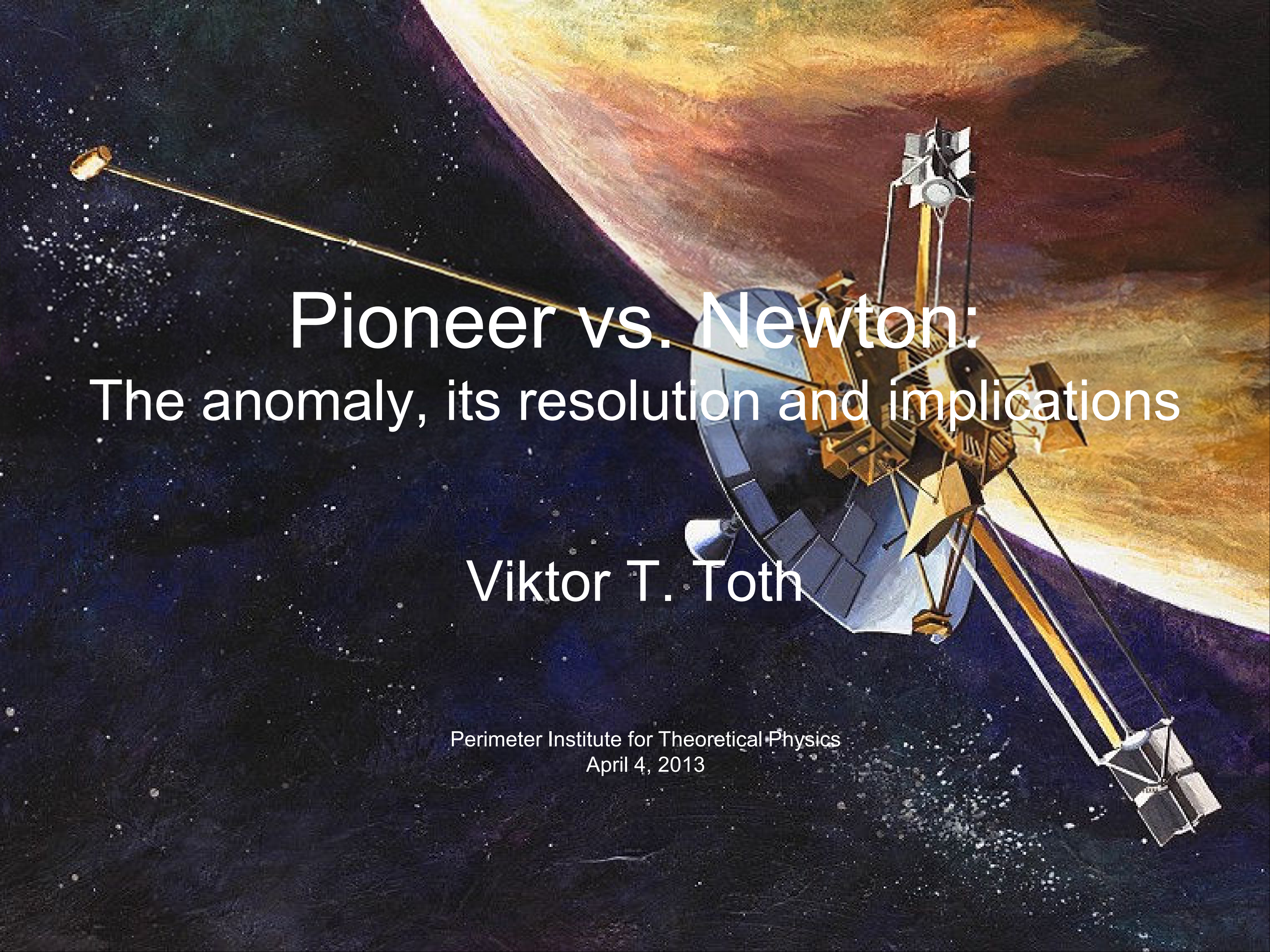


Pioneer vs. Newton:

The anomaly, its resolution and implications

Viktor T. Toth

Perimeter Institute for Theoretical Physics

April 4, 2013

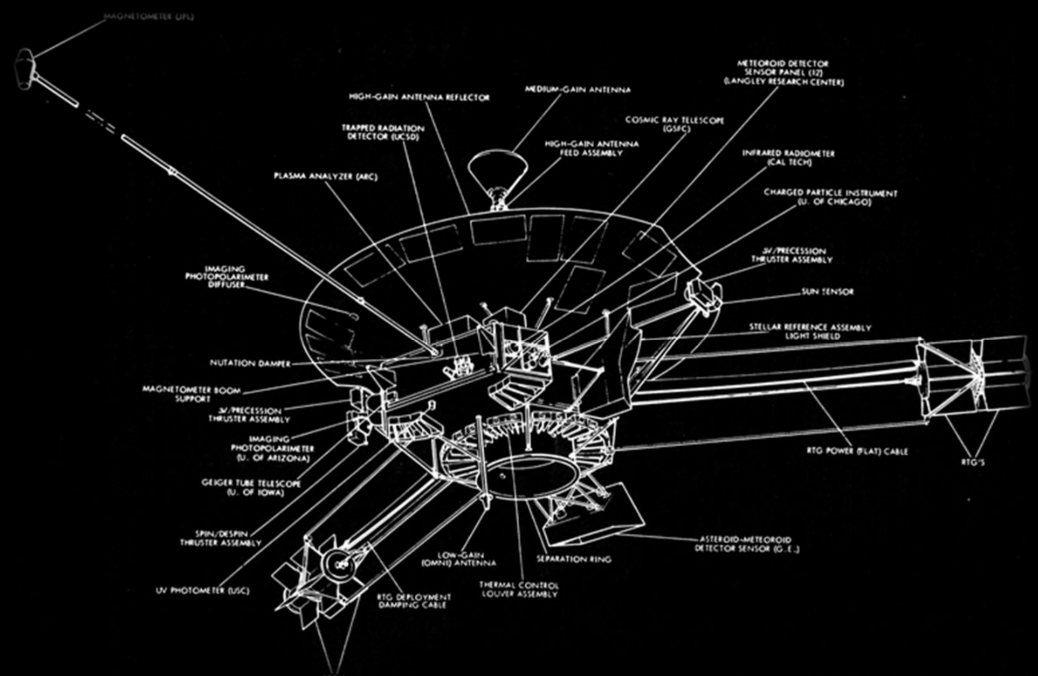
The Pioneer 10/11 missions

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




The Pioneer spacecraft

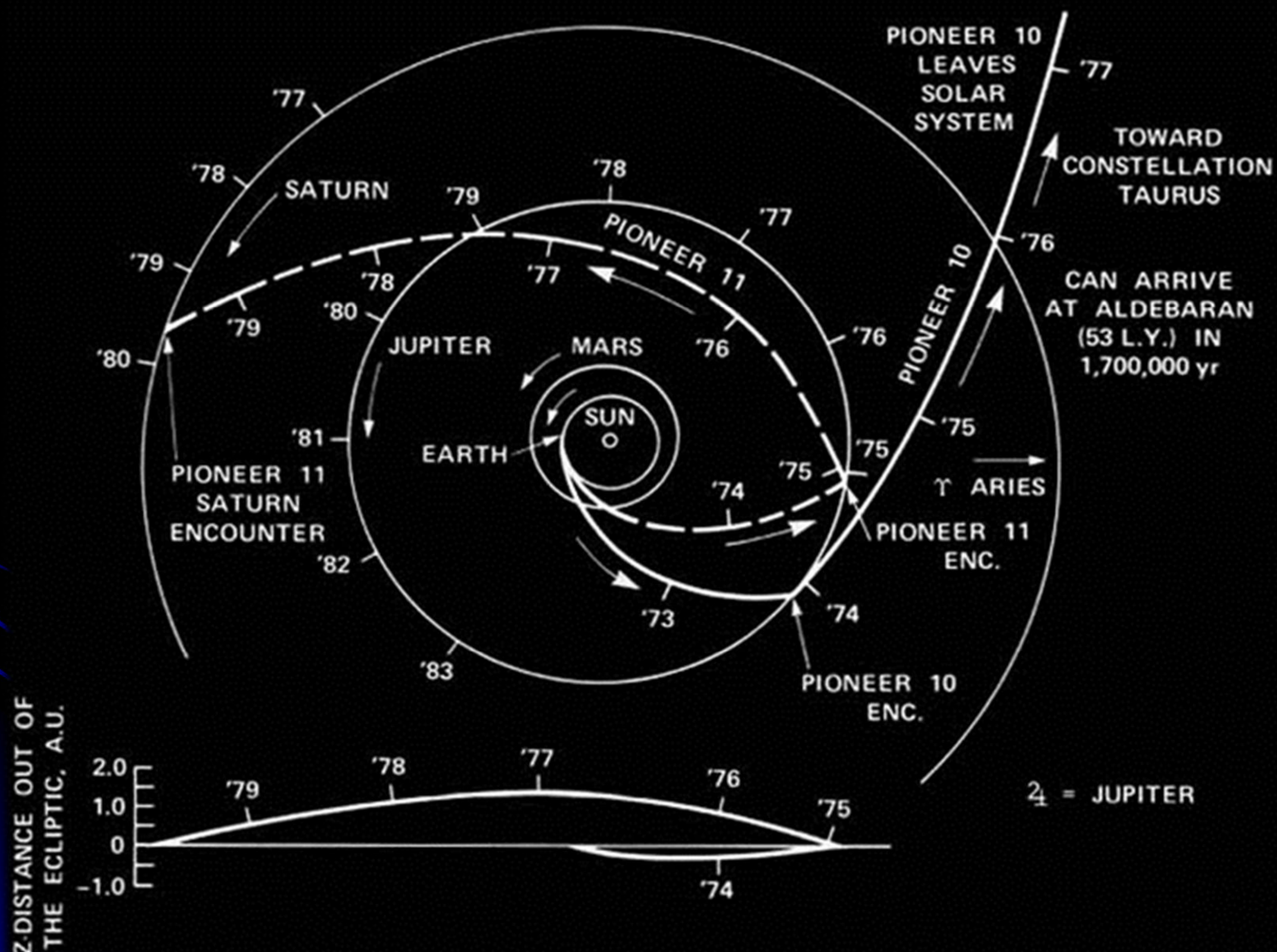
- Mass: ~250 kg
- Spin stabilized (4.8 rpm nominal)
- Radioisotope Thermoelectric Generators
- Electrical Power: ~160 W (at launch)
- 11 Scientific Instruments
- 2.75 m High Gain Antenna
- Transmitter: 8 W
- Data rate: 16-2048 bps



