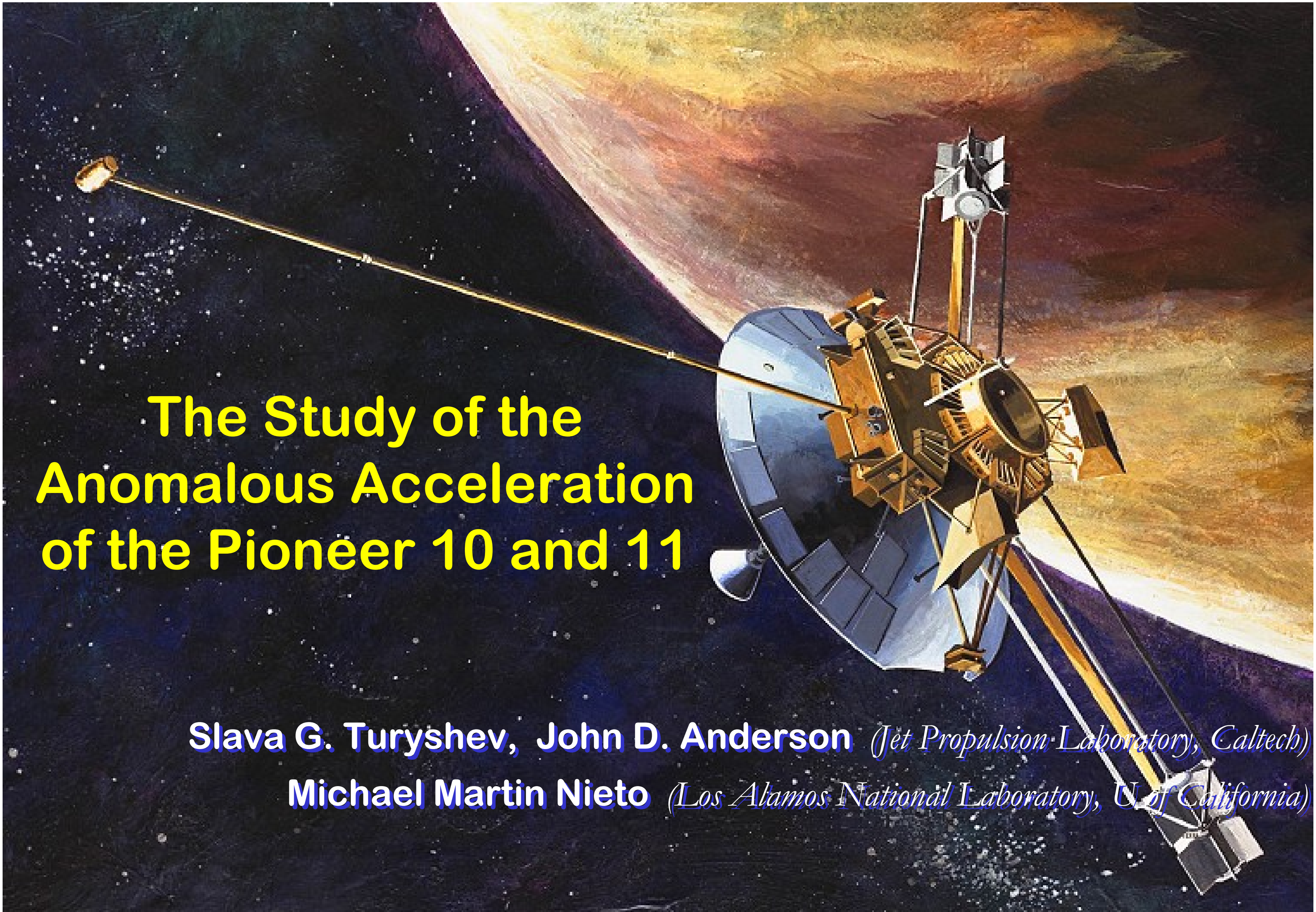


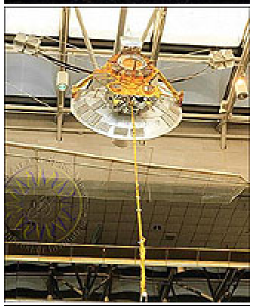
The Study of the Anomalous Acceleration of the Pioneer 10 and 11

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

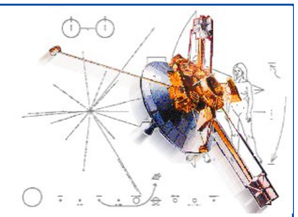
The XXII Texas Symposium on Relativistic Astrophysics
Stanford University, December 13-17, 2004

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

Conclusions and Outline:


- The Pioneer 10 and 11 anomalous acceleration:



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

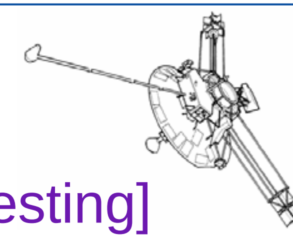
A line-of-sight constant acceleration *towards* the Sun:

  - 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

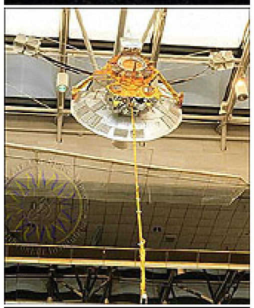
Possible Origin?

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



- A “win-win” situation, as both are important:
  - 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

