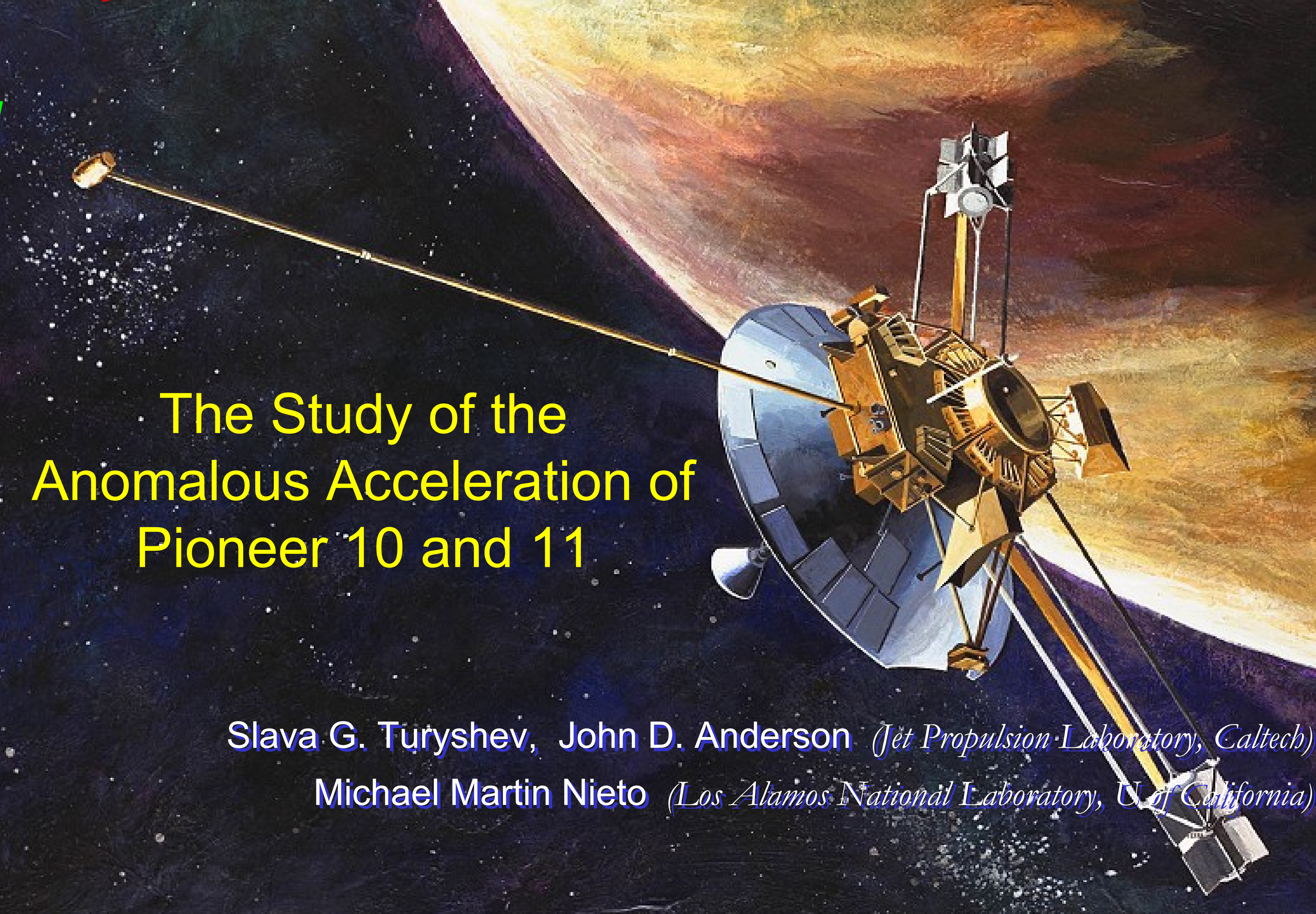


The Study of the Anomalous Acceleration of Pioneer 10 and 11

Slava G. Turyshev, John D. Anderson *(Jet Propulsion Laboratory, Caltech)*
Michael Martin Nieto *(Los Alamos National Laboratory, U of California)*

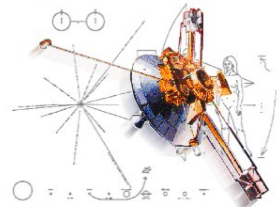
Journées du GREX 2004
Nice, France, 29 October 2004

Pioneer Collaboration:
John D. Anderson, Philip A. Laing, Eunice L. Lau, Michael Martin Nieto and Slava G. Turyshev

Conclusions & Outline:







- The Pioneer 10/11 anomalous acceleration:

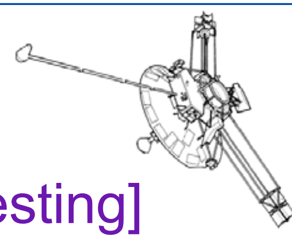
$$a_P = (8.74 \pm 1.33) \times 10^{-8}\ \text{cm/s}^2$$

A line-of-sight constant acceleration *towards* the Sun:

- – We find no mechanism or theory that explains the anomaly
- – Most plausible cause is systematics, yet to be demonstrated

Phys. Rev. D 65 (2002) 082004, gr-qc/0104064

Possible Origin?



- Conventional Physics [not yet understood]:
  - – Gas leaks, heat reflection, drag force, etc…
- New Physics [many proposals exist, some interesting]

- Both are important – a "win-win" situation:
  - – CONVENTIONAL explanation: improvement of spacecraft engineering for precise navigation & attitude control
  - – NEW physics: would be truly remarkable…

Pioneer 10/11 Mission

- Built: TRW (Northrop-Grumman Space Technology)
- Navigation: Jet Propulsion Laboratory, Caltech
- Project management: NASA Ames Research Center

	Pioneer 10	Pioneer 11
Launch	2 March 1972	5 April 1973
Planetary encounters	Jupiter 4 December 1973	Jupiter/Saturn 2 Dec 1974/1 Sep 1979
Mission status	Formally ended 31 March 1997	Last data received 1 October 1990
Distance from the Sun	$\sim$ 67 AU	$\sim$ 30 AU
Direction of motion	Star Aldebaran 2 million years	Constellation of Aquila 4 million years

Position of Pioneer 10 on 29 October 2004:

Distance from Sun	86.91 AU
Position, SE_lat SE_lon	$(3.0^\circ, 77.4^\circ)$
Speed relative to the Sun	12.24 km/sec
Distance from Earth	13.14 Gkm
Round-Trip Light Time	$\approx$ 24 hr 22 min

Last successful precession maneuver to point the spacecraft to Earth was accomplished on 11 Feb 2000 (distance from the Sun of 75 AU)

Pioneer 10/11 Spacecraft





Parameter (identical in design)		Pioneer 10/11
Main bus	Mass, kg	259 (224+36)
2×2 SNAP-19 RTG	Mass/distance, kg/m	13.6/3
Magnetometer	Mass/distance, kg/m	5/6
Moment of inertia, $\mathcal{I}_z$, kg m^2		588.3
High Gain Antenane	Diameter/depth, m	2.74/0.46
Maximal cross-section, m^2		5.914
Attitude control	Spin-stabilization, rpm	~4.28/7.8

Communication system (continuously @ 8 W)			Data available ($\lambda \simeq 13$ cm)
S-up, MHz	S-down, MHz	transp.ratio	
2110	2292	240/221	Doppler
Provide initial position, velocity, magnitudes of maneuvers			

- Pioneer 10/11 were excellent for dynamical astronomy:
  - Spacecraft design permits precise acceleration estimations, ~10^{-8} cm/s^2, unlike a Voyager-type 3-axis stabilization
- Accurate celestial mechanics experiments - one of the main objectives of the Pioneer extended missions

On-board Power and Heat





- **Heat & power source:** 2×2 SNAP-19 RTGs: Teledyne-Brown
  - $_{94}Pu^{238} \rightarrow {}_{92}U^{234} + {}_{2}He^{4}$
  - half life 87.74 years
  - Converts 5 to 6 % of released heat to electric power

Thermal system and on-board power:

Power available:
- before launch electric total 165 W (by 2001 ~ 61 W)
- needs 100 W to power all systems ($\in$ 24.3 W science instruments)

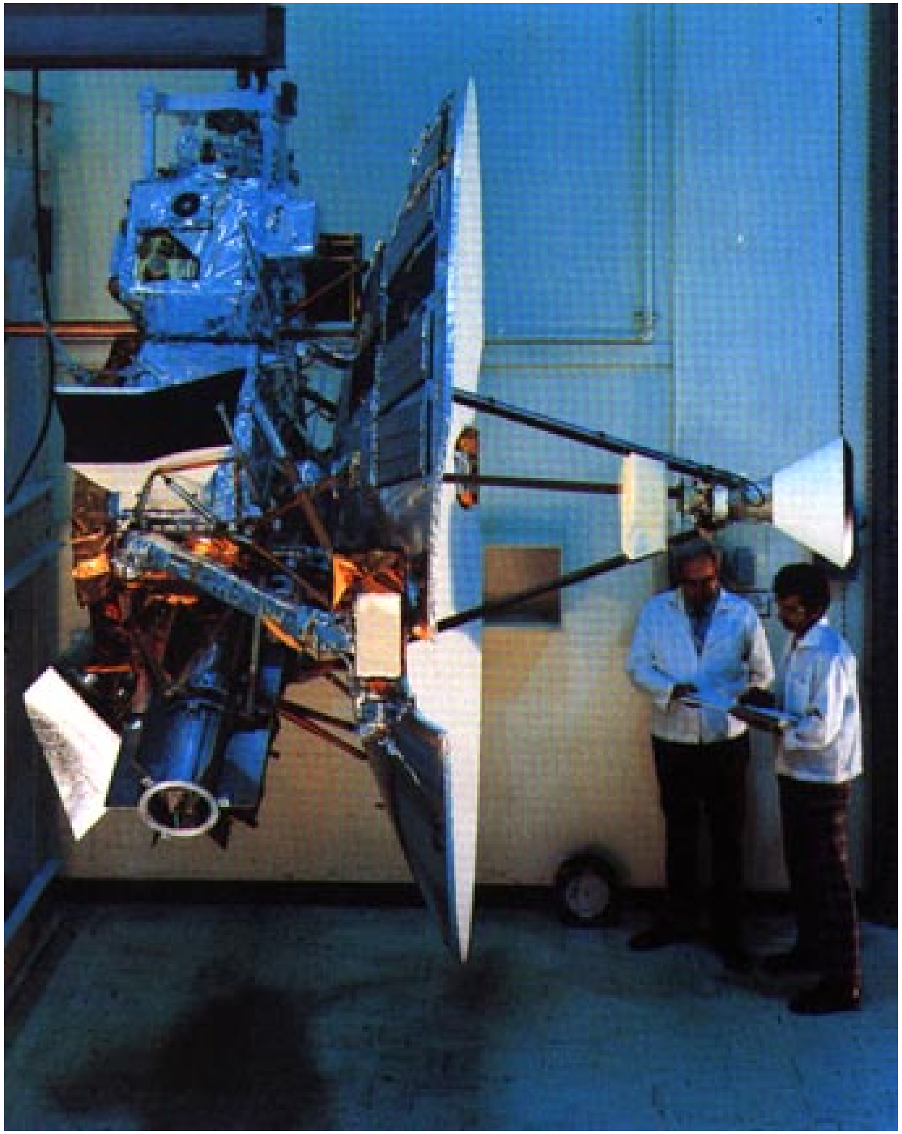
Heat provided:
- before launch thermal fuel total 2580 W (by 2001 ~ 2050 W)
- electric heaters; 12 one-W RHUs
- heat from the instruments (dissipation of 70 to 120 W)

Excess power/heat: if electric power was > 100 W ⇒
- thermally radiated into space by a shunt-resistor radiator, or
- charge a battery in the equipment compartment

Thermal control: ~ 0 - 90 F
- thermo-responsive louvers (bi-metallic springs) ~↓ 40 - ↑ 85 F
- insulation: multi-layered aluminized mylar and kapton blankets

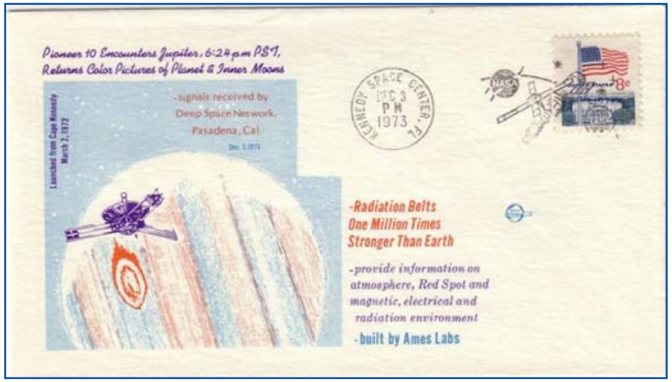
Design based on well understood process of on-board nuclear-to-electric energy conversion and heat dissipation within the craft

Pioneer F during checkout tests

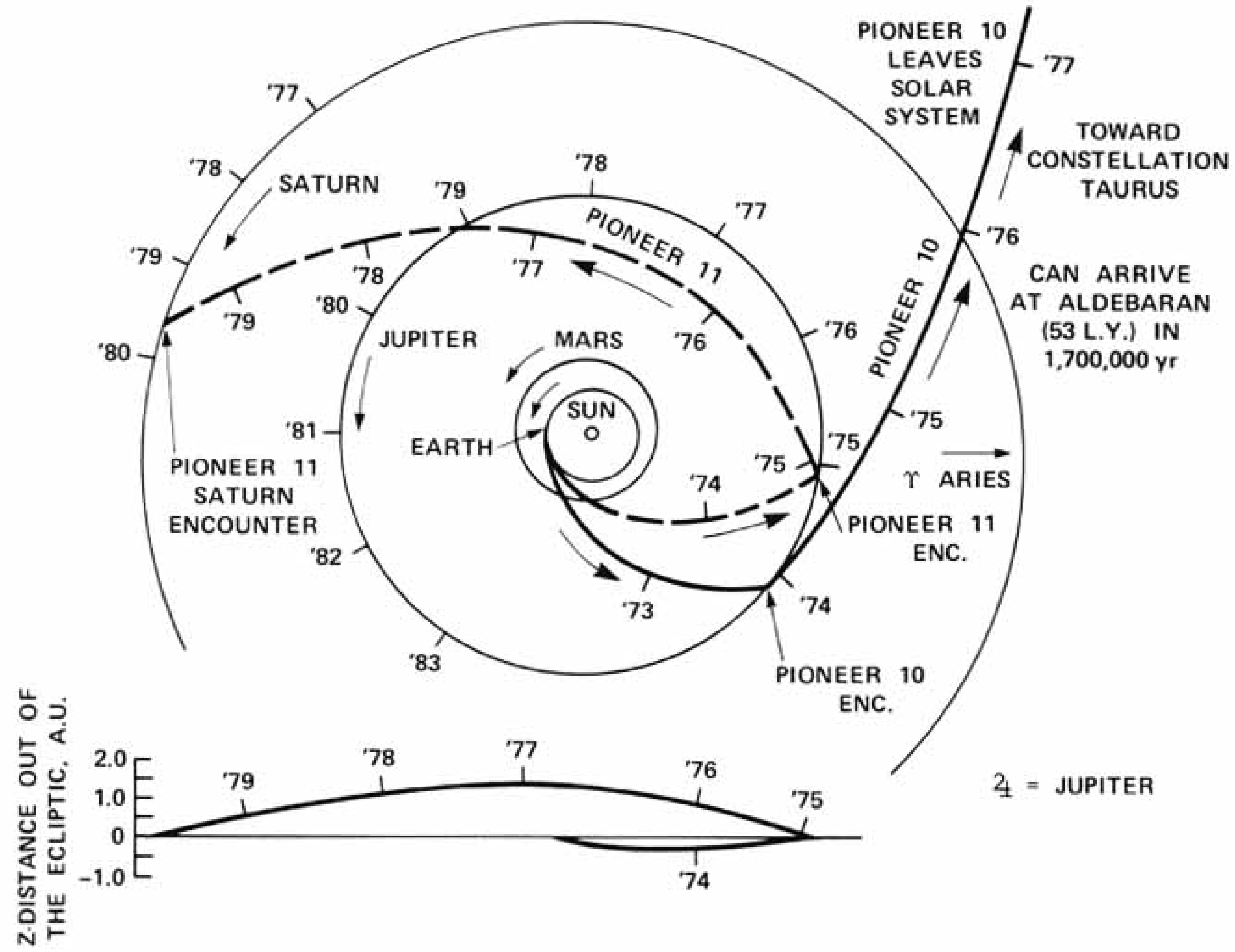


The Pioneer F spacecraft during a checkout with the launch vehicle third stage at Cape Kennedy. Pioneer F became Pioneer 10.

