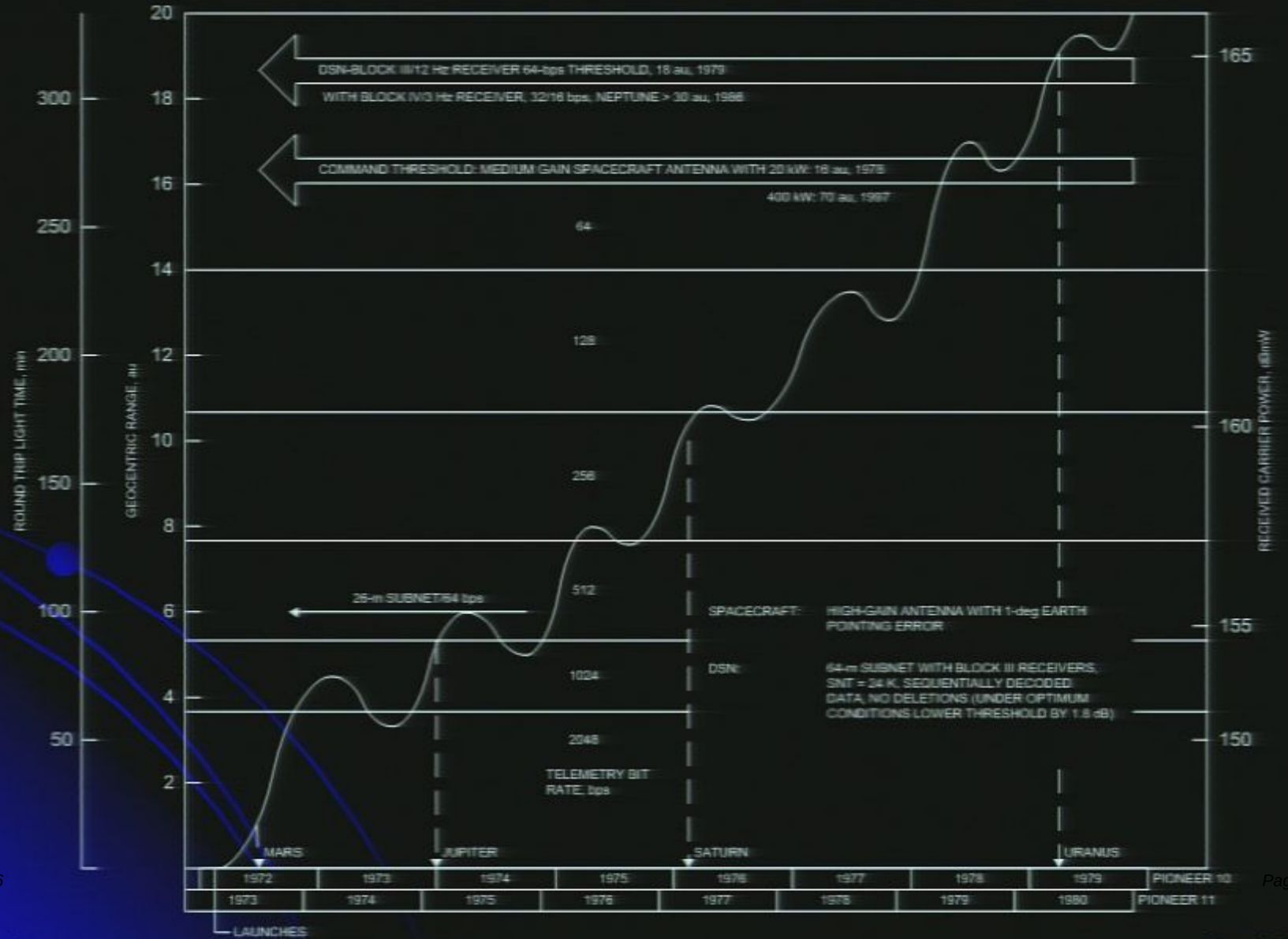
- Measurement and models must be accurate to better than 1 part in 10^{14} over 20 years.
- (IEEE 64-bit double precision floating point accuracy: less than 1 part in 10^{16}.)

Downlink power budget



Received power was –181 dBm (<10^{-21} W) at EOM

Downlink power budget



Noise is inevitable

- Some of it is random, some not
- Residuals have visible structure
- This explains the difference between unreasonably tight "formal errors" and realistic errors

Autocorrelation

- Statistical methods exist for estimating autocorrelation and the effective degrees of freedom (DOF) in unevenly sampled data
  - Computational difficulties
  - Stability of results
- If we use a crude estimate and assume that DOF = number of model parameters, we get "realistic errors"

Effect on residuals

- Detuning the model should increase residuals
- If increase is negligible, the error bars on the detuned parameters must be correspondingly large
- What is a negligible increase?

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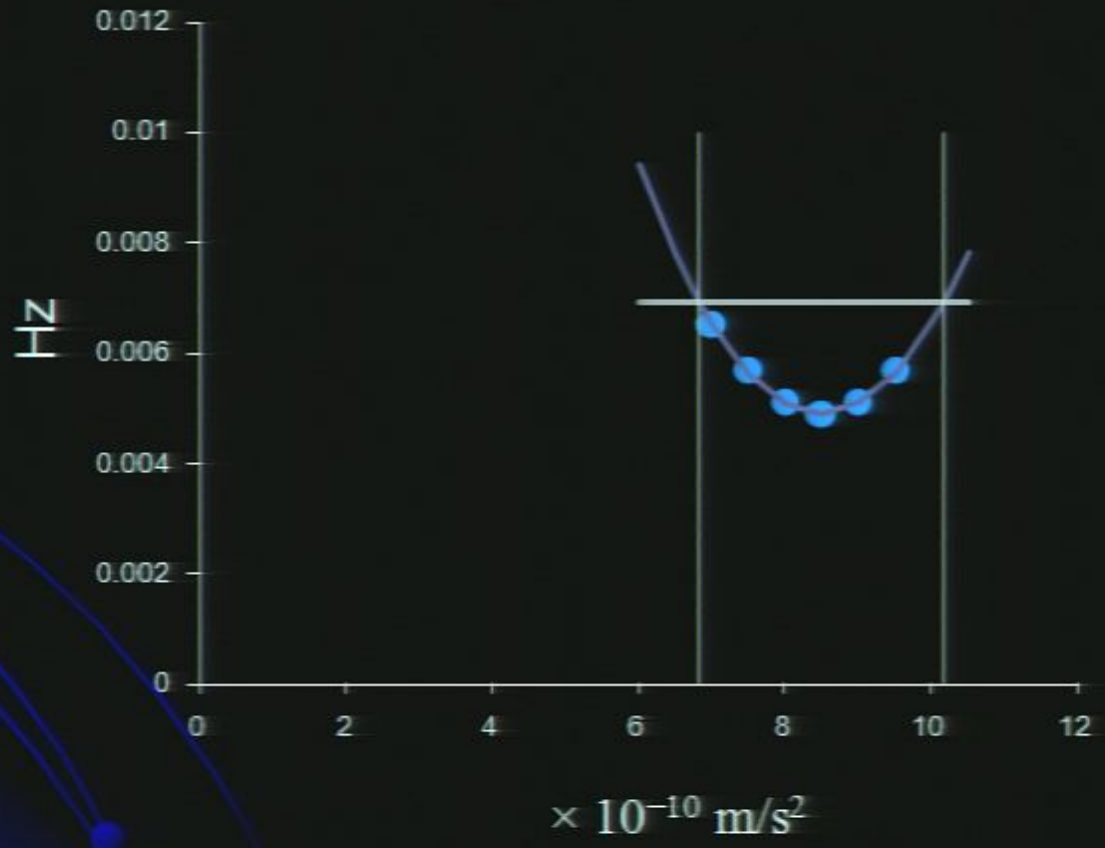

The "right way"

- Build a comprehensive thermal model
- Use all available data: Validate the model using redundant telemetry
- Incorporate the model into the orbit determination code to model the actual observable (Doppler)

Or the highway?

- Recovered the telemetry
- Constructed a “crude” geometric model
- Constructed a refined ray-traced model using simple isothermal surfaces but real material properties and power
- Built independent orbit determination code that incorporated the thermal recoil