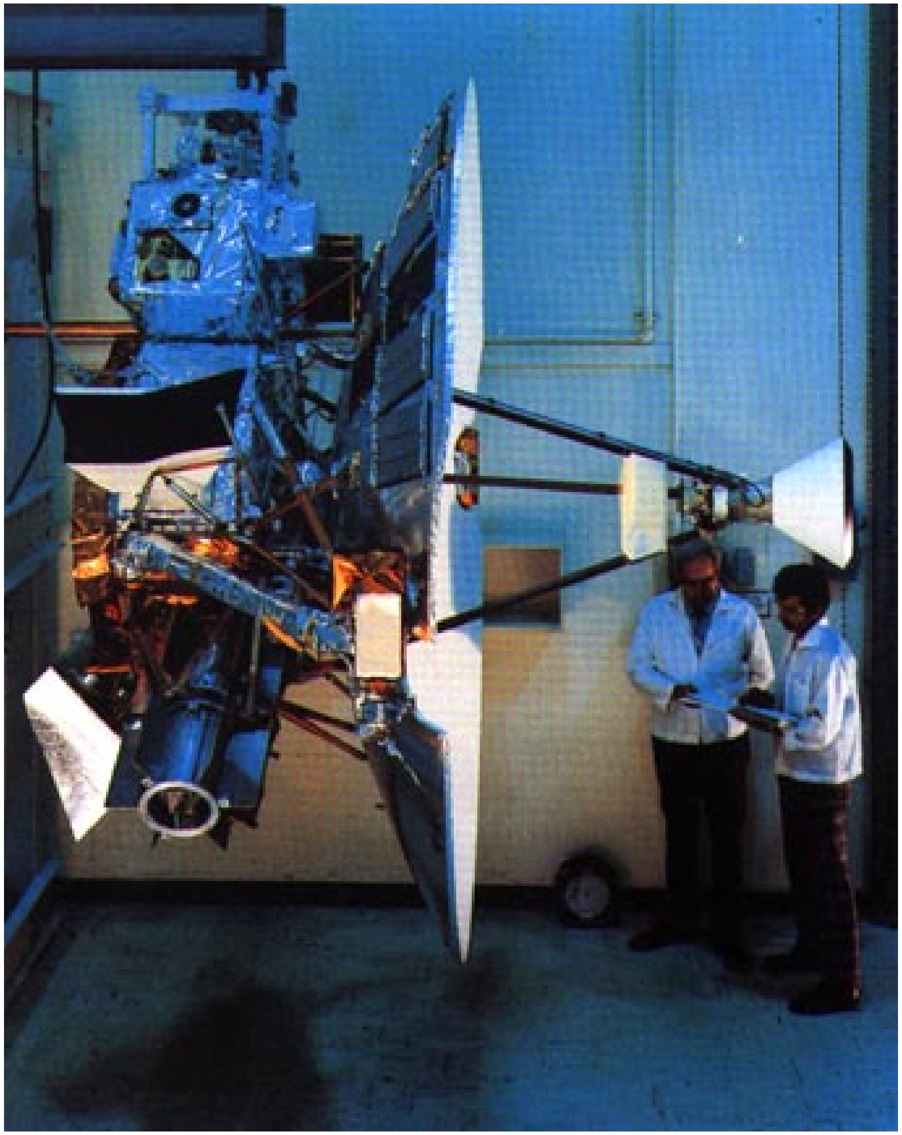
	Pioneer 10	Pioneer 11
Launch	2 March 1972	5 April 1973
Planetary encounters	Jupiter 4 December 1973	Jupiter/Saturn 2 Dec 1974/1 Sep 1979
Mission status Distance from the Sun	Formally ended 31 March 1997 $\sim$ 67 AU	Last data received 1 October 1990 $\sim$ 30 AU
Direction of motion	Star Aldebaran 2 million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

Position of Pioneer 10 on 15 December 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

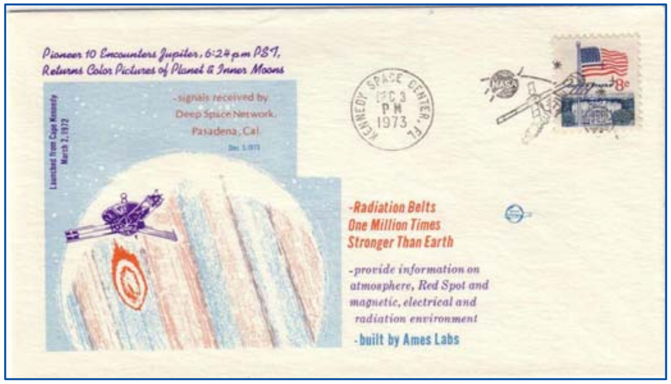
Last successful precession maneuver to point the spacecraft to Earth was accomplished on 11 Feb 2000 (distance from the Sun of 75 AU)

Pioneer F during checkout tests

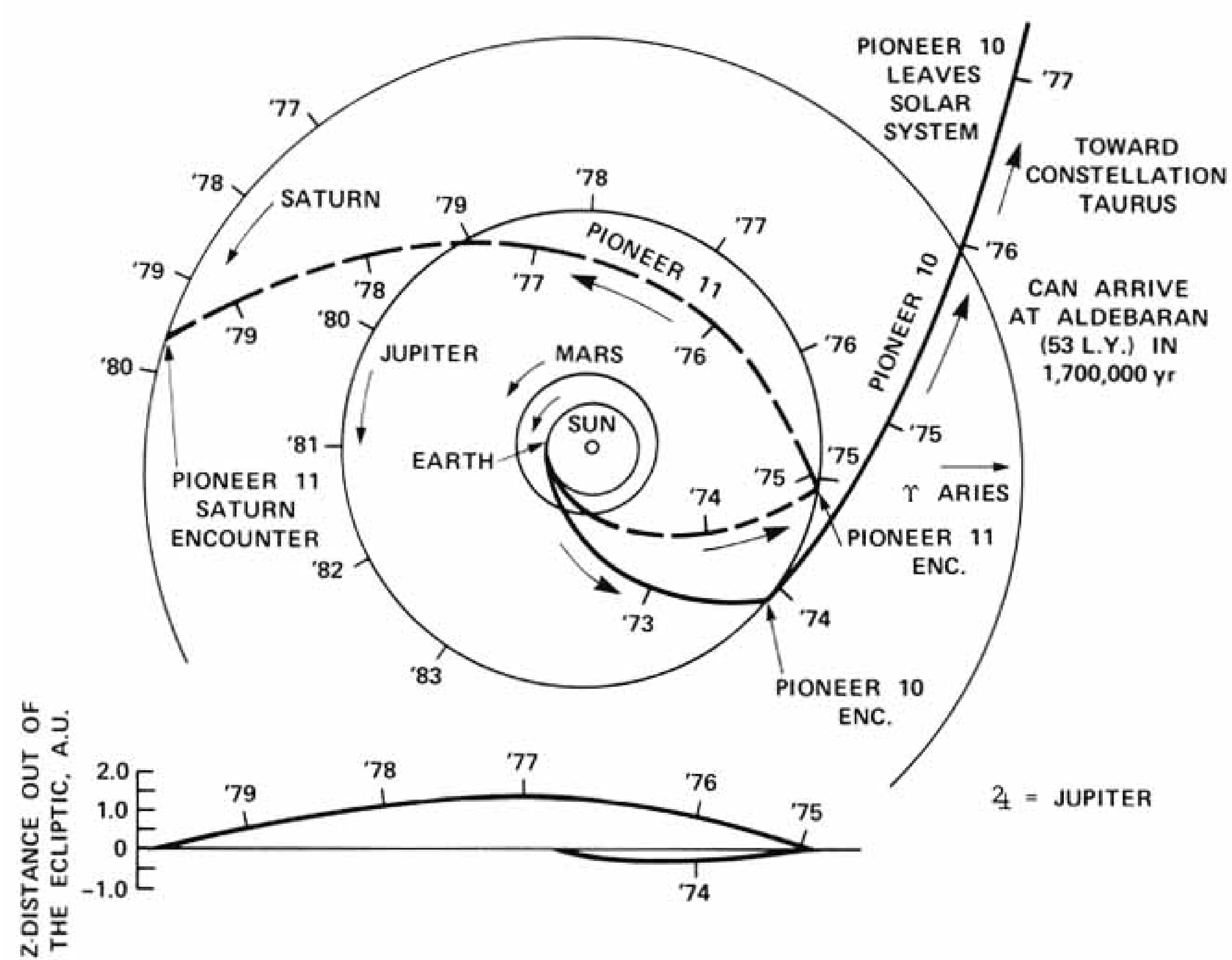


The Pioneer F spacecraft during a checkout with the launch vehicle third stage at Cape Kennedy. Pioneer F became Pioneer 10.