Pioneer 10 Launch: 2 March 1972

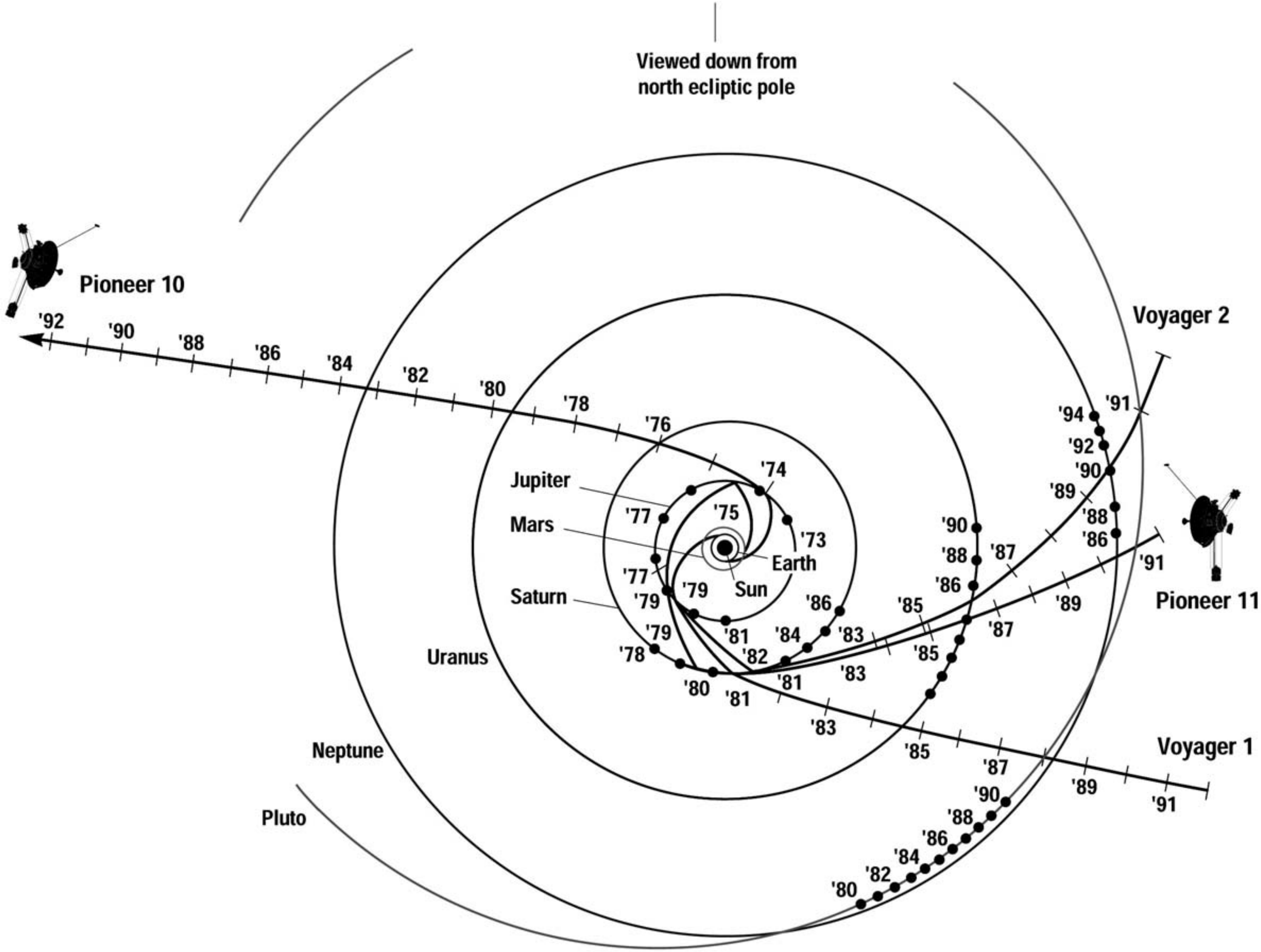


Pioneer 10/11: Main Missions



Trajectories for Pioneer 10 and 11 during the main mission phase

Trajectories of Pioneers and Voyagers



Ecliptic pole view of Pioneer 10, Pioneer 11, and Voyager trajectories. Digital artwork by T. Esposito. NASA ARC Image # AC97-0036-3.

Detection of the Anomaly

- Mid 1979 (search for Planet X with Pioneer 10):
  - Solar-radiation pressure away from the Sun became $< 5 \times 10^{-8}$ cm/s^2
  - Search for unmodeled accelerations started (~ 20AU)
- Early 1980 (Orbit Determination Analysis – ODP):
  - JPL analysis found the biggest systematic error in the accel residuals is a constant bias $a_P \sim (8 \pm 3) \times 10^{-8}$ cm/s^2 directed towards the Sun

Phys. Rev. D 65 (2002) 082004, gr-qc/0104064

An ODP plot of the early unmodeled accelerations of Pioneer 10 and Pioneer 11, from about 1981 to 1989 and 1977 to 1989, respectively

The Observed Anomaly

- In the 1995-98, from the JPL-ODP analysis we concluded:
  - There is an un-modeled acceleration towards the Sun

    $(8.09 \pm 0.20) \times 10^{-8}$ cm/s^2 for Pioneer 10

    $(8.56 \pm 0.15) \times 10^{-8}$ cm/s^2 for Pioneer 11
  - The error is determined with a 5-day BSF with radial accel as a stochastic parameter subject to white Gaussian noise (~500 independent 5-day samples of radial acceleration).
  - NO magnitude variation with distance over a range of 40 to 70 AU

PRL 81(1998) 2858-2861, gr-qc/9808081

The two-way Doppler anomaly to first order in (v/c) behaves as:

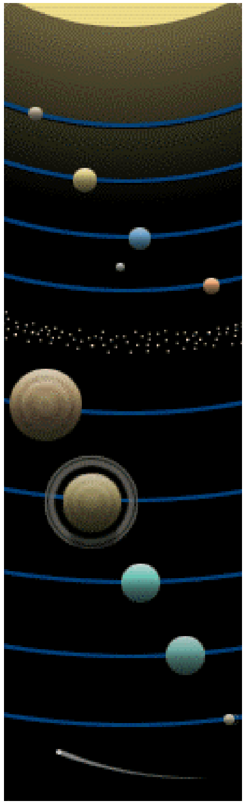
$$\nu_{\tt obs}(t) - \nu_{\tt model}(t) = -\,\nu_0 \frac{2\, a_P\, t}{c} \qquad \nu_{\tt model} = \nu_0 \left[1 - \frac{2\, v_{\tt model}(t)}{c}\right]$$

$$v_{\tt obs}(t) - v_{\tt model}(t) = -\,2\, a_P\, t$$

Equivalent forms of the Anomaly:

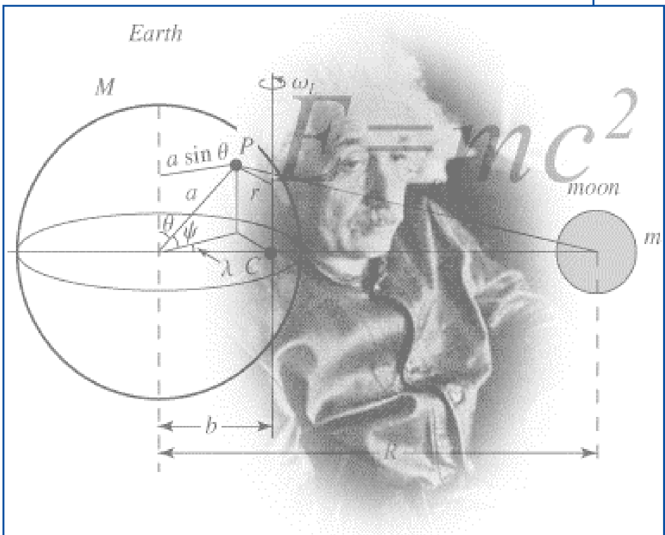
- Steady frequency drift: $-\,\mathbf{6 \times 10^{-9}\ Hz/s}$ $(\approx\mathbf{1.5\ Hz/8\ yrs})$
- Anomalous acceleration: $a_P = \mathbf{(8.65 \pm 0.03) \times 10^{-8}\ cm/s^2}$
- Clock acceleration: $a_t = -\,\mathbf{2.8 \times 10^{-18}\ s/s^2}$, $\quad a_P \equiv a_t c$

Modeling the Motion of Pioneer 10/11



- Relativistic eq.m. for celestial bodies are correct to $(v/c)^4$:
  - Relativistic grav. accelerations (EIH) 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 $(v/c)^2$:

$$
\begin{aligned}
\ddot{\mathbf{r}}_{i\,\text{point mass}} = \sum_{j\neq i} \frac{\mu_j(\mathbf{r}_j-\mathbf{r}_i)}{r_{ij}^3}\Bigg\{ & 1 - \frac{2(\beta+\gamma)}{c^2}\sum_{k\neq i}\frac{\mu_k}{r_{ik}} - \frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} \\
& + \gamma\left(\frac{v_i}{c}\right)^2 + (1+\gamma)\left(\frac{v_j}{c}\right)^2 - \frac{2(1+\gamma)}{c^2}\dot{\mathbf{r}}_i\cdot\dot{\mathbf{r}}_j \\
& - \frac{3}{2c^2}\left[\frac{(\mathbf{r}_i-\mathbf{r}_j)\cdot\dot{\mathbf{r}}_j}{r_{ij}}\right]^2 + \frac{1}{2c^2}(\mathbf{r}_j-\mathbf{r}_i)\cdot\ddot{\mathbf{r}}_j\Bigg\} \\
& + \frac{1}{c^2}\sum_{j\neq i}\frac{\mu_j}{r_{ij}^3}\{[\mathbf{r}_i-\mathbf{r}_j]\cdot[(2+2\gamma)\dot{\mathbf{r}}_i-(1+2\gamma)\dot{\mathbf{r}}_j]\}(\dot{\mathbf{r}}_i-\dot{\mathbf{r}}_j) \\
& + \frac{(3+4\gamma)}{2c^2}\sum_{j\neq i}\frac{\mu_j\ddot{\mathbf{r}}_j}{r_{ij}} \quad + \sum_{m=1}^{3}\frac{\mu_m(\mathbf{r}_m-\mathbf{r}_i)}{r_{im}^3} \quad + \sum_{c,s,m}\mathbf{F}
\end{aligned}
$$



$$
t_2 - t_1 = \frac{r_{21}}{c} + \frac{(1+\gamma)\mu_\odot}{c^3}\ln\left[\frac{r_1^\odot+r_2^\odot+r_{12}^\odot}{r_1^\odot+r_2^\odot-r_{12}^\odot}\right] + \sum_i \frac{(1+\gamma)\mu_i}{c^3}\ln\left[\frac{r_1^i+r_2^i+r_{12}^i}{r_1^i+r_2^i-r_{12}^i}\right]
$$

Standard Models of Non-Gravitational Forces





- Model accounts for many sources of non-grav. forces, including:
  - Solar radiation and wind pressure; the interplanetary media
  - Attitude-control propulsive maneuvers; gas leakage from the propulsion system
  - DSN antennae contributions to the spacecraft radio tracking data
  - Torques produced by above mentioned forces
- 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):
- Now [after Pioneer] model can be adjusted to include:
  - Effects of the recoil force due to emitted radio power
  - Anisotropic thermal radiation of spacecraft

- Unknown forces are routinely modeled as stochastic accels:
  - Exponentially correlated in time, with a variable time constant
  - Stochastic variable was sampled in 0-, 5-,10-day batches

Models Used to Explain the Anomaly

- Models and suggestions that failed to explain the anomaly:
  - Non-gravitational effects:
    - Solar pressure, solar wind, interplanetary medium
    - Precessional attitude control maneuvers and "gas leaks"
    - Nominal thermal radiation, plutonium half life
  - Some viscous drag force (ULY: solar radiation, maneuvers)
  - Gravity from the Kuiper belt; gravity from the Galaxy
  - Dark Matter distributed in a halo around the solar system
  - Drifting clocks, general relativity, the "speed of gravity"
  - Hardware problems at the DSN tracking stations
  - Errors in the planetary ephemerides
  - Errors in the values of the EOP, precession, and nutation;
  - Identical design of Pioneer 10/11 spacecraft (GLL, ULY: solar radiation, maneuvers)

