Title: The Pioneer Anomaly

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Abstract:

The Pioneer Anomaly:

The Data, Its Meaning, and a Future Test

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University of California

Perimeter Institute, Waterloo, Ontario

27 Sept. 2005

The original Pioneer Collaboration

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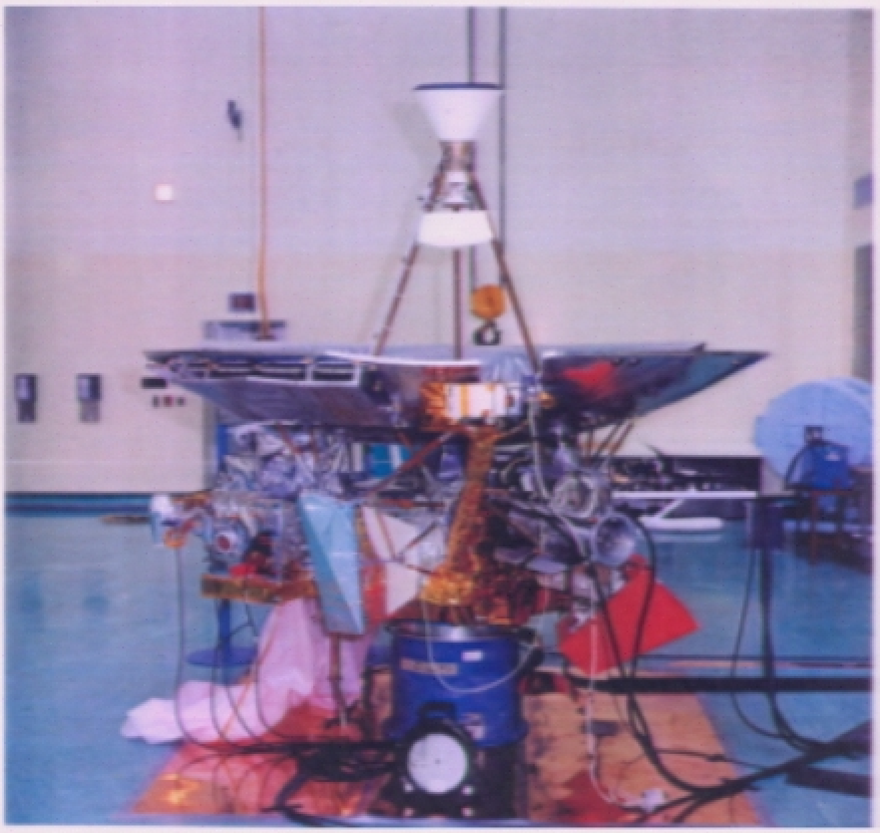
Phillip A. Laing	Aerospace*
Eunice L. Lau	JPL
Anthony S. Liu	Astro Sci*
Michael Martin Nieto	LANL
Slava G. Turyshev	JPL

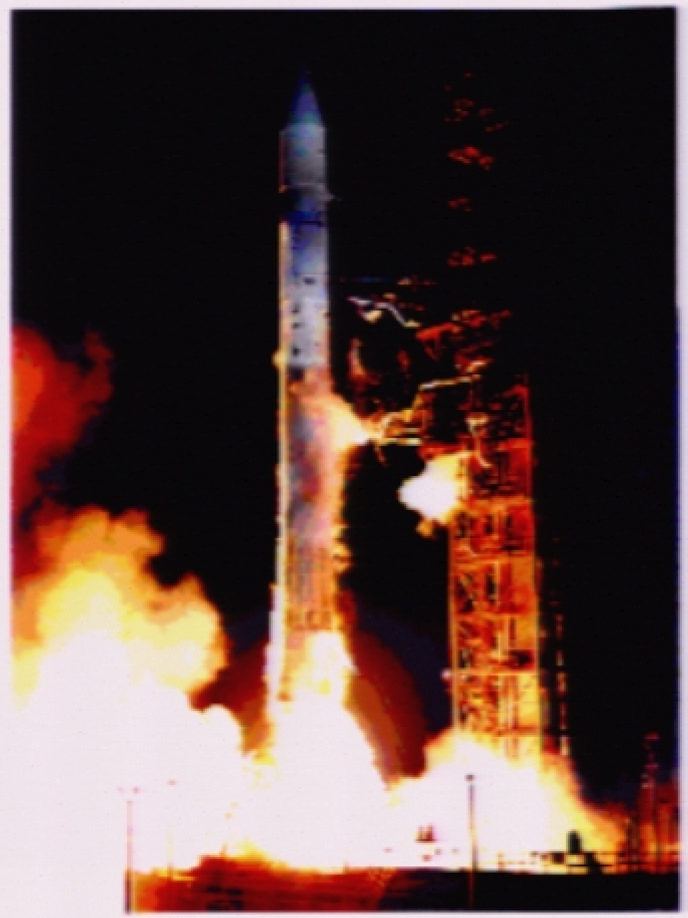
Phys. Rev. Lett. **81**, 2858-2861 (1998), gr-qc/9808081
Phys. Rev. D **65**, 082004/1-50 (2002), gr-qc/0104064