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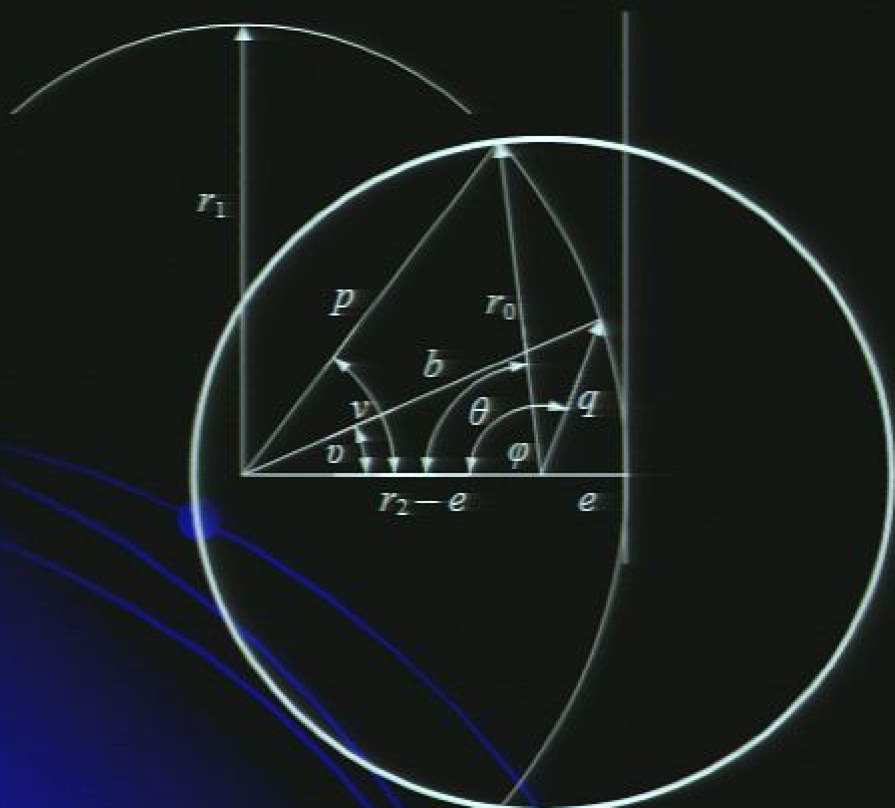
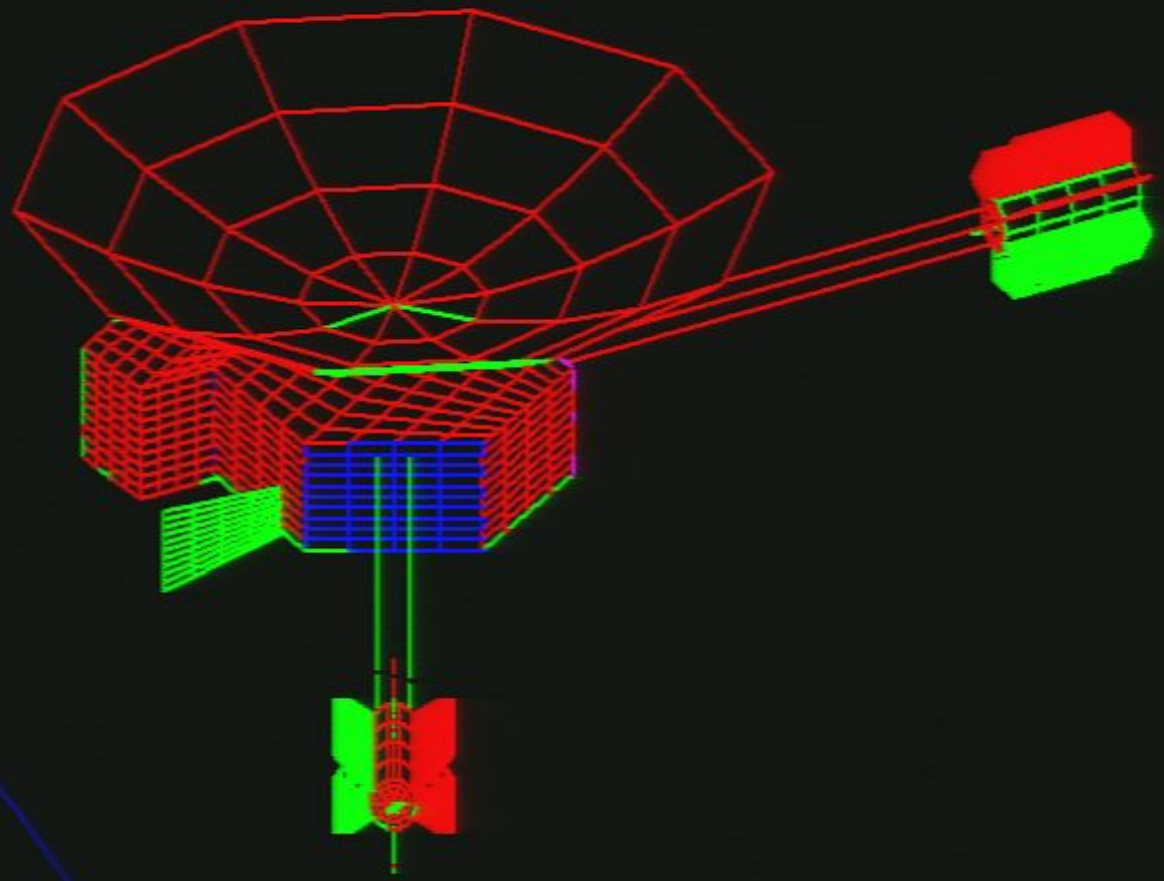
A simple model



0.008897107518

A more complicated model



More results

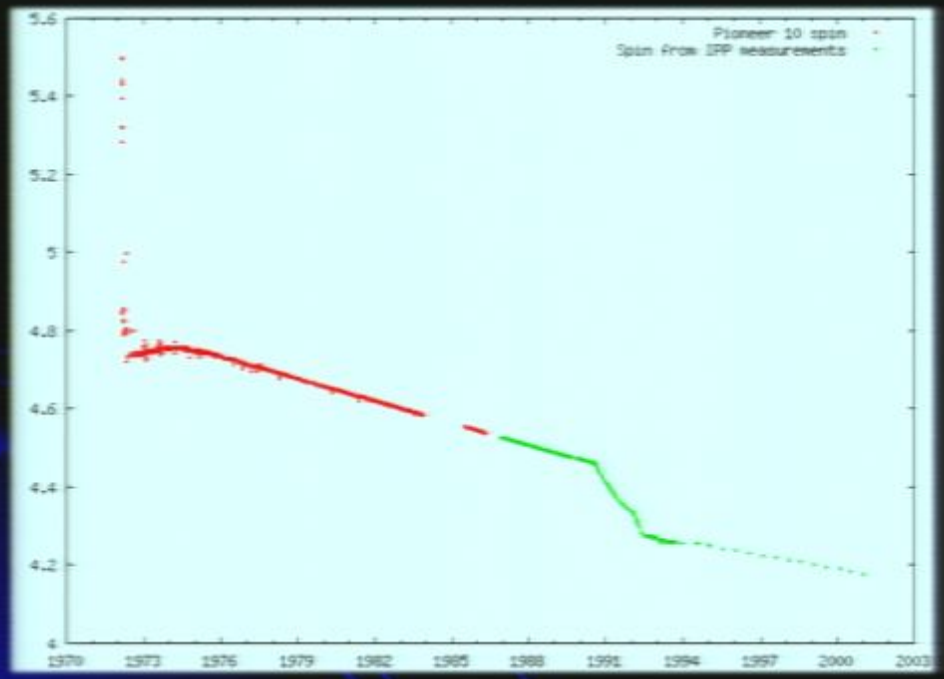
- Thrust and spin rate change

```
fe_elec
Iteration 1: Thrust = -36.436 / 94.8192
Iteration 2: Thrust = -37.2946 / 99.5209
Iteration 3: Thrust = -37.3916 / 100.052
Iteration 4: Thrust = -37.403 / 100.114
Iteration 5: Thrust = -37.4044 / 100.122
Iteration 6: Thrust = -37.4045 / 100.122
Iteration 7: Thrust = -37.4045 / 100.123
Iteration 8: Thrust = -37.4045 / 100.123
Iteration 9: Thrust = -37.4045 / 100.123
Iteration 10: Thrust = -37.4045 / 100.123
DONE.
```

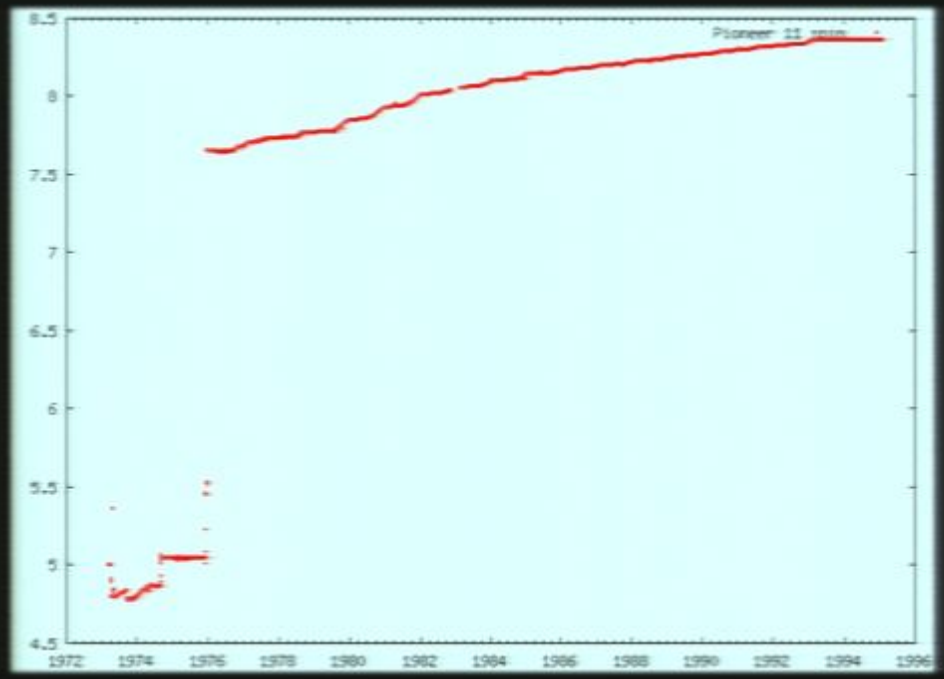
```
fe_rtg
Iteration 1: Thrust = -0.0130118 / 0.869754, Torque(0.00721829,0.494318,0.00466599)
Iteration 2: Thrust = -0.0107575 / 0.986882, Torque(0.00146408,0.335283,0.01585)
Iteration 3: Thrust = -0.0104659 / 0.999871, Torque(-0.000599535,0.311347,0.0123182)
Iteration 4: Thrust = -0.0104445 / 1.00114, Torque(-0.000857704,0.309028,0.0117846)
Iteration 5: Thrust = -0.0104432 / 1.00125, Torque(-0.000883748,0.30882,0.0117335)
Iteration 6: Thrust = -0.0104431 / 1.00126, Torque(-0.000886127,0.308802,0.0117291)
Iteration 7: Thrust = -0.010443 / 1.00126, Torque(-0.000886442,0.3088,0.0117287)
Iteration 8: Thrust = -0.010443 / 1.00126, Torque(-0.000886456,0.3088,0.0117287)
Iteration 9: Thrust = -0.010443 / 1.00126, Torque(-0.000886456,0.3088,0.0117287)
DONE.
```