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

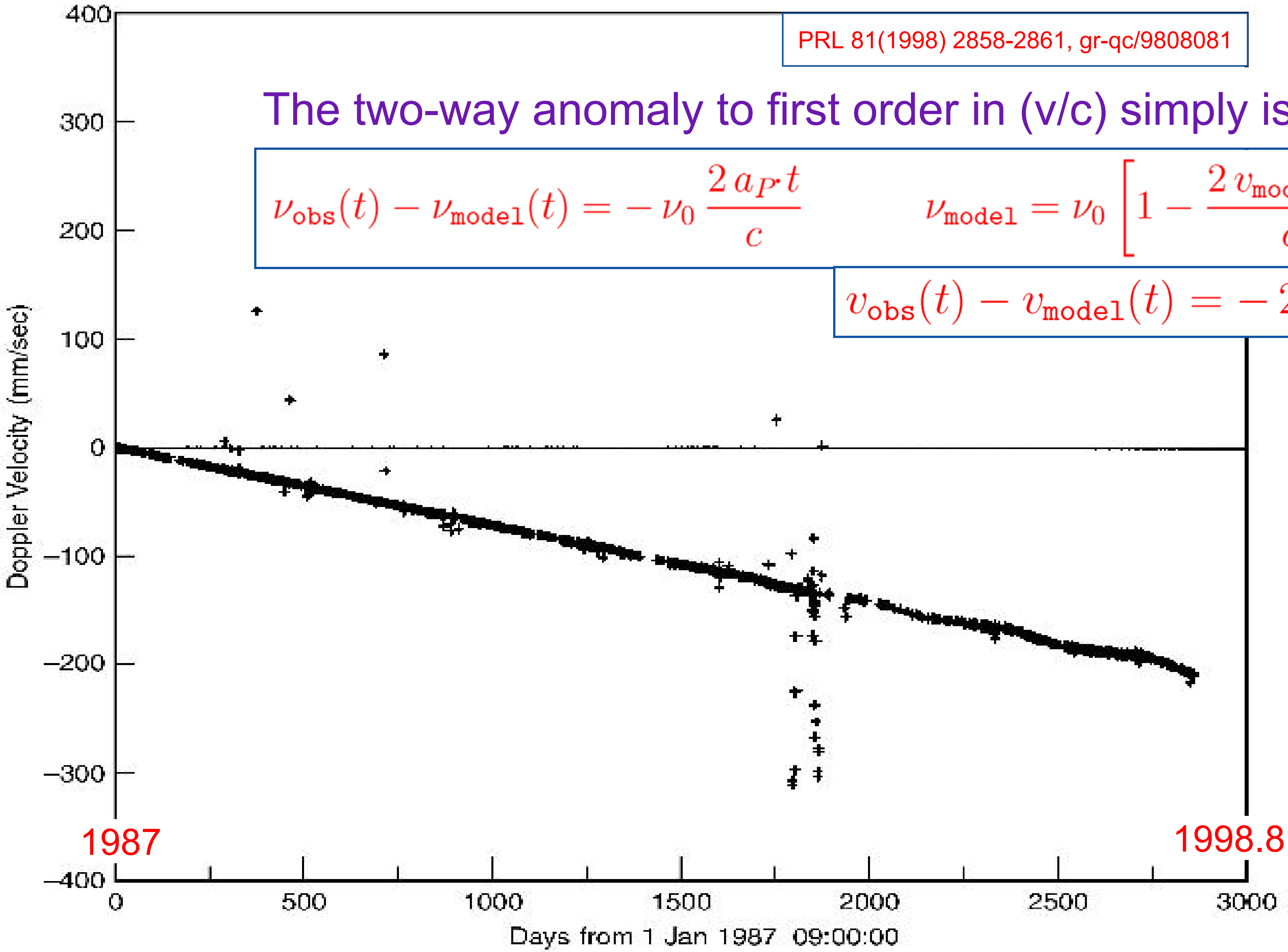
The Pioneer Anomaly

PRL 81(1998) 2858-2861, gr-qc/9808081

The two-way anomaly to first order in (v/c) simply is:

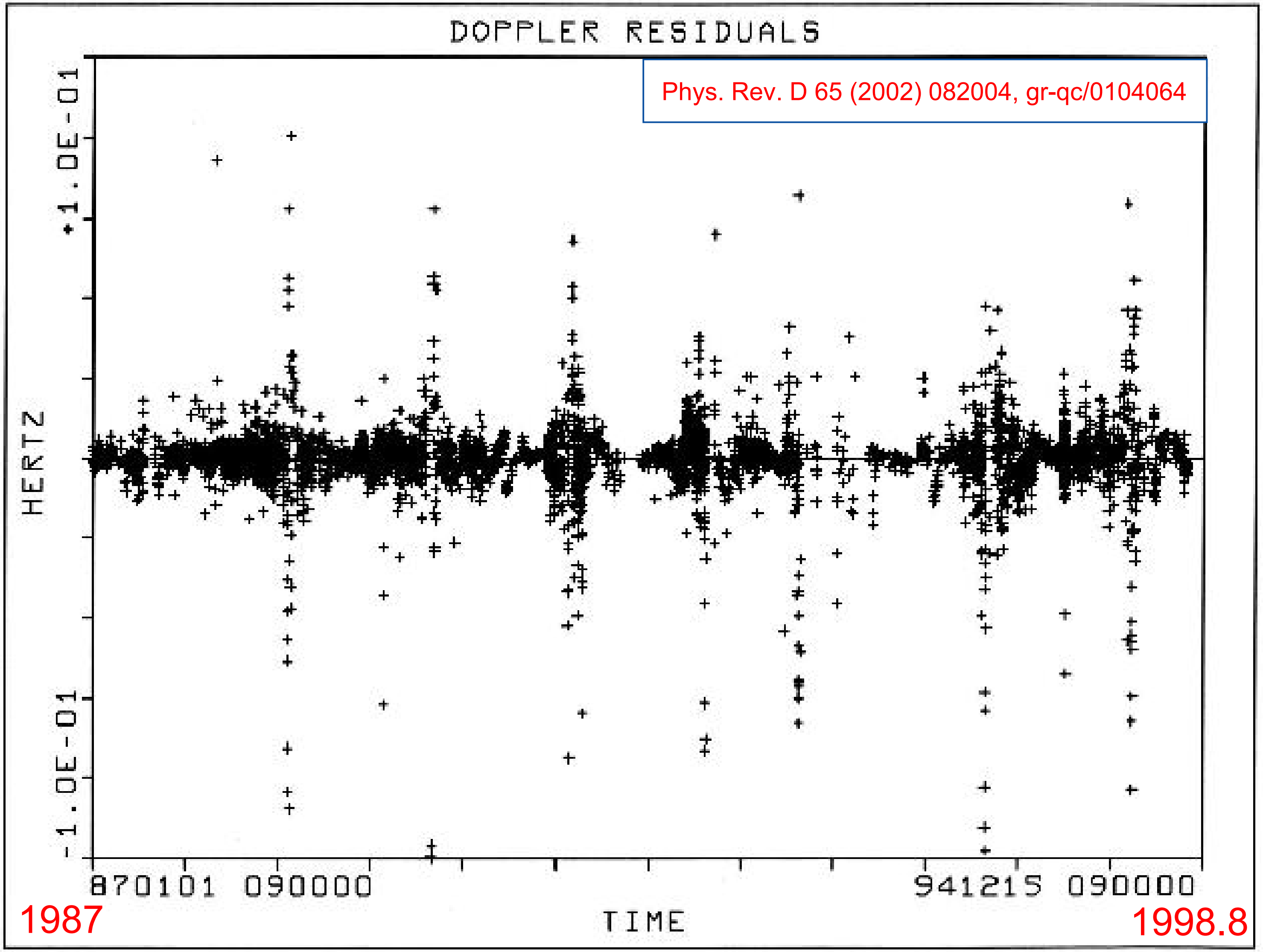
$$\nu_{\rm obs}(t) - \nu_{\rm model}(t) = -\nu_0 \frac{2 a_P t}{c} \qquad \nu_{\rm model} = \nu_0 \left[1 - \frac{2 v_{\rm model}(t)}{c}\right]$$

$$v_{\rm obs}(t) - v_{\rm model}(t) = -2 a_P t$$



CHASMP two-way Doppler residuals (observed Doppler velocity minus model Doppler velocity) for Pioneer 10 vs time. [1 Hz is equal to 65 mm/s range change per second]

The Pioneer Anomaly



Adding 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. The quality of the fit may be determined by the ratio of residuals to the downlink carrier frequency, $\nu_0 \approx 2.29$ GHz.

Sources of External Systematic Error [PRD, 2002]

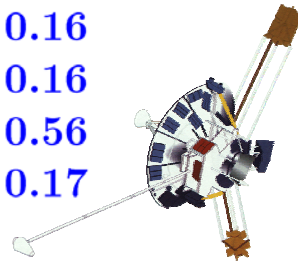
Error budget constituents	Bias 10^{-8} cm/s^2	Uncertainty, 10^{-8} cm/s^2
⇛ Solar radiation pressure		$\pm\ 0.001$
⇛ From the mass uncertainty	$+0.03$	$\pm\ 0.01$
⇛ Solar wind		$\pm < 10^{-5}$
⇛ The effects of the solar corona		$\pm\ 0.02$
⇛ Electro-magnetic Lorentz forces		$\pm < 10^{-4}$
⇛ Influence of the Kuiper belt's gravity		$\pm\ 0.03$
⇛ Influence of the Earth orientation		$\pm\ 0.001$
⇛ Mechanical and phase stability of DSN antennae		$\pm < 0.001$
⇛ Phase stability and clocks		$\pm < 0.001$
⇛ DSN station location		$\pm < 10^{-5}$
⇛ Troposphere and ionosphere		$\pm < 0.001$

Error budget constituents	Bias 10^{-8} cm/s^2	Uncertainty, 10^{-8} cm/s^2
⇛ Numerical stability of least-squares estimation		$\pm\ 0.02$
⇛ Accuracy of consistency/model tests		$\pm\ 0.13$
⇛ Mismodeling of maneuvers		$\pm\ 0.01$
⇛ Mismodeling of the solar corona		$\pm\ 0.02$
⇛ Annual/diurnal terms		$\pm\ 0.32$

Interesting, but not a major source of concern!

Sources of On-board Systematic Error [PRD, 2002]

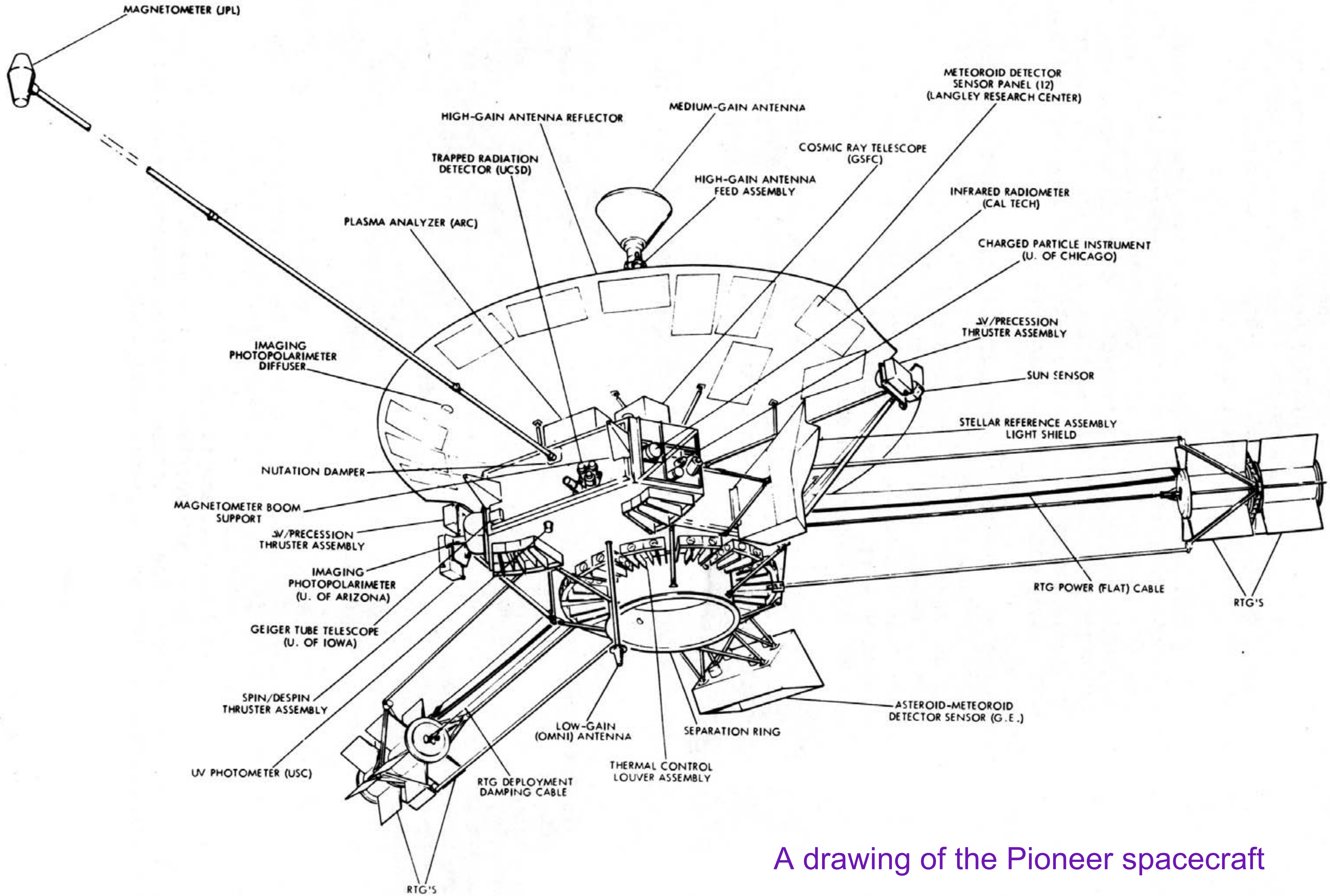
Error budget constituents	Bias 10^{-8} cm/s^2	Uncertainty, 10^{-8} cm/s^2
⇛ Radio beam reaction force	+1.10	± 0.11
⇛ Thermal/propulsion effects from RTGs:		
⇛ RTG heat reflected off the craft	−0.55	± 0.55
⇛ Differential emissivity of the RTGs		± 0.85
⇛ Non-isotropic radiative cooling of s/c		± 0.16
⇛ Expelled He produced within the RTGs	+0.15	± 0.16
⇛ Propulsive mass expulsion: gas leakage		± 0.56
⇛ Variation between s/c determinations	+0.17	± 0.17