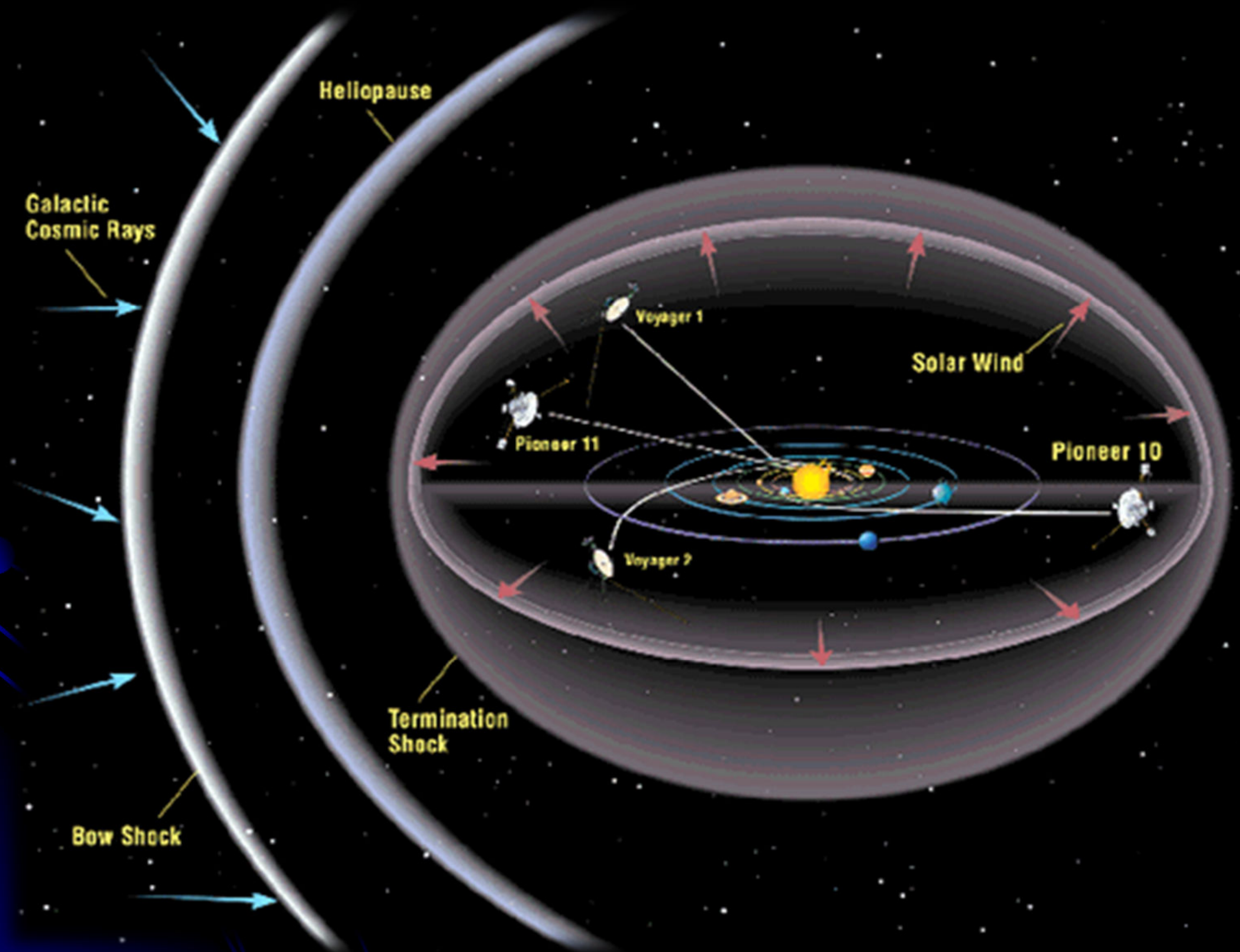
Mission objectives

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

Pioneer orbits – early years

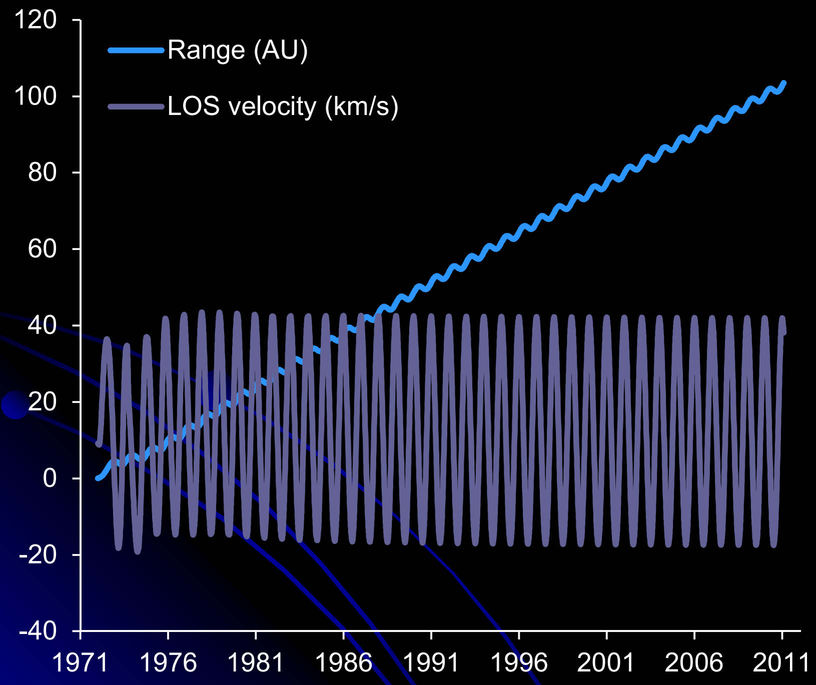


Pioneer and Voyager orbits through the outer solar system

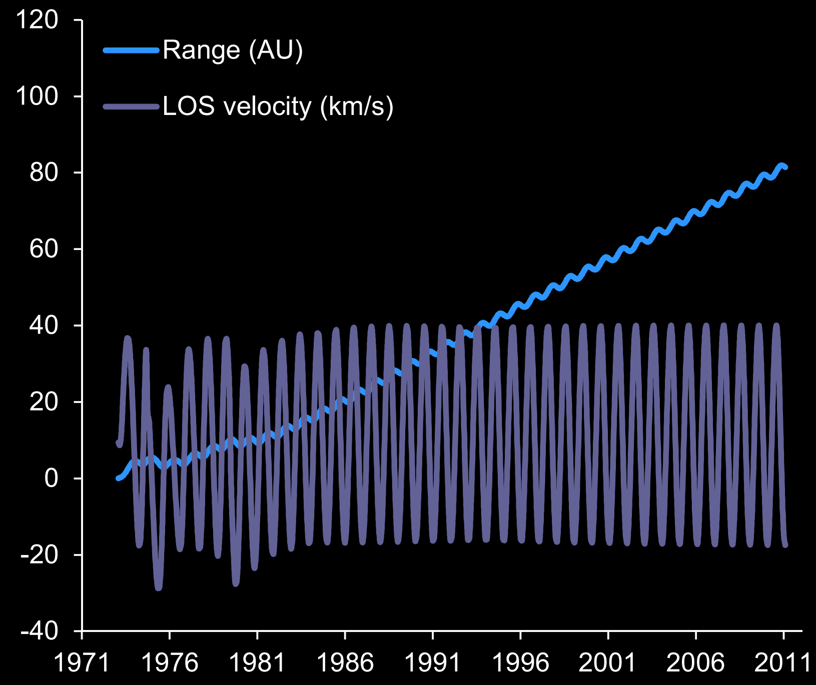


Distance and geocentric velocity

Pioneer 10



Pioneer 11



Orientation maneuvers

- Few maneuvers needed for spinning spacecraft
- Few maneuvers → clean navigational 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
- 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)

Eddington's parameters

- In a simplified first approximation (ignoring acceleration-dependent and nonlinear terms), the PPN* metric reads:

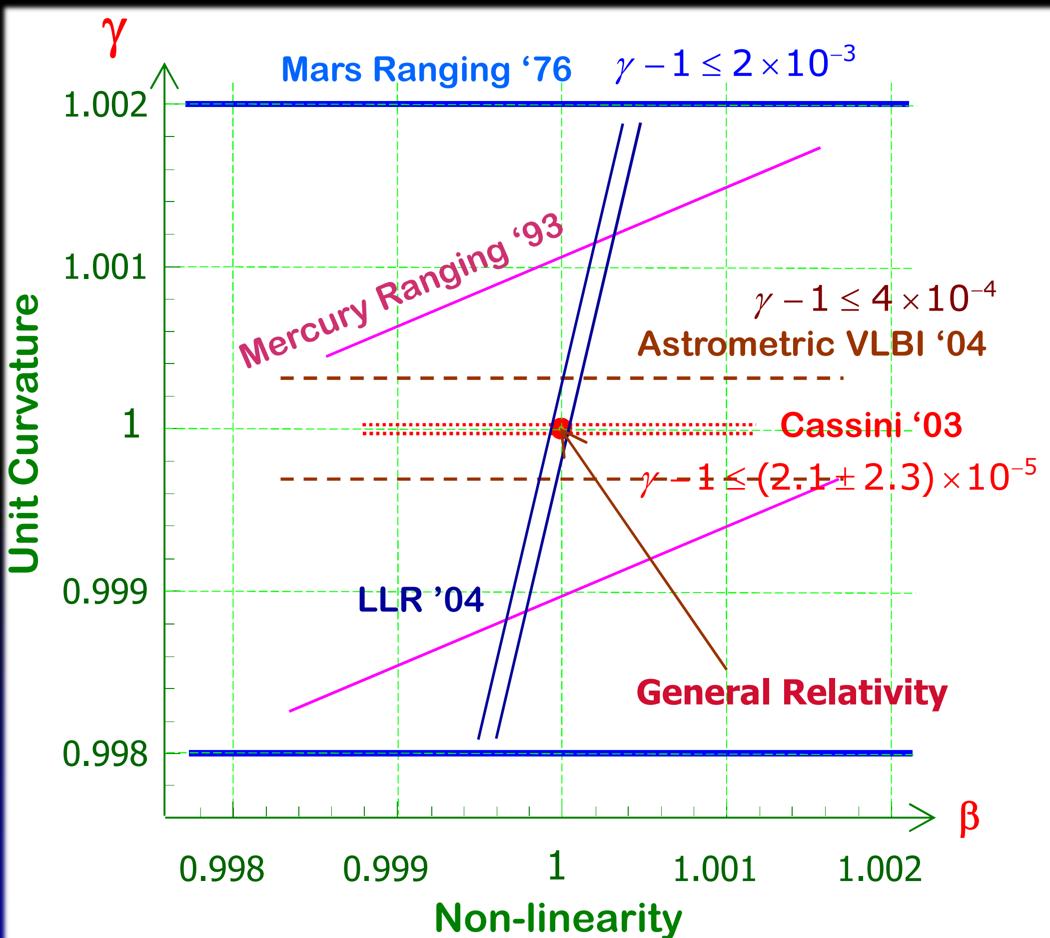
$$g_{11} = g_{22} = g_{33} = -1 + \frac{2\gamma}{c^2}\phi,$$
$$g_{44} = 1 - \frac{2}{c^2}\phi + \frac{2\beta}{c^4}\phi^2,$$

where $\phi = Gm/r$ is the Newtonian gravitational potential.

- For general relativity, $\beta = \gamma = 1$.

*Parameterized Post-Newtonian

Experimental general relativity



$$g_{11} = g_{22} = g_{33} = -\left(1 + \frac{2\gamma}{c^2}\sum_{j\ne i}\frac{\mu_j}{r_{ij}}\right)$$

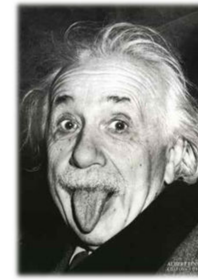
$$g_{pq} = 0 \quad (p,q = 1,2,3;\ p \ne q)$$

$$g_{14} = g_{41} = \frac{2+2\gamma}{c^3}\sum_{j\ne i}\frac{\mu_j \dot{x}_j}{r_{ij}}$$

$$g_{24} = g_{42} = \frac{2+2\gamma}{c^3}\sum_{j\ne i}\frac{\mu_j \dot{y}_j}{r_{ij}}$$

$$g_{34} = g_{43} = \frac{2+2\gamma}{c^3}\sum_{j\ne i}\frac{\mu_j \dot{z}_j}{r_{ij}}$$

$$g_{44} = 1 - \frac{2}{c^2}\sum_{j\ne i}\frac{\mu_j}{r_{ij}} + \frac{2\beta}{c^4}\left(\sum_{j\ne i}\frac{\mu_j}{r_{ij}}\right)^2 - \frac{1+2\gamma}{c^4}\sum_{j\ne i}\frac{\mu_j \dot{s}_j{}^2}{r_{ij}} + \frac{2(2\beta-1)}{c^4}\sum_{j\ne i}\frac{\mu_j}{r_{ij}}\sum_{k\ne j}\frac{\mu_k}{r_{jk}} - \frac{1}{c^4}\sum_{j\ne i}\mu_j\frac{\partial^2 r_{ij}}{\partial t^2}$$

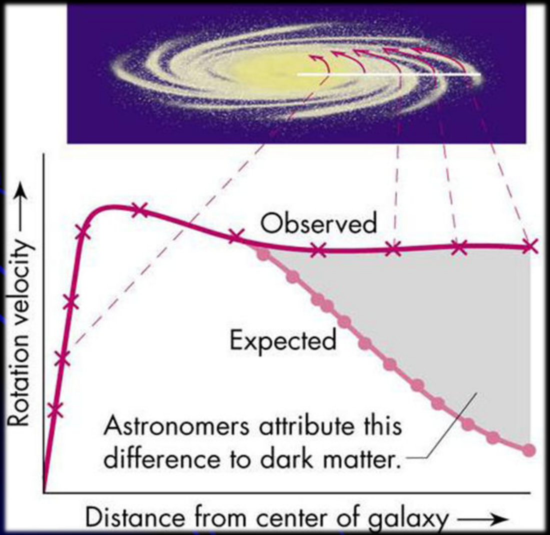


Albert Einstein
(1879-1955)

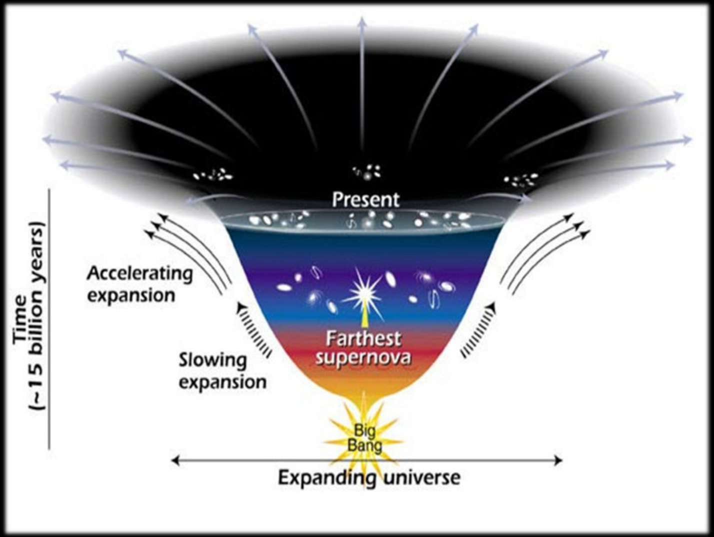
Parameterized Post-Newtonian (PPN) formalism
From Moyer (JPL Publication 00-7)

Gravity misbehaves on cosmic scales

- Galaxies do not rotate as expected
- Supernovae, microwave background show accelerated expansion



Dark matter?



Dark energy?

Or in the outer solar system!