Spin history

Pioneer 10 spin

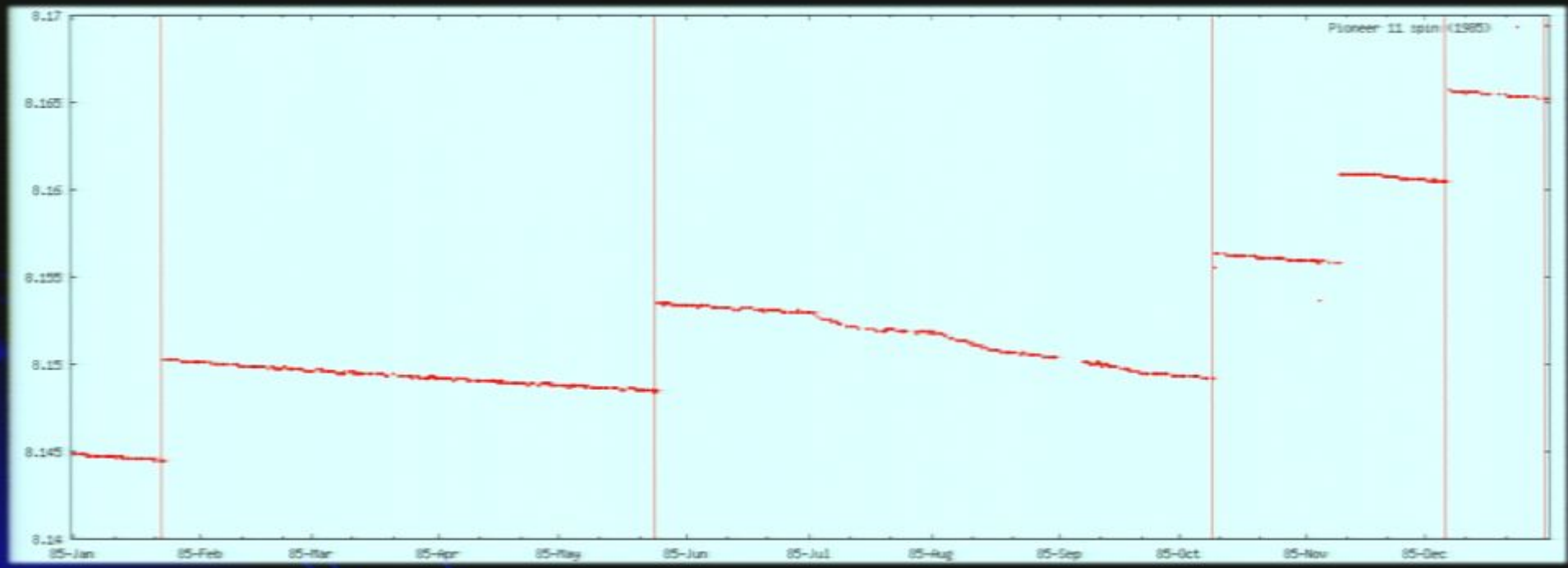


Pioneer 11 spin



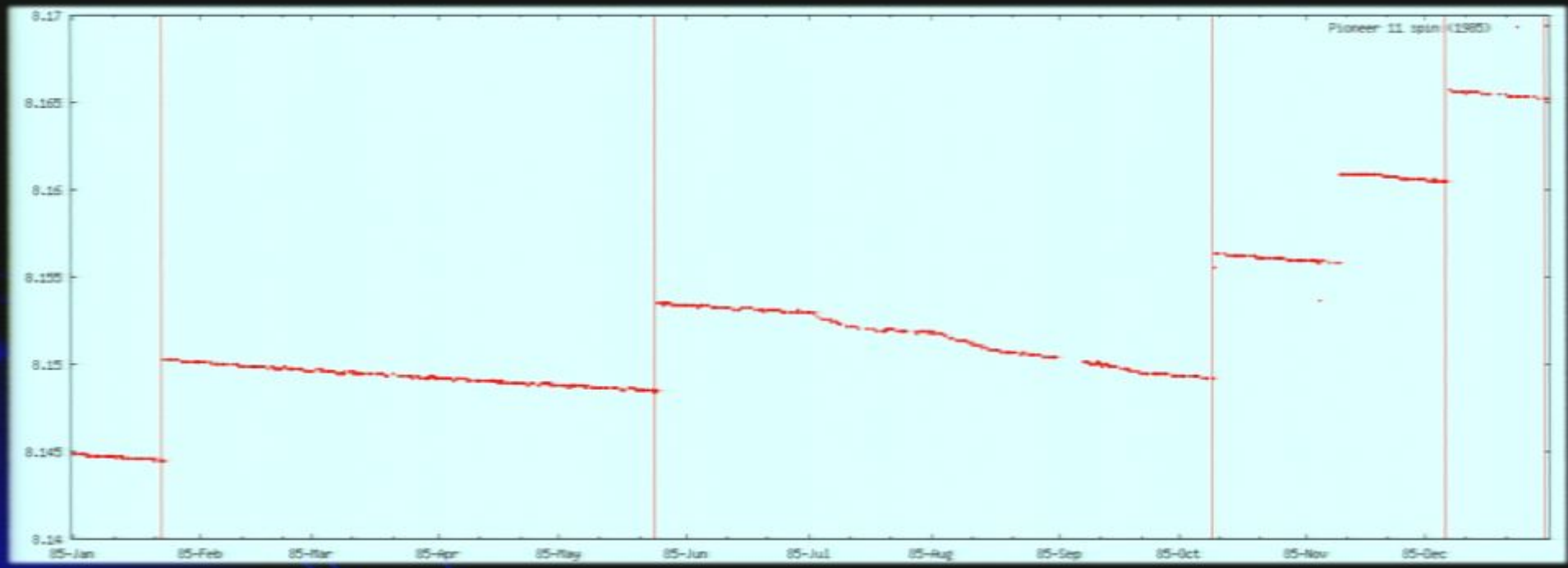
Spin history

Pioneer 11 spin detail (1985)



Spin history

Pioneer 11 spin detail (1985)



Spin history

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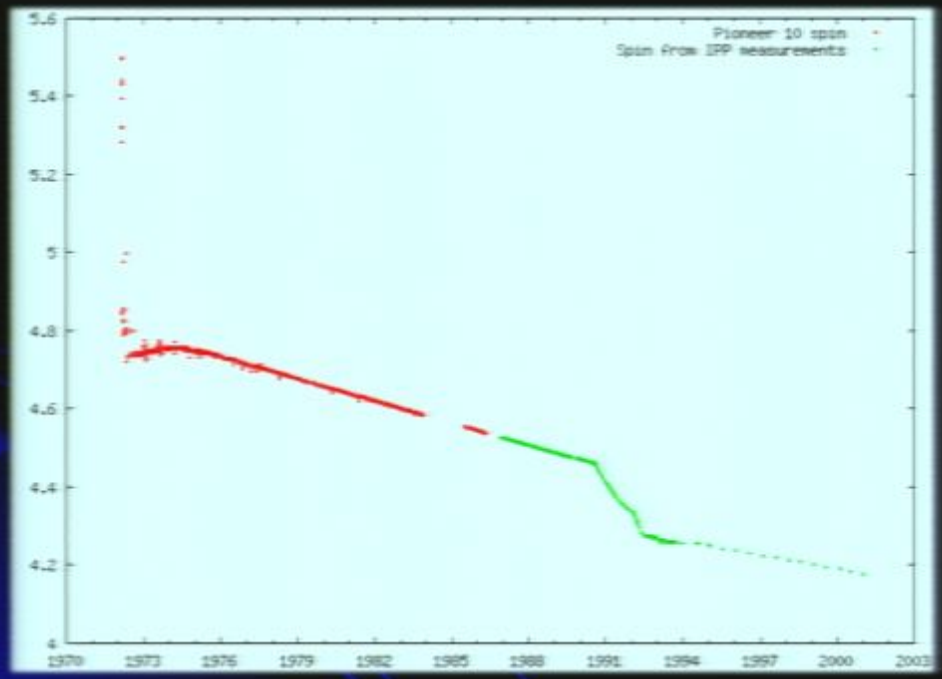
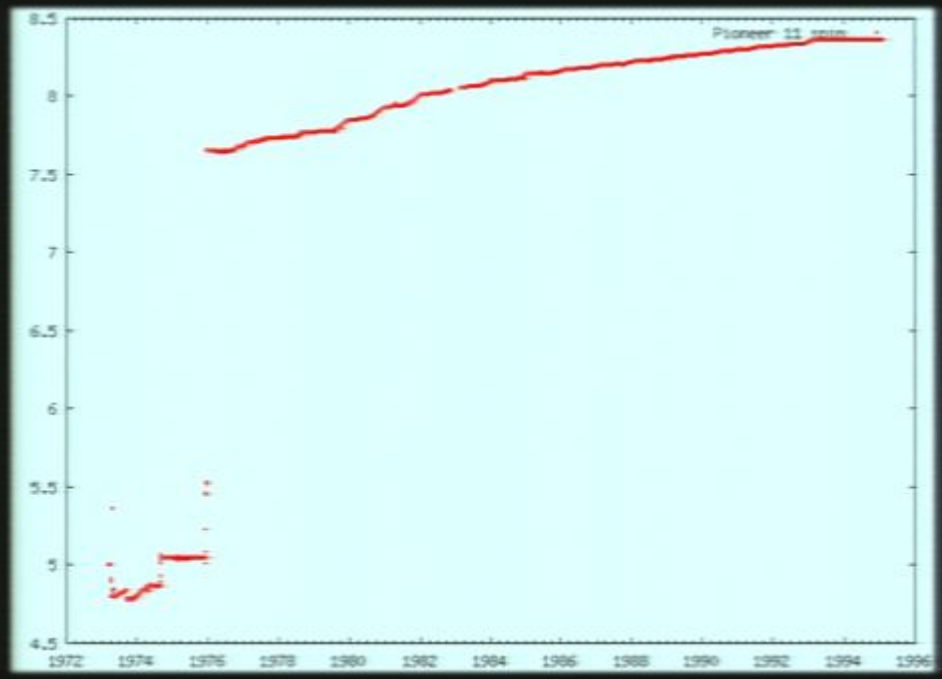