Pioneer 10 Launch: 2 March 1972

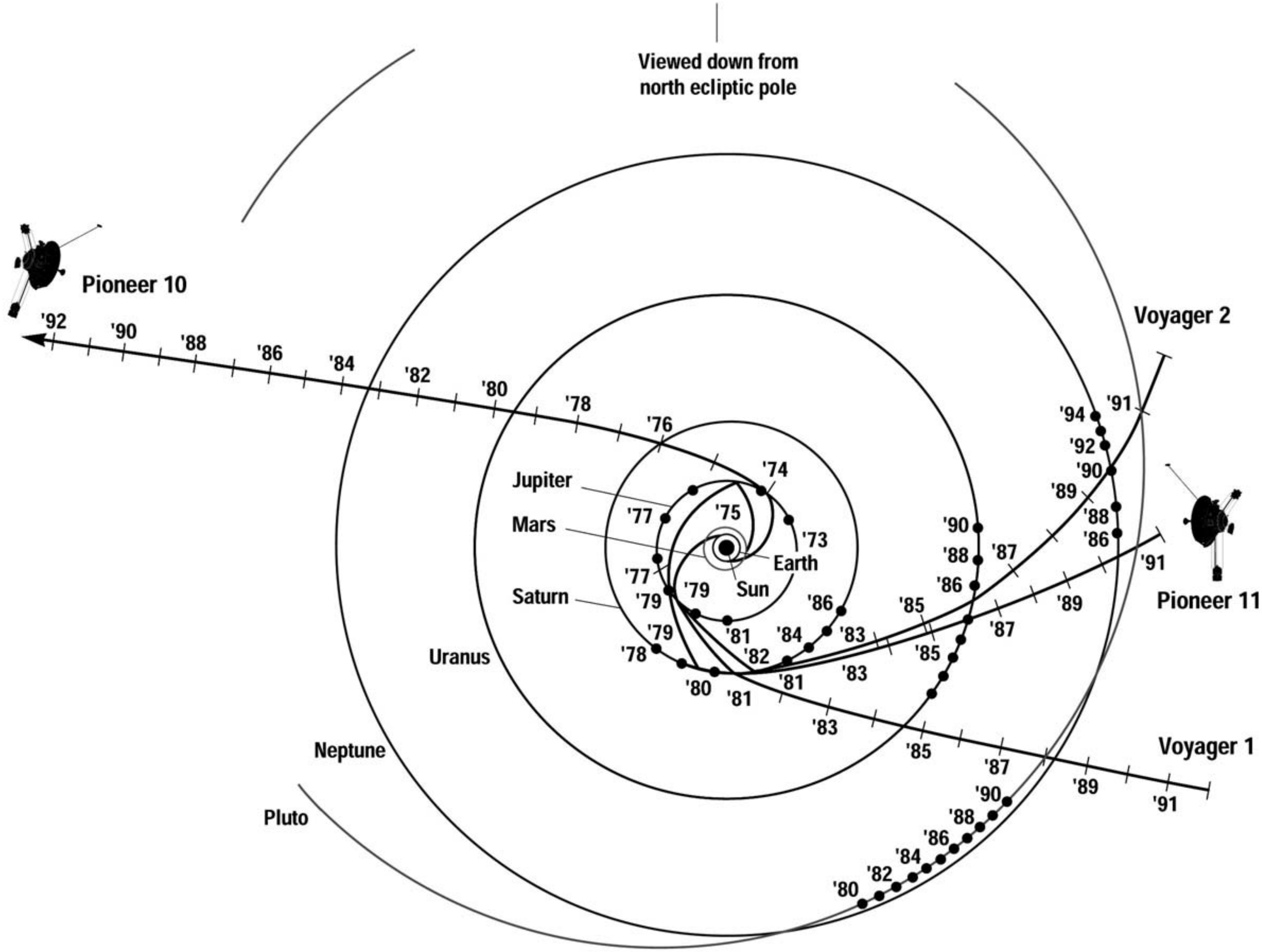


Pioneer 10/11: Main Missions



Trajectories for Pioneer 10 and 11 during the main mission phase

Trajectories of Pioneers and Voyagers

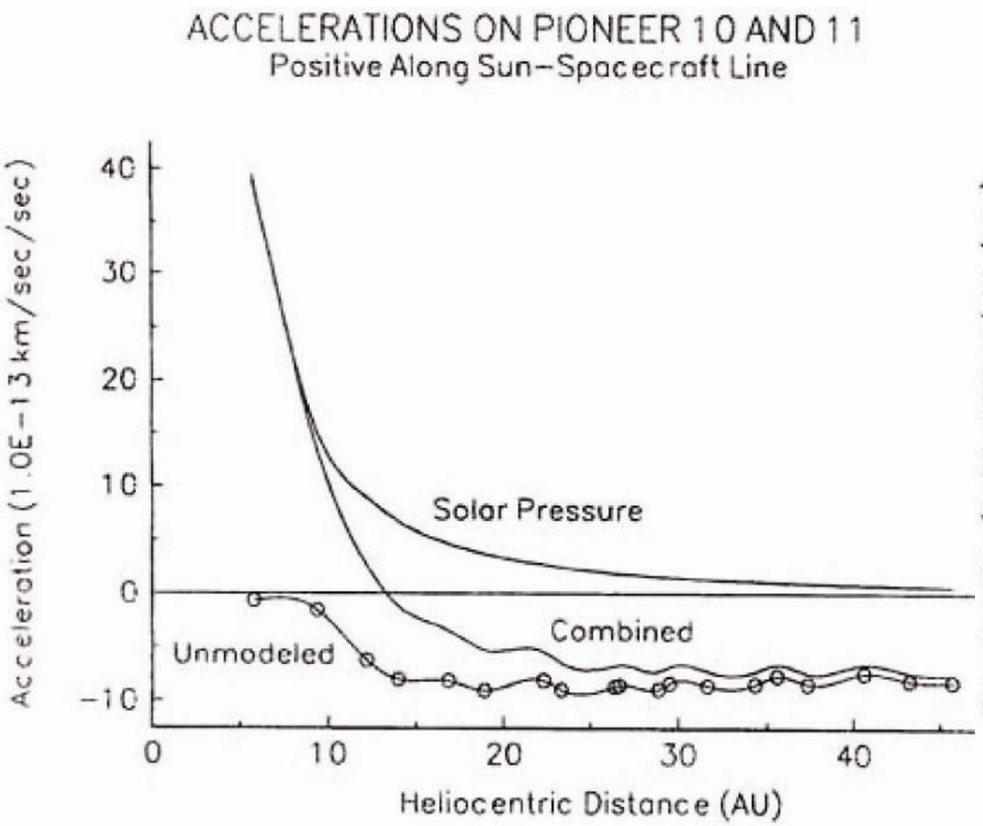


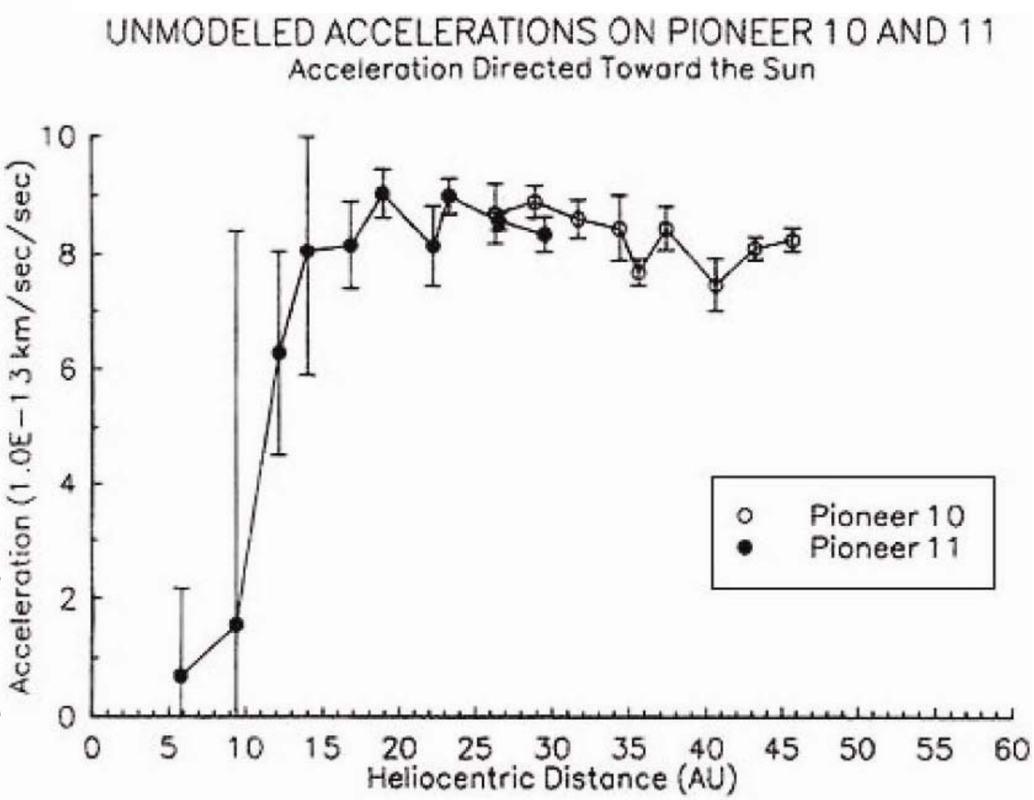
Ecliptic pole view of Pioneer 10, Pioneer 11, and Voyager trajectories. Digital artwork by T. Esposito. NASA ARC Image # AC97-0036-3.