Pioneer DSN antenna at Goldstone

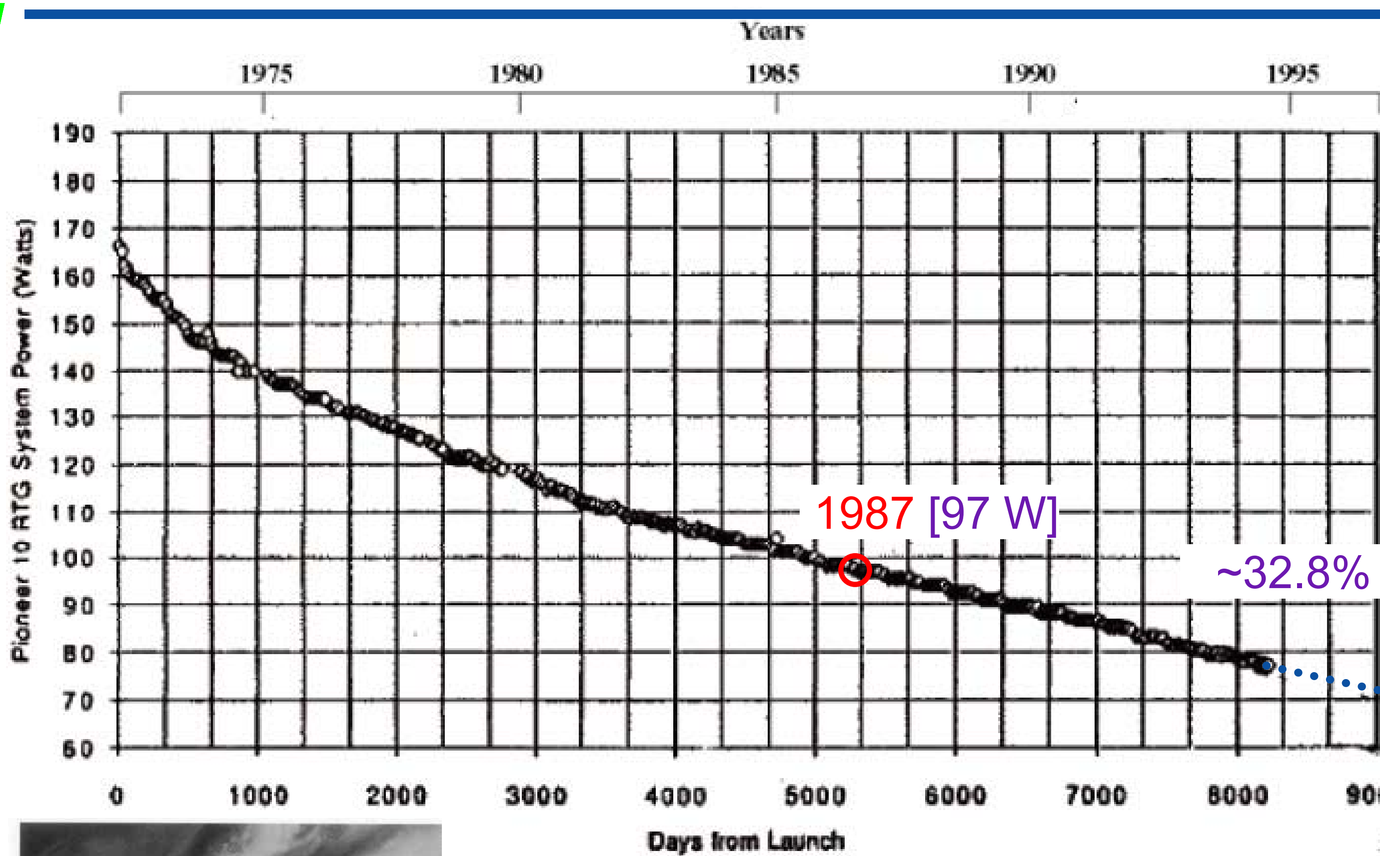
Phys. Rev. D 65 (2002) 082004, gr-qc/0104064

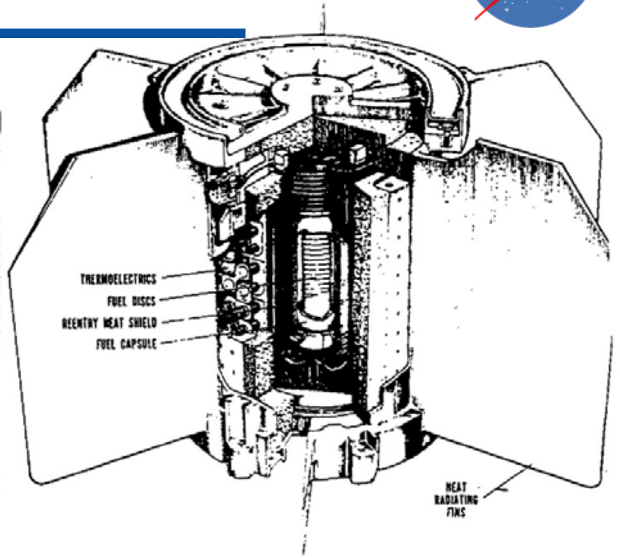
Pioneer 10/11 spacecraft



A drawing of the Pioneer spacecraft

On-board Power and Heat





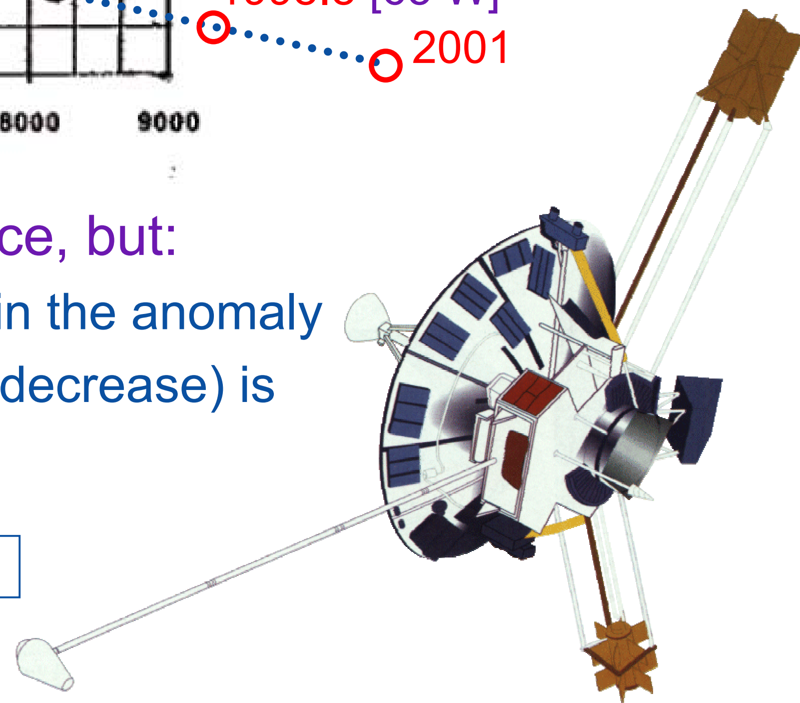
SNAP 19/PIONEER RADIOISOTOPE THERMOELECTRIC GENERATOR

Pioneer 10

Heat is clearly important source, but:

- NOT strong enough to explain the anomaly
- Exponential decay (or linear decrease) is NOT seen in the anomaly a_P

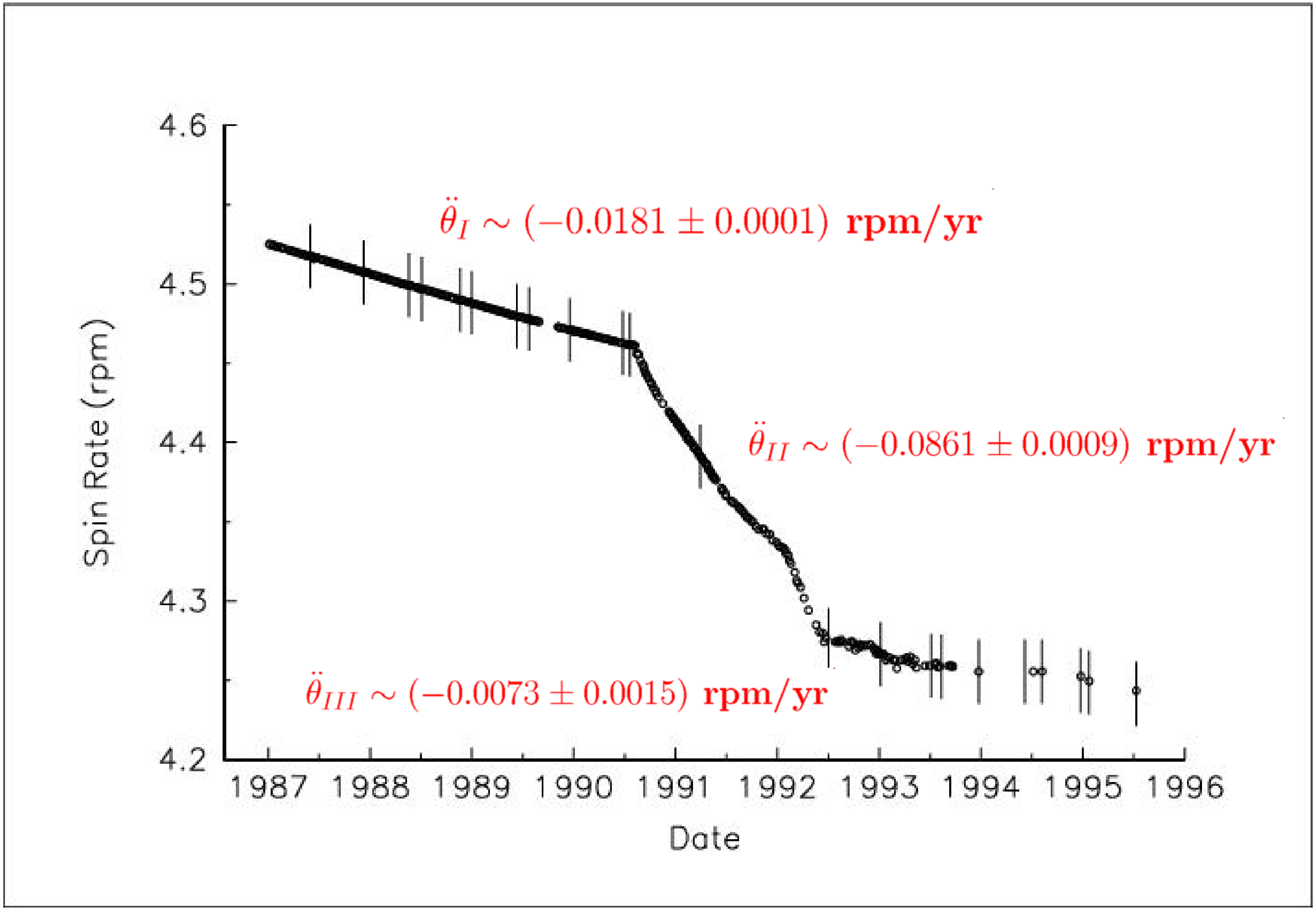
IJMP A 17 (2002) 875-885, gr-qc/0107022



New Focus: the Pioneer 10 Spin History





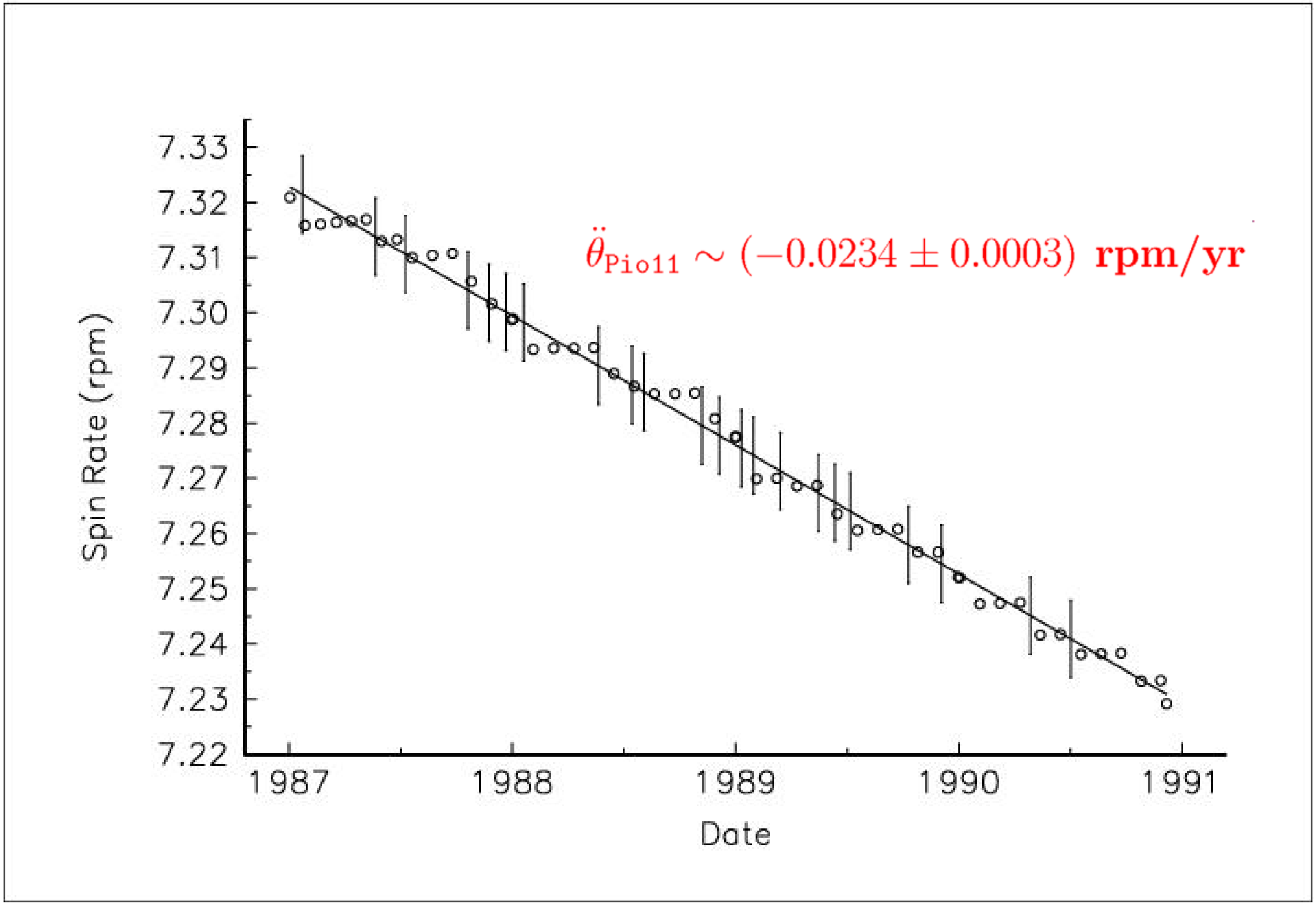


Most spacecraft show "spin-down" behavior usually due to structure tiredness, connection loosening, etc.