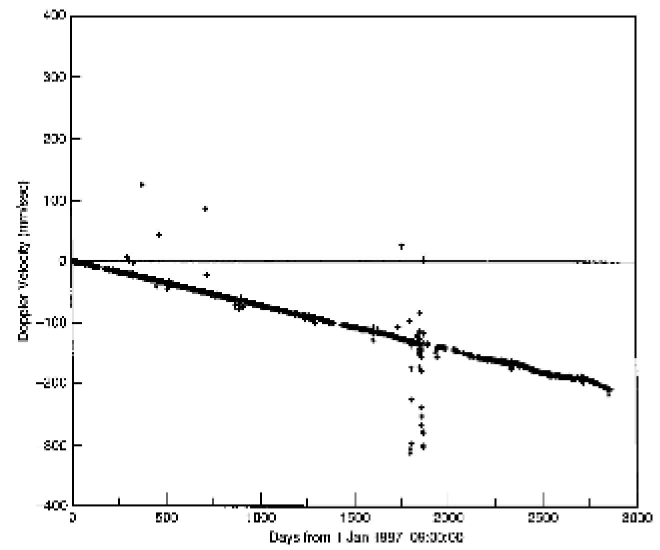
VOLUME 81, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1998

Indication, from Pioneer 10/11, Galileo, and Ulysses Data, of an Apparent Anomalous, Weak, Long-Range Acceleration

John D. Anderson,[1,*] Philip A. Laing,[2,†] Eunice L. Lau,[1,‡] Anthony S. Liu,[3,§] Michael Martin Nieto,[4,||] and Slava G. Turyshev[1,¶]

Radio metric data from the Pioneer 10/11, Galileo, and Ulysses spacecraft indicate an apparent anomalous, constant, acceleration acting on the spacecraft with a magnitude $\sim 8.5 \times 10^{-8}$ cm/s^2, directed towards the Sun. Two independent codes and physical strategies have been used to analyze the data. A number of potential causes have been ruled out. We discuss future kinematic tests and possible origins of the signal. [S0031-9007(98)07300-1]

We conclude, from the JPL-ODP analysis, that there is an unmodeled acceleration a_P towards the Sun of $(8.09 \pm 0.20) \times 10^{-8}$ cm/s^2 for Pioneer 10 and of $(8.56 \pm 0.15) \times 10^{-8}$ cm/s^2 for Pioneer 11. The error is determined by use of a five-day batch sequential filter with radial acceleration as a stochastic parameter subject to white Gaussian noise ($\sim$500 independent five-day samples of radial acceleration) [4,5]. *No magnitude variation of a_P with distance was found,* within a sensitivity of 2×10^{-8} cm/s^2 over a range of 40 to 60 AU.

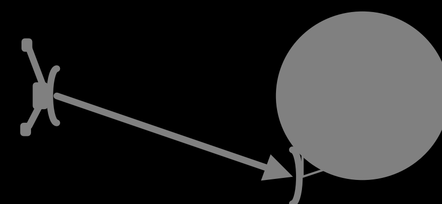


Discovery of the Anomaly

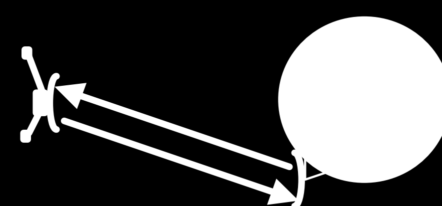
- Search began in 1979 (for “Planet X”)
- Anomaly first detected in 1980
- Initial JPL ODP analysis in 1990-95
- Aerospace Corporation confirms: 1996-98
- Independent confirmation by Markwardt (2002), Olsen (2005), Toth (2009)
- Only limited stretches of data were studied; no telemetry, no formal thermal model.

Analysis of Doppler data

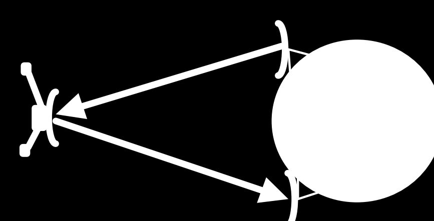
- All observations are two-way or three-way Doppler
- One-way Doppler



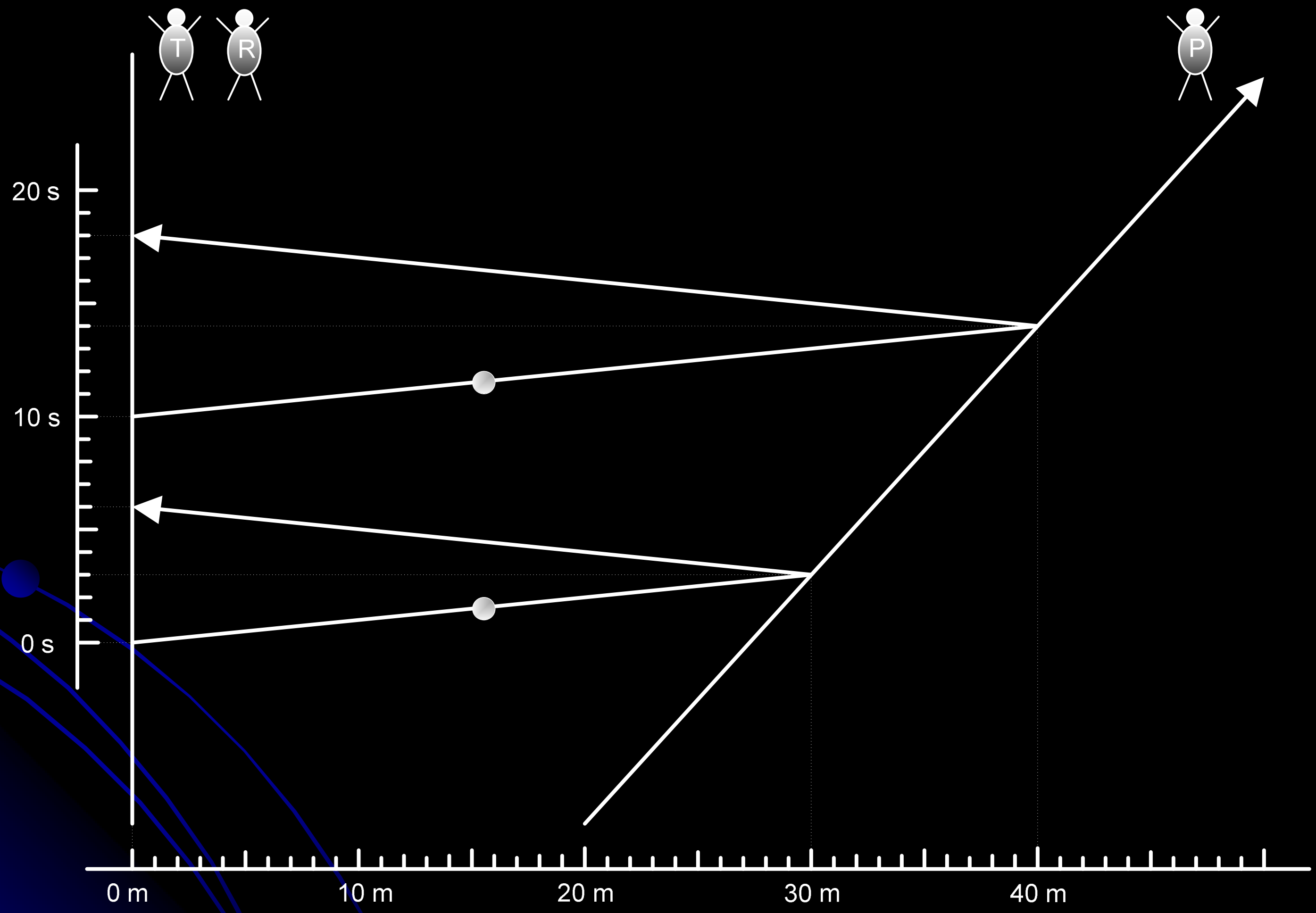
- Two-way Doppler



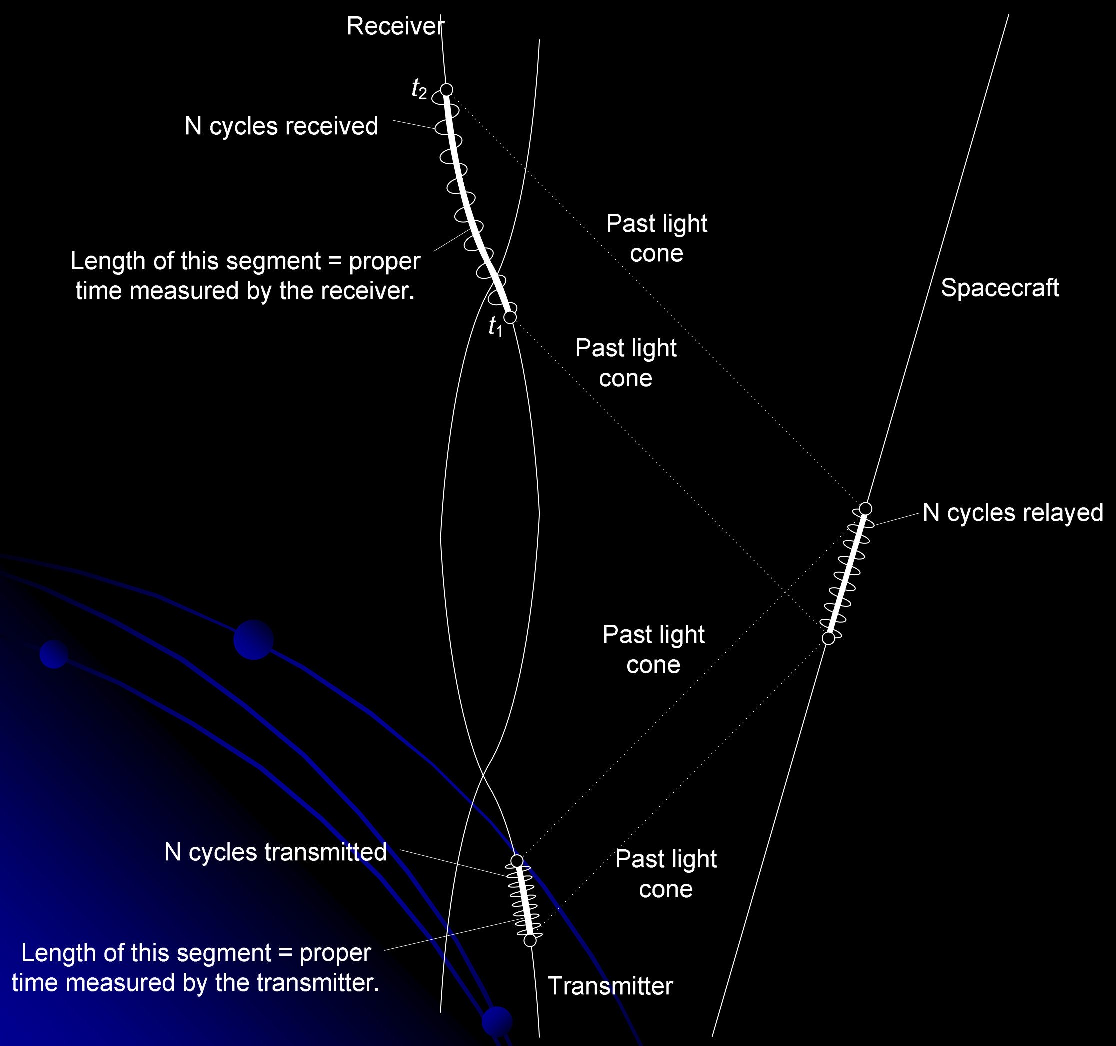
- Three-way Doppler



Two-way (or three-way) Doppler



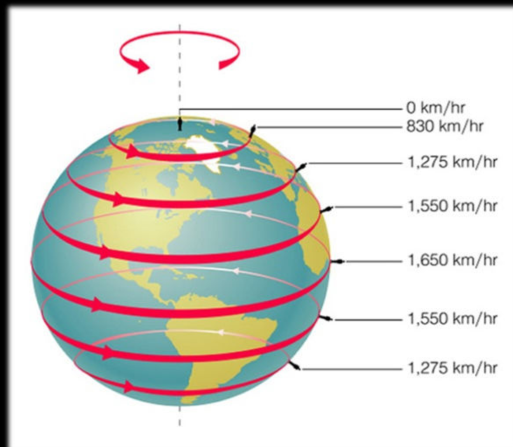
Doppler measurements

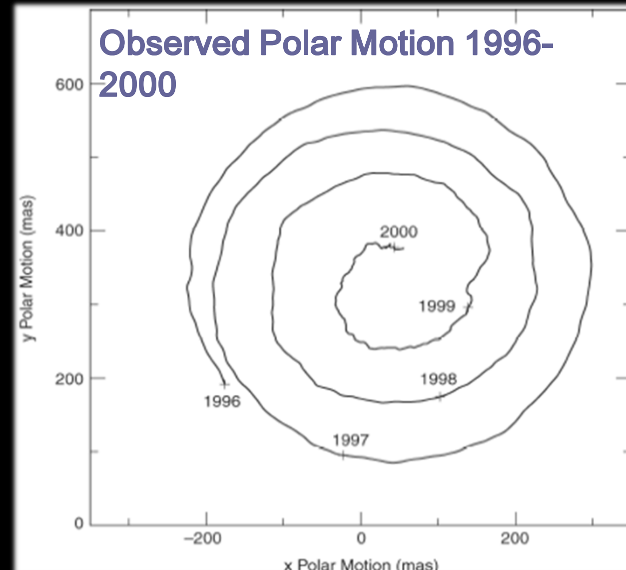


- A measurement at the receiver is made between t_1 and t_2
- These two instances of time are projected back onto the spacecraft's and then the transmitter's modeled world line; model accounts for
  - Post-Newtonian gravity of major solar system bodies
  - Maneuvers
  - Small non-gravitational forces (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.