A) THE DATA

Pioneer F (10) at the Cape

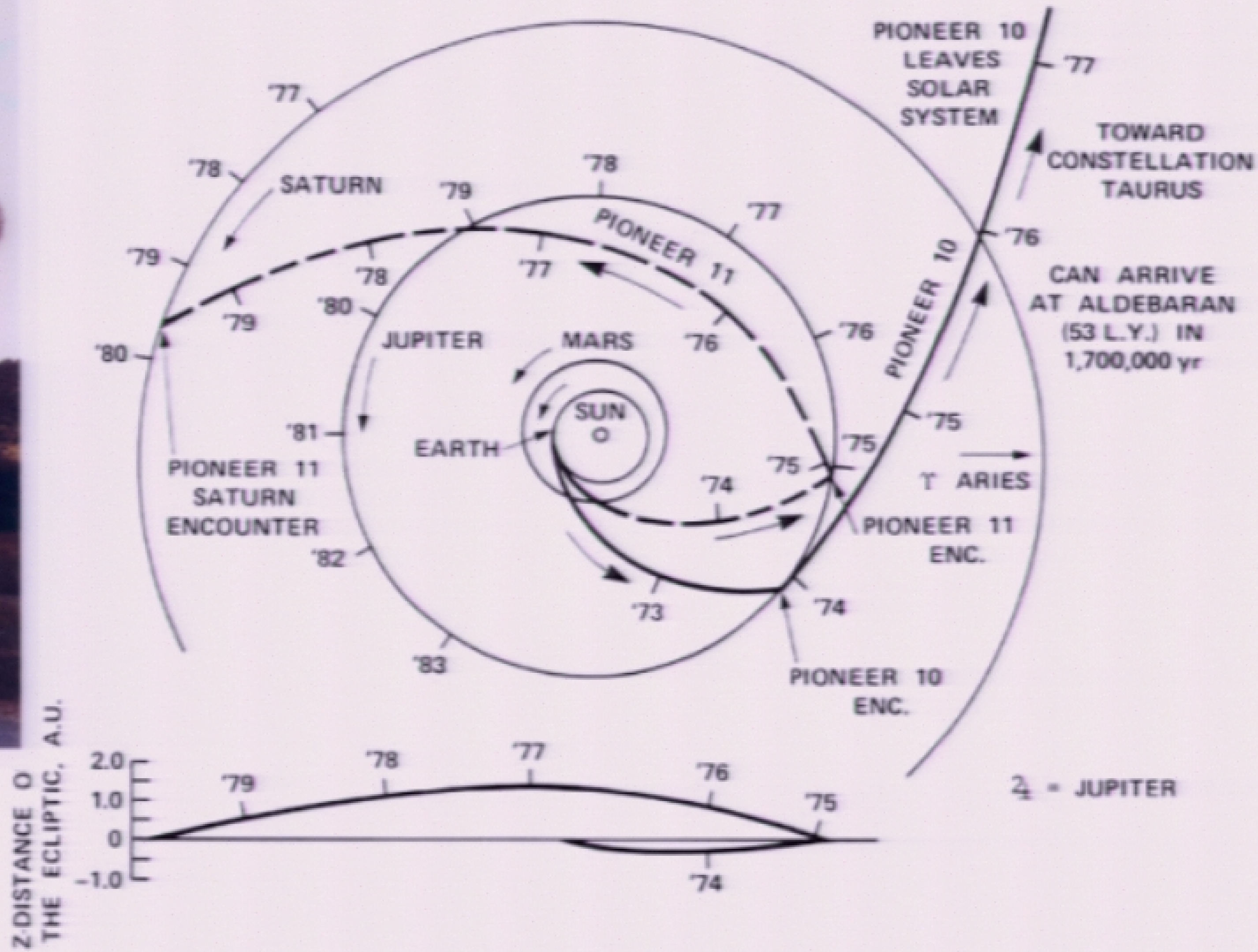


Pioneer 10: 2 March 1972



Meanwhile …

Pioneer 10/11: Main Missions



Meanwhile …

Pioneers in the galaxy

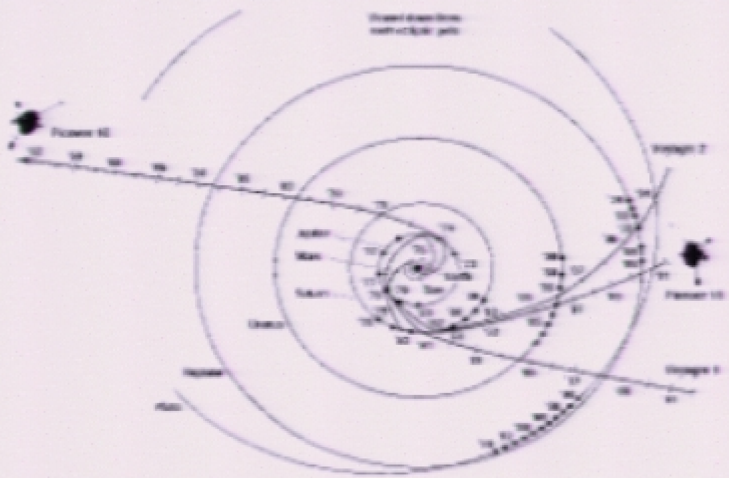


Figure 5. Nearby interstellar medium ... - Netscape

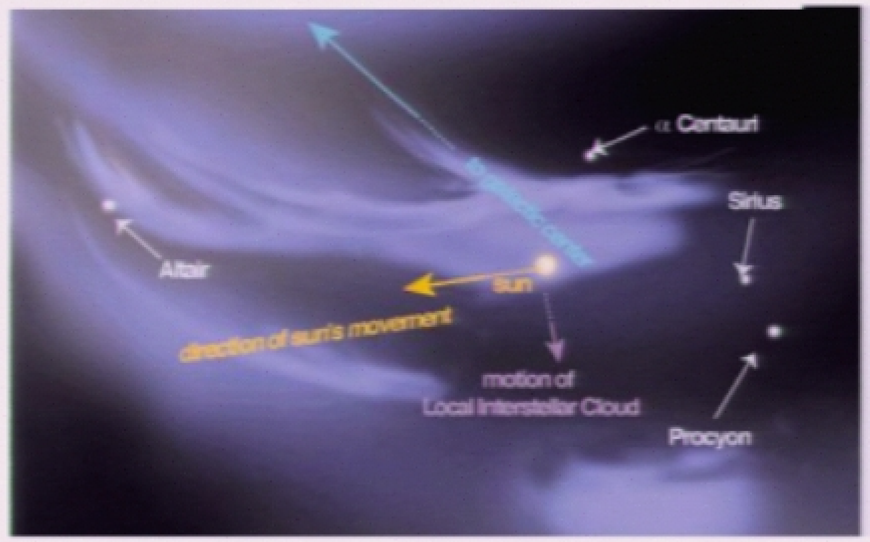
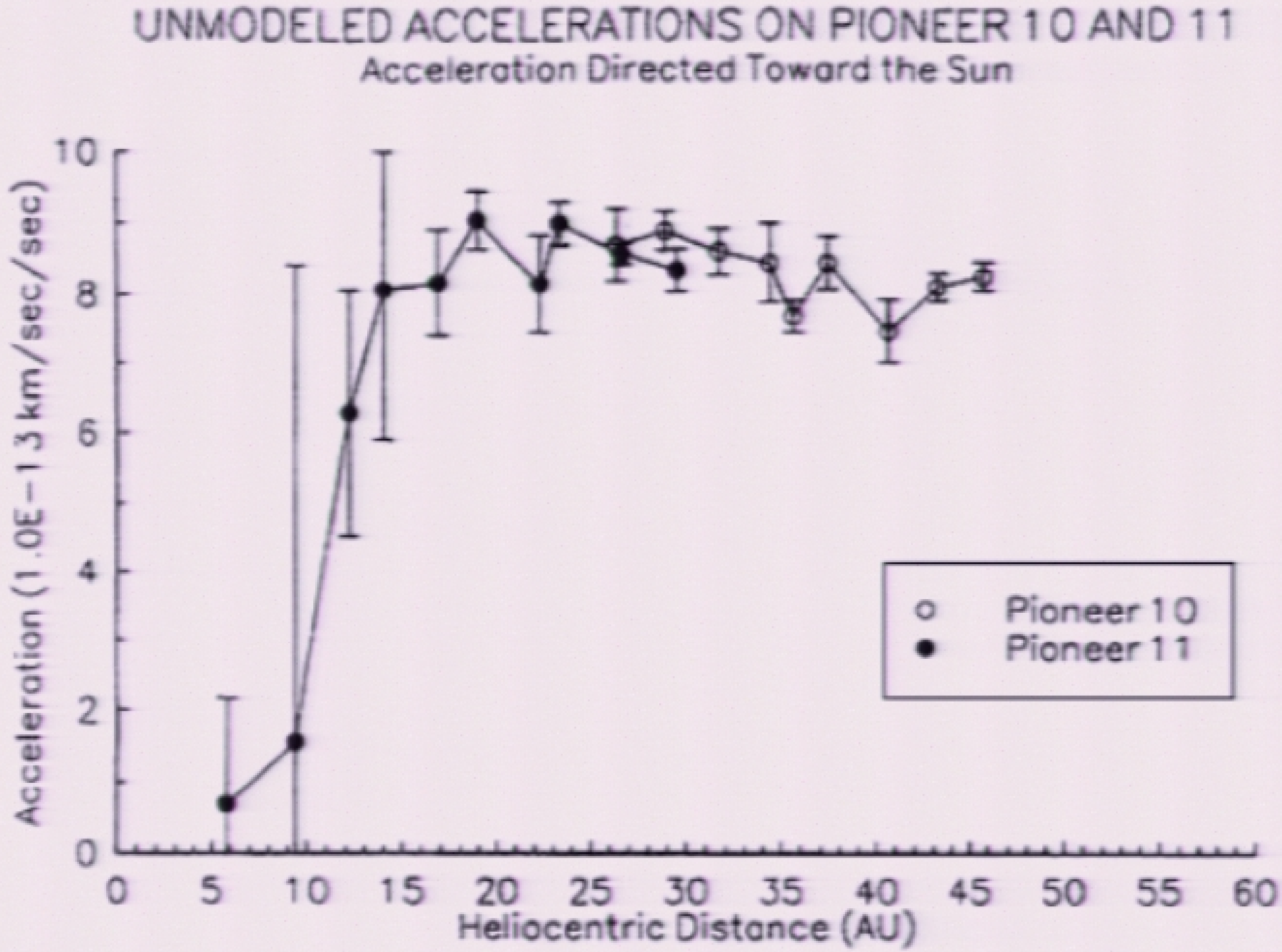


Figure 5. Nearby interstellar medium--within 10 light-years of the sun--is dominated by a shell of material, the Local Interstellar Cloud *(violet)*, that flows outwards from the Scorpius-Centaurus association. This part of the shell is moving *(violet arrow)* perpendicularly to the sun's motion in space and so cuts across its path *(yellow arrow)*. The boundaries of the clouds are based on optical and ultraviolet observations of some nearby stars (such as Sirius, Alpha Centauri and Altair), which reveal the relative amounts of the gases in front of the stars. The motions are shown with respect to nearby stars.