Pioneer 11 spin



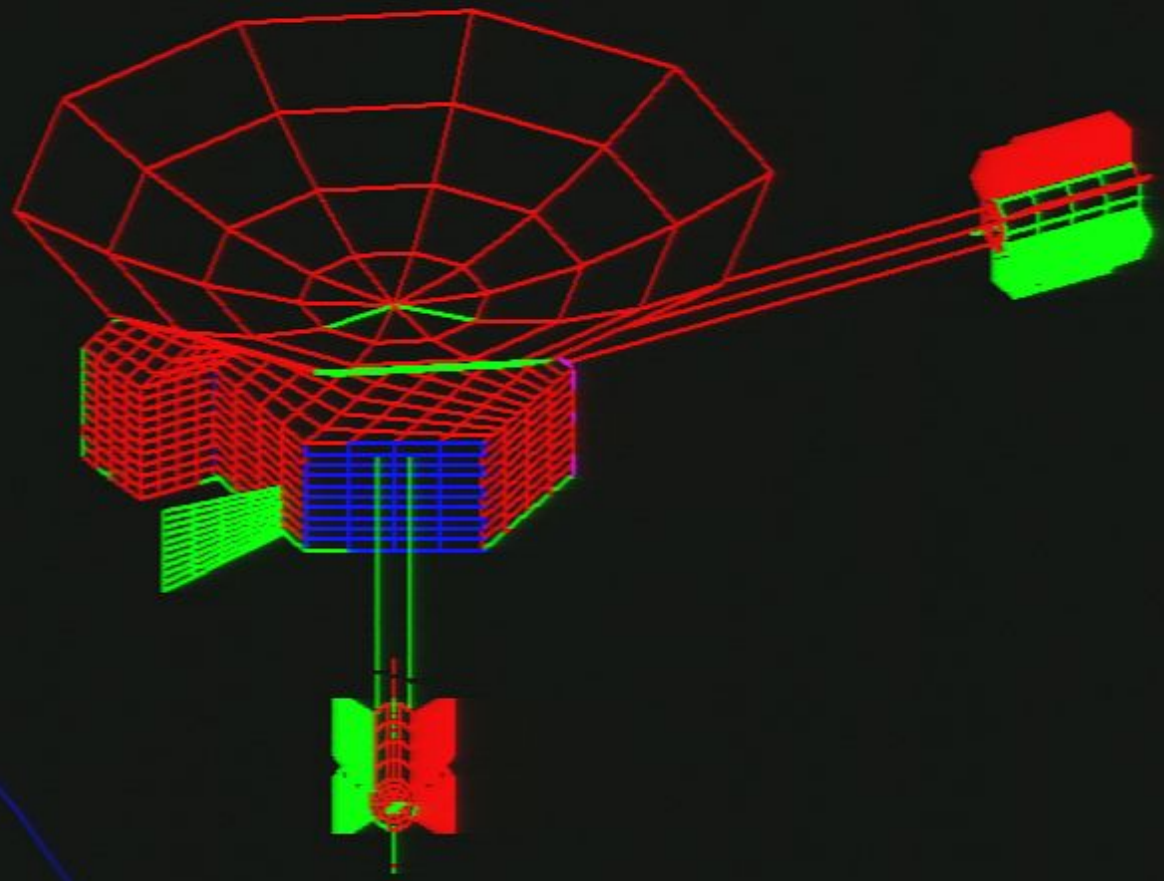
More results

- Thrust and spin rate change

```
fe_elec
Iteration 1: Thrust = -36.436 / 94.8192
Iteration 2: Thrust = -37.2946 / 99.5209
Iteration 3: Thrust = -37.3916 / 100.052
Iteration 4: Thrust = -37.403 / 100.114
Iteration 5: Thrust = -37.4044 / 100.122
Iteration 6: Thrust = -37.4045 / 100.122
Iteration 7: Thrust = -37.4045 / 100.123
Iteration 8: Thrust = -37.4045 / 100.123
Iteration 9: Thrust = -37.4045 / 100.123
Iteration 10: Thrust = -37.4045 / 100.123
DONE.
```

```
fe_rtg
Iteration 1: Thrust = -0.0130118 / 0.869754, Torque(0.00721829,0.494318,0.00466599)
Iteration 2: Thrust = -0.0107575 / 0.986882, Torque(0.00146408,0.335283,0.01585)
Iteration 3: Thrust = -0.0104659 / 0.999871, Torque(-0.000599535,0.311347,0.0123182)
Iteration 4: Thrust = -0.0104445 / 1.00114, Torque(-0.000857704,0.309028,0.0117846)
Iteration 5: Thrust = -0.0104432 / 1.00125, Torque(-0.000883748,0.30882,0.0117335)
Iteration 6: Thrust = -0.0104431 / 1.00126, Torque(-0.000886127,0.308802,0.0117291)
Iteration 7: Thrust = -0.010443 / 1.00126, Torque(-0.000886442,0.3088,0.0117287)
Iteration 8: Thrust = -0.010443 / 1.00126, Torque(-0.000886456,0.3088,0.0117287)
Iteration 9: Thrust = -0.010443 / 1.00126, Torque(-0.000886456,0.3088,0.0117287)
DONE.
```