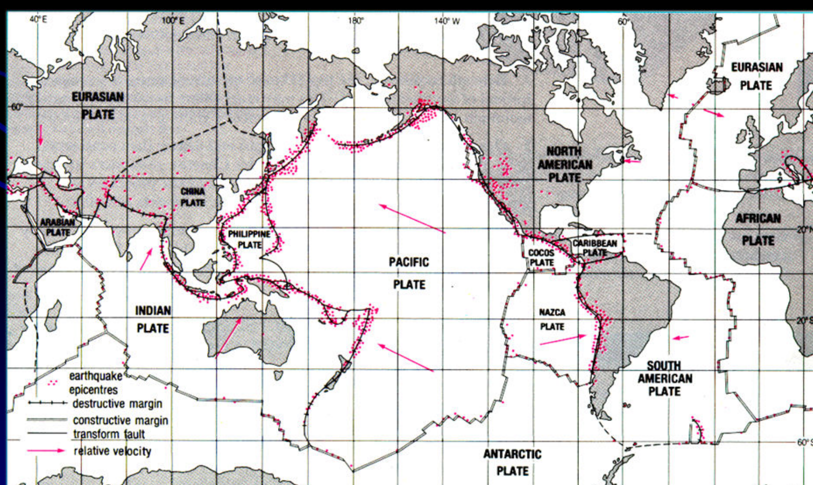
Terrestrial effects

Earth Rotation

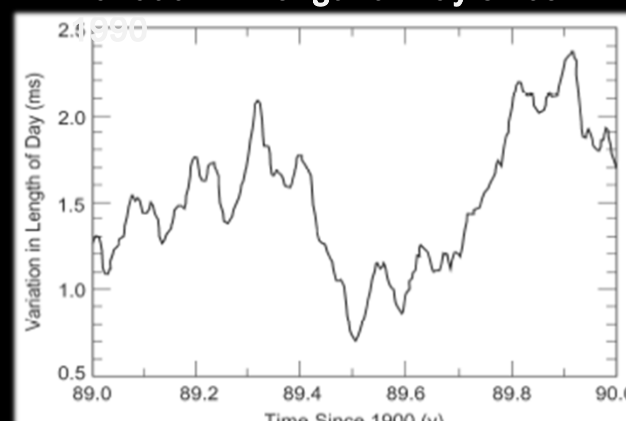




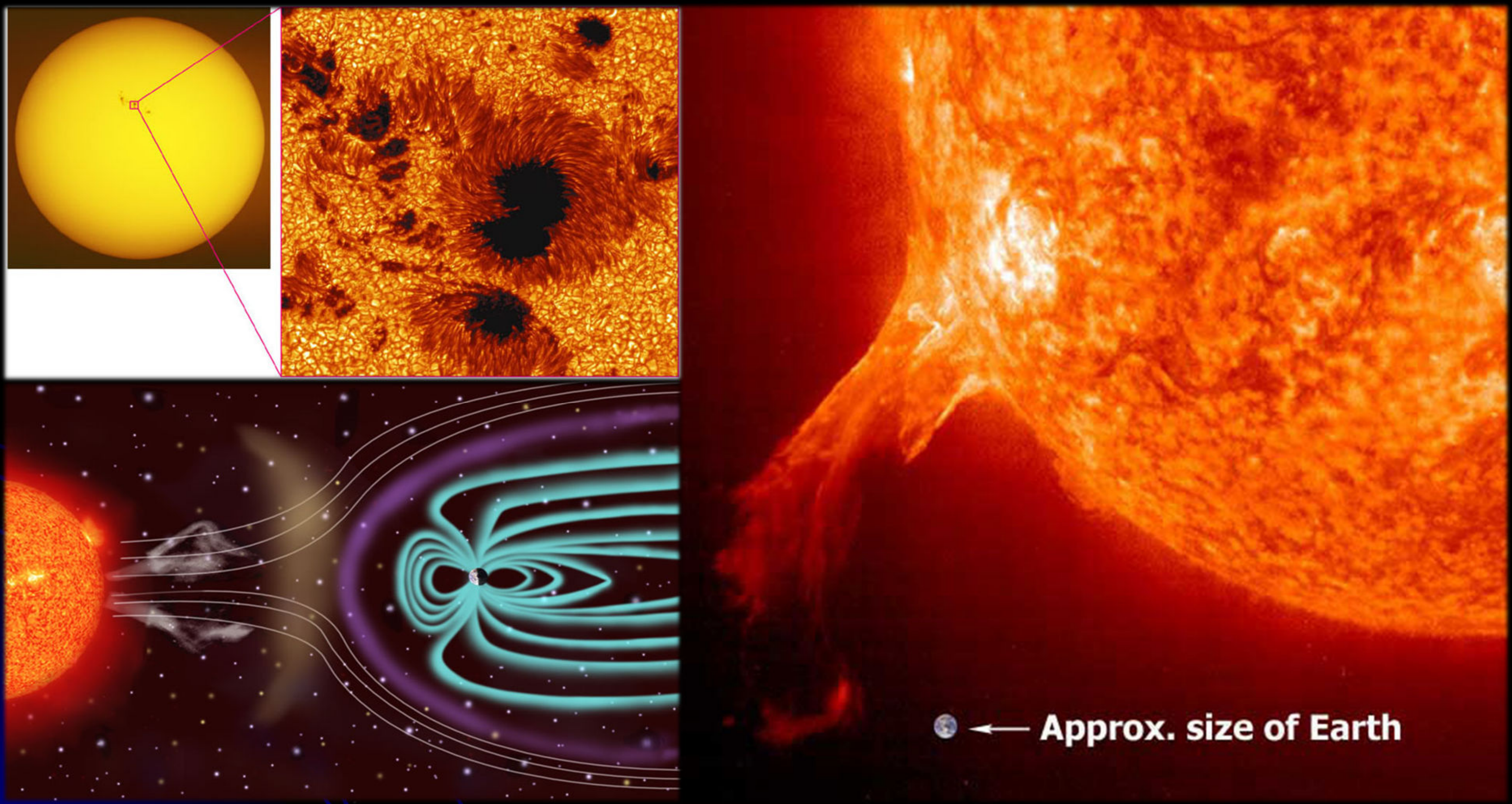
Tectonic Plate Motion



Variation in Length of Day since

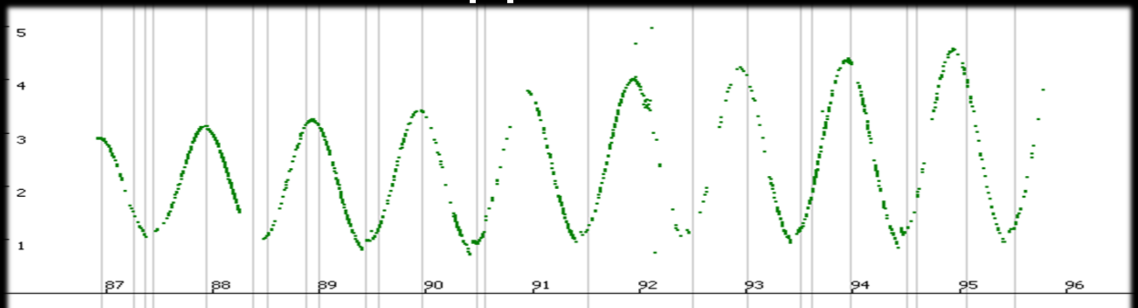


Solar effects

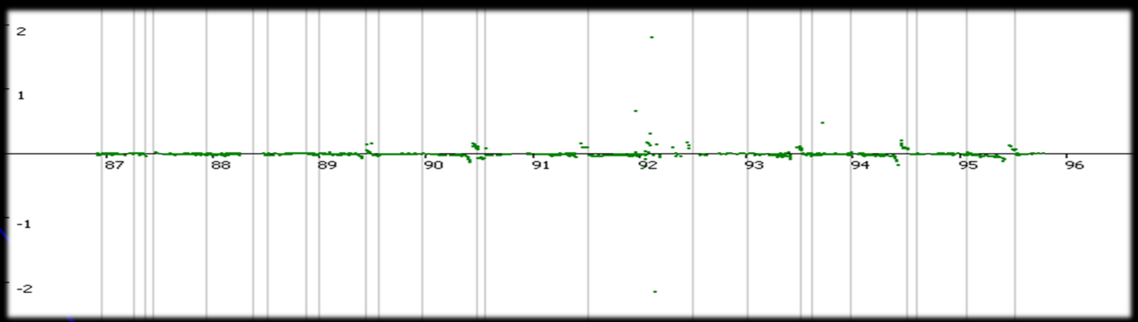


Doppler fits

- Model predicts spacecraft motion and Doppler
- Antenna measures actual Doppler
- Difference is called the "Doppler Residual"
- "Bad" fit:



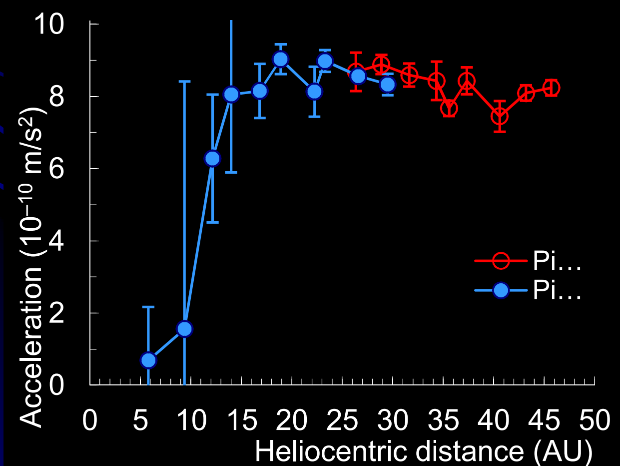
- "Good" fit:

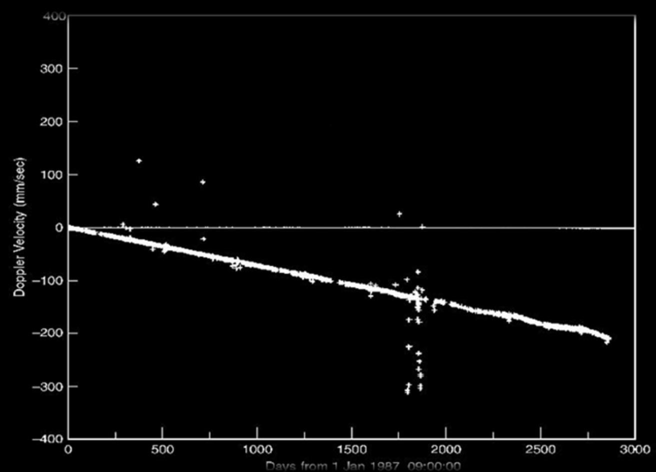


- Accuracy is measured in mHz!

The Pioneer Anomaly is NOT

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

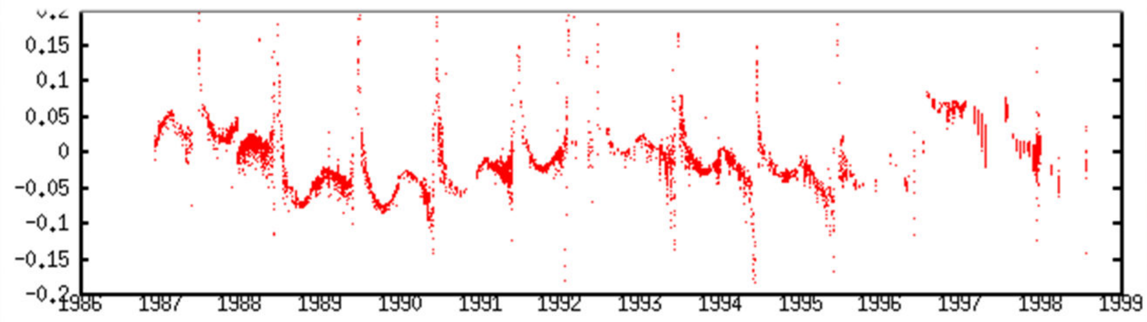




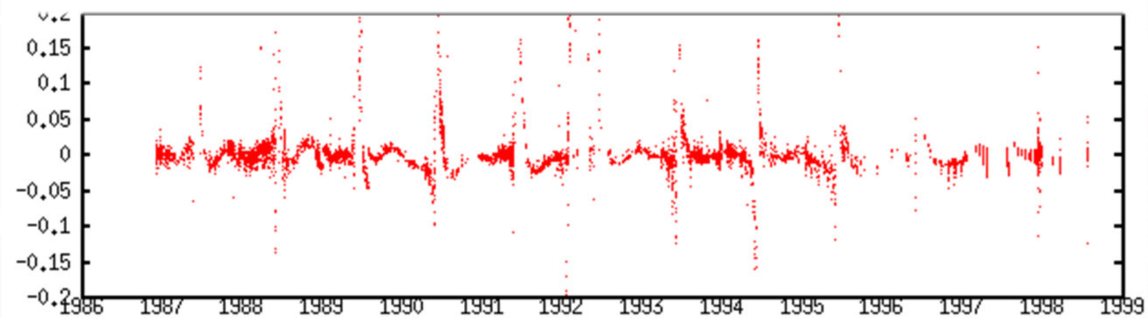
The Pioneer Anomaly IS

The Pioneer Anomaly IS

this:



instead of this:



Interpreting the residual

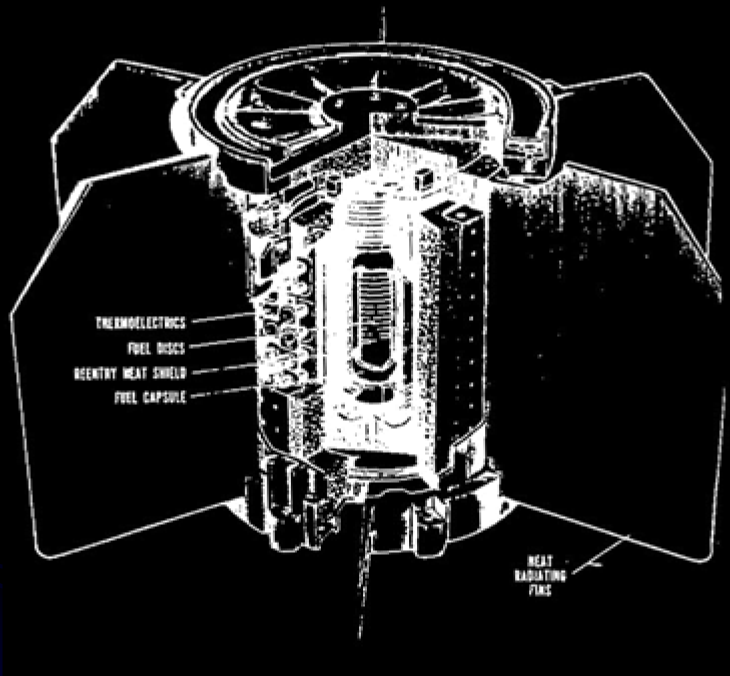
- Frequency drift: $(5.99 \pm 0.01)\times 10^{-9}$ Hz/s (@ ~2 GHz)
- Velocity change: $(8.74 \pm 1.33)\times 10^{-10}$ m/s^2
- Clock acceleration: $(2.92 \pm 0.44)\times 10^{-18}$ s/s^2
- Velocity change (acceleration) is the "conventional" interpretation
- Effect small by engineering standards, but huge by the standards of gravity physics (first order effect, not second order correction!)