Linda Huff

Early Data



UNMODELED ACCELERATIONS ON PIONEER 10 AND 11
Acceleration Directed Toward the Sun
Acceleration (1.0E−13 km/sec/sec)
Heliocentric Distance (AU)
Pioneer 10
Pioneer 11
0
2
4
6
8
10
0
5
10
15
20
25
30
35
40
45
50
55
60

As preparing for 1994 talk on gravity and anti-matter (see Bled Proceedings), John emailed:

By the way, the biggest systematic in our acceleration residuals is a bias of

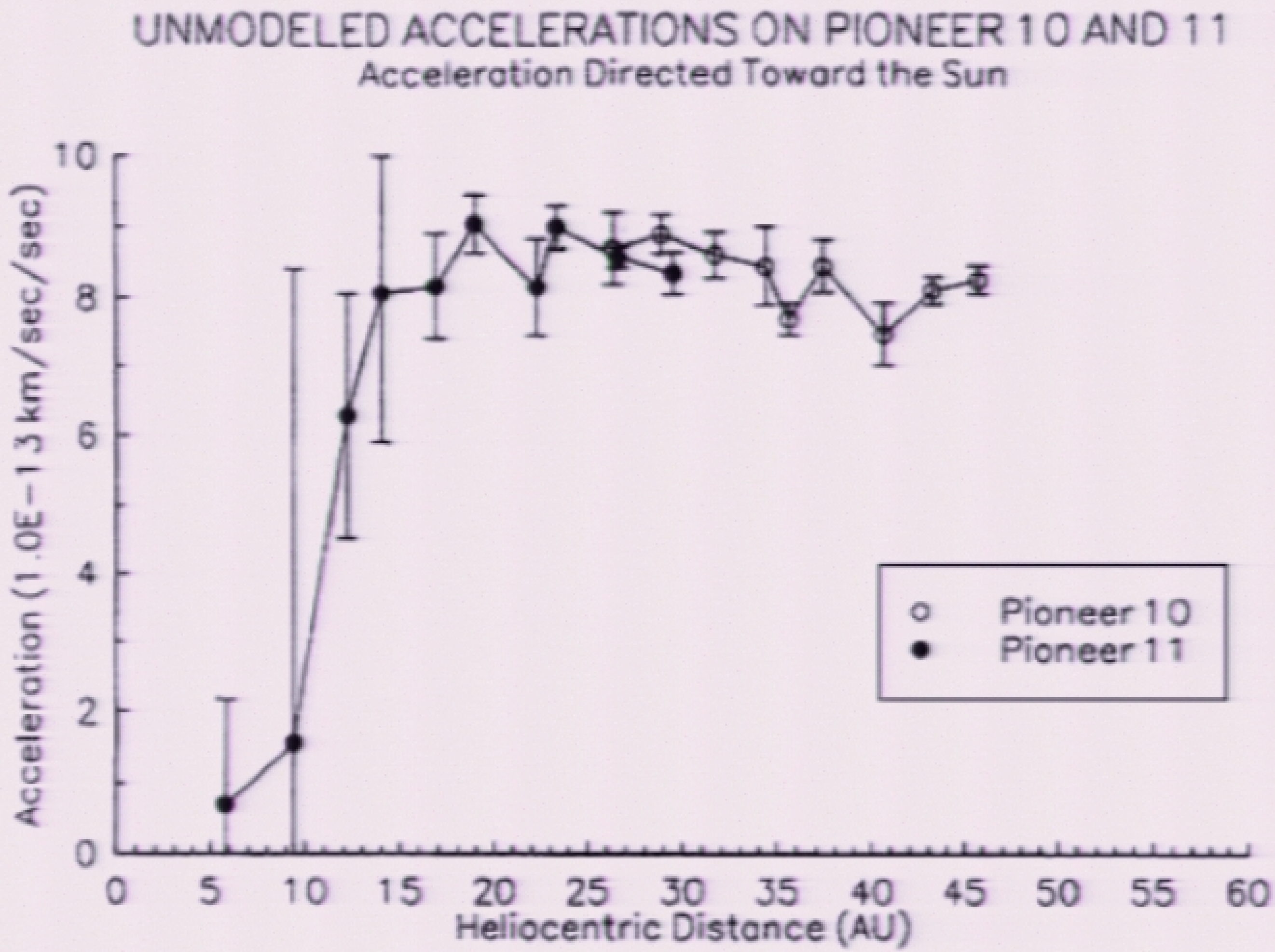
8 X 10^-13 km/s^2

directed toward the Sun.

This is 8 Angstroms/s^2 !!

$a_N = 5.93 \times 10^{-6}$ km/s^2, at 1 AU

Early Data



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THE EXTERNAL REACTIONS

1) "IT MUST BE A GLITCH THAT WILL GO AWAY WITH TIME. THIS CODE WORKS!"

2) IT DID NOT GO AWAY. "BUT WHO CARES? IT IS SMALL AND THINGS WORK WELL ENOUGH."