A more complicated model



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DONE.
```

```
fe_rtg
Iteration 1: Thrust = -0.0130118 / 0.869754, Torque(0.00721829,0.494318,0.00466599)
Iteration 2: Thrust = -0.0107575 / 0.986882, Torque(0.00146408,0.335283,0.01585)
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Iteration 4: Thrust = -0.0104445 / 1.00114, Torque(-0.000857704,0.309028,0.0117846)
Iteration 5: Thrust = -0.0104432 / 1.00125, Torque(-0.000883748,0.30882,0.0117335)
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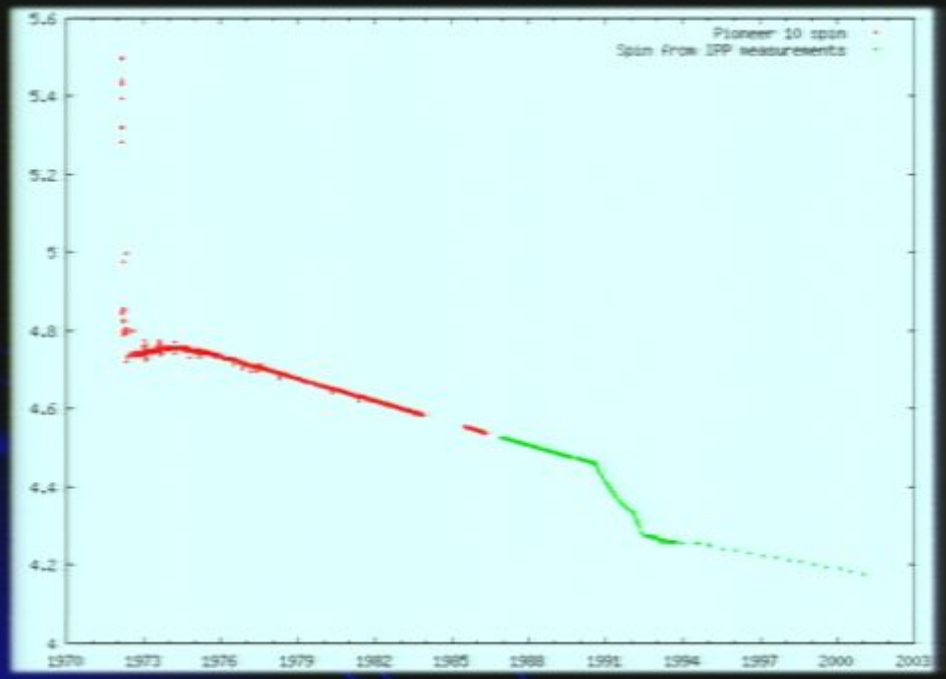
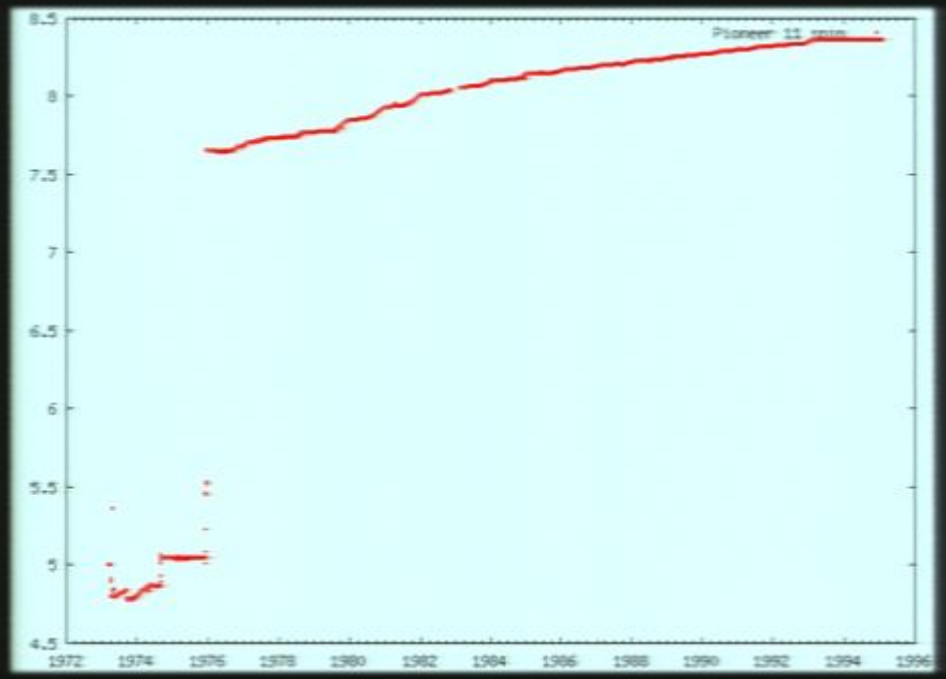
DONE.
```

Spin history

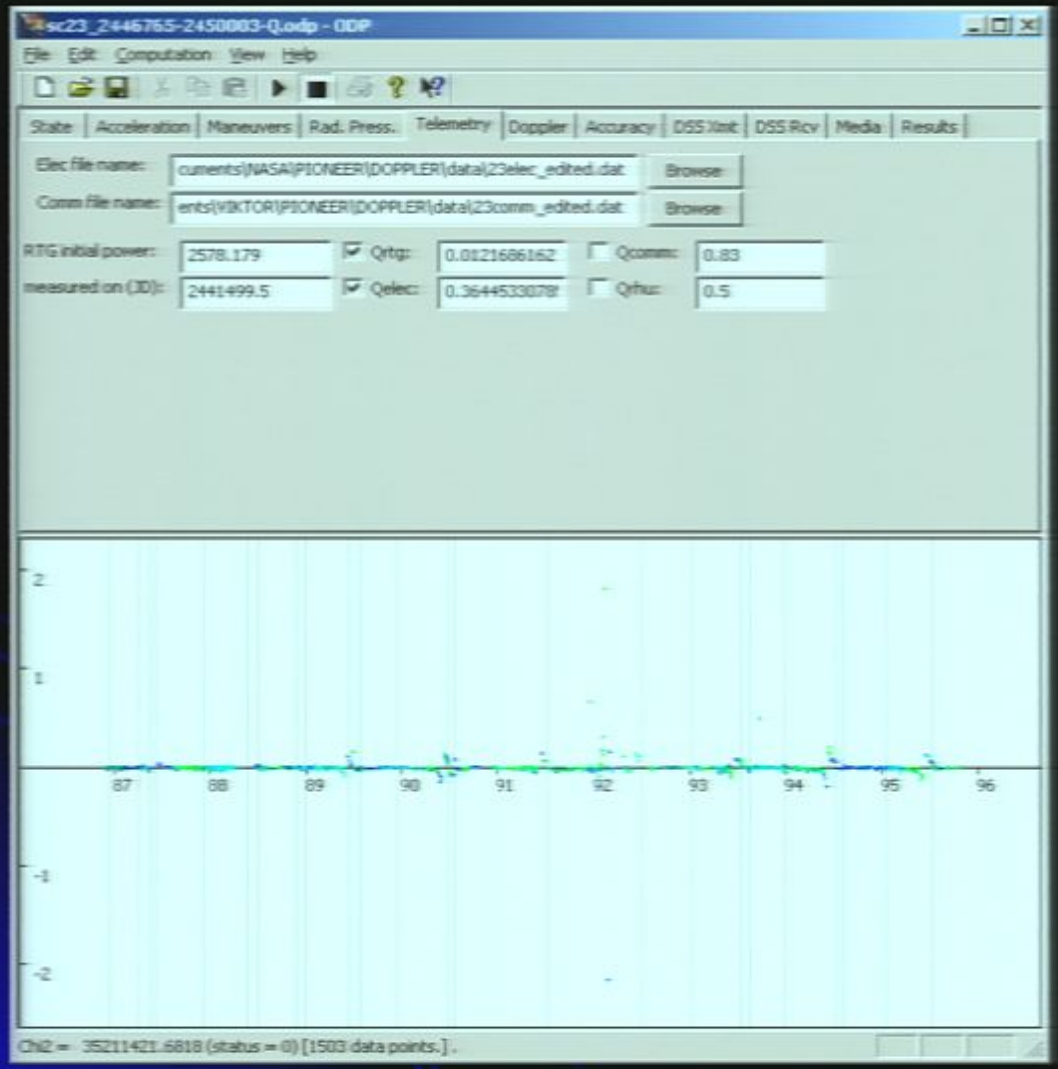
Pioneer 10 spin

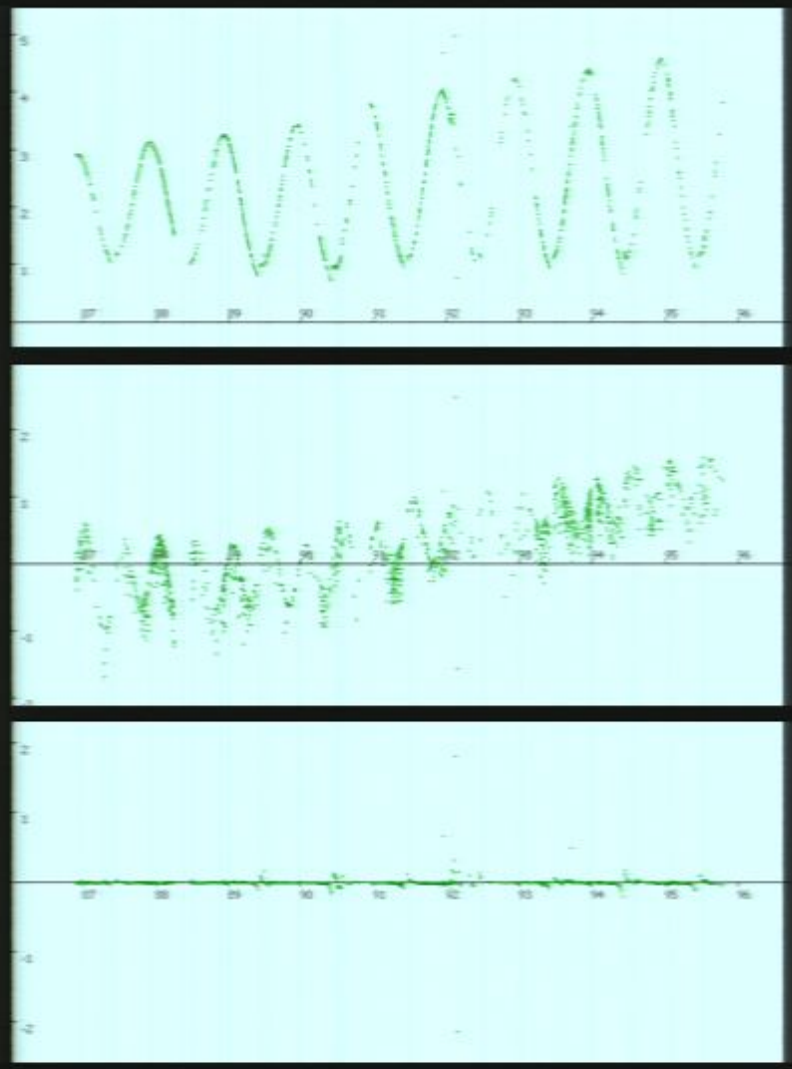


Pioneer 11 spin



Orbit determination with on-board forces





Some results

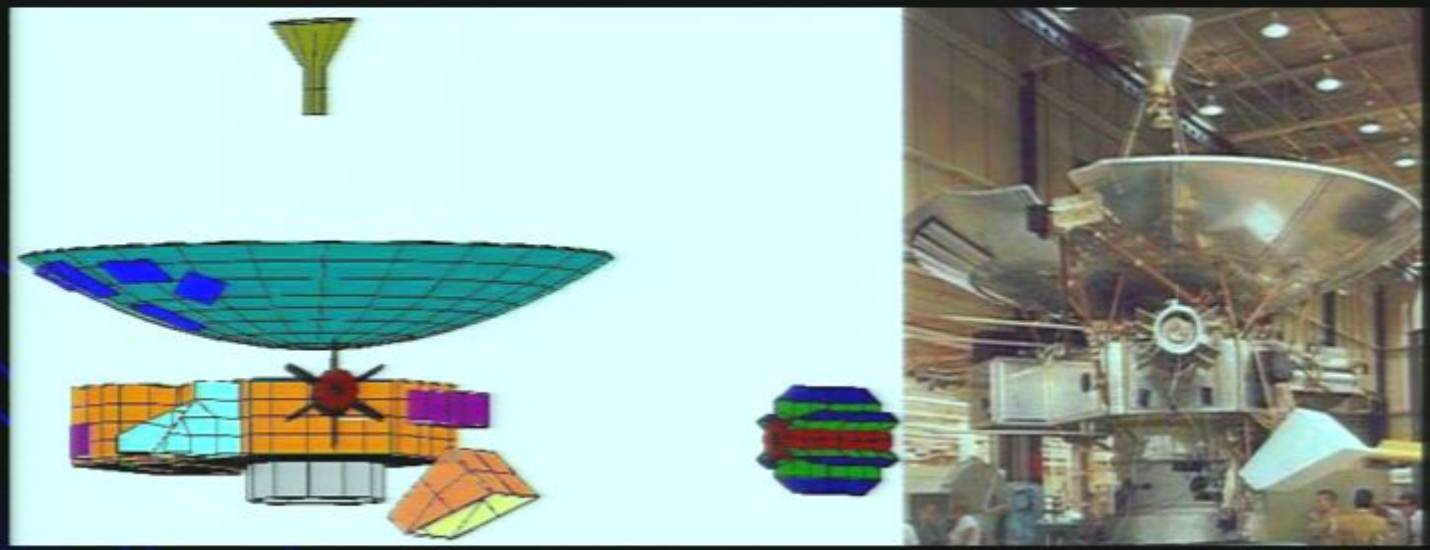
- Confirmed the presence of the Doppler anomaly
- Verified that the recoil force is indeed a linear function of RTG and electrical heat
- Recoil force yields good Doppler fit
  or conversely
- Doppler data can be used to estimate the recoil force coefficients

Still not good enough

- Insufficiently detailed model (isothermal surfaces, no heat conduction, no individual instruments)
- Untested methodology
- Untested software

The real McCoy

- Report on the “definitive” model is on its way.



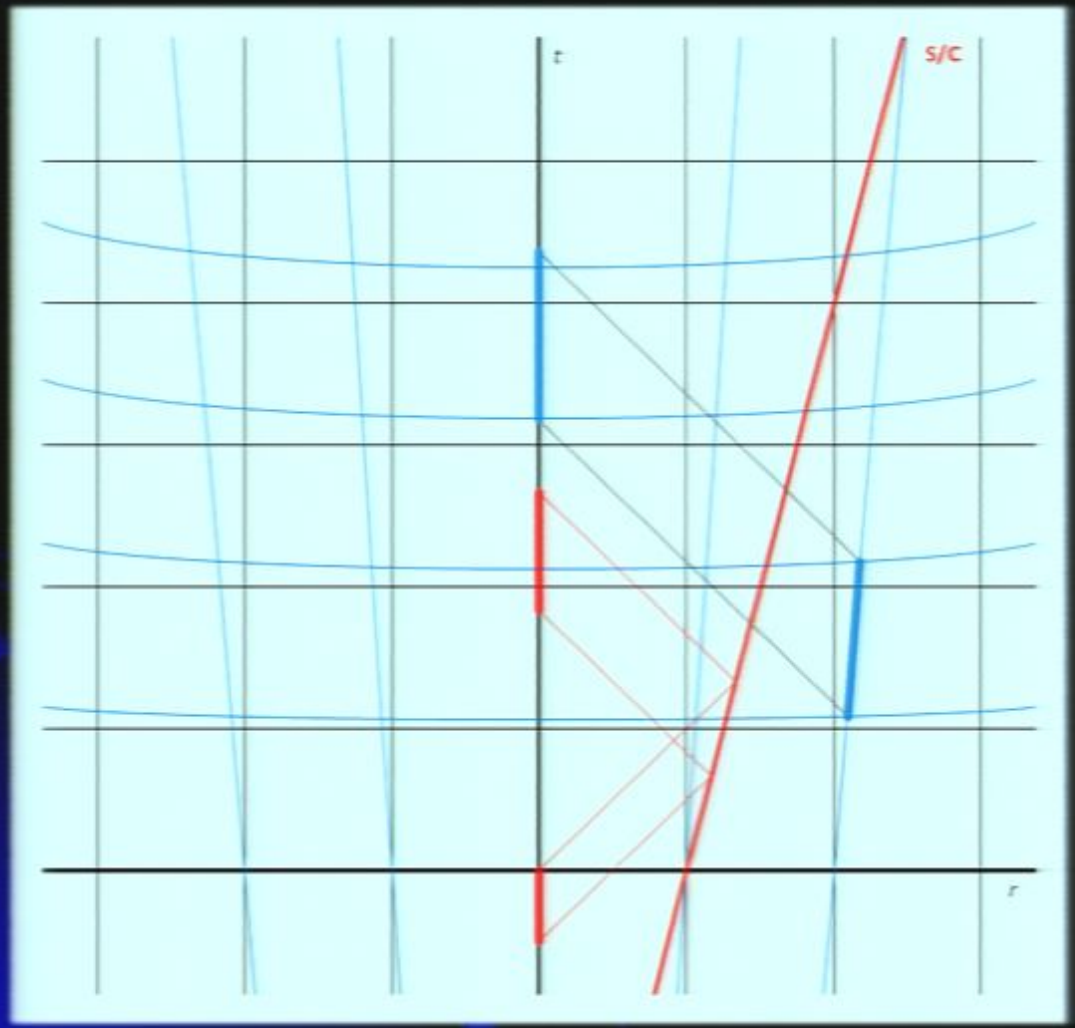
The biggest known unknown

- RTG coating: "three mils of zirconia [ZrO_2] in a sodium silicate binder"
- Some similar paints gained emittance in thermal vacuum chamber tests
- Other paints lost emittance
- This specific paint was never tested
- RTG exterior temperatures may also play a role
- A 5% decrease in emissivity can result in a 50% increase in the RTG anisotropy; a roughly 25% error in the overall thermal recoil force

So what if it is not all thermal?

- Numerical coincidences (e.g., $|a_P| \approx cH_0$) are certainly destroyed even if the sign can be explained somehow
- Do not assume constancy
- Do not assume direction