Analysis of the anomaly

- May be systematic or “new physics”
- Alternatives proposed include
  - Gravity modification (MOND, MSTG, Yukawa potential)
  - Dark matter
  - Cosmological origin ($|a_P| \approx cH_0$: coincidence?)
- The magnitude of the thermal recoil force due to on-board generated heat was not fully investigated
- Let me establish the case for thermal recoil:

The case for thermal recoil

Pioneer power source



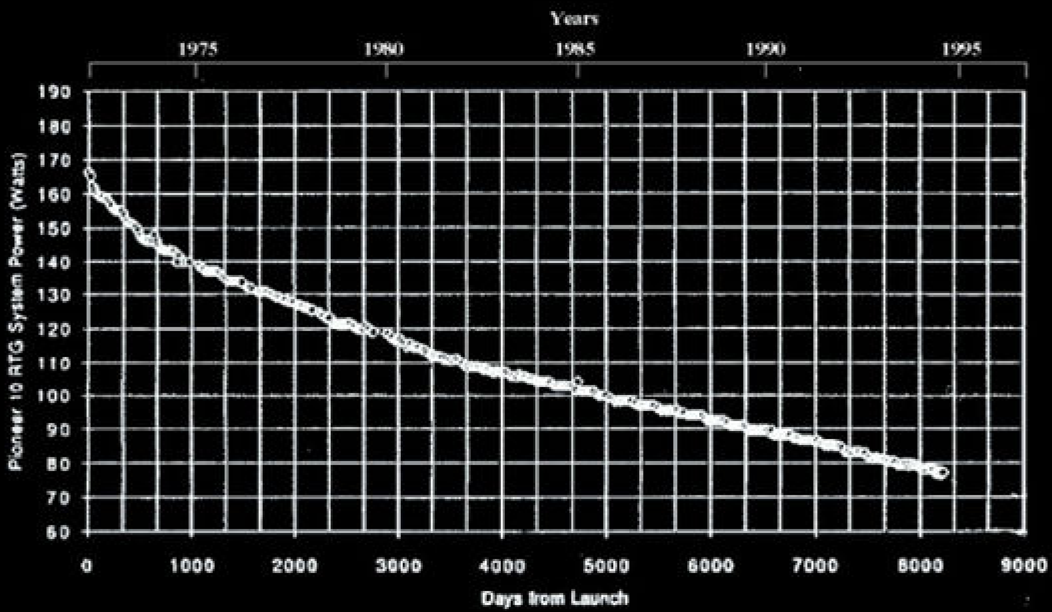
SNAP 19/PIONEER RADIOISOTOPE THERMOELECTRIC GENERATOR

RTG Thermal Power: ~650W

Electrical Power: ~40W

4 RTGs per spacecraft

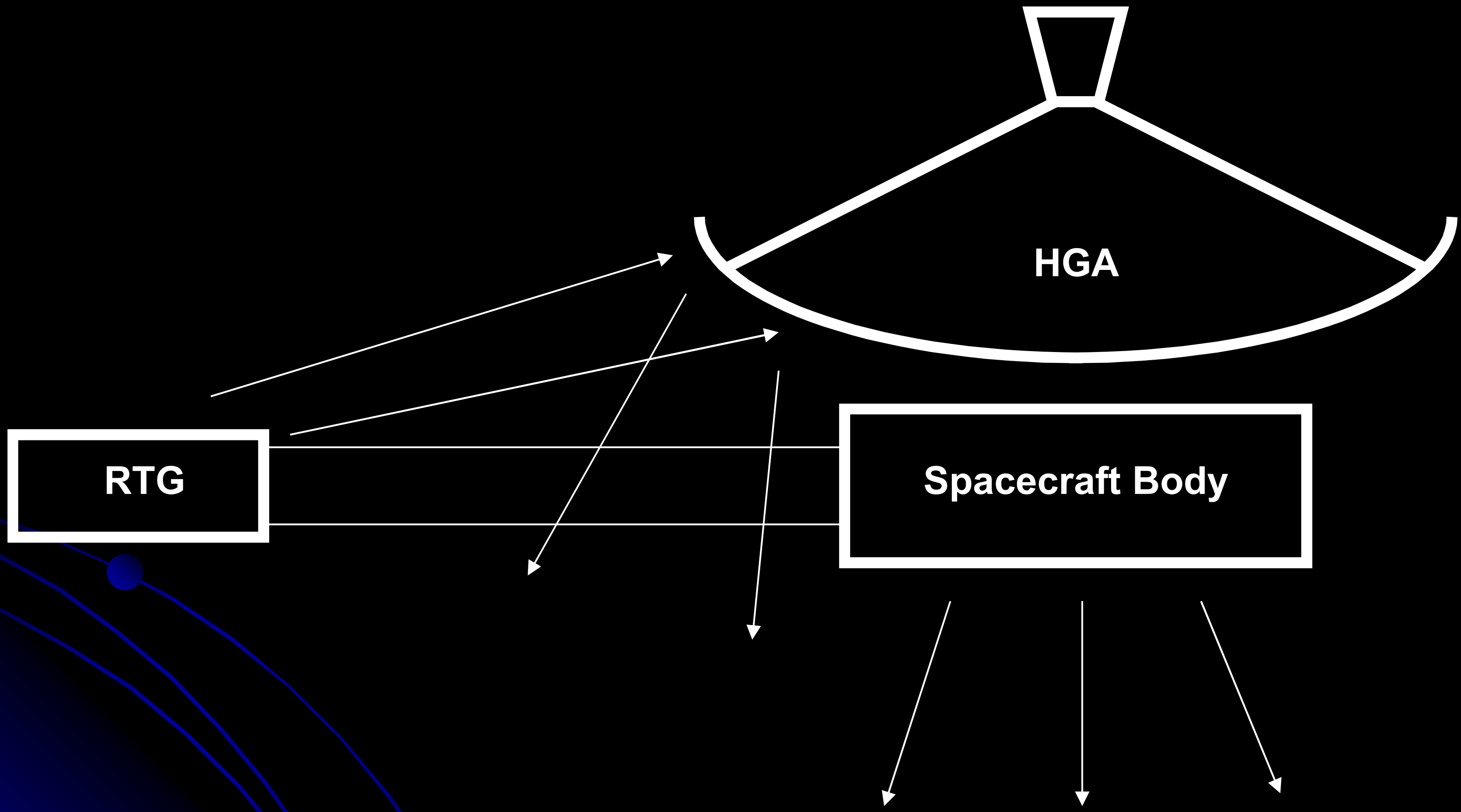
~4.6 kg ^{238}Pu on board



Thermal analysis

- The question: What recoil force is generated by on-board heat?
- Heat sources are easily enumerated:
  - RTG waste heat (~2.5 kW)
  - Electrical heat (~100 W)
  - RHUs (~10 W)
  - Propulsion system (transient)

Thermal recoil geometry



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) explains acceleration

...but dismissed prematurely?

- Dismissed using "back-of-the-envelope" estimates
- "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 thermal hypothesis

- 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

Limits on accuracy

- Spacecraft were built 40 years ago
- Documentation is incomplete, some saved from dumpster
- Some material properties unknown
- Effects of deep space exposure unknown

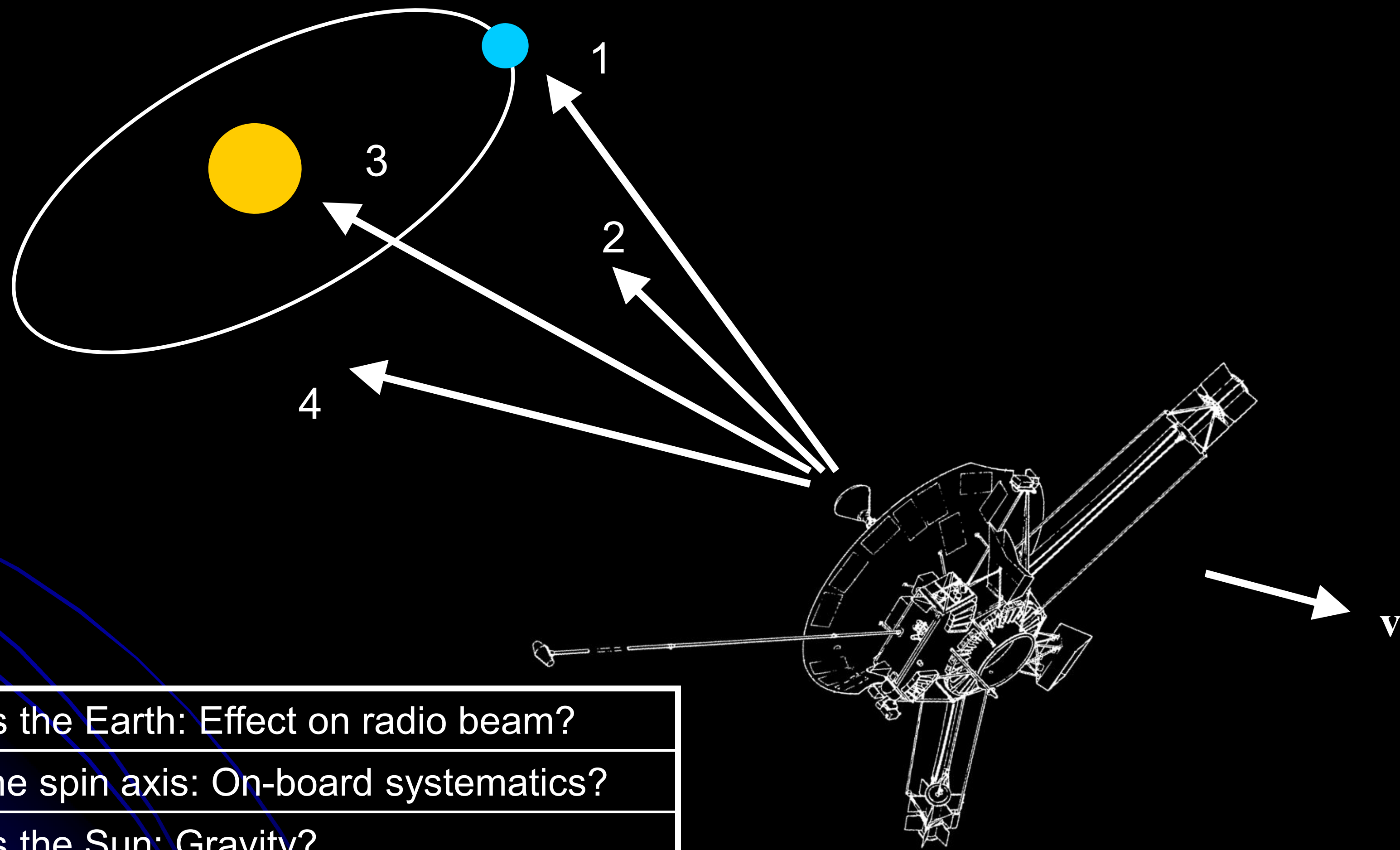
New effort

- Recovered all telemetry from both craft
- Recovered twice the Doppler data
- Recovered project documentation
- New Doppler analysis
- Comprehensive thermal analysis
- New ways to integrate thermal model and trajectory reconstruction

New Doppler analysis

- Using twice the amount of previously available data:
  - ~20 years for Pioneer 10
  - ~10 years for Pioneer 11
- Spot checks possible using early data spans prior to major planetary encounters

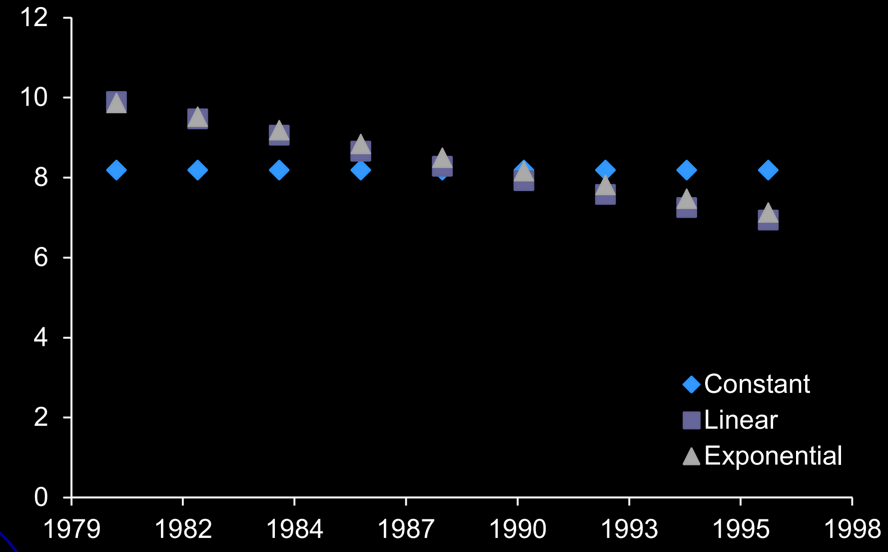
The question of direction



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?~~

Temporal behavior

- Is the acceleration constant or variable?