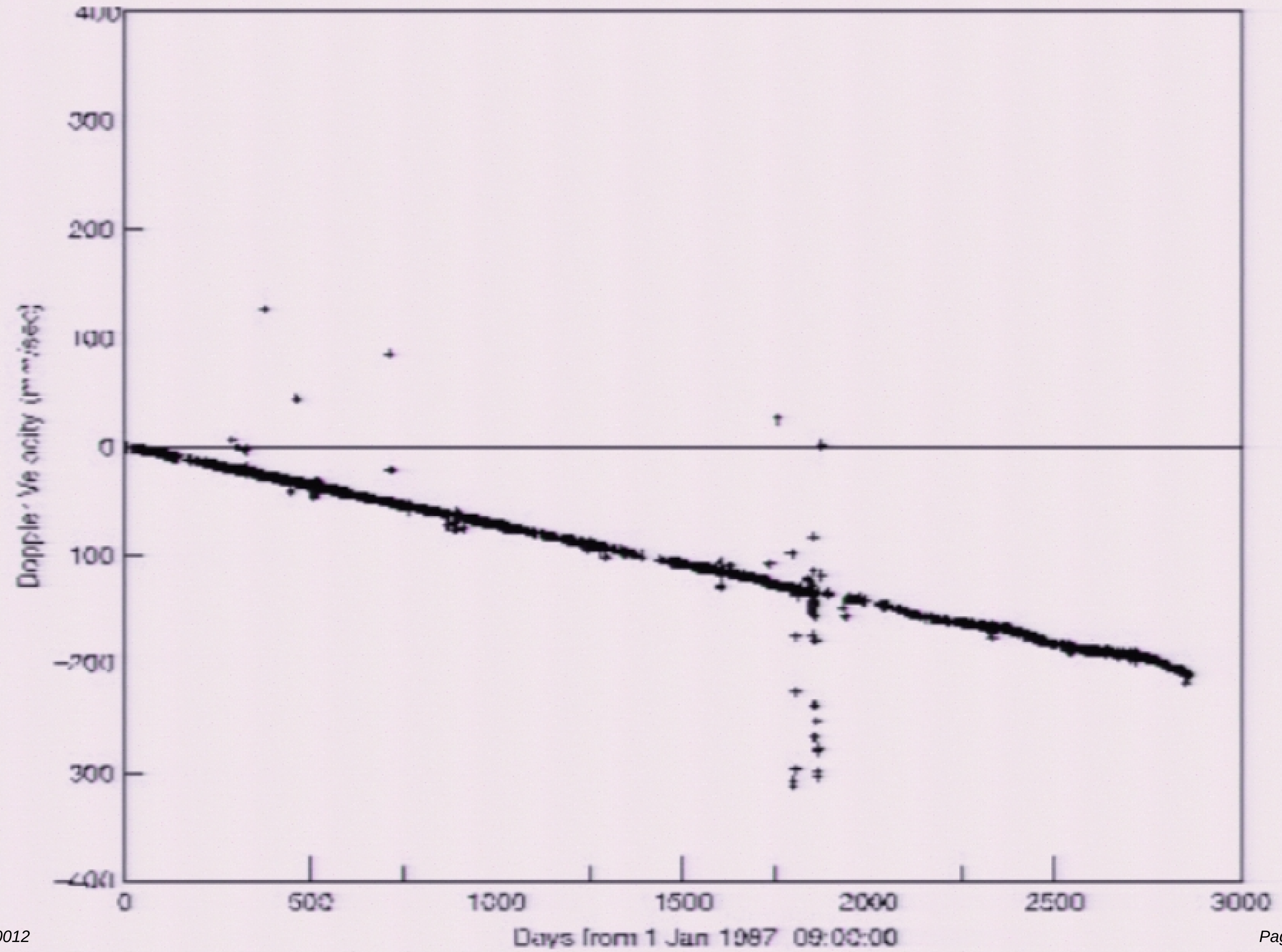
3) THEN WE STARTED STRONLY ASSERTING THAT THE EFFECT REALLY IS IN THE DATA.

4) "WELL, IT MUST BE THE CODE AFTER ALL. DON'T BOTHER US ANY MORE UNLESS YOU SHOW US IT IS NOT THE CODE."