Detection of the Anomaly

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

- 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





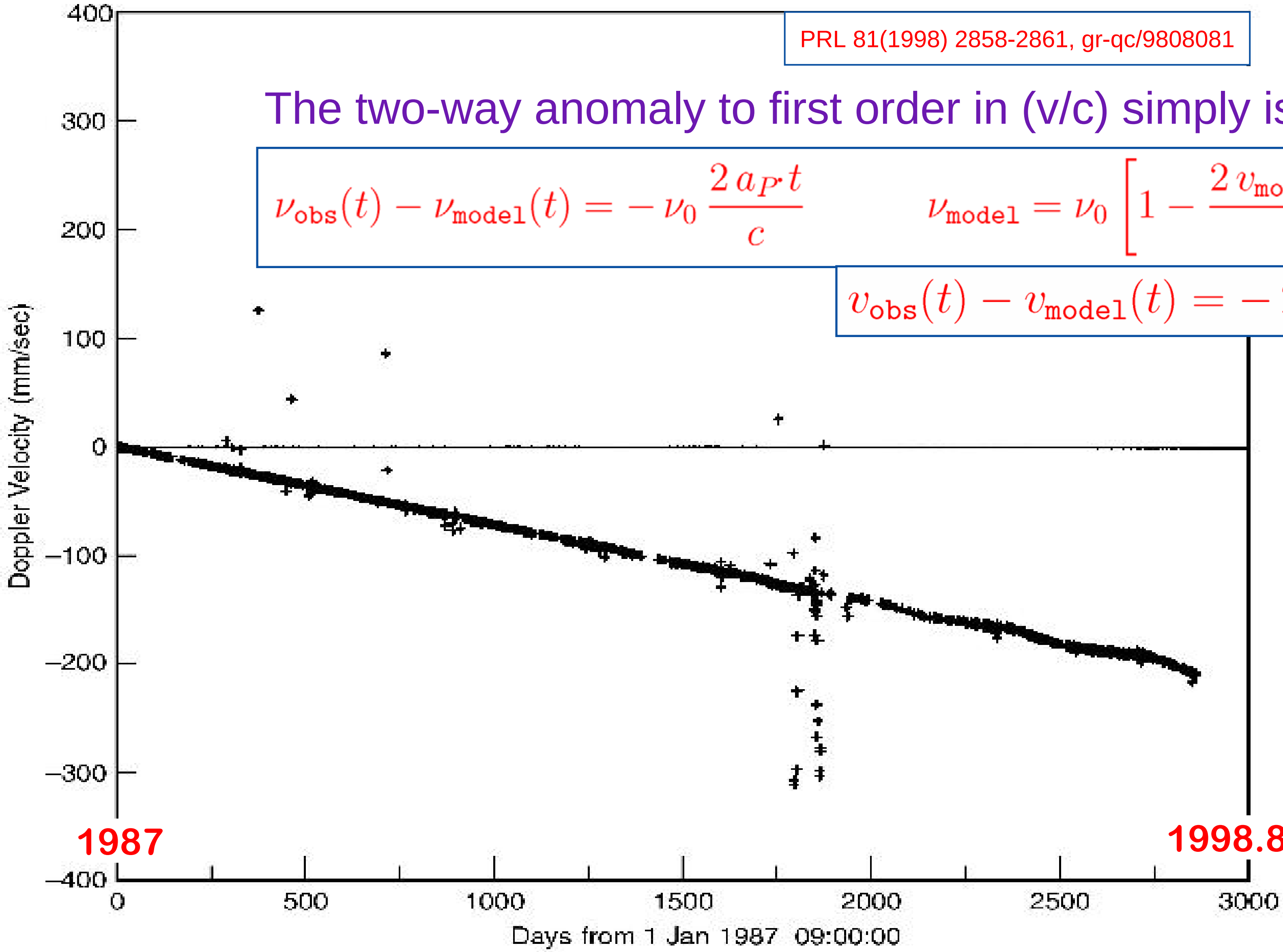
The Pioneer Anomaly

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

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

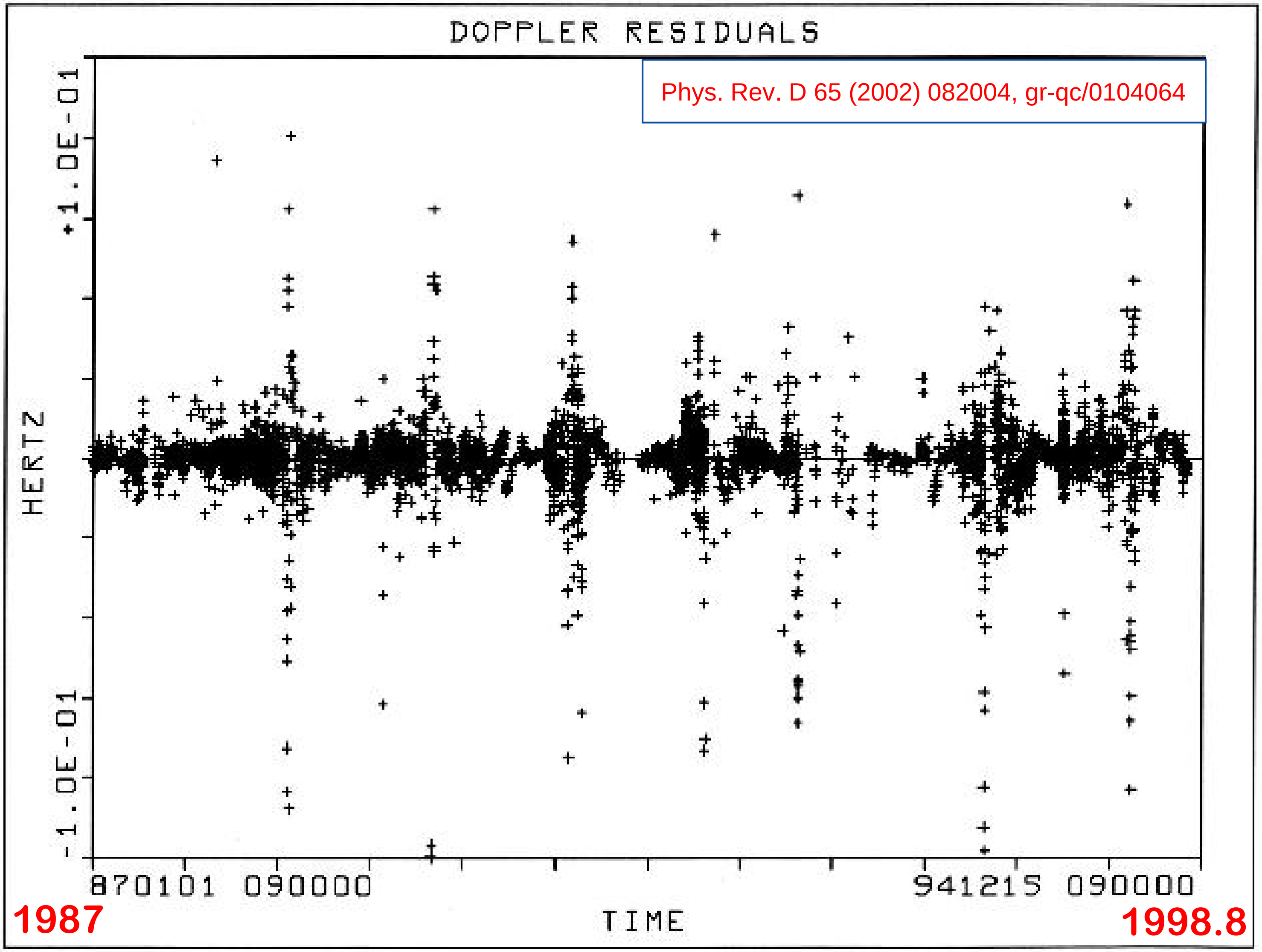
$$\nu_{\mathrm{obs}}(t) - \nu_{\mathtt{model}}(t) = -\,\nu_0\,\frac{2\,a_P\,t}{c} \qquad \nu_{\mathtt{model}} = \nu_0\left[1 - \frac{2\,v_{\mathtt{model}}(t)}{c}\right]$$

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