Pioneer 11 Spin History

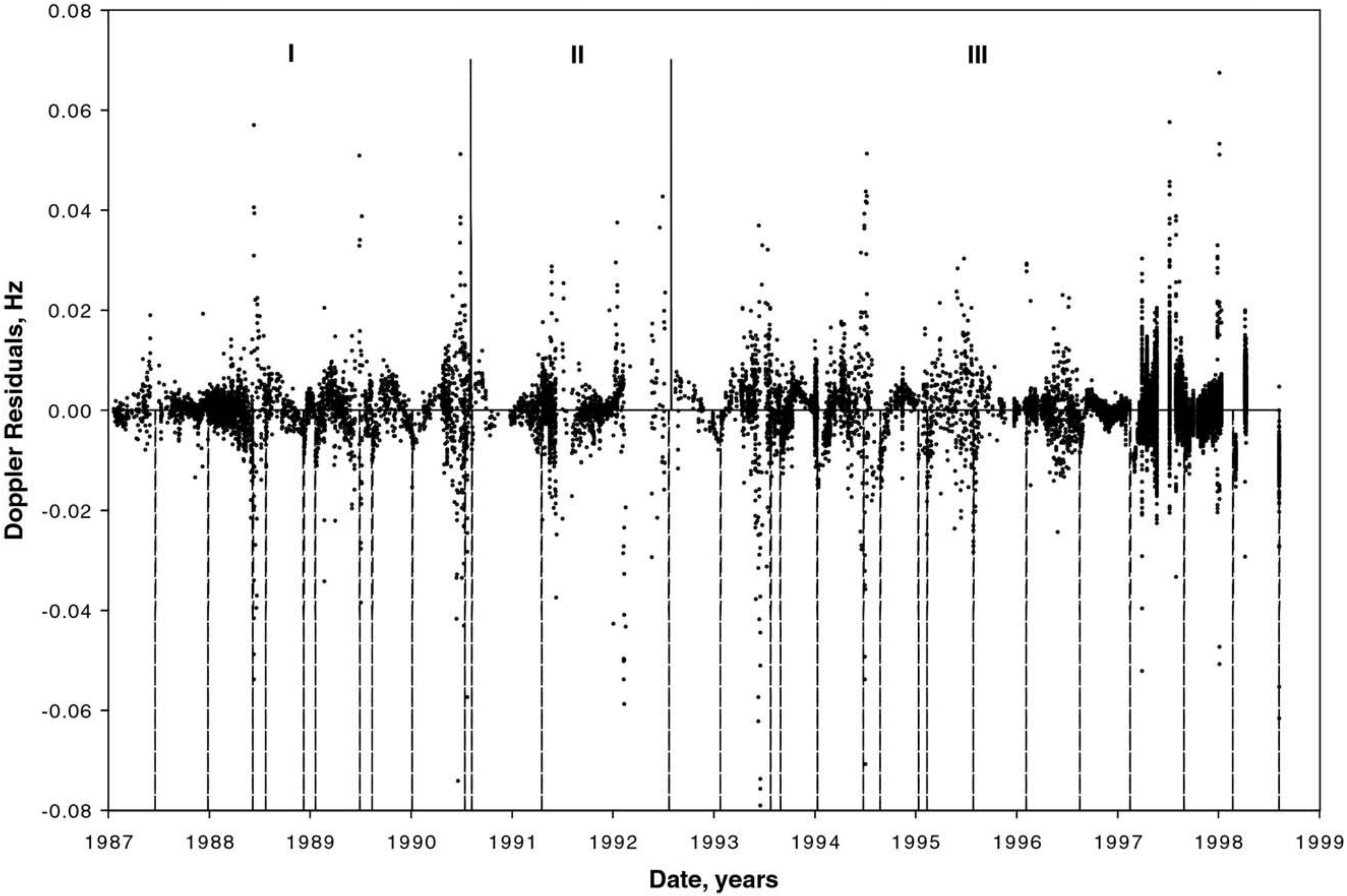






Causes for "de-spin" are different: Pioneer 11 spin increases in between the maneuvers, leaking thruster?

ODP/Sigma residuals



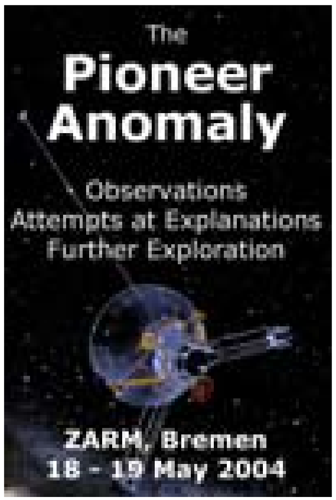
ODP/Sigma Doppler residuals in Hz for the entire Pioneer 10 data span. The two solid vertical lines indicate the boundaries between data Intervals I/II and II/III. Maneuver times are indicated by the vertical dashed lines.

The Pioneer Anomaly: Summary

- Our latest result for the Pioneer 10/11 anomalous acceleration:

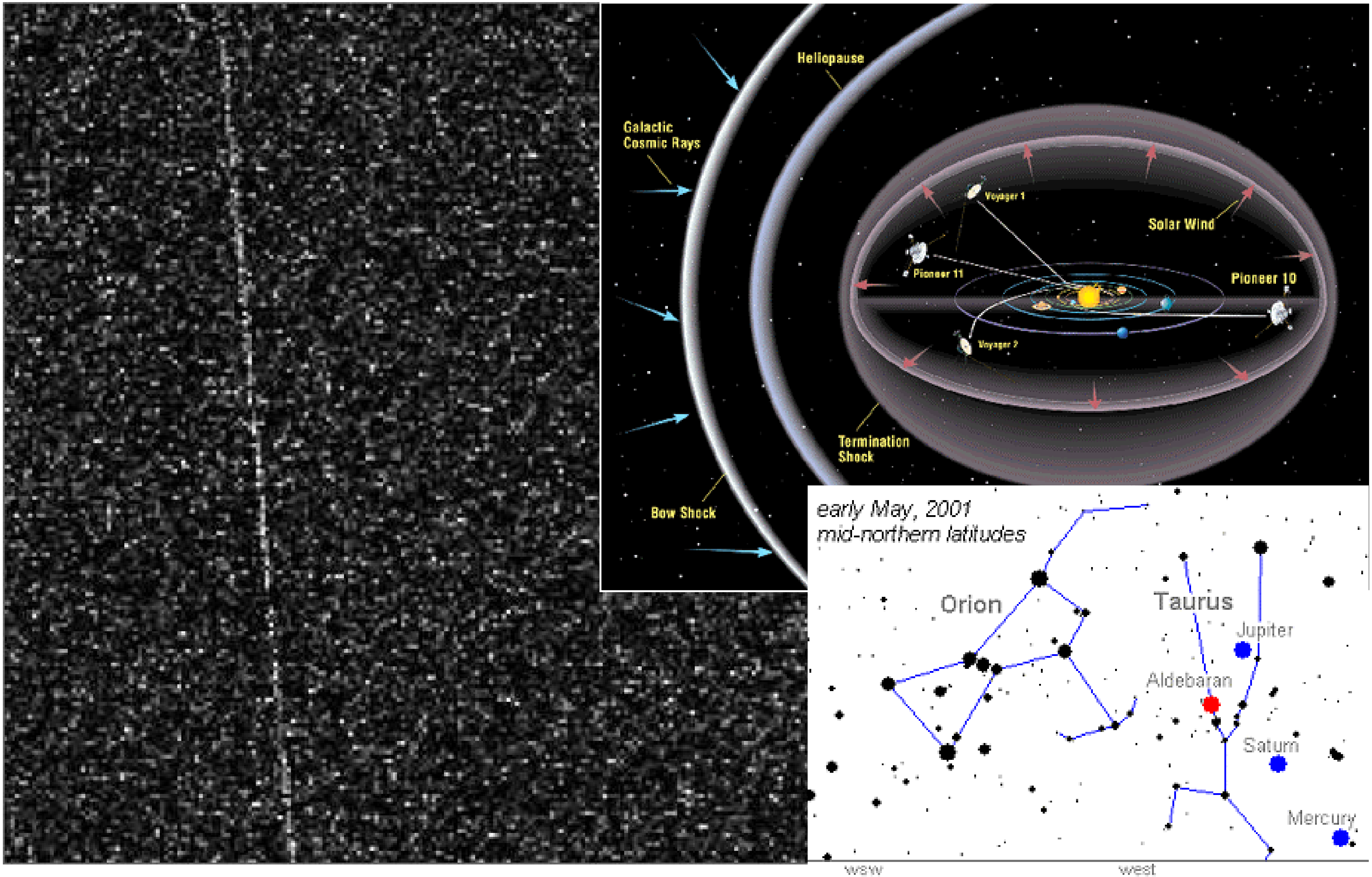
$$a_P = (8.74 \pm 1.33) \times 10^{-8}\ \mathrm{cm/s^2}$$

  A line of sight constant acceleration of the s/c toward the Sun:
  - We find no mechanism or theory that explains the anomaly;
  - The most plausible cause is a systematic, yet to be demonstrated.
- Behavior of the Anomaly:
  - We have no real idea how far out the anomaly goes;
  - a_P continues out roughly as a constant from ~10 AU;
  - Constancy: temporal and spatial variations less then 3.4%;
  - Amplified (or turned on) for hyperbolic, escape trajectories (?)
- Three Different Codes Used:
  - JPL Orbit Determination Program [DPODP various generations];
  - Aerospace Corp [CHASPM/POEAS];
  - GSFC [“brewed” by Craig Markward in 2003, data from NSSDC].
- Next Steps:
  - Early data processing [work initiated at JPL: fly-byes, entire data set]
  - A European study of the PA recently initiated (ZARM, Bremen)



esa Science & Technology
Science Programme
European Space Agency

Meanwhile… Pioneer 10 @ Arecibo



Pioneer 10, as seen by 305 m antenna at Arecibo Observatory, Puerto Rico


One “data point”… we need more!


Thank You!

Solutions for Different Data Intervals

Determinations of the anomalous value for a_P from Intervals of Pioneer 10 and Pioneer 11 data in units of 10^{-8} cm/s^2

<table>
<tr><th>Program/Estimation method</th><th>Pio 10 (I)</th><th>Pio 10 (II)</th><th>Pio 10 (III)</th><th>Pio 11</th></tr>
<tr><td>Sigma, WLS,
no solar corona model</td><td>8.02 ± 0.01</td><td>8.65 ± 0.01</td><td>7.83 ± 0.01</td><td>8.46 ± 0.04</td></tr>
<tr><td>Sigma, WLS,
with solar corona model</td><td>8.00 ± 0.01</td><td>8.66 ± 0.01</td><td>7.84 ± 0.01</td><td>8.44 ± 0.04</td></tr>
<tr><td rowspan="2">Sigma, BSF,
1-day batch,
with solar corona model</td><td>7.82 ± 0.29</td><td>8.16 ± 0.40</td><td>7.59 ± 0.22</td><td rowspan="2">8.49 ± 0.33</td></tr>
<tr><td colspan="3">7.77 ± 0.16</td></tr>
<tr><td>CHASMP, WLS,
no solar corona model</td><td>8.25 ± 0.02</td><td>8.86 ± 0.02</td><td>7.85 ± 0.01</td><td>8.71 ± 0.03</td></tr>
<tr><td>CHASMP, WLS,
with solar corona model</td><td>8.22 ± 0.02</td><td>8.89 ± 0.02</td><td>7.92 ± 0.01</td><td>8.69 ± 0.03</td></tr>
<tr><td>CHASMP, WLS, with
corona, weighting, and F10.7</td><td>8.25 ± 0.03</td><td>8.90 ± 0.03</td><td>7.91 ± 0.01</td><td>8.91 ± 0.04</td></tr>
</table>

A Mission to Test the Pioneer Anomaly



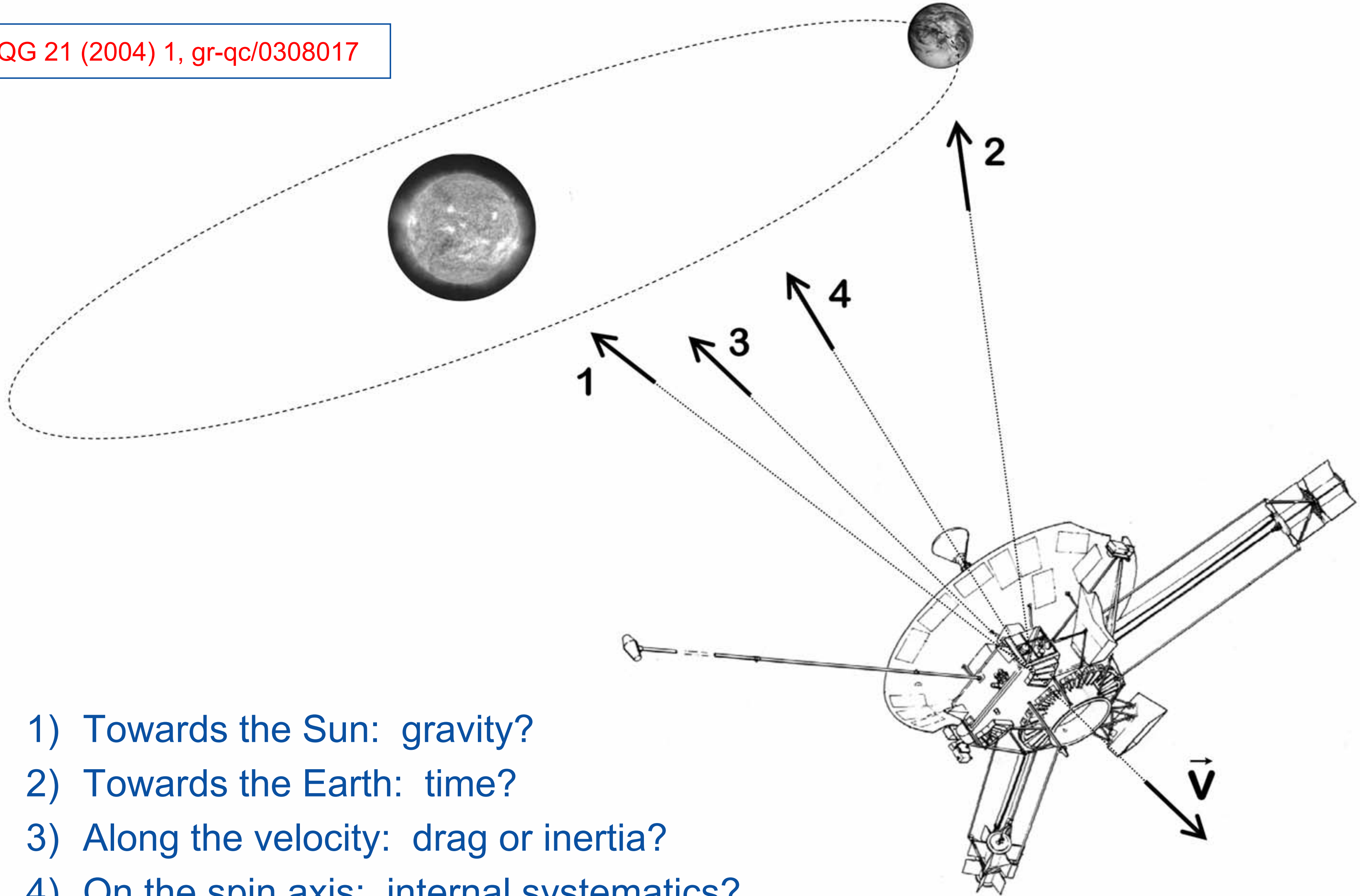


- **Mission Objectives:**
  - To search for any unmodeled small acceleration affecting the spacecraft motion at the level of $<0.1 \times 10^{-8}$ cm/s^2
  - Determine the physical origin of any anomaly, if found.
- **Unique Features:**
  - A standard spacecraft bus that allows thermal louvers to be on the sides for symmetric fore/aft thermal rejection.
  - Fore/aft symmetric design with twin antennae (``yo-yo'' concept).
- **With Off-the-Shelf Technology:**
  - Accuracy $\sigma_{\mathbf{a}} \sim 0.06 \times 10^{-8}$ cm/s^2 is achievable in about 5 years
  - GIVEN THAT the thrusters are reliable and gas leaks can be eliminated or monitored to a high enough accuracy
- **New Technology?**
  - FAST ORBIT TRANSFER using solar sails, nuclear propulsion
  - DRAG-FREE systems would help, but are not sufficient
  - DC ACCELEROMTERS are very useful
  - OPTICAL COMM very good, but currently very expensive
  - THRUSTERS: good performance and high repeatability are needed

Minimal investment in new technologies would enable not only to test the Anomaly, but also to uniquely determine its Origin.