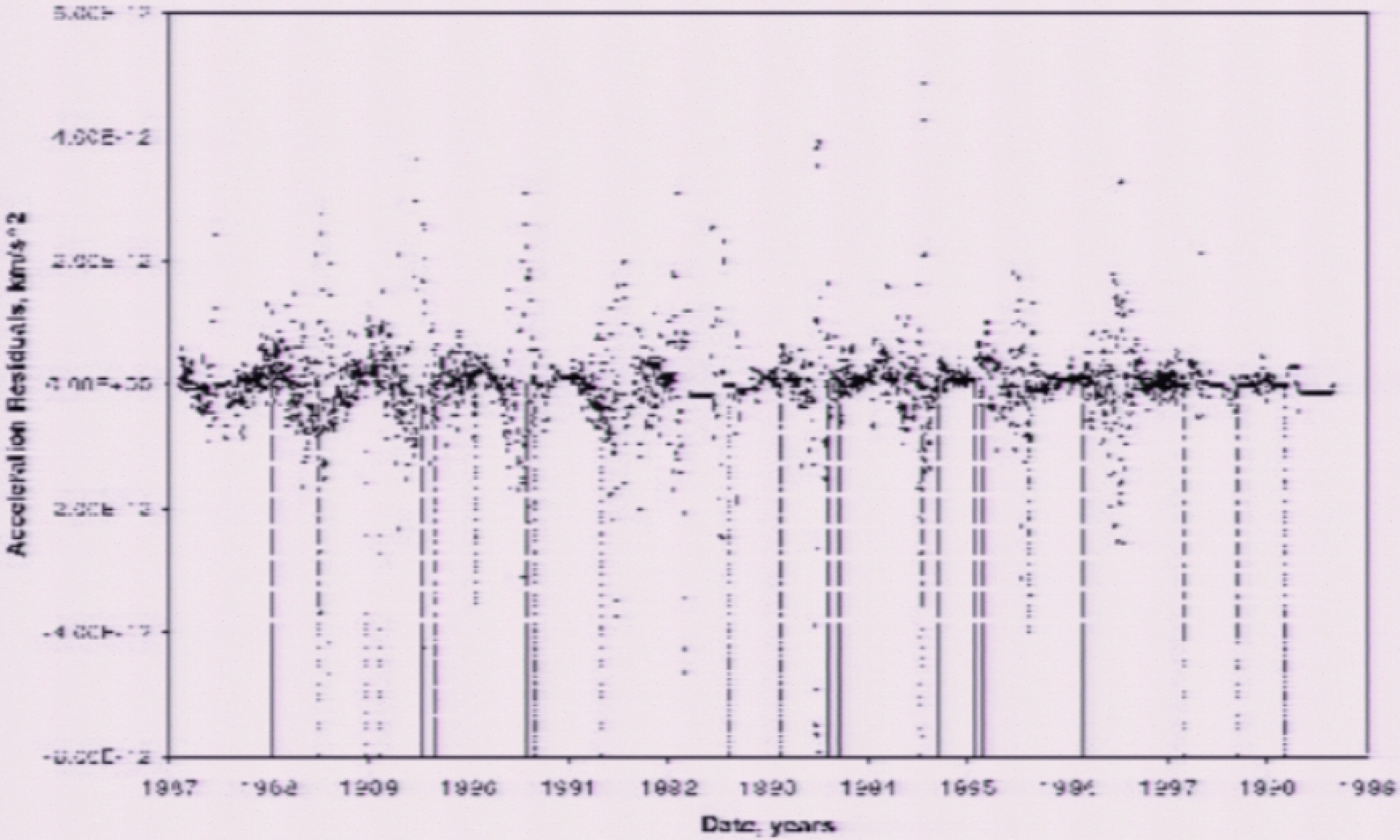
… MUMBLE GRUMBLE

5) FINALLY ANOTHER CODE was used besides ODP… CHASMP.

From CHASMP (Aerospace)



ODP results (JPL)



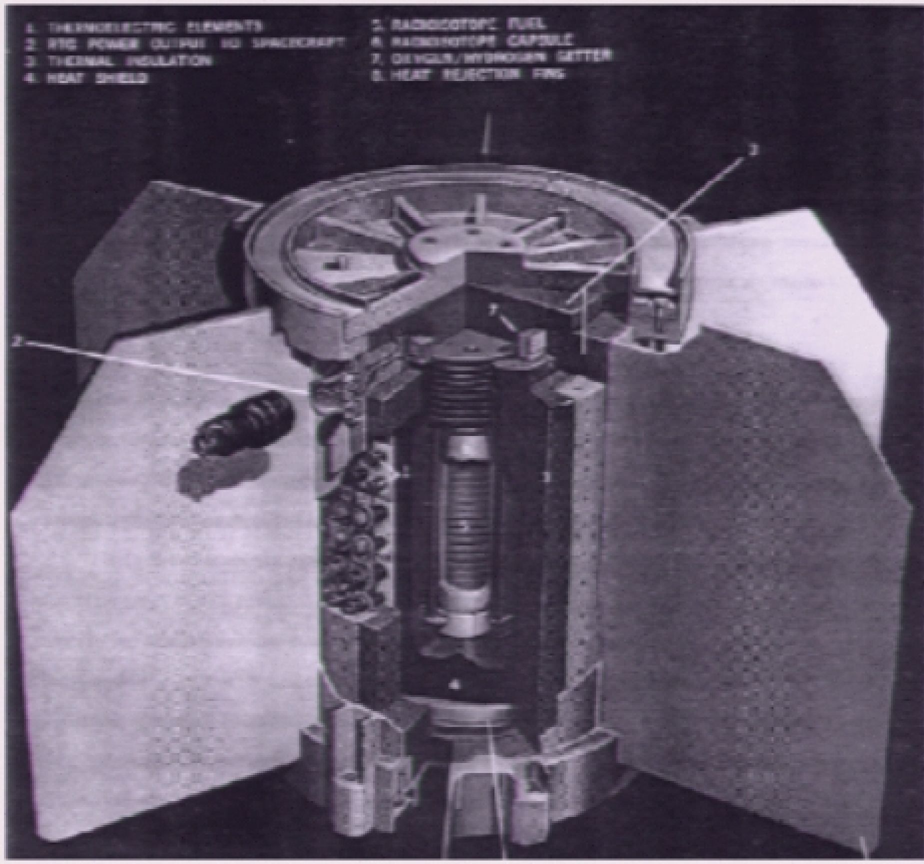
Error Budget: A Summary of Biases and Uncertainties