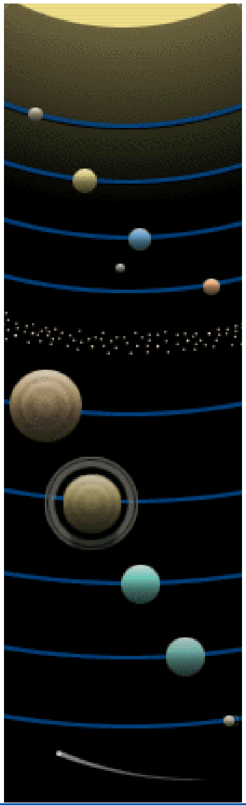
CHASMP two-way Doppler residuals (observed Doppler velocity minus model Doppler velocity) for Pioneer 10 vs time. [1 Hz is equal to 65 mm/s range change per second]

The Pioneer Anomaly



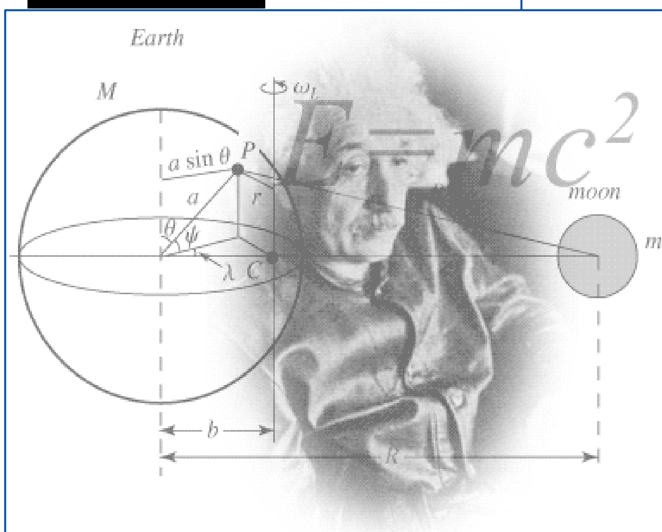
Adding one more parameter to the model – a constant radial acceleration – led to residuals distribution ~ zero Doppler velocity with a systematic variation ~3.0 mm/s. The quality of the fit may be determined by the ratio of residuals to the downlink carrier frequency, $\nu_0 \approx$ 2.29 GHz.