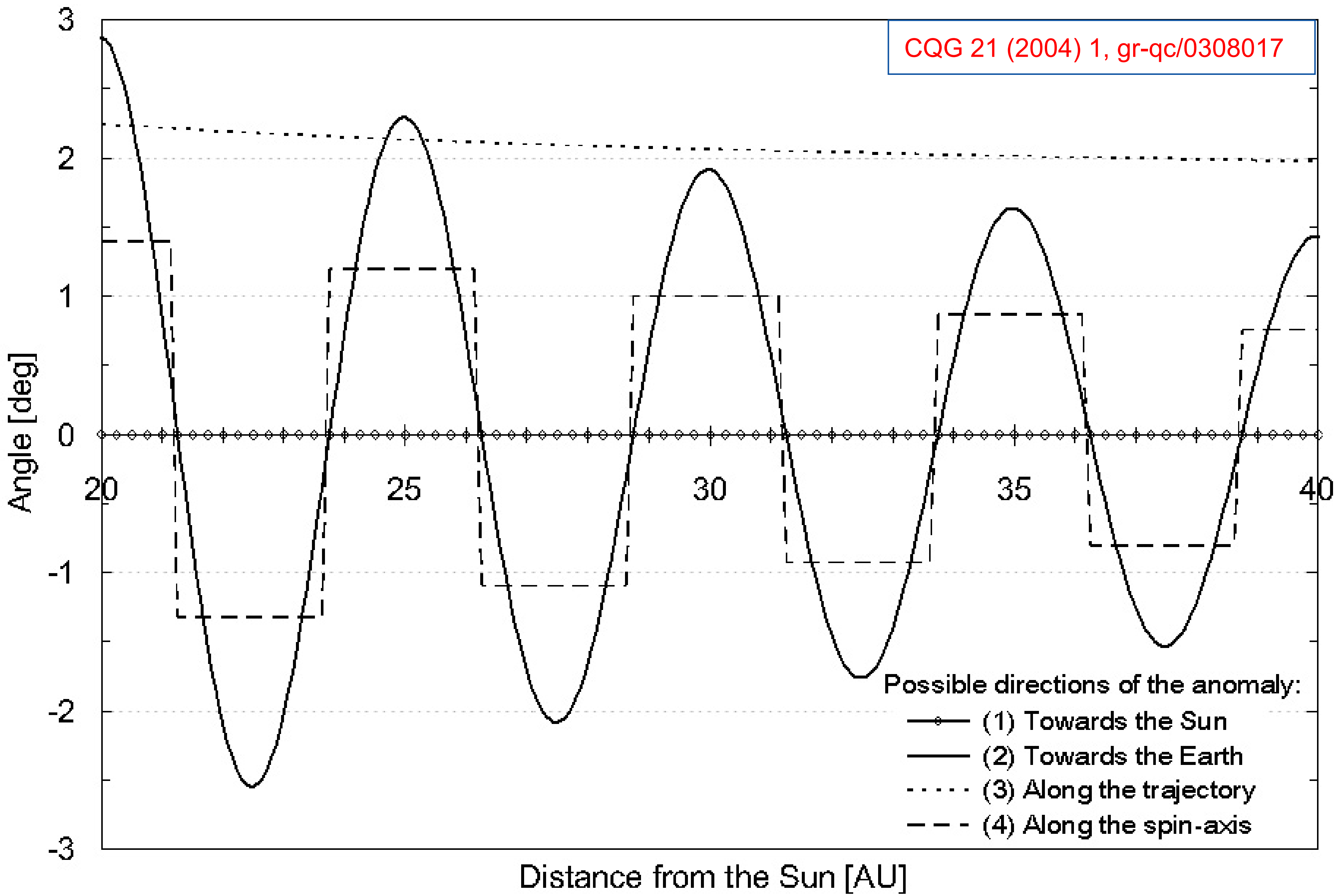
Finding Direction of the Pioneer Anomaly

CQG 21 (2004) 1, gr-qc/0308017



1) Towards the Sun: gravity?
2) Towards the Earth: time?
3) Along the velocity: drag or inertia?
4) On the spin axis: internal systematics?

Directional Modulation of the Anomaly



Clearly different behavior; easy to separate.

Lessons Learned from the Pioneers





- **Attitude Control:**
  - 3D ACCELERATION SENSITIVITY: <0.01 $\times 10^{-8}$ cm/s^2 for each axis
  - Spin-stabilized (preferred)
  - If 3D stabilization – use of DC accelerometers and reaction wheels
- **Navigation & Communication:**
  - 3D ACCELERATION SENSITIVITY: <0.01 $\times 10^{-8}$ cm/s^2 for each axis
  - POINTING: control 6 μrad; knowledge 3 μrad; stability 0.1 μrad/s
  - COMM: X and Ka band with significant dual-band tracking
  - DATA TYPES: Doppler, range, ΔDOR, and VLBI
- **Thermal Design:**
  - ENTIRE SPACECRAFT: heat-balanced & heat-symmetric
  - KNOWLEDGE of all heat sources – RTGs, electronics, thrusters, etc
  - ACTIVE CONTROL of all heat dissipation channels within & outward
  - PRECISE KNOWLEDGE of 3D vector of thermal recoil force
  - If spin-stabilized – thermal louvers are on the sides of the bus
  - If 3D stabilization – harder to balance recoil forces and torques

Investigation emphasized effects previously thought to be insignificant: rejected thermal radiation, gas leaks, radio beam.

Lessons Learned from the Pioneers (2)

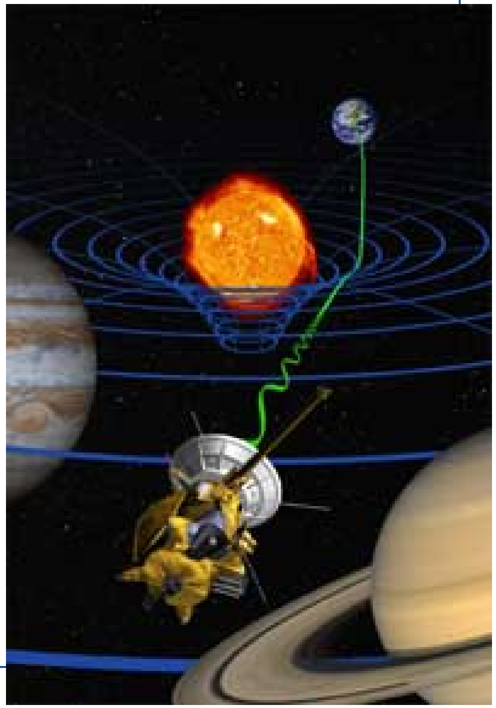




- On-board Power – RTGs:
  - LOCATION: must provide thermal and inertial balance & stability
  - If spin-stabilized – position as farther as practical from the bus
  - If 3D stabilization – balance, balance, balance! (see below)
- Propulsion System:
  - Precisely calibrated thrusters, propellant lines & fuel gauges
  - AUTONOMOUS real-time control of their performance
- Symmetric Design (“Yo-Yo” concept):
  - FORE/AFT SYMMETRIC design with TWO identical Cassegrain antennae transmitting in opposite directions, and
  - ROTATE the craft once in a while (done for Pioneer “Earth acquisition maneuver”, took ~2.5 hours and 0.5 kg of fuel)
- Mission Design:
  - TRAJECTORY: a hyperbolic solar system escape trajectory >15 AU from the Sun – possibly in the plane of ecliptic, co-moving with the solar system's direction within the galaxy
  - FAST TRANSFER ORBIT – spacecraft moving with a velocity of 5 AU or more per year, reaching 15 AU in 3 years time or less
  - Heavy class launch vehicle (Delta IV, Proton, Ariane class)
  - Solar sail, or nuclear propulsion at least to 15 AU

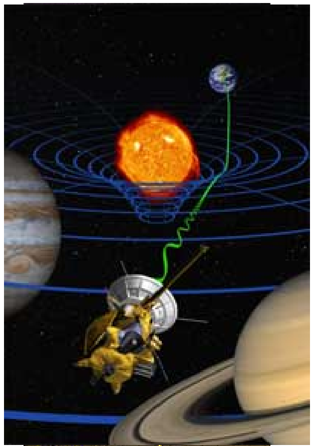
Other Possibilities to Study the Anomaly

- Experimental possibilities:
  - The 305-meter antenna of the Arecibo Observatory in Puerto Rico might be able to detect Pioneer's signal for a longer time
  - The existing data for Pioneer 10 [complete to July 2000]
    - High-rate data from 1978 to Jan 1987: not used in our analysis:
    - Study FLYBYS!
- Current or near future missions:
  - Cassini [RTGs very close]:
    - Heat recoil force ~40×10^{-8} cm/s^2
  - GP-B [in orbit]
    - Acceleration resolution at ~ 1×10^{-8} m/s^2
    - Earth polar circular ~ 92 min orbit,
  - LISA Pathfinder [launch 2006]
    - Acceleration resolution at ~ 1×10^{-12} cm/s^2
    - Multiple noise cancellation strategies

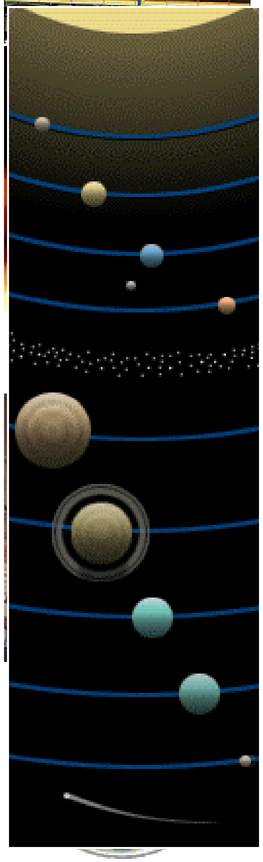


Technology exists to further test the Pioneer Anomaly

Are There Any Other Possibilities?



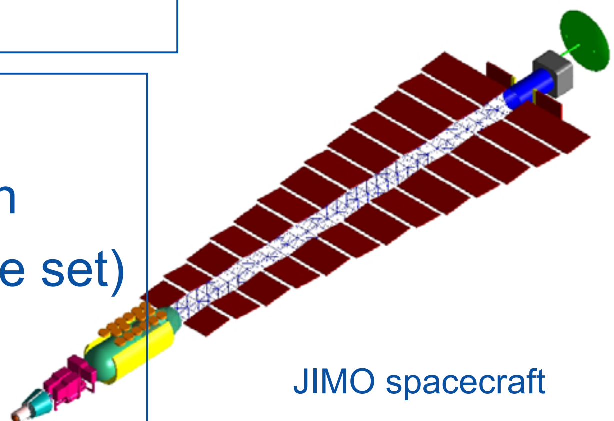
Cassini spacecraft



- Future missions:
  - JIMO [~2012]:
    - Nuclear reactor [unlimited power / weight]
    - Focus on technology, very minimal science
  - Pluto-Kiuper [>2014]:
    - The launch data is uncertain at the moment
    - A mission from the Prometheus family?
  - Solar Probe [>2016]:
    - a low-mass module may be ejected during solar flyby – out of the plane of the ecliptic
  - Interstellar Probe [>2020]

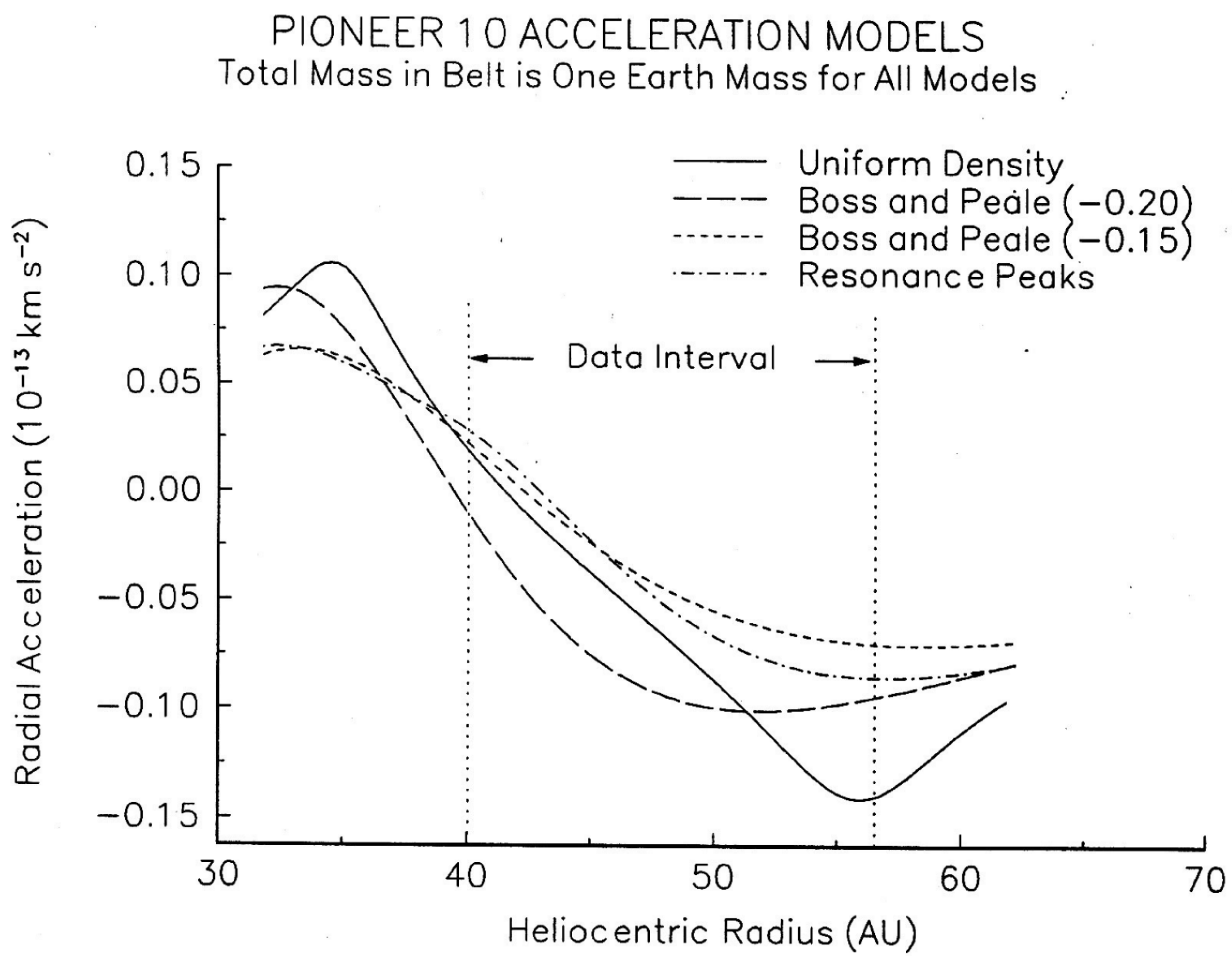
GP-B Launch 04-20-2004

- Today's reality:
  - The anomaly source is still unknown
  - Analysis of early data (and the entire set)
  - Needs a wider community support
  - Pioneer is a low priority for NASA
  - Designated mission today is hard, but…



JIMO spacecraft

Dust in the Kuiper Belt



Possible acceleration caused by dust in the Kuiper belt.