The sign of a_P vs. cH_0

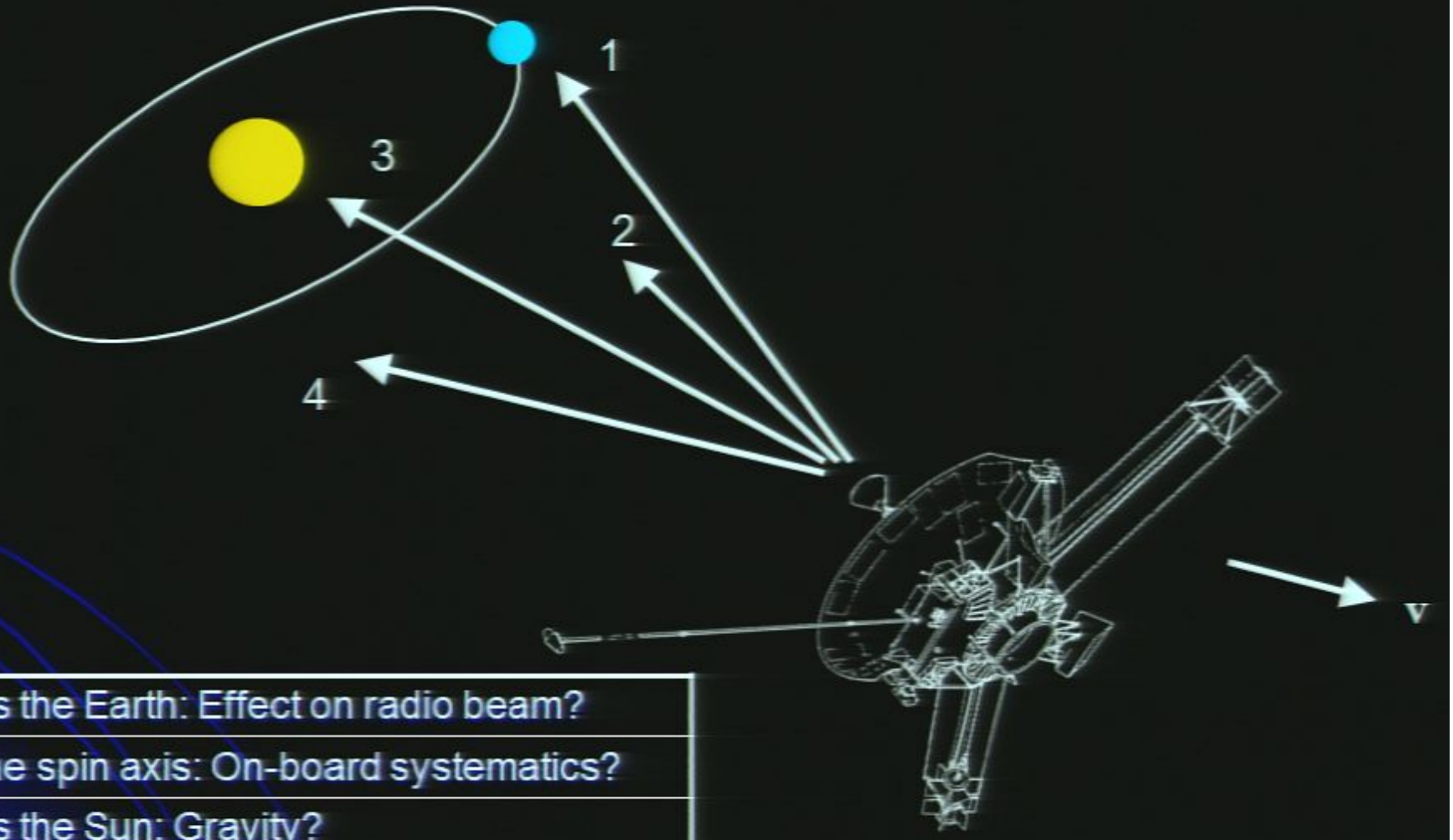


- Much has been said about a_P having the wrong sign for a cosmological origin
- This argument is not universally valid: an example is a conformal metric
  - The light of a distant star (blue) appears redshifted in accordance with Hubble's law
  - A radio signal of unit duration (half unit, actually, for drawing convenience) sent to a receding spacecraft S/C will be returned with a redshift. However, in the conformally transformed coordinate system, less time will appear to have elapsed, resulting in an apparent, small, additional blue shift. Ref: Hill, Phys. Rev. D (68) 232 (1945).

Temporal behavior

- These models yield equally good residuals

Unknown direction



1.	Towards the Earth: Effect on radio beam?
2.	Along the spin axis: On-board systematics?
3.	Towards the Sun: Gravity?
4.	Opposite the direction of motion: Drag force?

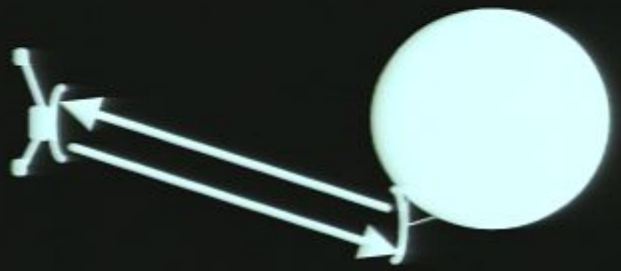
Beware of traps

- All observations are two-way or three-way Doppler
- Doppler analysis is about counting ~~beets~~ ~~beasts~~ beats

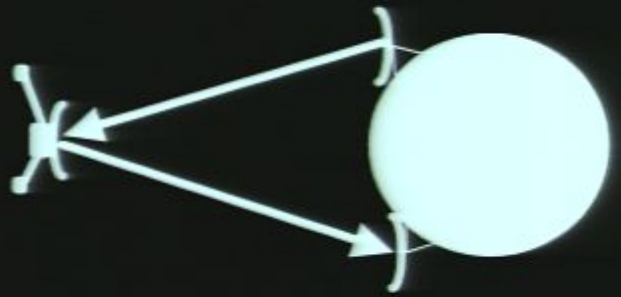
Doppler measurements

- One-way Doppler

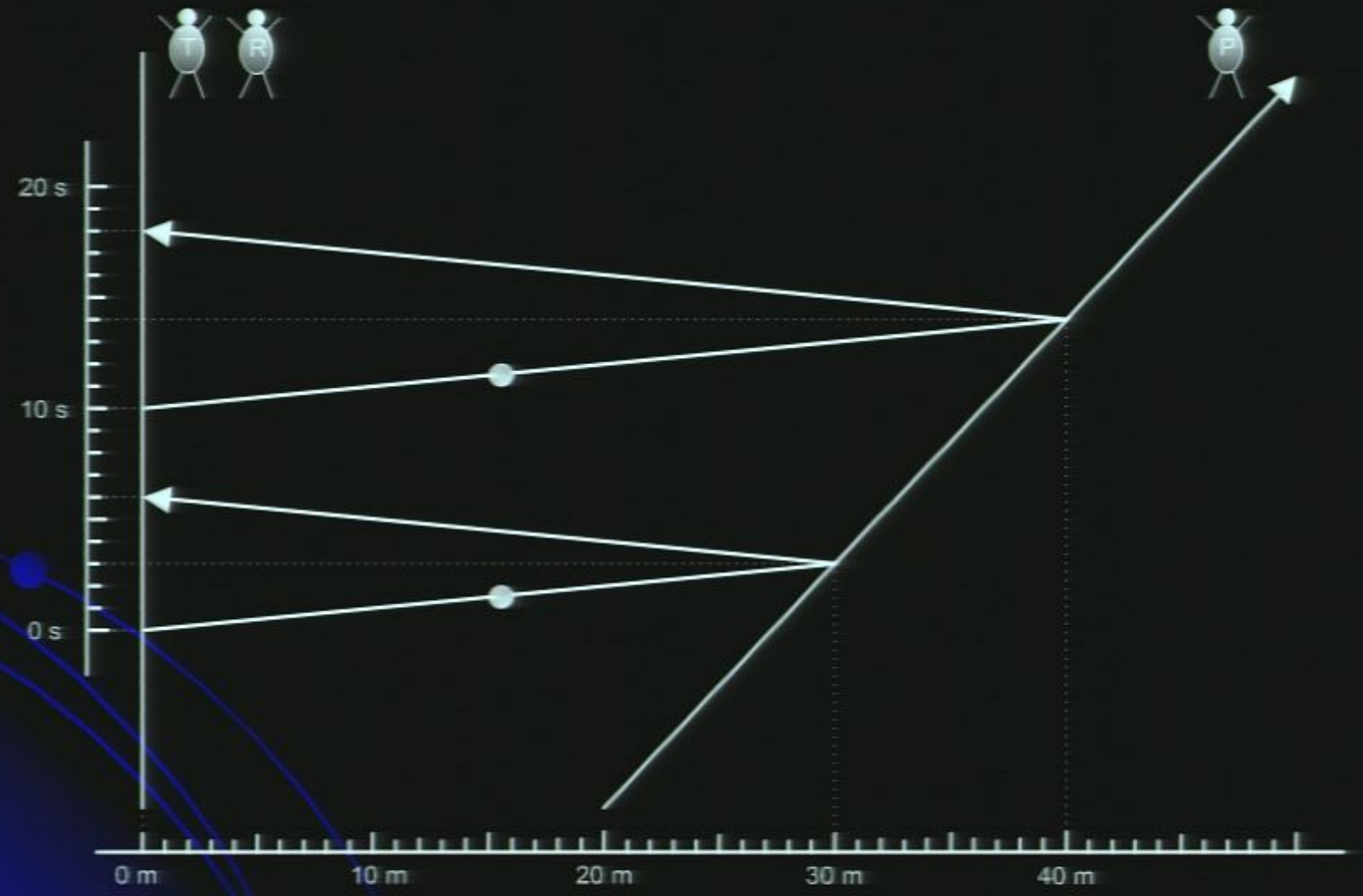
- Two-way Doppler



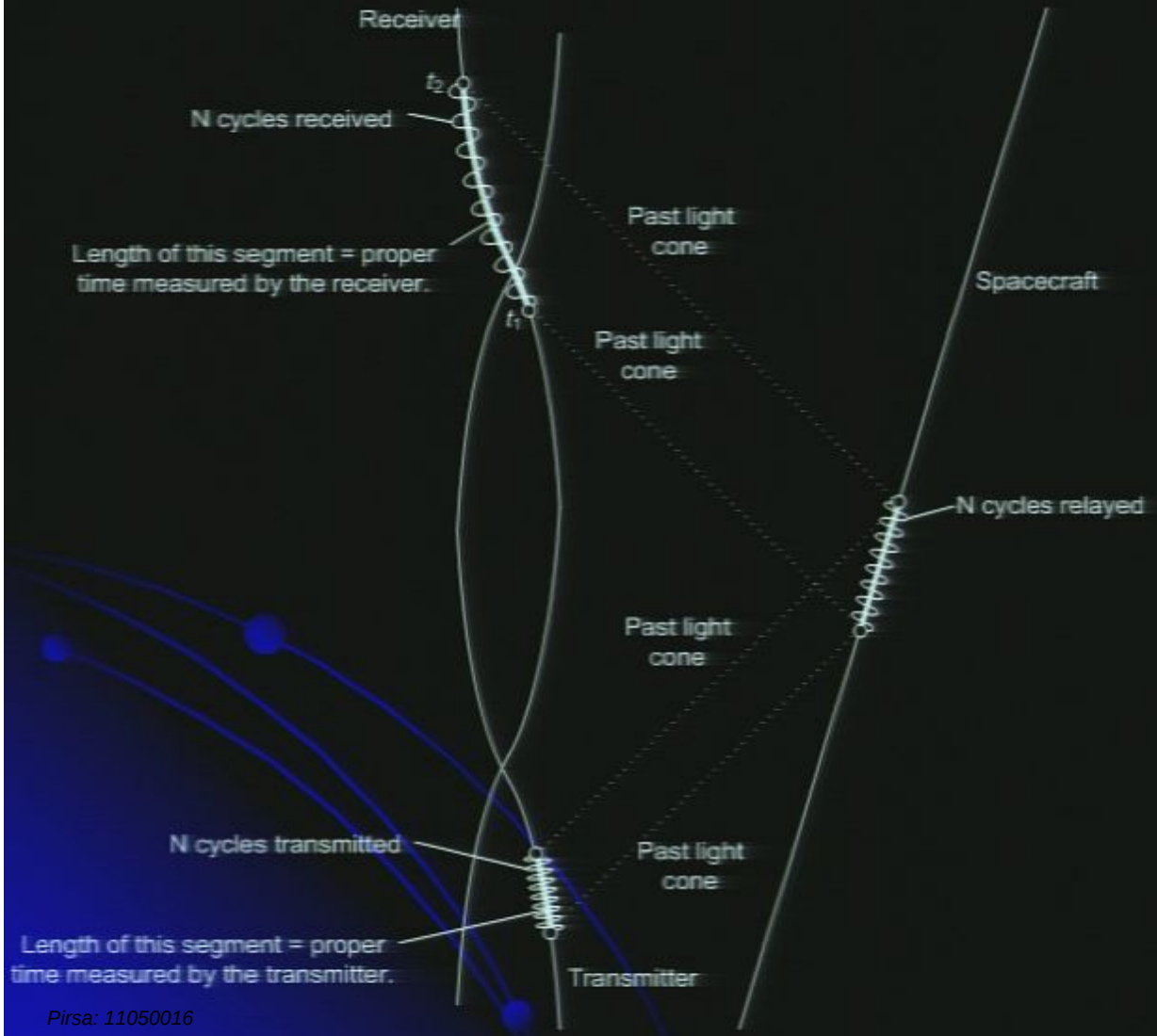
- Three-way Doppler



Two-way (or three-way) Doppler



Doppler measurements

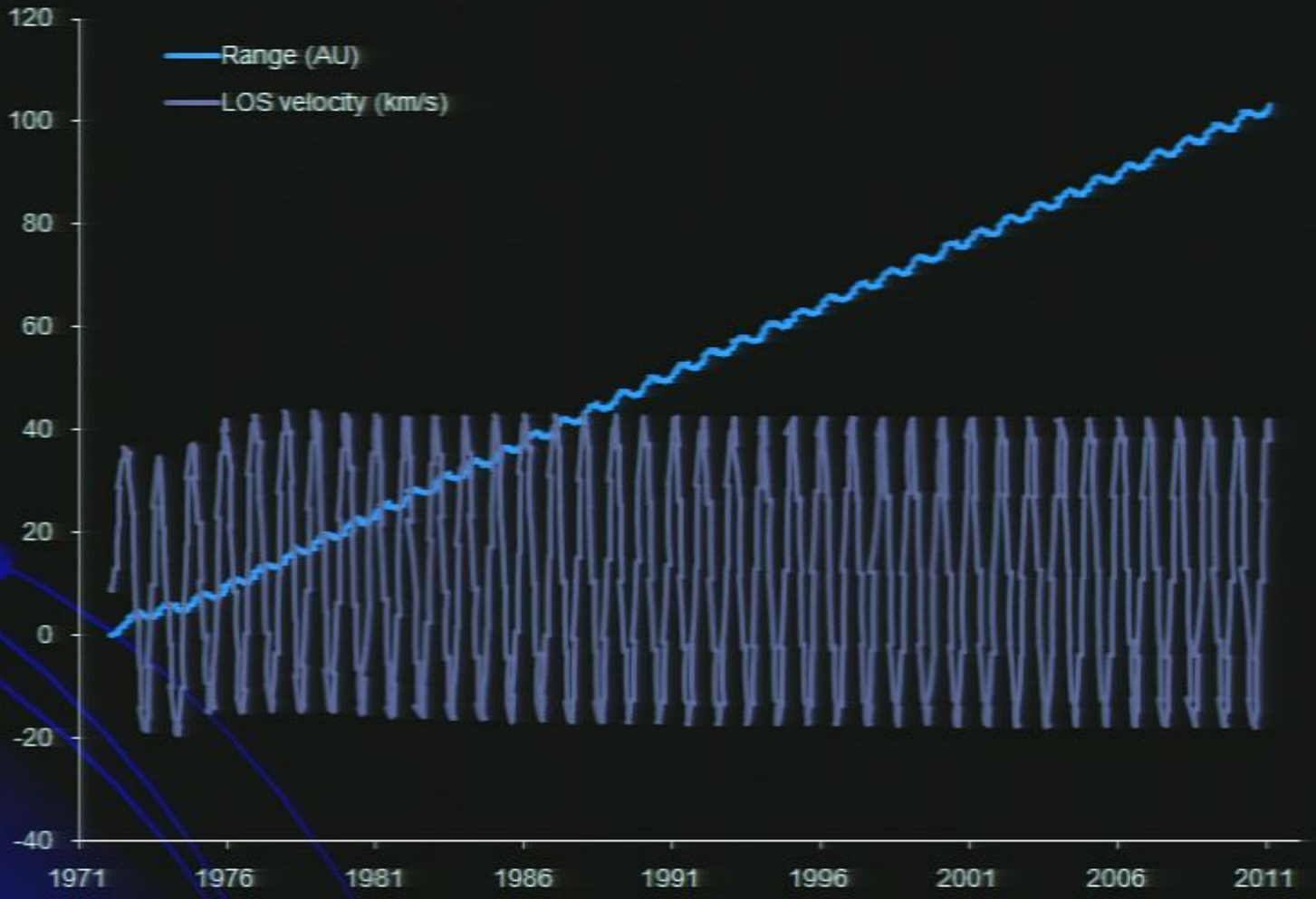


- A measurement at the receiver is made between t_1 and t_2
- These two instances of time are projected back onto the spacecraft's and then the transmitter's modeled world line; model accounts for
  - Post-Newtonian gravity of major solar system bodies
  - Maneuvers
  - Small non-gravitational forces (e.g., propellant leaks)
  - Shapiro delay
  - Effects of interplanetary medium (solar plasma)
  - Effects of the atmosphere
  - Motion of ground stations (tides, continental drift)
- The number of cycles transmitted is computed from the transmitter's known frequency
- This is then compared to the actual cycle count observed at the receiver