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's tides; lunar physical librations

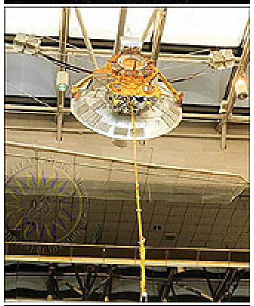
$$
\begin{aligned}
\ddot{\mathbf{r}}_{i_{\text{point mass}}} = \sum_{j\neq i} \frac{\mu_j(\mathbf{r}_j-\mathbf{r}_i)}{r_{ij}^3}\Bigg\{1 &- \frac{2(\beta+\gamma)}{c^2}\sum_{k\neq i}\frac{\mu_k}{r_{ik}} - \frac{2\beta-1}{c^2}\sum_{k\neq j}\frac{\mu_k}{r_{jk}} \\
&+ \gamma\left(\frac{v_i}{c}\right)^2 +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



- Models for light propagation are to $(v/c)^2$:

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

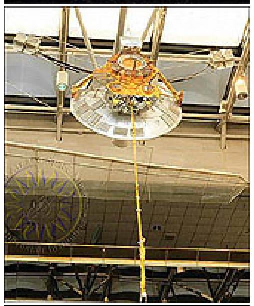
Standard Models of Non-Gravitational Forces


- 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

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

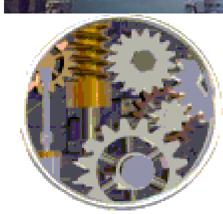
Error budget constituents	Bias 10^{-8} cm/s^2	Uncertainty, 10^{-8} cm/s^2
⇛ Numerical stability of least-squares estimation		$\pm$ 0.02
⇛ Accuracy of consistency/model tests		$\pm$ 0.13
⇛ Mismodeling of maneuvers		$\pm$ 0.01
⇛ Mismodeling of the solar corona		$\pm$ 0.02
⇛ Annual/diurnal terms		$\pm$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

Interesting, but not a major source of concern!

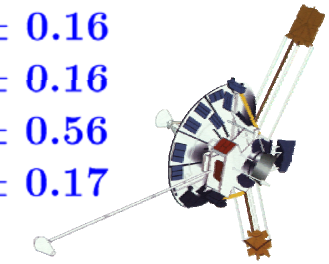
Sources of On-board Systematic Error [PRD, 2002]







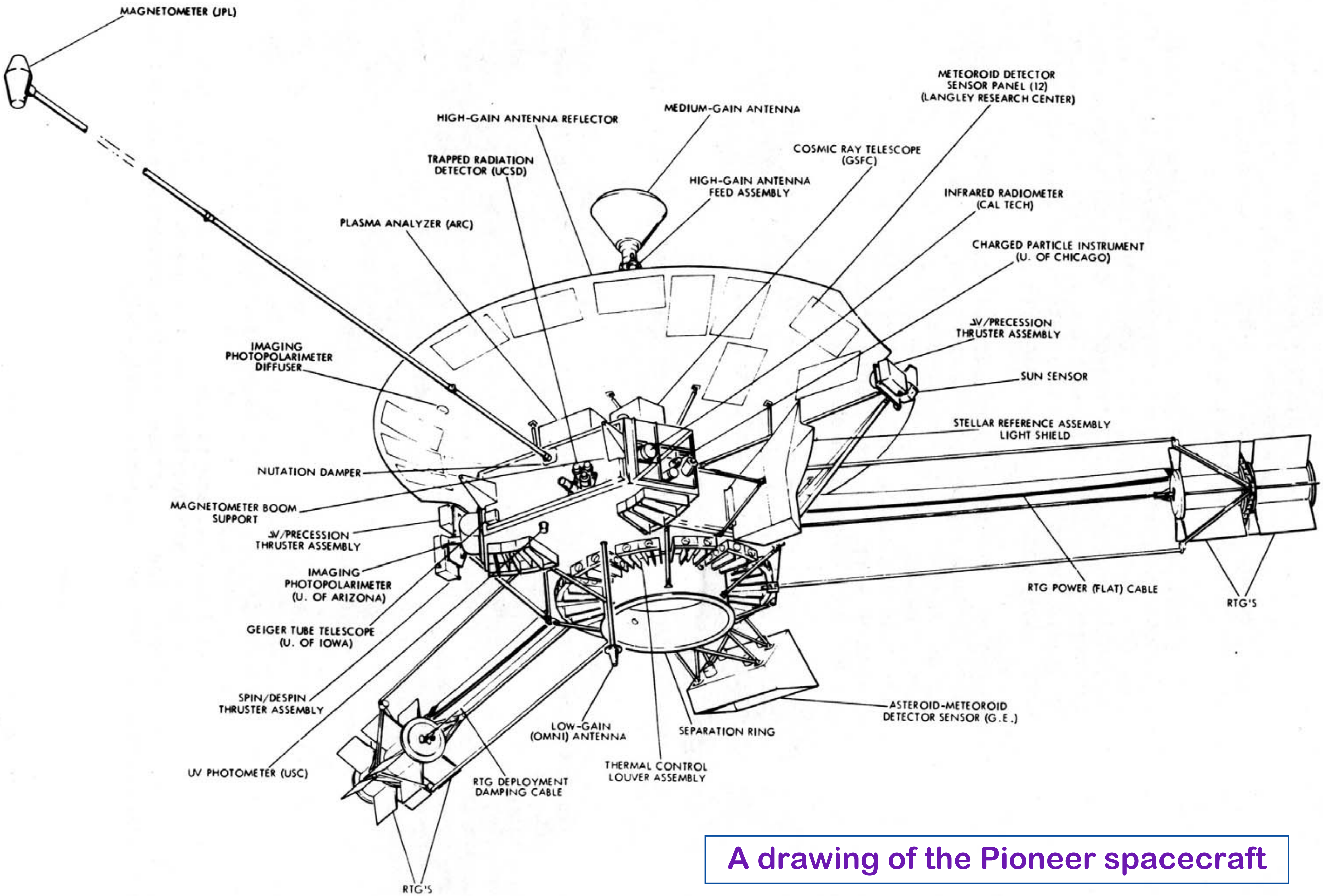
Error budget constituents	Bias 10^{-8} cm/s^2	Uncertainty, 10^{-8} cm/s^2
⇛ Radio beam reaction force	+1.10	± 0.11
⇛ Thermal/propulsion effects from RTGs:		
⇛ RTG heat reflected off the craft	–0.55	± 0.55
⇛ Differential emissivity of the RTGs		± 0.85
⇛ Non-isotropic radiative cooling of s/c		± 0.16
⇛ 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