The navigational solution

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

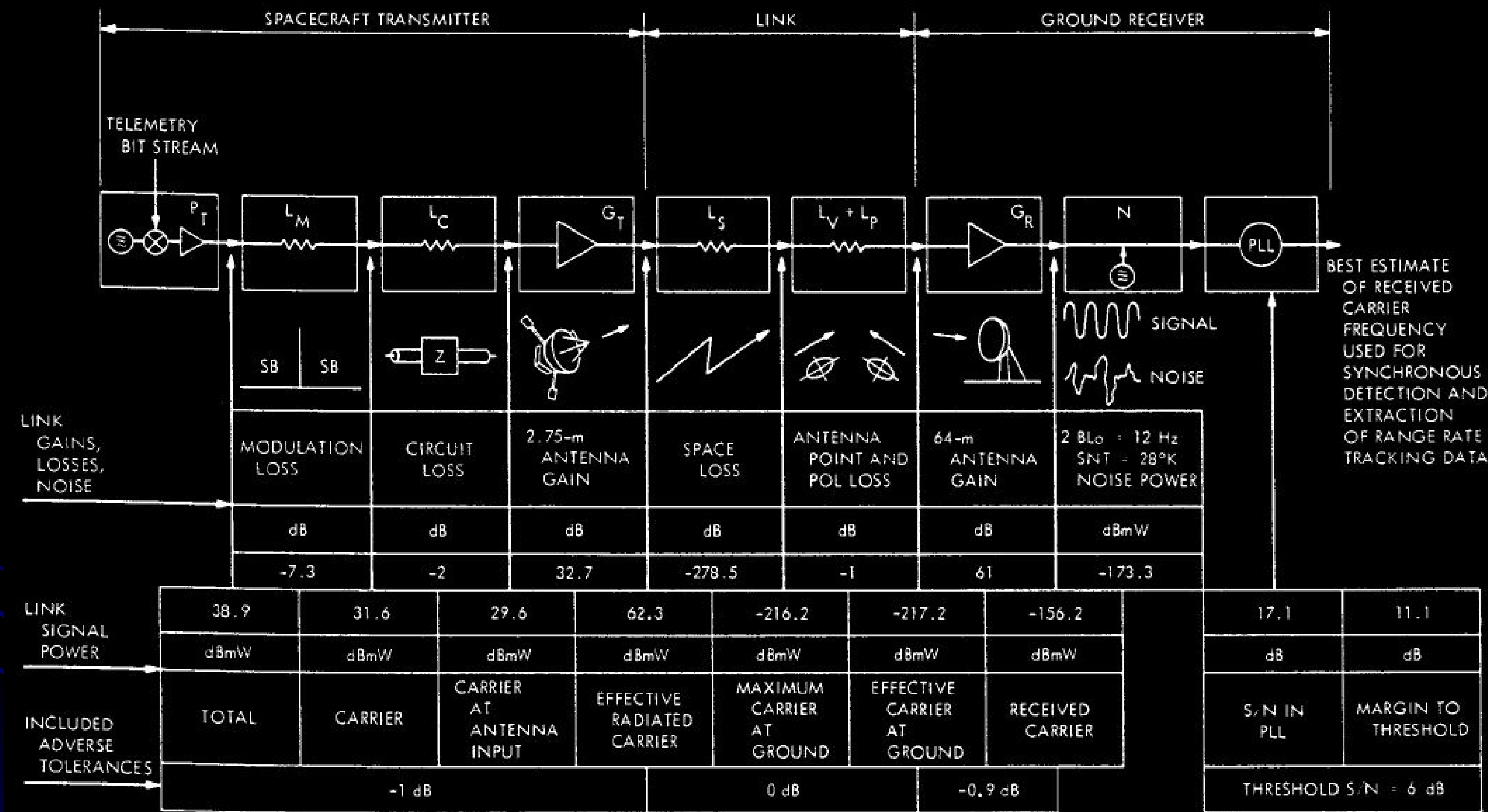
The goodness of fit

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

Accuracy

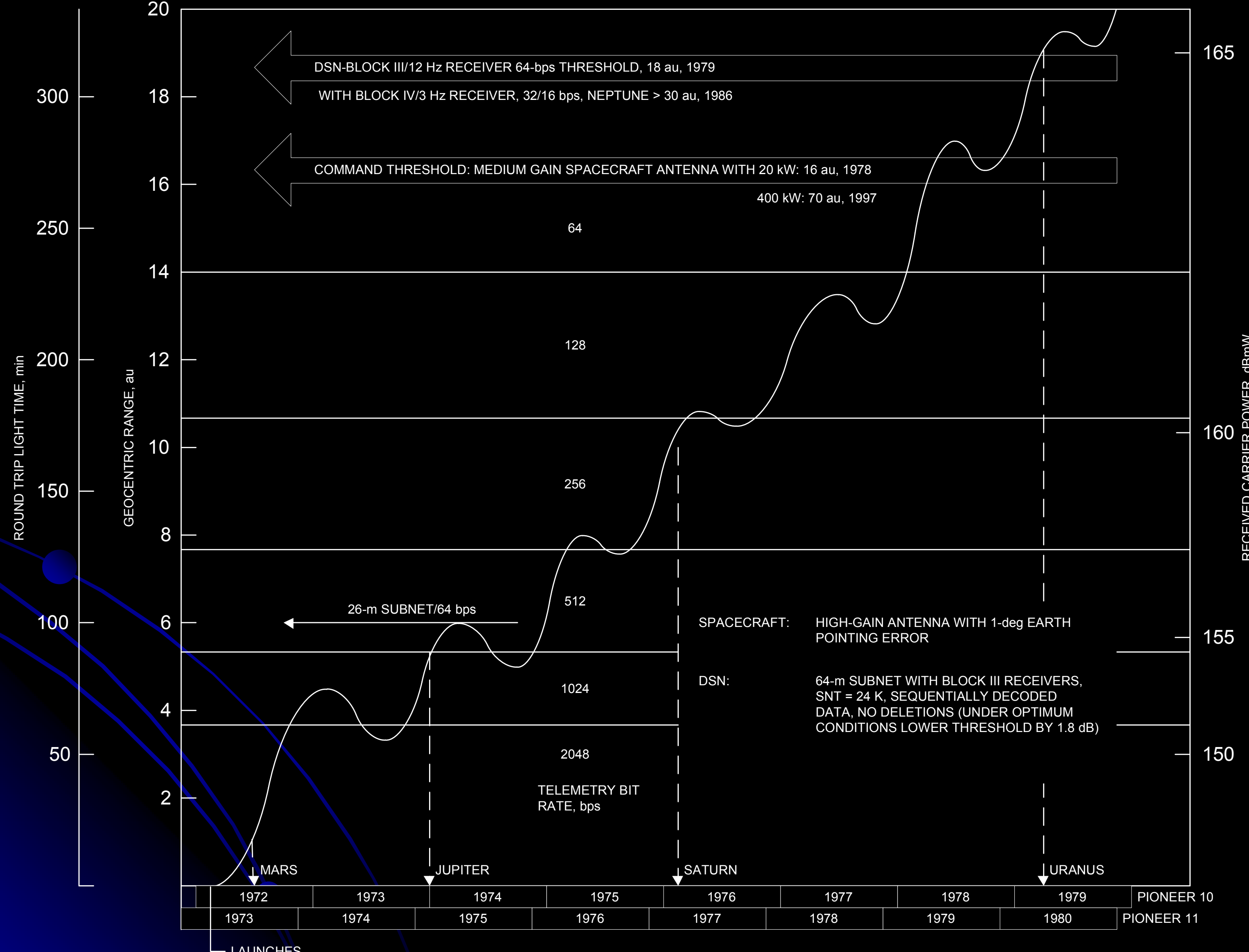
- 2.29 GHz radio signal is modeled with an accuracy of ~2 mHz over a 20 year span
- Measurement and models must be accurate to better than 1 part in 10^{14}
- (IEEE 64-bit double precision floating point accuracy: about 1 part in 10^{16})

Downlink power budget



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

Downlink power budget



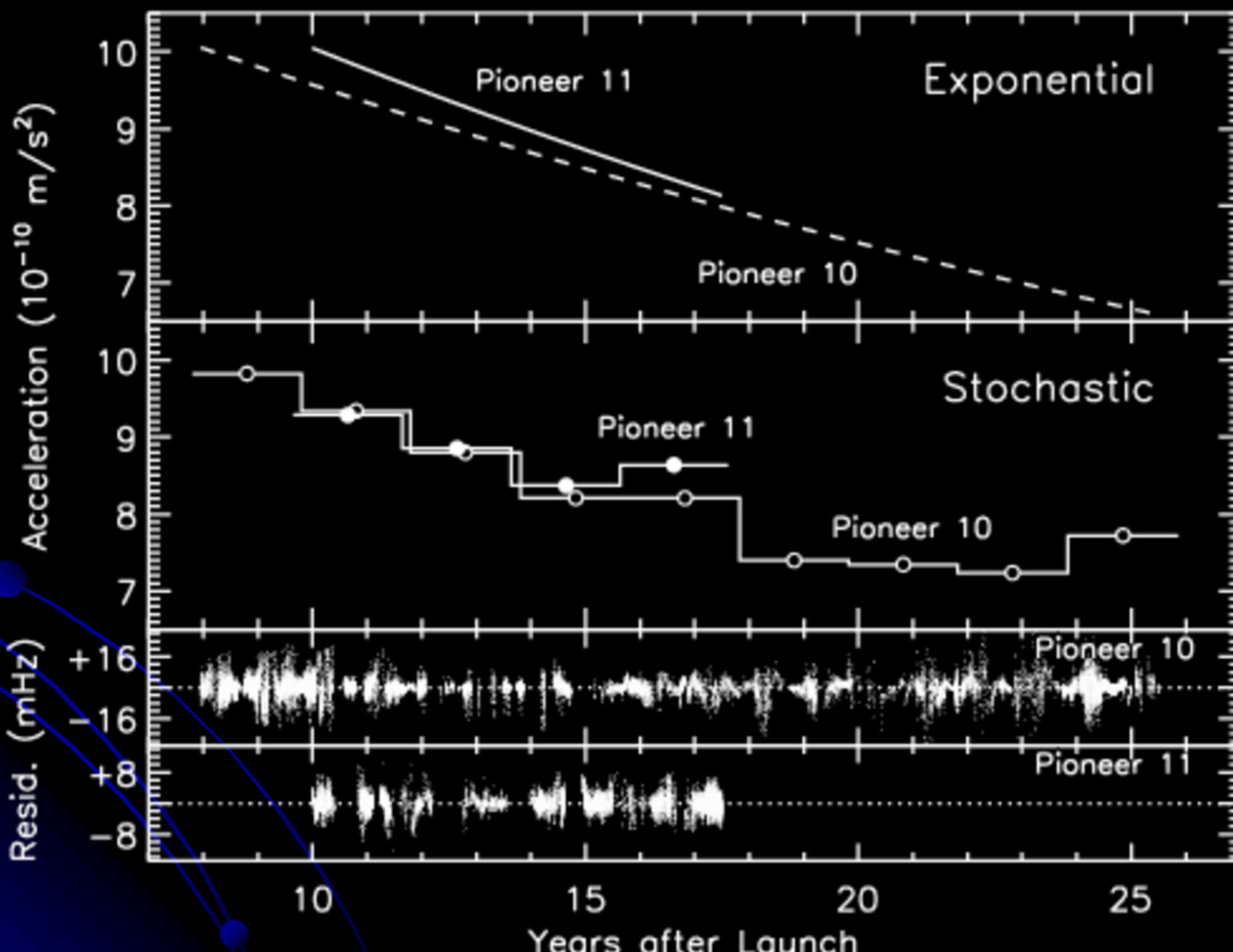
Doppler analysis results

- The anomaly is confirmed with all available Doppler data
- Temporal decay is possible
- Earth direction is possible

Formal vs. “realistic” errors

- Prior studies always quoted very small “formal” errors
- Each Doppler data point was treated as an independent error degree of freedom
- In reality, most of the error is due to systematics: instead of tens of thousands, only a few dozen error degrees of freedom
- Taking this into account, formal and “realistic” errors agree ($\sim 1.5\times10^{-10}$ m/s^2)

Stochastic and exponential models

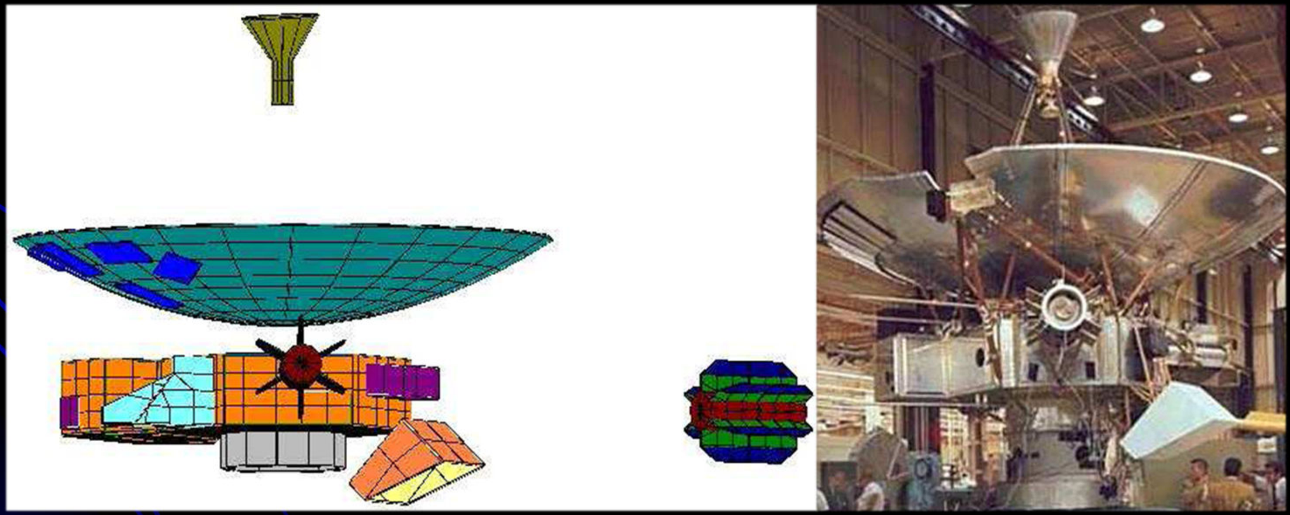


New thermal analysis

- Comprehensive thermal model
- Use of all available data: Validate the model using redundant telemetry
- Model incorporated into the orbit determination code to reconstruct the actual observable (Doppler)