- Model is iteratively refined to reduce the residual difference.

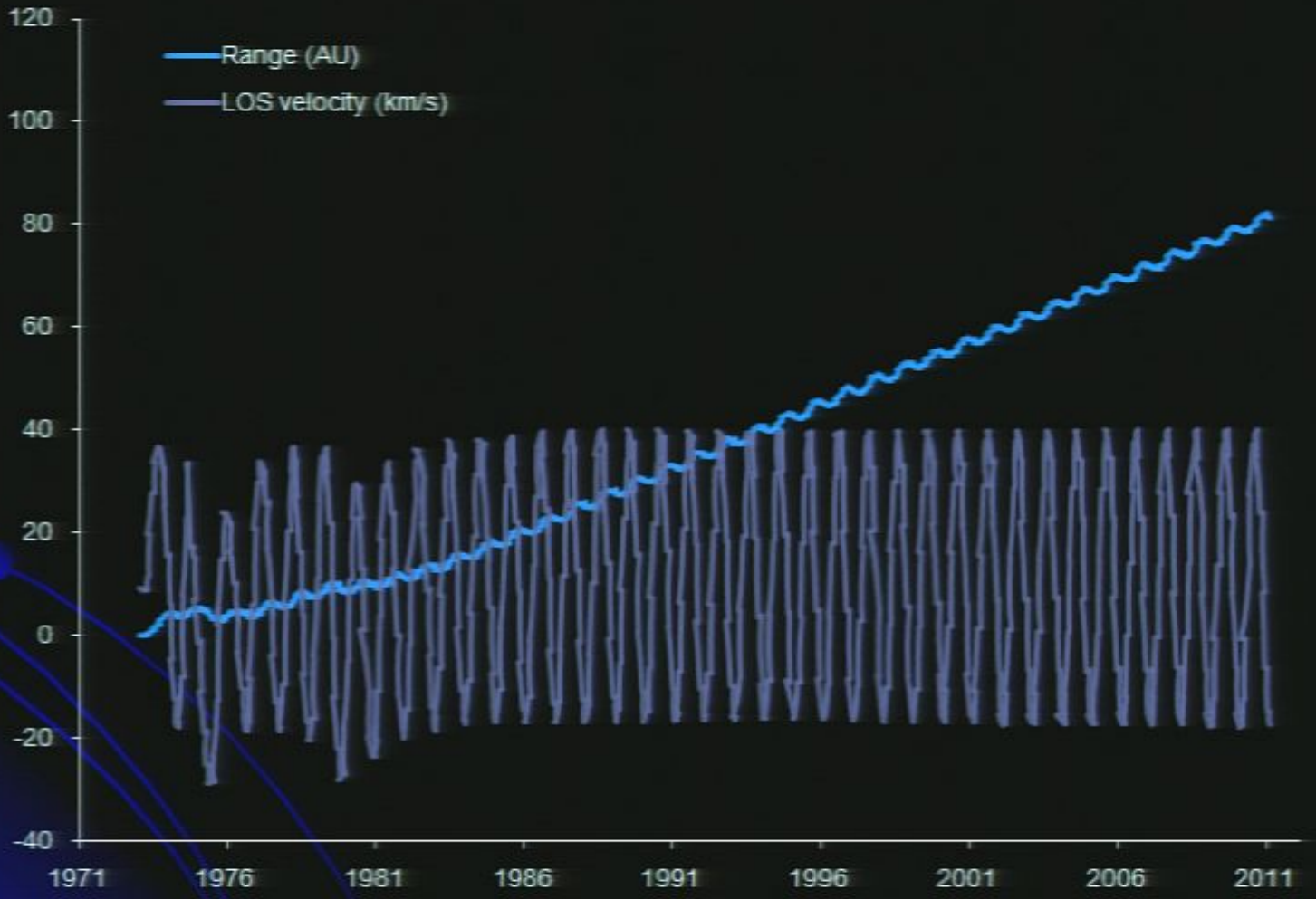
Effects on the signal

- Solutions that depend on the path length (or travel time) of the signal are in trouble:
  - The geocentric velocity of the spacecraft is −20…+40 km/s
  - The spacecraft-Earth distance is not monotonously increasing

Distance and geocentric velocity
Pioneer 10



Distance and geocentric velocity
Pioneer 11



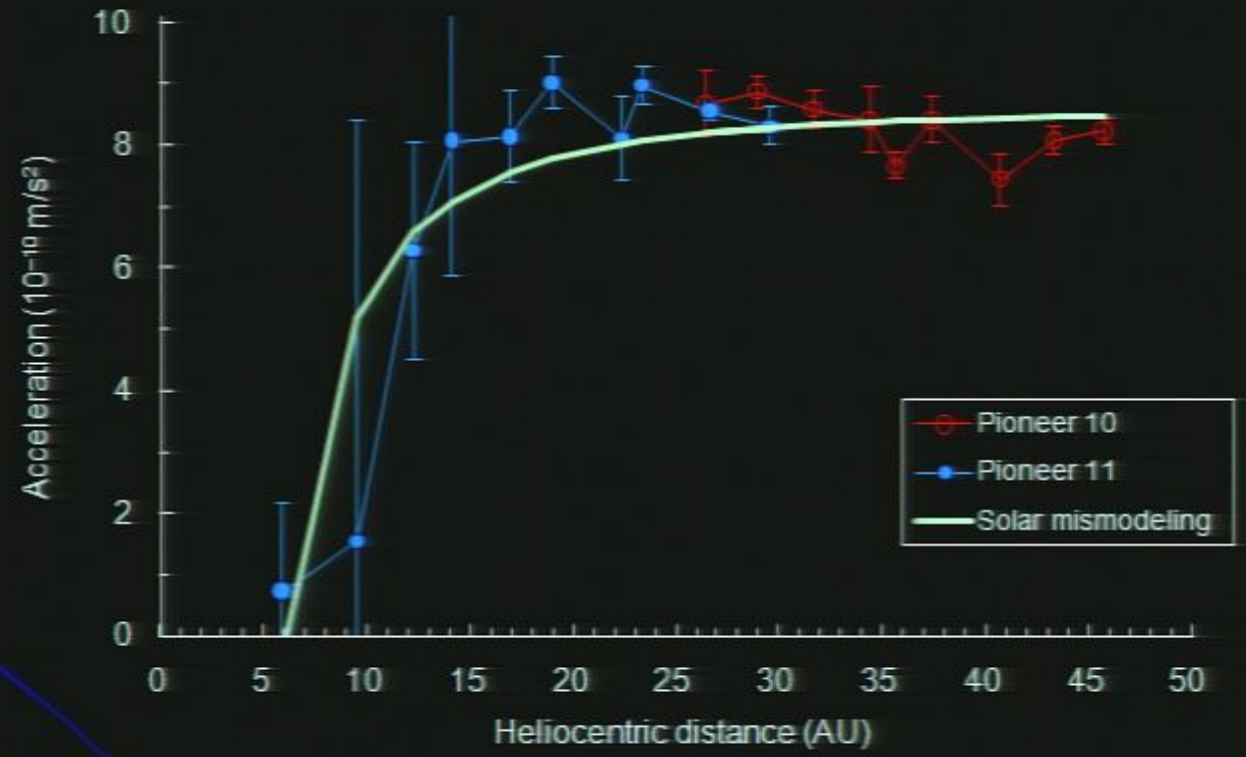
The solar system

- Not all orbits are well known but the orbit of Saturn is known quite well thanks to Cassini
- Solution must not predict the wrong planetary orbits

Onset

- The onset is almost certainly a model artifact
- Solar mismodeling can lead to apparent onset

Onset



- At 6 AU, spacecraft still receives >225 W of solar heating

The flyby anomaly

- Instantaneous small velocity change near perigee
- Completely unlike the Pioneer anomaly
- Quite possibly a modeling artifact: use of different, accelerating reference frames

Other spacecraft

- New Horizons: no funding for Doppler tracking; opportunity to confirm “onset” lost
- Voyagers: 3-axis stabilized
- Other spacecraft: wrong orbit, large RTGs, frequent maneuvers, etc.

Summary

- For the foreseeable future, Pioneer 10 and 11 remain the largest scale precision gravitational experiment ever conducted
- Ability to test post-Einsteinian gravity in the solar system would be marvelous
- Far more likely, this was just a wild goose chase
- Lessons to be learned:
  - Limits on navigational accuracy
  - Importance of preserving raw data and original documents
  - Dangers of “back of the envelope” estimation of small forces

Thank you!

- Questions?

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References

- ***The Pioneer Anomaly*, Slava G. Turyshev and Viktor T. Toth, Living Revs. Relativity 13, (2010), 4**
- *The Puzzle of the Flyby Anomaly*, Slava G. Turyshev and Viktor T. Toth, Space Science Reviews 148(1), 169-174 (2010)