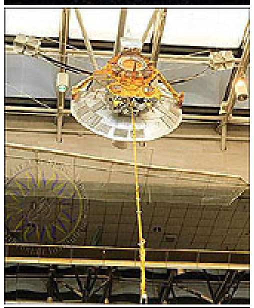
Phys. Rev. D 65 (2002) 082004, gr-qc/0104064

Pioneer 10/11 spacecraft



A drawing of the Pioneer spacecraft

On-board Power and Heat


- **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 (∈ 24.3 W science instruments)

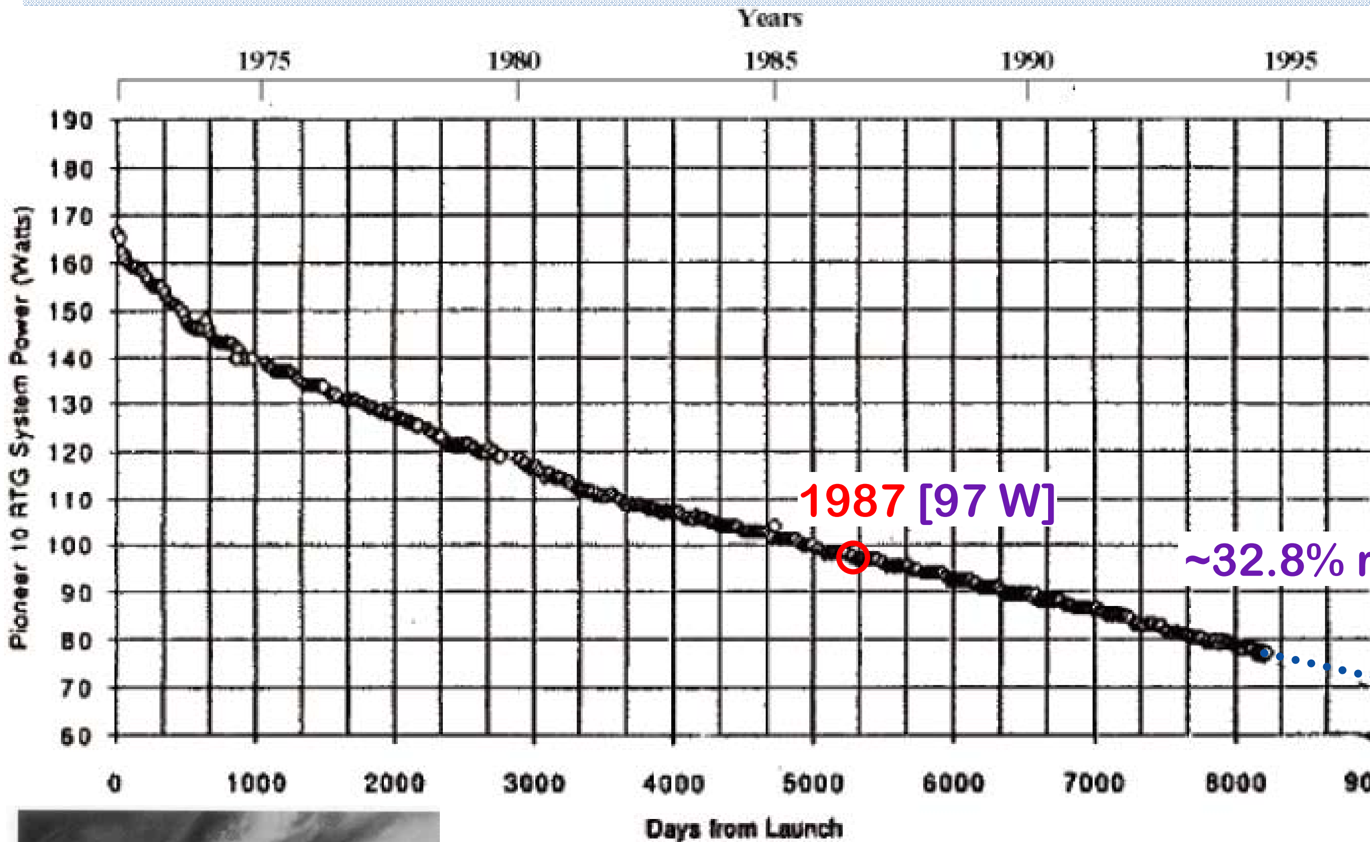
Heat provided:
- before launch thermal fuel total 2580 W (by 2001 ~ 2050 W)
- electric heaters; 12 one-W RHUs
- heat from the instruments (dissipation of 70 to 120 W)

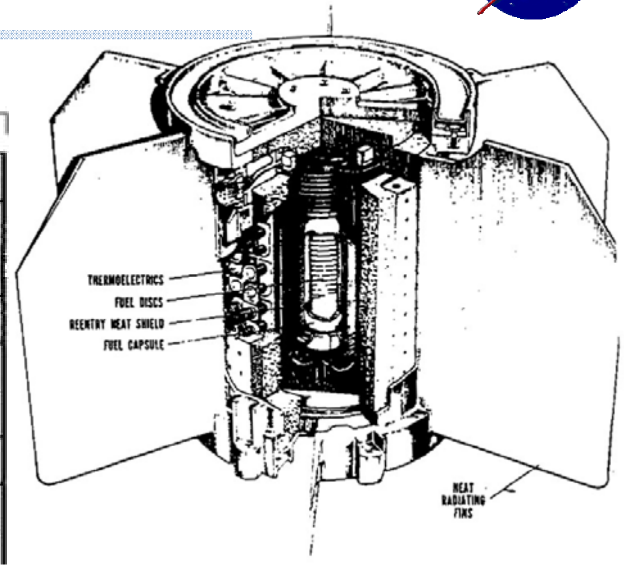
Excess power/heat: if electric power was > 100 W ⇒
- thermally radiated into space by a shunt-resistor radiator, or
- charge a battery in the equipment compartment