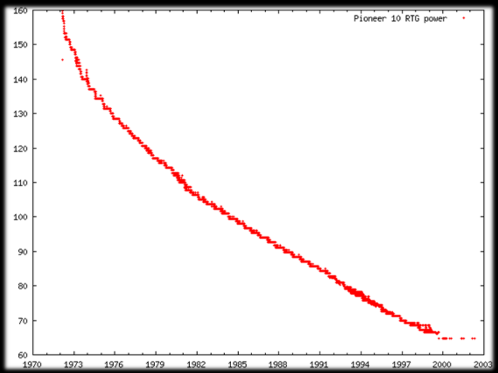
A comprehensive model

- Constructed by JPL engineers using "industry standard" tools and expertise

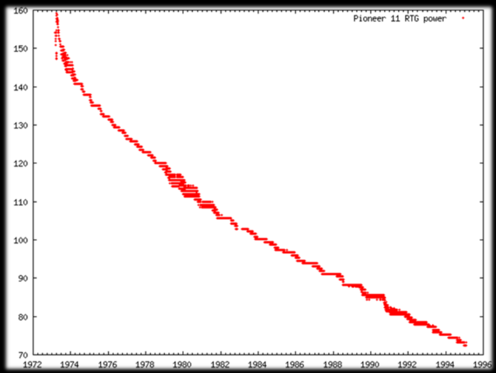


Use of on-board telemetry

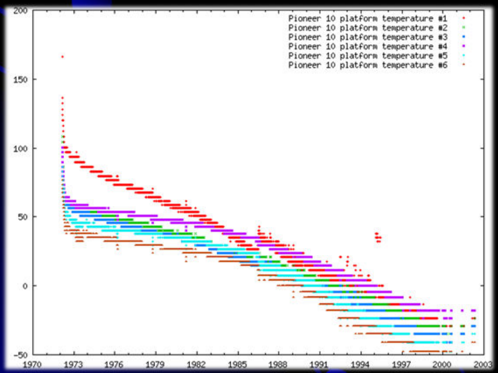
Pioneer 10 RTG power



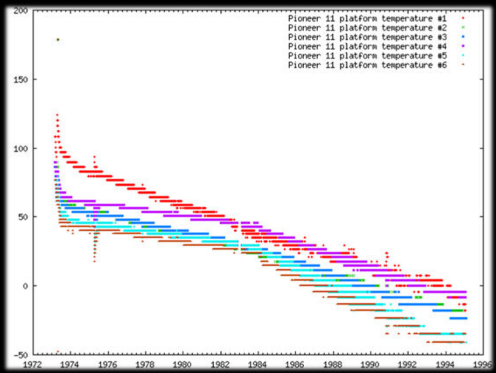
Pioneer 11 RTG power



Pioneer 10 platform temperatures



Pioneer 11 platform temperatures



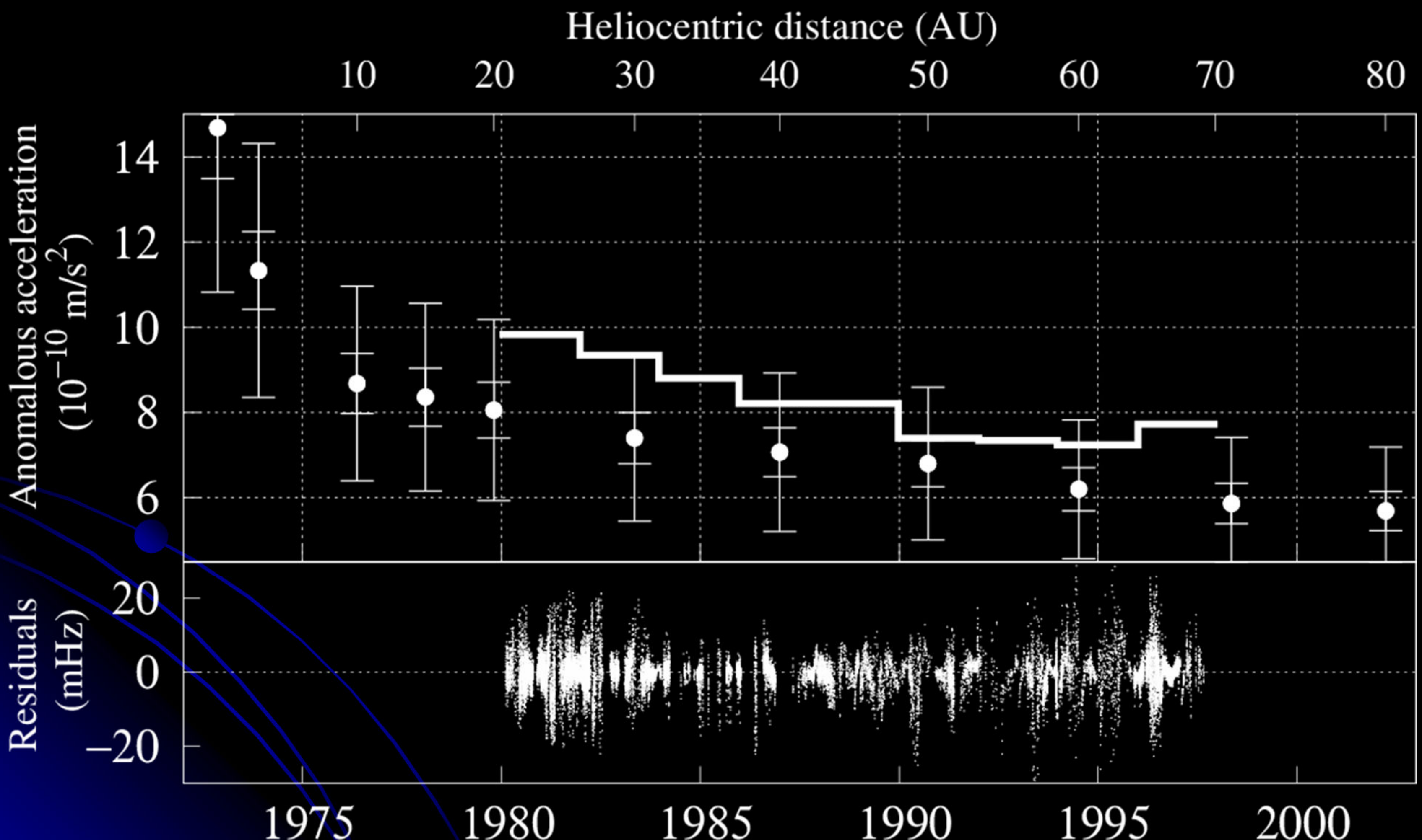
Significance of spin

- 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

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

Thermal results



Linear behavior

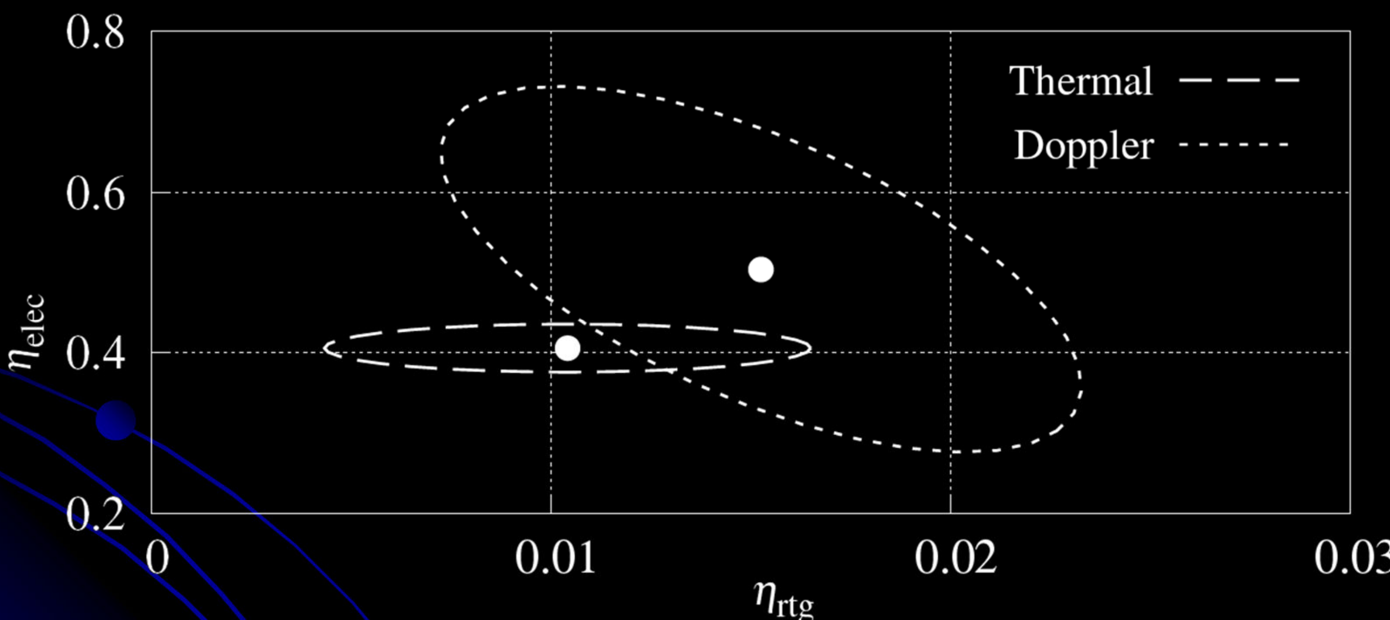
- The two significant non-transient heat sources are electrical and RTG:

$$F \approx c^{-1}\Sigma\eta_i Q_i \qquad (i = \text{rtg, elec})$$

- 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

Comparison

- The η parameters can be estimated independently from thermal analysis or from Doppler fits



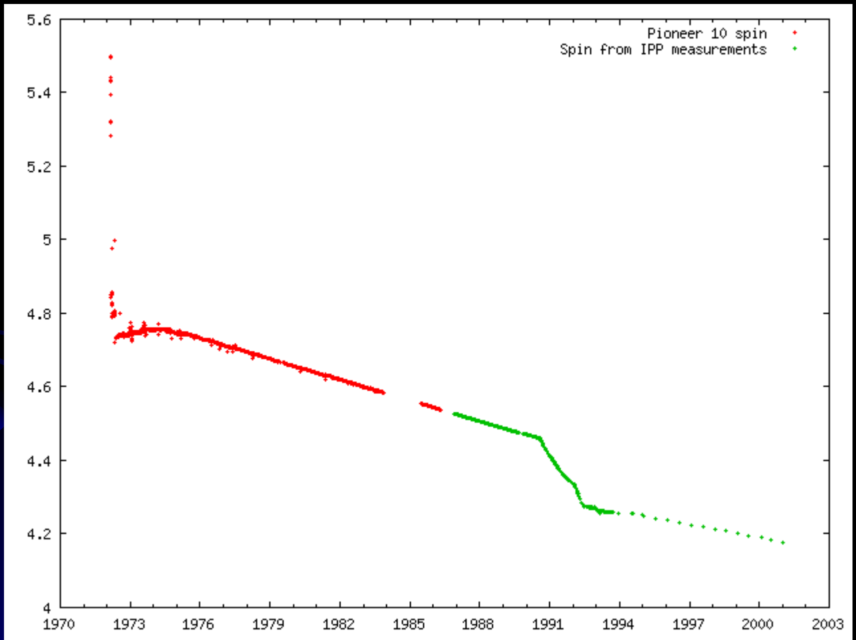
- No statistically significant anomaly remains

Some open questions

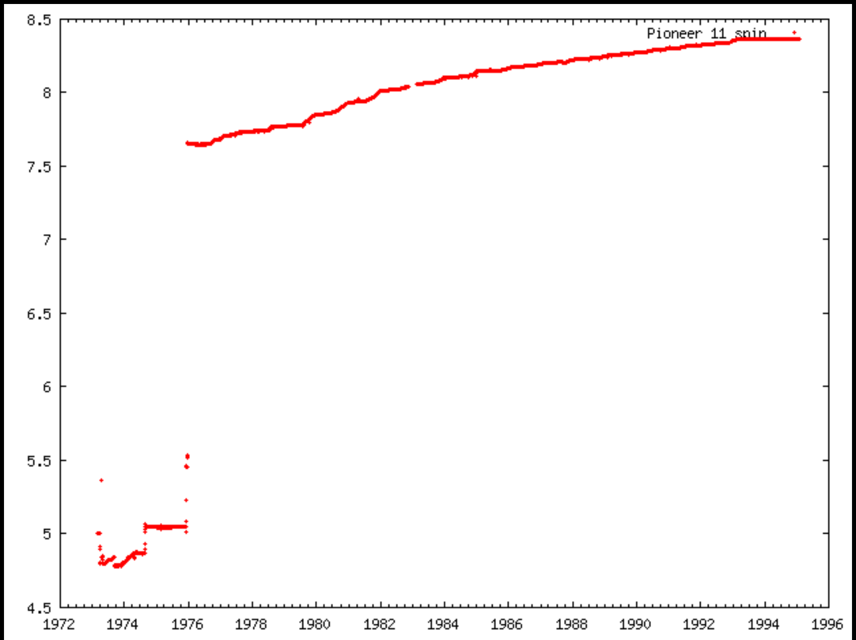
- Behavior of Pioneer 11 (no surprises expected)
- Analysis of spin rate change
- Onset and solar mismodeling
- Outgassing of surface materials
- Autocorrelation analysis
- RTG coating properties
- Using DSN signal strength measurements