Suggested Explanations: Familiar Physics

- A new manifestation of known physics? Interplanetary dust:
  - i) additional gravitational frequency shift; ii) resistance of s/c antennae as they transverse the dust
  - Contradicts to known properties of the interplanetary medium. Density varies greatly within the KB; not large enough to produce acceleration ~a_P
- Dark matter – hard to understand:
  - A spherically-symmetric distribution of matter, with $\rho \sim r^{-1}$ produces a constant acceleration inside the distribution.
  - To produce a_P even only out to 50 AU would require the total dark matter $> 3 \times 10^{-4} M_\odot$
  - Ephemeris accuracy allows $\sim 10^{-6} M_\odot$ of DM within orbit of Uranus
- Modification of gravity – a Yukawa force:

$$V(r) = -\frac{GMm}{(1+\alpha)r}\left[1 + \alpha e^{-r/\lambda}\right] \quad \Rightarrow \quad a_P = -\frac{\alpha a_{\mathtt{Newtonian@1AU}}}{2(1+\alpha)}\left(\frac{1AU}{\lambda}\right)^2$$

  - α is the new coupling strength relative to Newtonian gravity, and λ is the new force's range. For instance, $\alpha = -1 \times 10^{-3}$ for $\lambda = 200$ AU

Suggested Explanations: MOND & New Physics

- MOND (MOdified Newtonian Dynamics):
  - Gravitational acceleration of a massive body is $a \propto 1/r^2$ for some constant $a_0 \ll a$ and $a \propto 1/r$ for $a_0 \gg a$
  - Depending on the value of *H*, the Hubble constant, $a_0 \approx a_P$ Indeed, if *H* = *82* km/s/Mpc,

$$a_H = cH \rightarrow 8 \times 10^{-8}\ \mathrm{cm/s^2}$$

  - Variations of MOND to account for the Pioneer anomaly
  - Viking ranging data limit any unmodeled radial acceleration on Earth and Mars to $\leq 0.1 \times 10^{-8}$ cm/s^2 $\Rightarrow$ if the anomalous radial acceleration acting on spinning spacecraft is gravitational in origin, it is not universal.

- Observation $a_P \sim cH$, stimulated many suggestions:
  - Gravity of the solar system is not static w.r.t. the cosmic expansion
  - 5-D Kaluza-Klein with a time-varying scale factor for 5-th dimension
  - Effect of a scale-dependent cosmological term in the Grav. action
  - Cosmological models with a time-varying Newtonian *G(t)*

Suggested Explanations: New Physics




- Several scalar-field ideas have also appeared:
  - Long-range scalar field, with oscillatory decline in a_P, d>≈100 AU
  - Self-interactions of a scalar condensate could be the origins of both Milgrom's inertia modification and also of the Pioneer effect.
  - Flavor oscillations of neutrinos in the Brans-Dicke theory of gravity may produce a QM phase shift of neutrinos
  - A theory of conformal gravity with dynamical mass generation
- Phenomenological time models:
  - Drifting Clocks; Quadratic Time Augmentation; Carrier Frequency Drift; Speed of Gravity
    - Rejected: poor fits / inconsistent solutions among spacecraft
- Quadratic in time model (pseudo-acceleration, less likely):

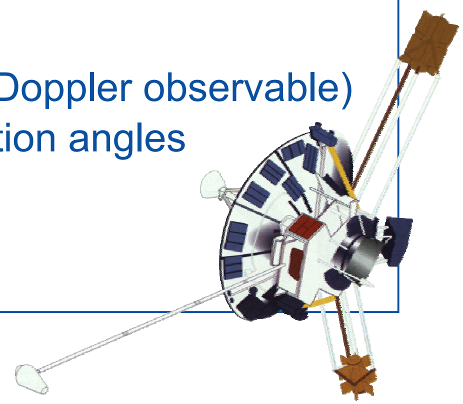
$$\Delta\mathtt{TAI} = \mathtt{TAI}_{\mathtt{received}} - \mathtt{TAI}_{\mathtt{sent}} \quad \rightarrow \quad \Delta\mathtt{TAI} + \frac{1}{2}a_{\mathtt{quad}} \cdot \left(\mathtt{TAI}^2_{\mathtt{received}} - \mathtt{TAI}^2_{\mathtt{sent}}\right)$$

  - Mimics a line of sight acceleration of s/c, and could be thought of as an expanding space model. Note that a_{quad} affects only the data.

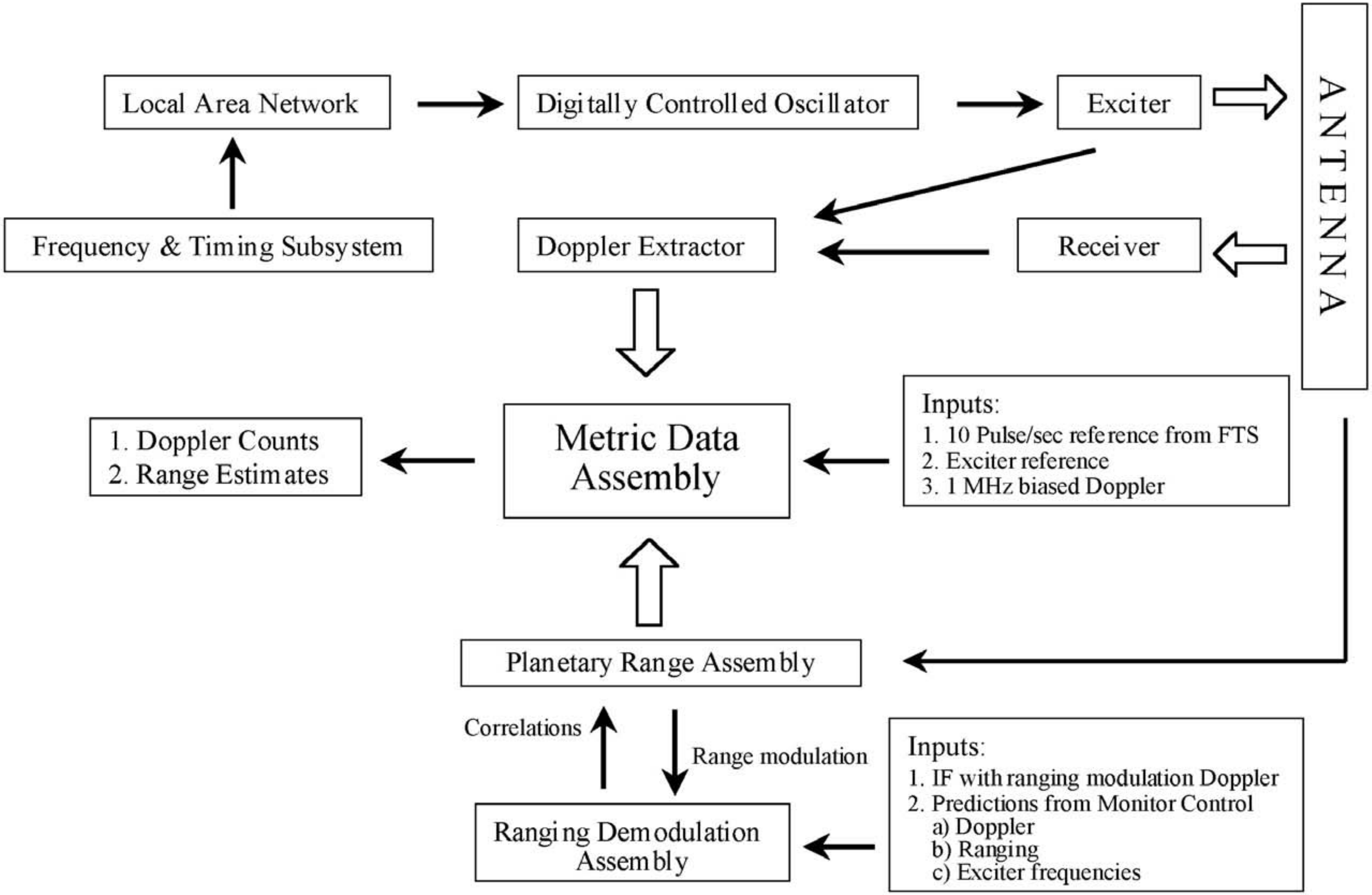
Initial PRL paper was cited ~108 times, including ~ 78 papers with suggested mechanisms to explain the anomaly.

Data Acquisition and Preparation

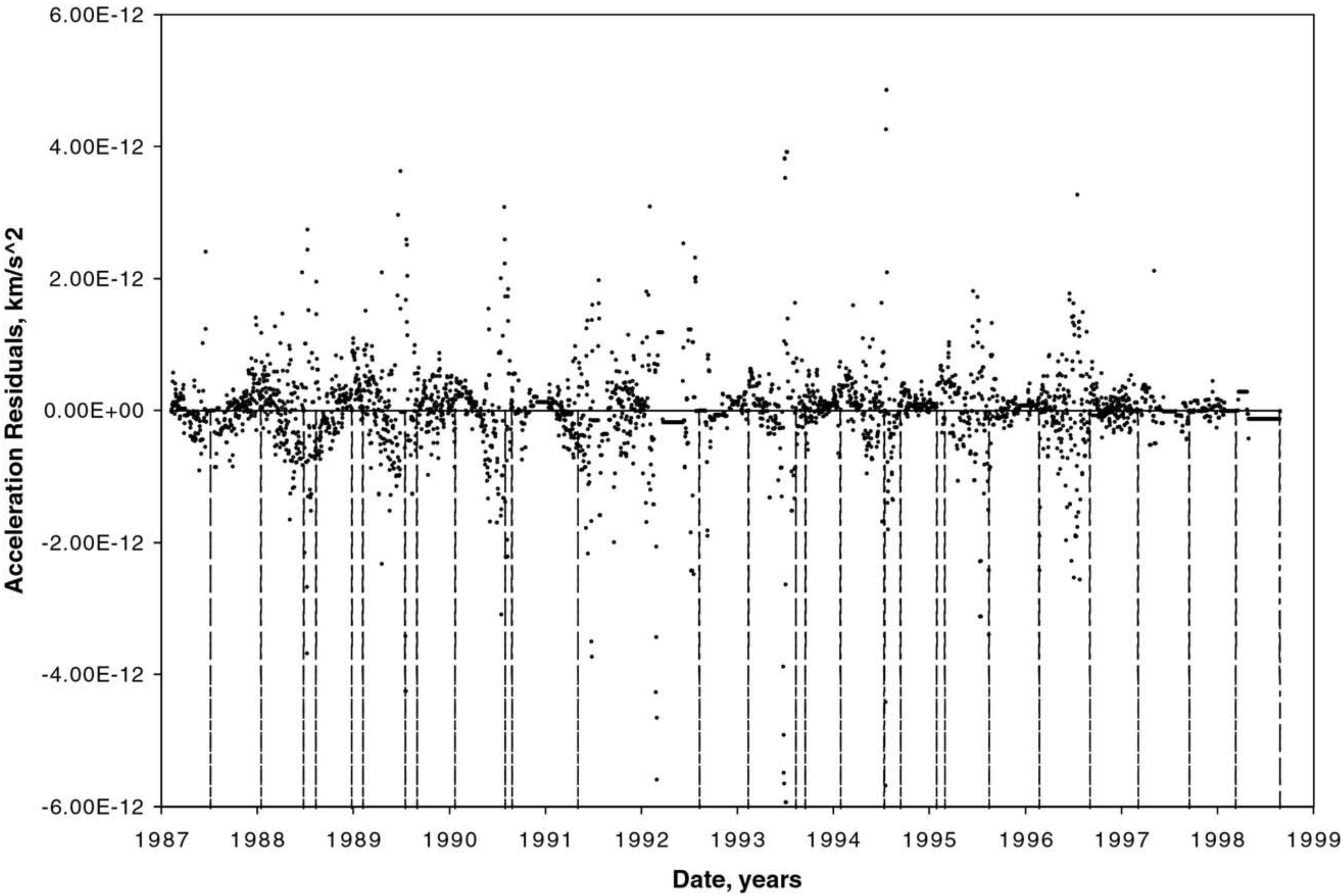
- Data acquisition with JPL's Deep Space Network (DSN):
  - Goldstone, California; Robledo de Chavela, near Madrid, Spain; Tidbinbilla, near Canberra, Australia.
  - The DSN Frequency and Timing System: At its center is an H-maser that produces a precise and stable reference frequency with Allan deviations of $(1.3 - 1.0)\times 10^{-12}$, for a 10^3 sec Doppler integration time (for the S-band)
- Radio Doppler and range techniques, the most common for navigation
  - Calculations of the motion of a spacecraft are made on the basis of the range time-delay and/or the Doppler shift in the signals
- Data types: $\Rightarrow$ Pioneer craft have only 2-and 3-way S-band Doppler
  - GLL has S-band range data near the Earth. ULY has 2-/3-way S-up/X-down Doppler and range, S-up/S-down: processed S-up/X-down Doppler and range
- Data preparation and data weighting
  - Considerable effort has gone into estimating measurement errors: to provide the data weights necessary to accurately estimate the parameter adjustments and their associated uncertainties
  - To correct for the Earth's tropospheric refraction (affects Doppler observable) the data can be deweighted for low DSN antennae elevation angles
- Spin calibration of the data:
  - to correct for a Doppler bias due to spinning antennae



Data Collection by the DSN



QDP/Sigma 1-day batch residuals



ODP/Sigma 1-day batch-sequential acceleration residuals using the entire Pioneer 10 data set. Maneuver times are indicated by the vertical dashed lines.