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

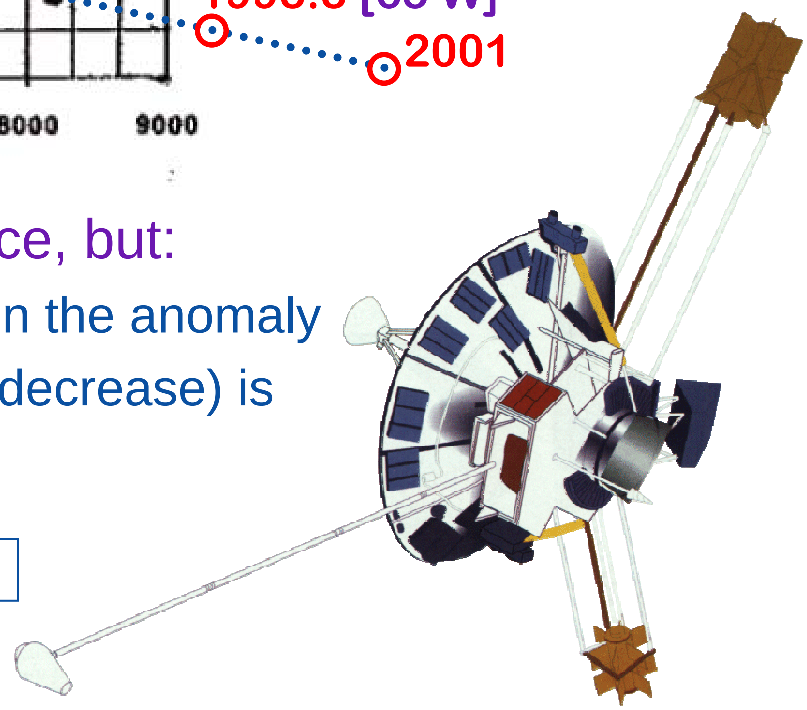
On-board Power and Heat





SNAP 19/PIONEER RADIOISOTOPE THERMOELECTRIC GENERATOR

Pioneer 10

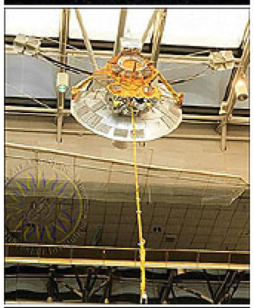


Heat is clearly important source, but:

- 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

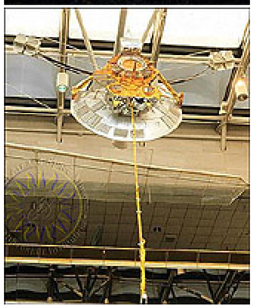
Models Used to Explain the Anomaly



- 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)
  - Dust in the outer solar system

Many more models had been proposed and investigated

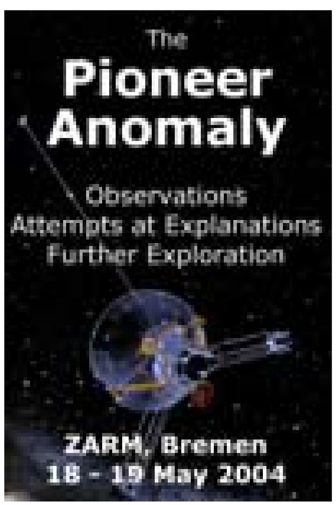
The Pioneer Anomaly: Summary



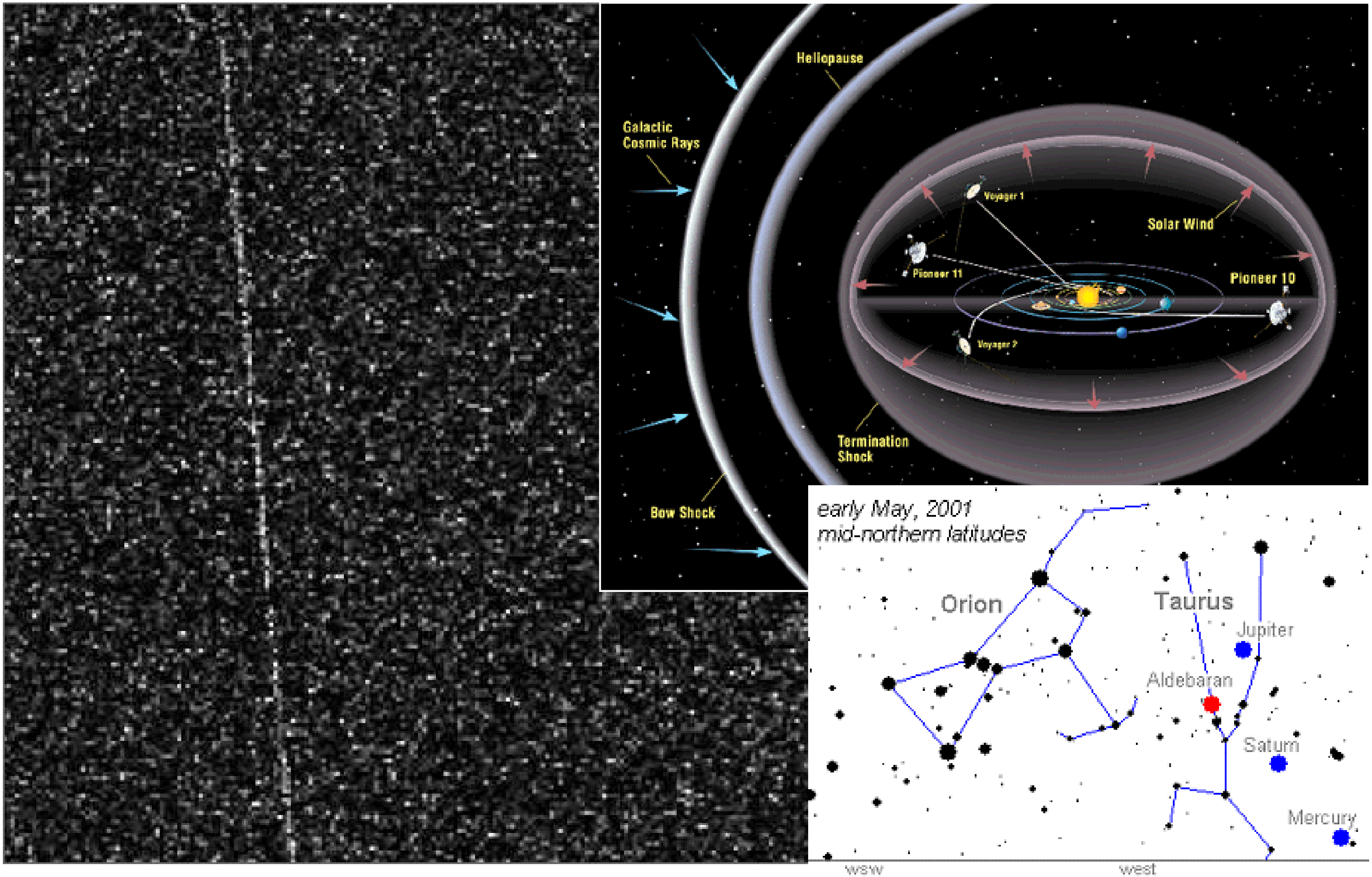
- Our latest result for the Pioneer 10/11 anomalous acceleration:

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

  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 [by Craig Markward in 2003, data from NSSDC].
- Next Steps:
  - Early data processing [work initiated at JPL: fly-byes, entire data set]
  - Focus on different segments: close-in (direction of the anomaly), planetary flyby (amplification during flyby), long duration (constancy)
  - A European study of the PA recently initiated (ZARM, Bremen)



Meanwhile… Pioneer 10 @ Arecibo



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


One “data point”… we need more!