Spin history

Pioneer 10 spin

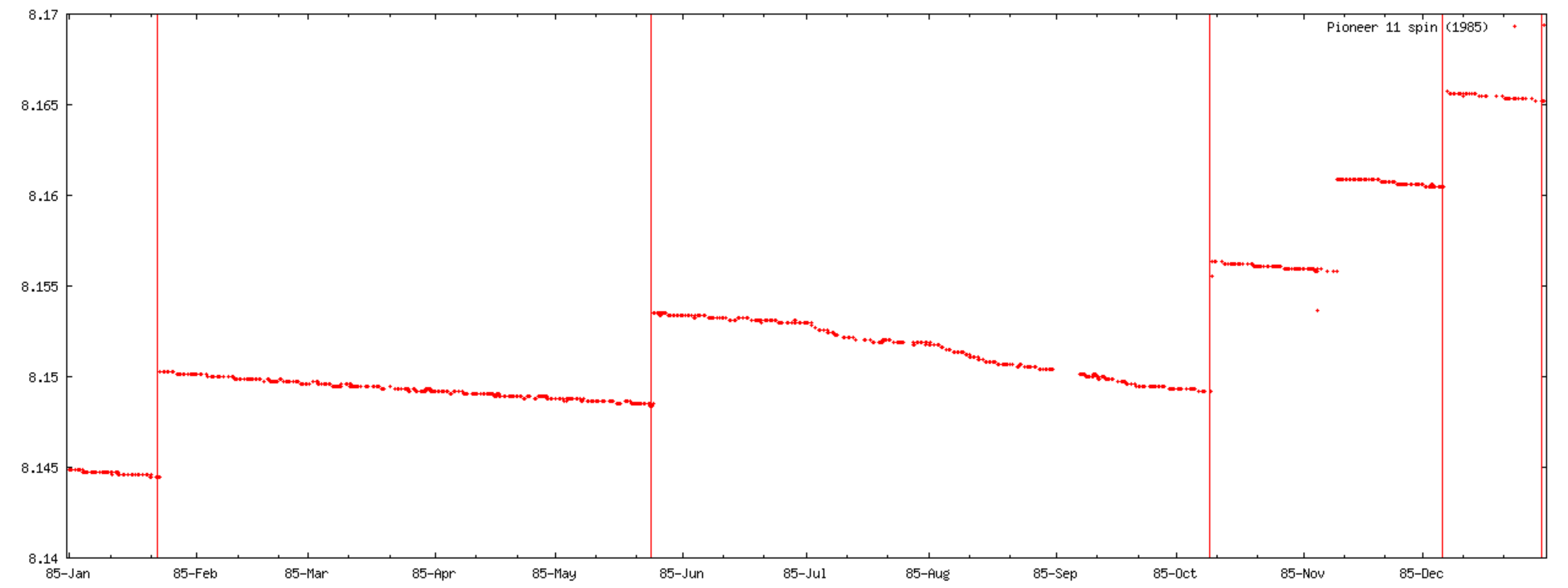


Pioneer 11 spin

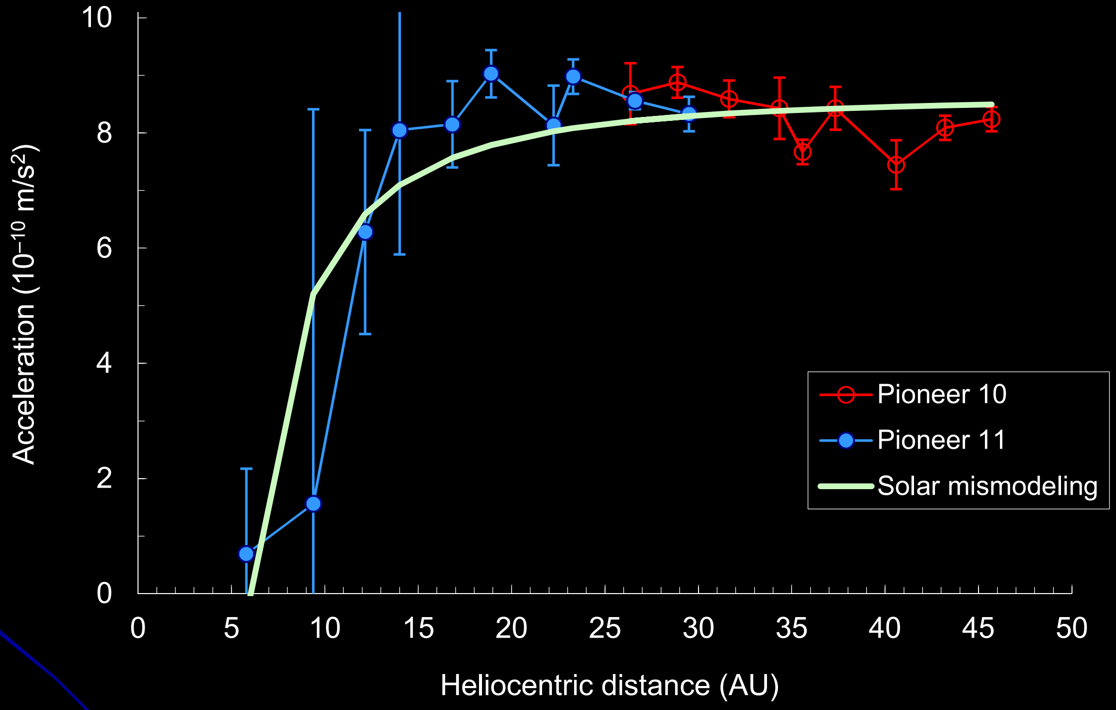


Spin detail

Pioneer 11 spin detail (1985)



Onset



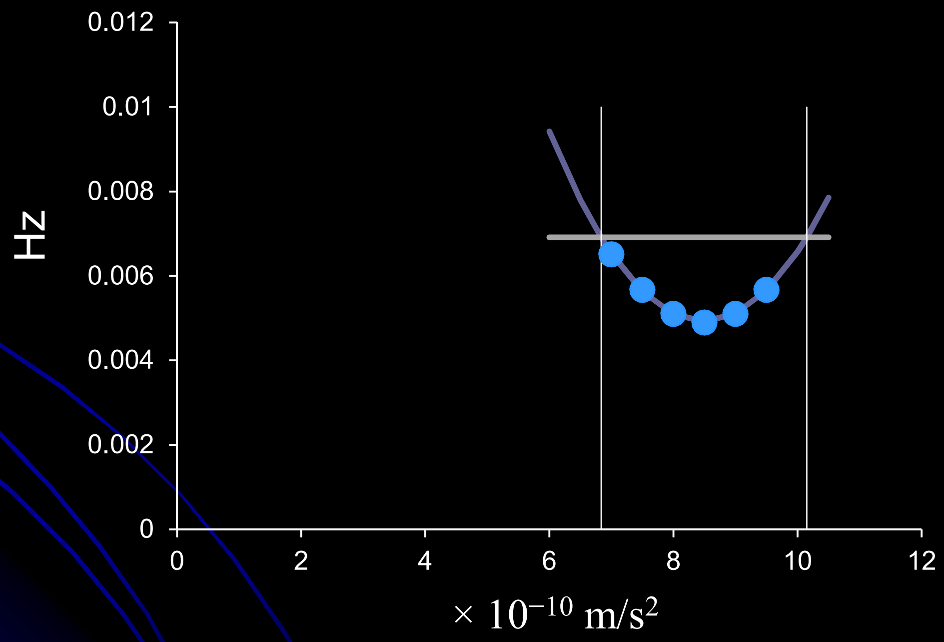
- At 6 AU, spacecraft still receives >225 W of solar heating
- Onset likely an artifact of solar pressure mismodeling

Autocorrelation

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

Effect on residuals

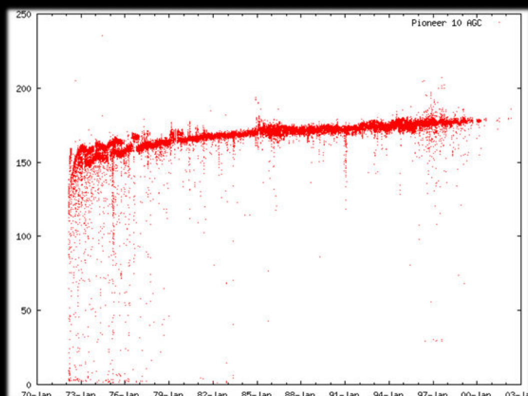
- Detuning the model increases residuals

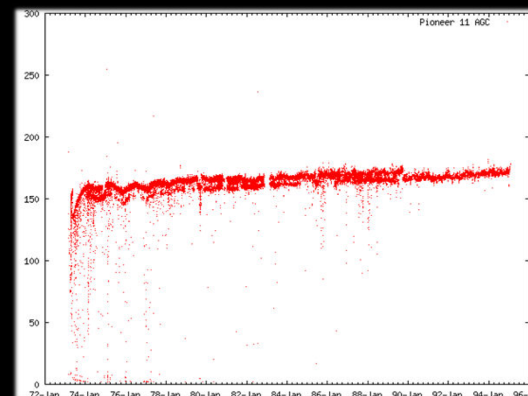


DSN AGC

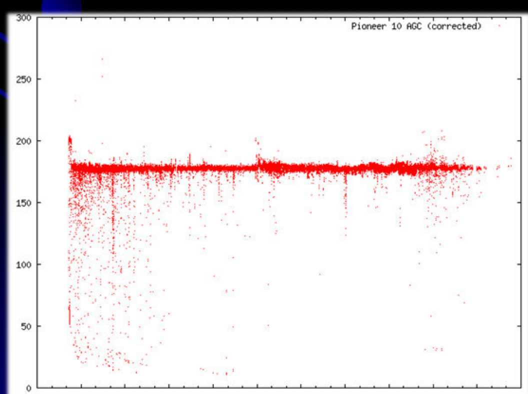
Pioneer 10 AGC

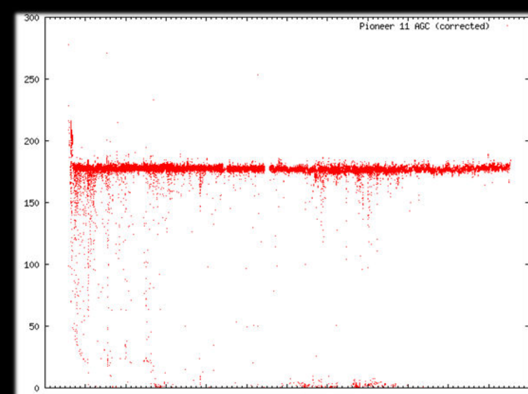
Pioneer 11 AGC





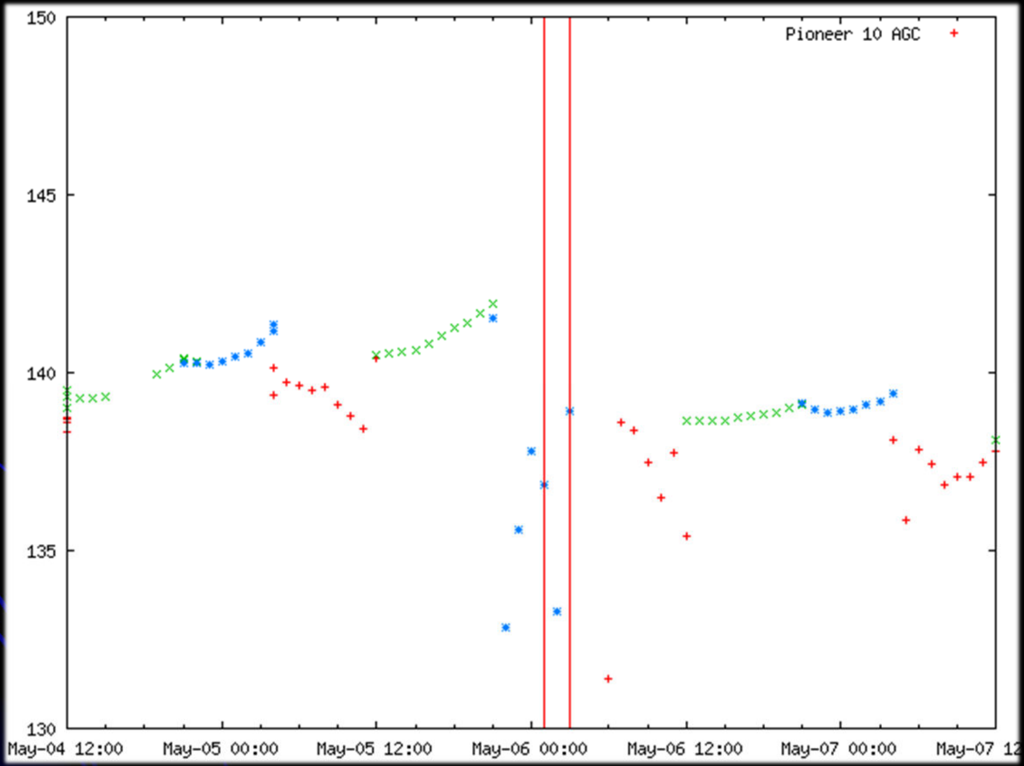
(corrected for distance, antenna size)





DSN AGC detail

Pioneer 10 AGC, May 4-7 1972. Maneuver occurred on May 6; slight improvement in signal strength confirmed in AGC.



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.
- Pioneer 10 and 11 remain the most precisely navigated spacecraft in the outer solar system to date and for the foreseeable future

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 have been marvelous
- The anomaly was probably 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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