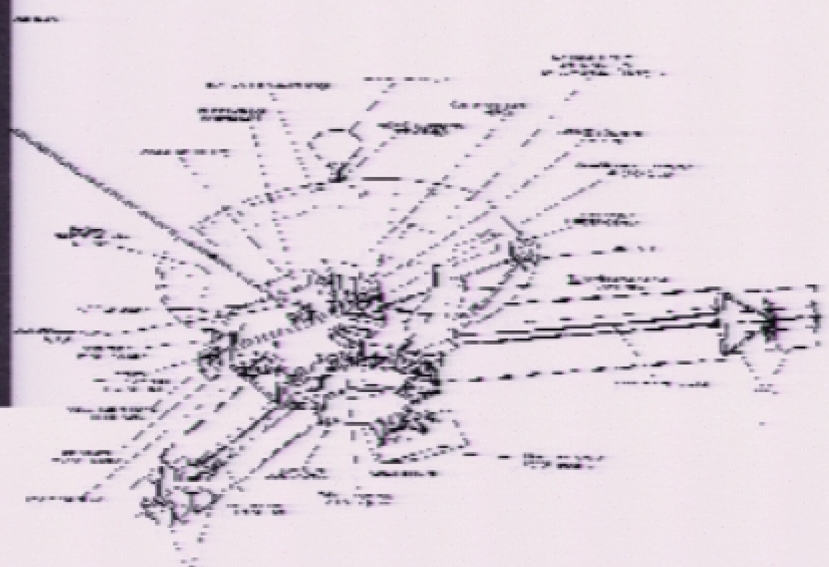
Item	Description of error budget constituents	Bias 10^{-8} cm/s^2	Uncertainty, 10^{-8} cm/s^2
1	Systematics generated external to the spacecraft:		
	a) Solar radiation pressure and mass	+0.03	±0.01
	b) Solar wind		$\pm < 10^{-5}$
	c) Solar corona		±0.02
	d) Electro-magnetic Lorentz forces		$\pm < 10^{-4}$
	e) Influence of the Kuiper belt's gravity		±0.03
	f) Influence of the Earth orientation		±0.001
	g) Mechanical and phase stability of DSN antennae		$\pm < 0.001$
	h) Phase stability and clocks		$\pm < 0.001$
	i) DSN station location		$\pm < 10^{-5}$
	j) Troposphere and ionosphere		$\pm < 0.001$
2	On-board generated systematics:		
	a) Radio beam reaction force	+1.10	±0.11
	b) RTG heat reflected off the craft	−0.55	±0.55
	c) Differential emissivity of the RTGs		±0.85
	d) Non-isotropic radiative cooling of the spacecraft		±0.48
	e) Expelled Helium produced within the RTGs	+0.15	±0.16
	f) Gas leakage		±0.56
	g) Variation between spacecraft determinations	+0.17	±0.17
3	Computational systematics:		
	a) Numerical stability of least-squares estimation		±0.02
	b) Accuracy of consistency/model tests		±0.13
	c) Mismodeling of maneuvers		±0.01
	d) Mismodeling of the solar corona		±0.02
	e) Annual/diurnal terms		±0.32
	Estimate of total bias/error	+0.90	±1.33

$$a_P = a_{P(\mathrm{exper})} + b_P \pm \sigma_P, \qquad a_{P(\mathrm{exper})} = (7.84 \pm 0.01) \times 10^{-8} \mathrm{cm/s^2}$$

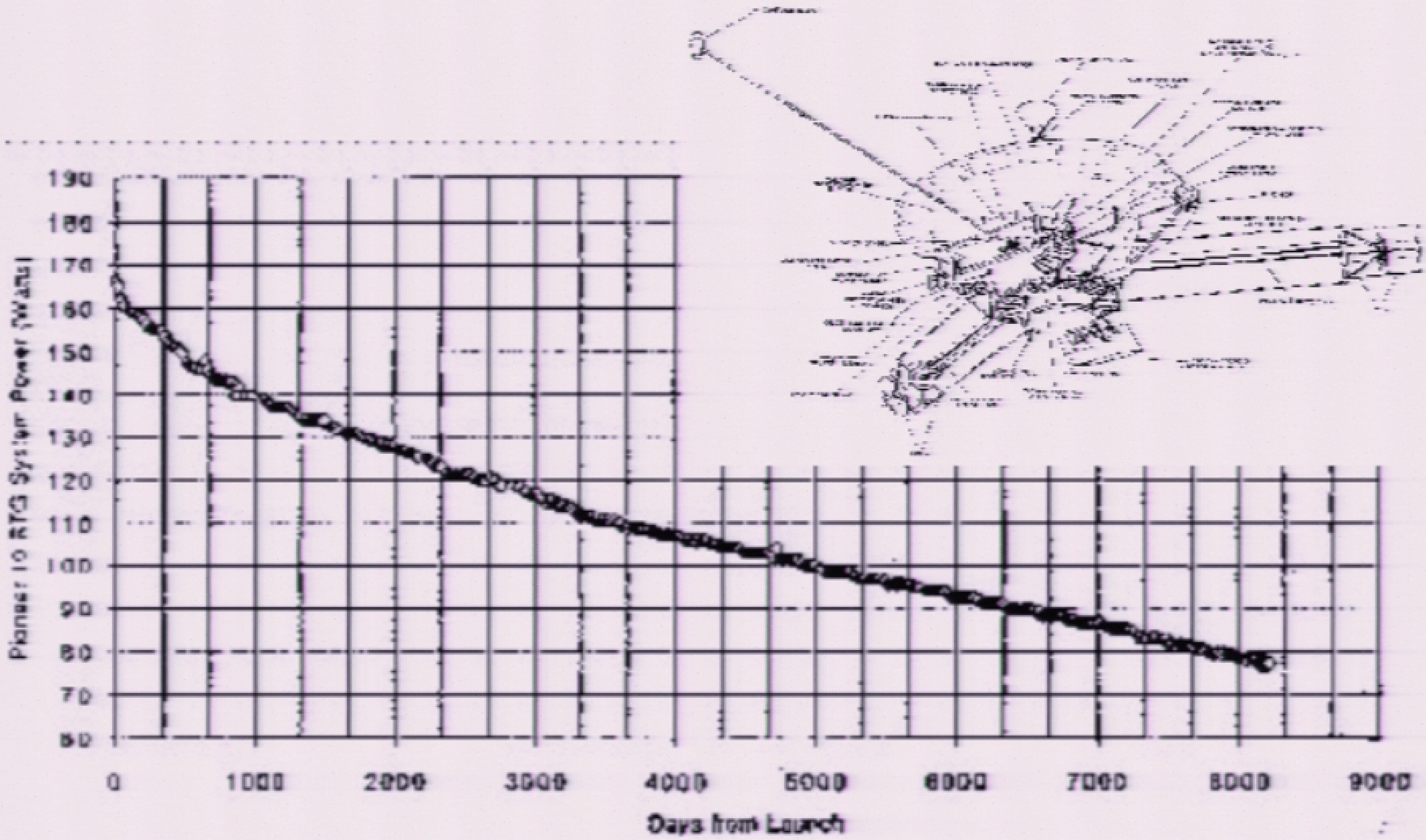
$$a_P = (8.74 \pm 1.33) \times 10^{-8}\ \mathrm{cm/s^2} \sim (8.7 \pm 1.3) \times 10^{-8}\ \mathrm{cm/s^2}.$$