The Observed Anomaly

The two-way Doppler anomaly to first order in (v/c) behaves as:

$$\nu_{\text{obs}}(t) - \nu_{\texttt{model}}(t) = -\,\nu_0 \frac{2\,a_P\,t}{c} \qquad \nu_{\texttt{model}} = \nu_0 \left[1 - \frac{2\,v_{\texttt{model}}(t)}{c}\right]$$

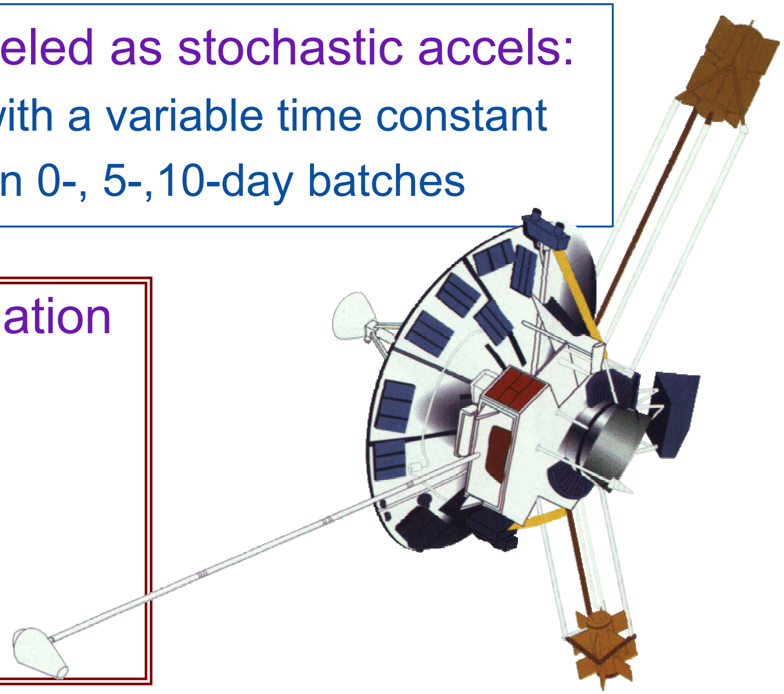
$$v_{\text{obs}}(t) - v_{\texttt{model}}(t) = -\,2\,a_P\,t$$

Equivalent forms (PRL, 1997):

- Steady frequency drift: $-\,6 \times 10^{-9}$ **Hz/s** ($\approx$**1.5 Hz/8 yrs**)
- Anomalous acceleration: $a_P = (8.65 \pm 0.03) \times 10^{-8}$ **cm/s²**
- Clock acceleration: $a_t = -\,2.8 \times 10^{-18}$ **s/s²**, $\quad a_P \equiv a_t c$

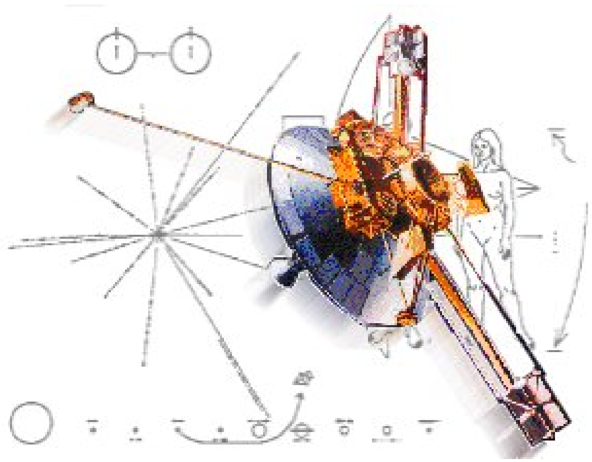
- Unknown forces are routinely modeled as stochastic accels:
  - Exponentially correlated in time, with a variable time constant
  - Stochastic variable was sampled in 0-, 5-,10-day batches

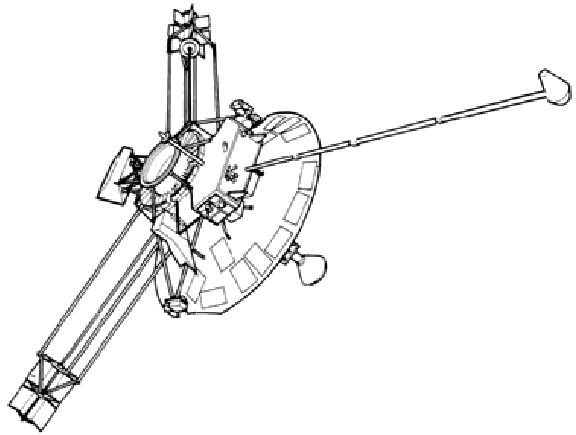
- Basic methods of spacecraft navigation
  - Relativistic equations of motion;
  - Small non-gravitational forces;
  - Data acquisition and preparation.
- The latest (2002) results:
  - An error budget for the anomaly.



Outline for This Talk:

- **The Pioneer Anomaly:**
  - Pioneer spacecraft and missions
  - JPL OD process: data and models
  - Initial detection for PA
  - How unique these condition?
- **Recent Analysis:**
  - JPL ODP process
  - Aerospace Corporation
  - Error budget
  - Attempts to explain
- **Lessons Learned & Next Steps:**
  - Missions of interest
  - A designated mission concept
  - How to get support? NASA? ESA?

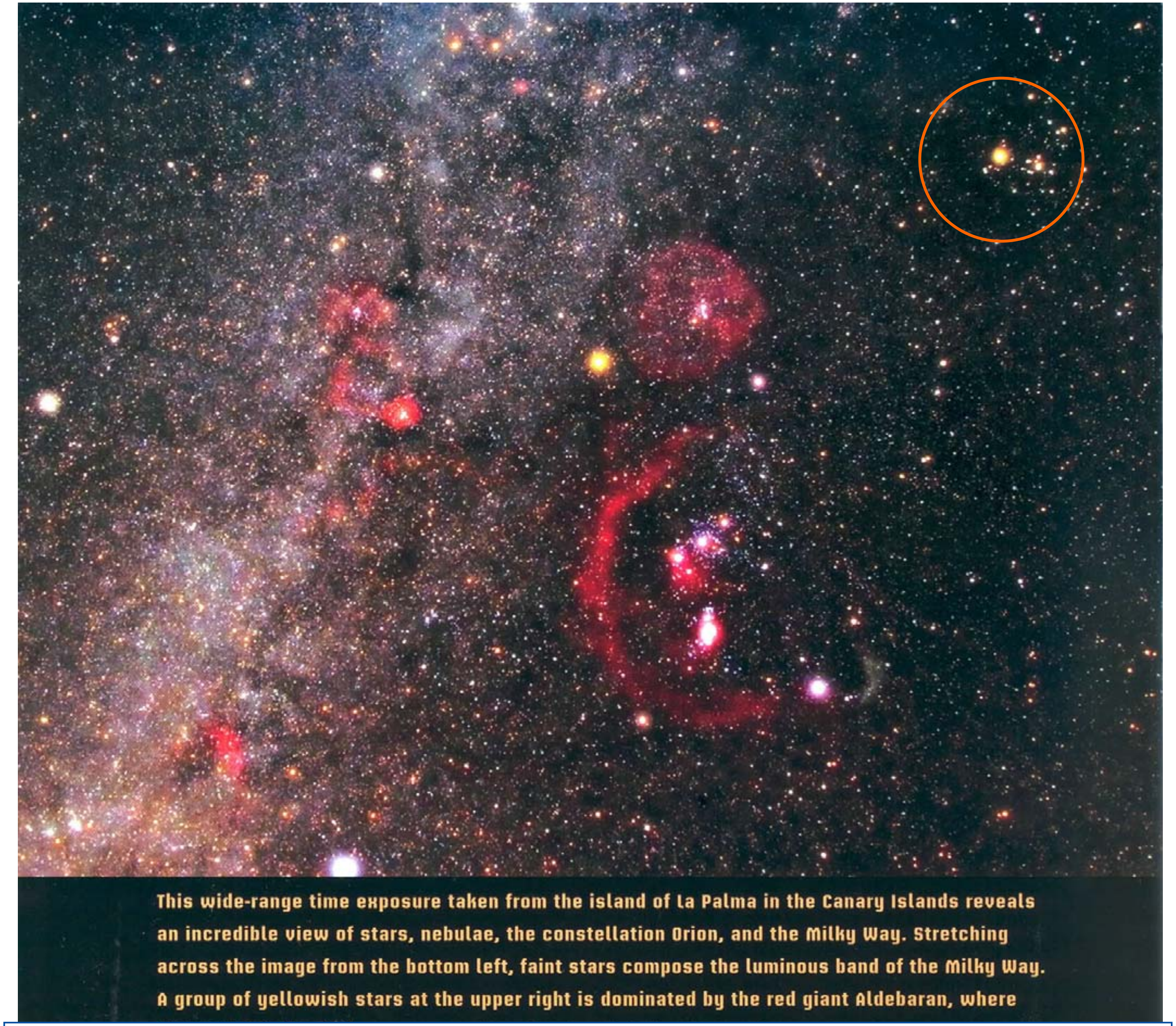




This Talk will Cover:

- PA history, analysis, lessons learned, and mission to test the PA

A Long Journey Ahead…



A group of yellowish stars at the upper right is dominated by the red giant Aldebaran, where Pioneer 10 is heading.

Typical JPL ODP Output





- One data point of Pioneer 10 (spacecraft #23) …..

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HICOMP=     0  CAMERA=     0  UPLINK=     1  CHANEL=     0  WBMODE=     0  MODFLG=     0  SOBJSG=   352  SOBJID=     0  VALID =     0
PICTUR=     0  UPRCVR=     1  RERAMP=     0  VLBIFG=     0  RFQTYP=     0  DPLCNL=     0  ODFMT =     0
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TRAXAZ= 0.0                     UDELAY= 0.0
CMPUTD= 2.892965278131659D+05   LITMT1=-1.905516152720878D+08   LITMT2=-1.905228831559969D+08   LITMT3=-1.904941498164381D+08
HRANGL= 2.641938793634032D+02   DECLIN= 2.565385670180101D+01   AZMUTH= 6.656540802980680D+01   ELVATN= 1.220495211596171D+01
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FQT1E = 2.110701120000000D+09   FQT2S = 0.0                     FQT2E = 0.0                     ANOMLY= 1.163801170878523D+02
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Typical CHASPM Output

- Several data points of Pioneer 10 (spacecraft #23) …..

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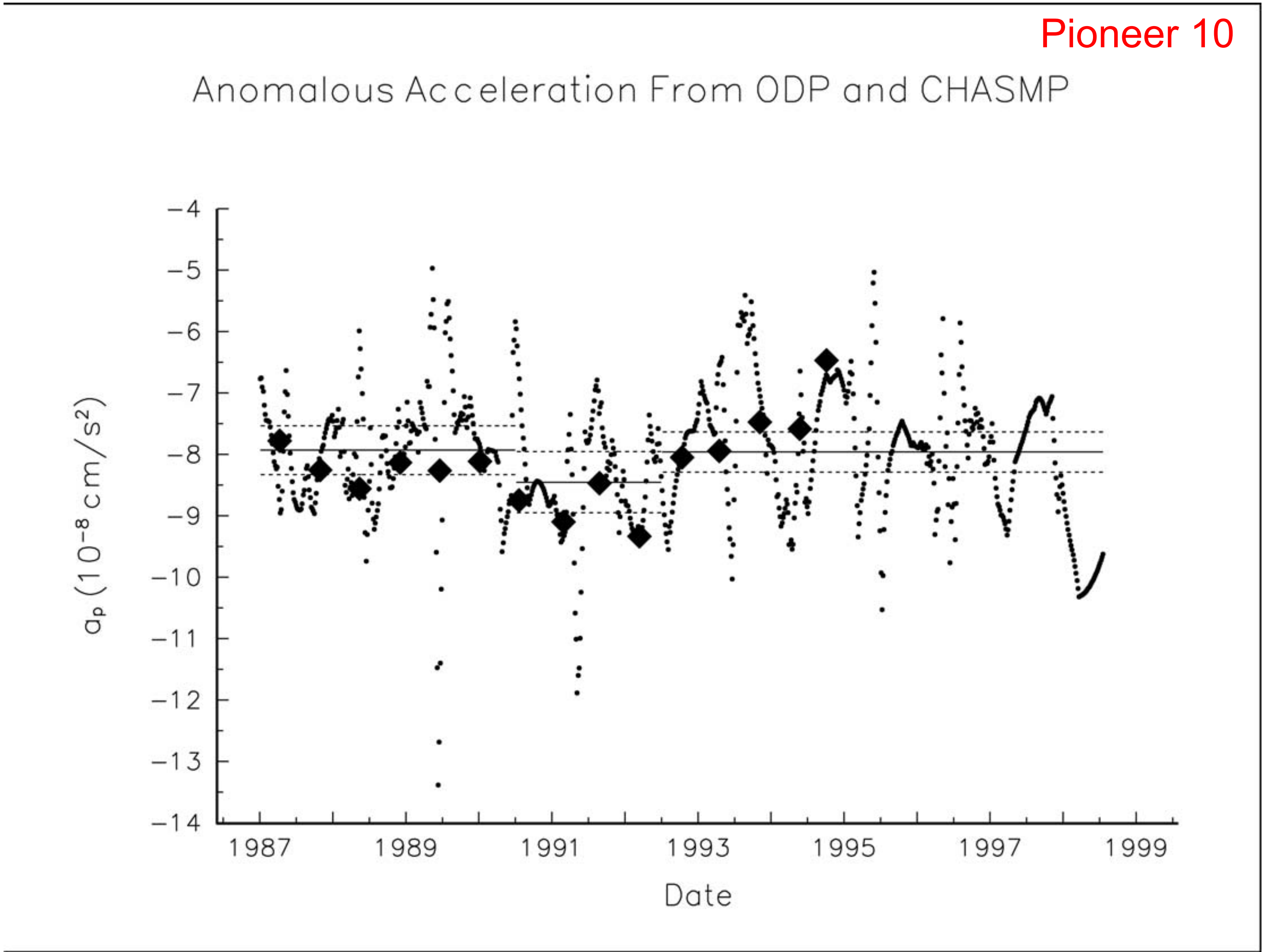
```

Consistency Between ODP and CHASPM



ODP: 5-day sample averages of using BSF with a 200-day correl time (dots). Solid lines – mean values of a_P in three Intervals; dashed lines – large BSF computational error bounds. CHASMP: The 200-day accel values using CHASMP – solid squares.