- *The Pioneer Anomaly in the Light of New Data*, Slava G. Turyshev and Viktor T. Toth, Space Science Reviews 148(1), 149-167 (2010)
- *Thermal recoil force, telemetry, and the Pioneer anomaly*, Viktor T. Toth and Slava G. Turyshev, Phys. Rev. D. 79, 043011 (2009)
- *Independent analysis of the orbits of Pioneer 10 and 11*, Viktor T. Toth, Int. J. Mod. Phys. D18 (2009) 5, 717-741
- *The Study of the Pioneer Anomaly: New Data and Objectives for New Investigation*, Slava G. Turyshev, Viktor T. Toth, Larry R. Kellogg, Eunice. L. Lau, Kyong J. Lee, Int. J. Mod. Phys. D15 (2006) 1, 1-56

References

- *The constancy of the Pioneer anomalous acceleration*, Øystein Olsen, Astron. Astrophys. 463, 393 (2007)
- *Conventional Forces can Explain the Anomalous Acceleration of Pioneer 10*, Louis K. Scheffer, Phys. Rev. D. 67, 084021 (2003)
- *Independent Confirmation of the Pioneer 10 Anomalous Acceleration*, Craig B. Markwardt, arXiv:gr-qc/0208046 (2002)
- *Study of the anomalous acceleration of Pioneer 10 and 11*, John D. Anderson, Philip A. Laing, Eunice L. Lau, Anthony S. Liu, Michael Martin Nieto and Slava G. Turyshev, Phys. Rev. D. 65, 082004 (2002)
- *Comment on "Indication, from Pioneer 10/11, Galileo, and Ulysses Data, of an Apparent Anomalous, Weak, Long-Range Acceleration"* , J. I. Katz, Phys. Rev. Lett. 83, 1892 (1999)
- *Prosaic Explanation for the Anomalous Accelerations Seen in Distant Spacecraft*, E. M. Murphy, Phys. Rev. Lett. 83, 1890 (1999)
- *Indication, from Pioneer 10/11, Galileo, and Ulysses Data, of an Apparent Anomalous, Weak, Long-Range Acceleration*, John D. Anderson, Philip A. Laing, Eunice L. Lau, Anthony S. Lium Michael Martin Nieto and Slava G. Turyshev, Phys. Rev. Lett. 81, 2858 (1998)

BOOKS

- *Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation*, Theodore D. Moyer, John Wiley & Sons (2005)
- *Foundations of Radiation Hydrodynamics*, Dimitri Mihalas and Barbara Weibel-Mihalas, Dover Publications (1999)

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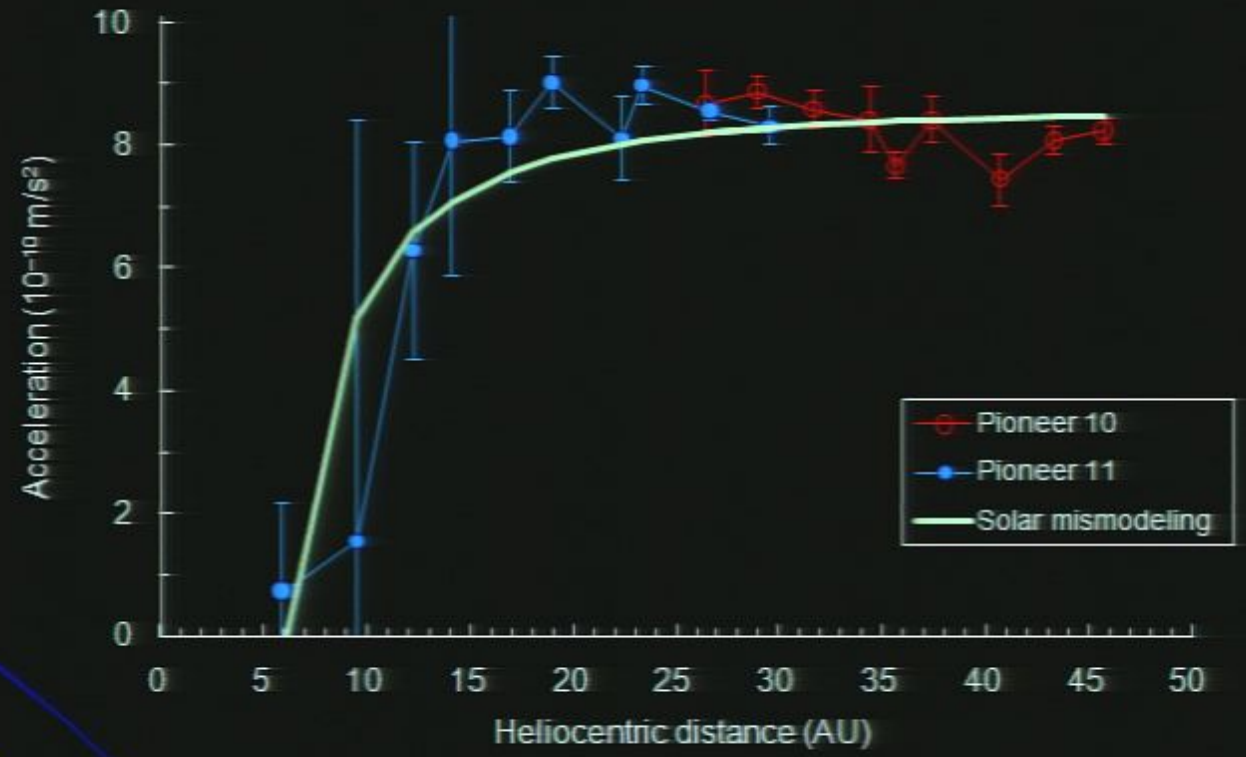

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