SNAP19 RTGs


1. THERMOELECTRIC ELEMENTS
2. RTG POWER OUTPUT TO SPACECRAFT
3. THERMAL INSULATION
4. HEAT SHIELD
5. RADIOISOTOPE FUEL
6. RADIOISOTOPE CAPSULE
7. OXYGEN/HYDROGEN GETTER
8. HEAT REJECTION FINS

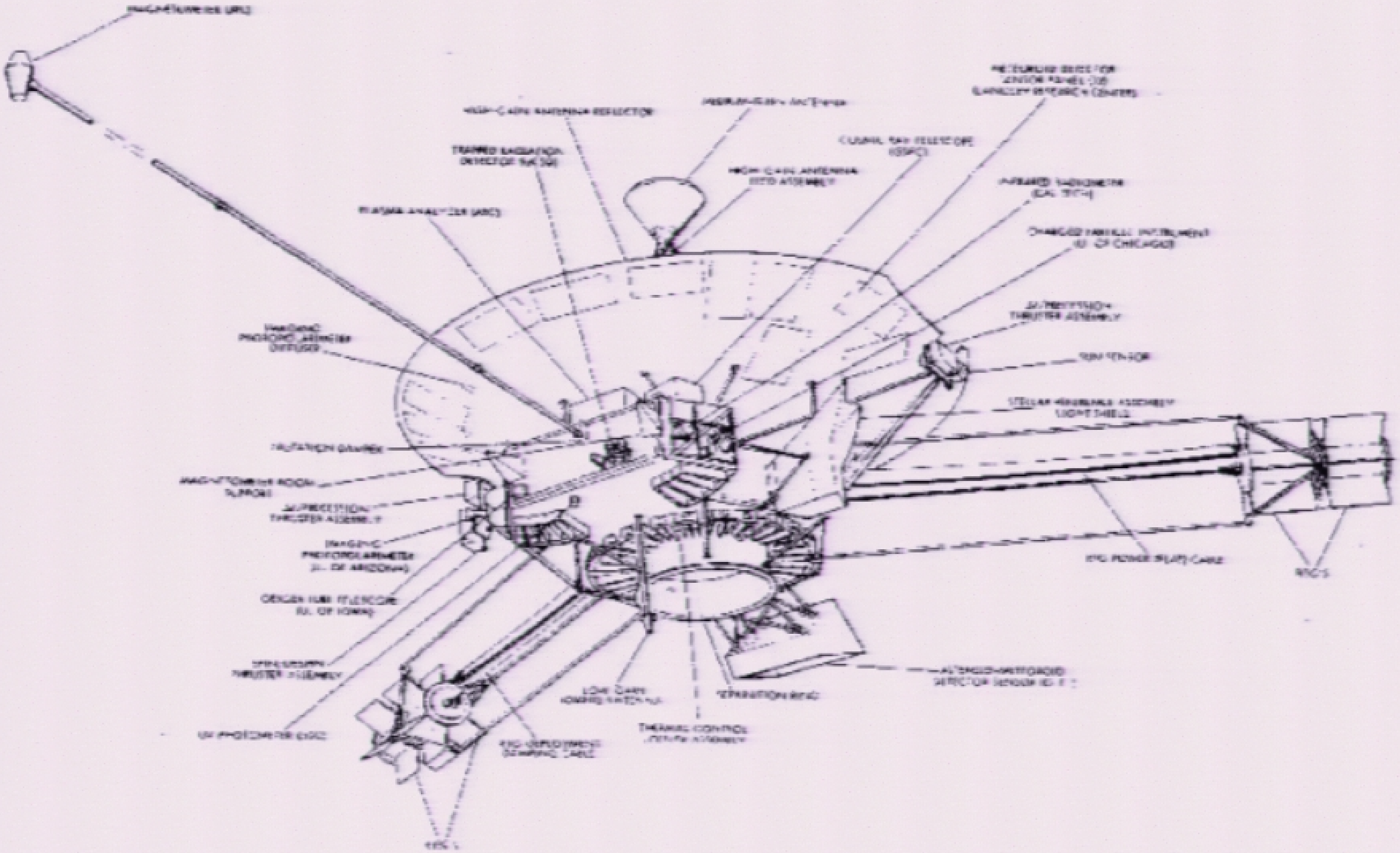


Electrical power



1987.0* 1998.8*

B) THE DATA'S MEANING



What do we really "know" from the big study?

- For Pioneer 10: between ~40-70.5 AU (1987.0-1998.5)

  $a_{P(expt)}^{Pio\ 10} = (7.84 \pm 0.01) \times 10^{-8}\ cm/s^2$

- For Pioneer 11: between ~22.4-31.7 AU (1987.0-1990.8)

  $a_{P(expt)}^{Pio\ 11} = (8.55 \pm 0.02) \times 10^{-8}\ cm/s^2$

- Analysis for both Pioneers with systematics:

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

SEEN only on these small (~250 kg) craft on hyperbolic orbits.
NOT SEEN on large, bound, astronomical bodies.

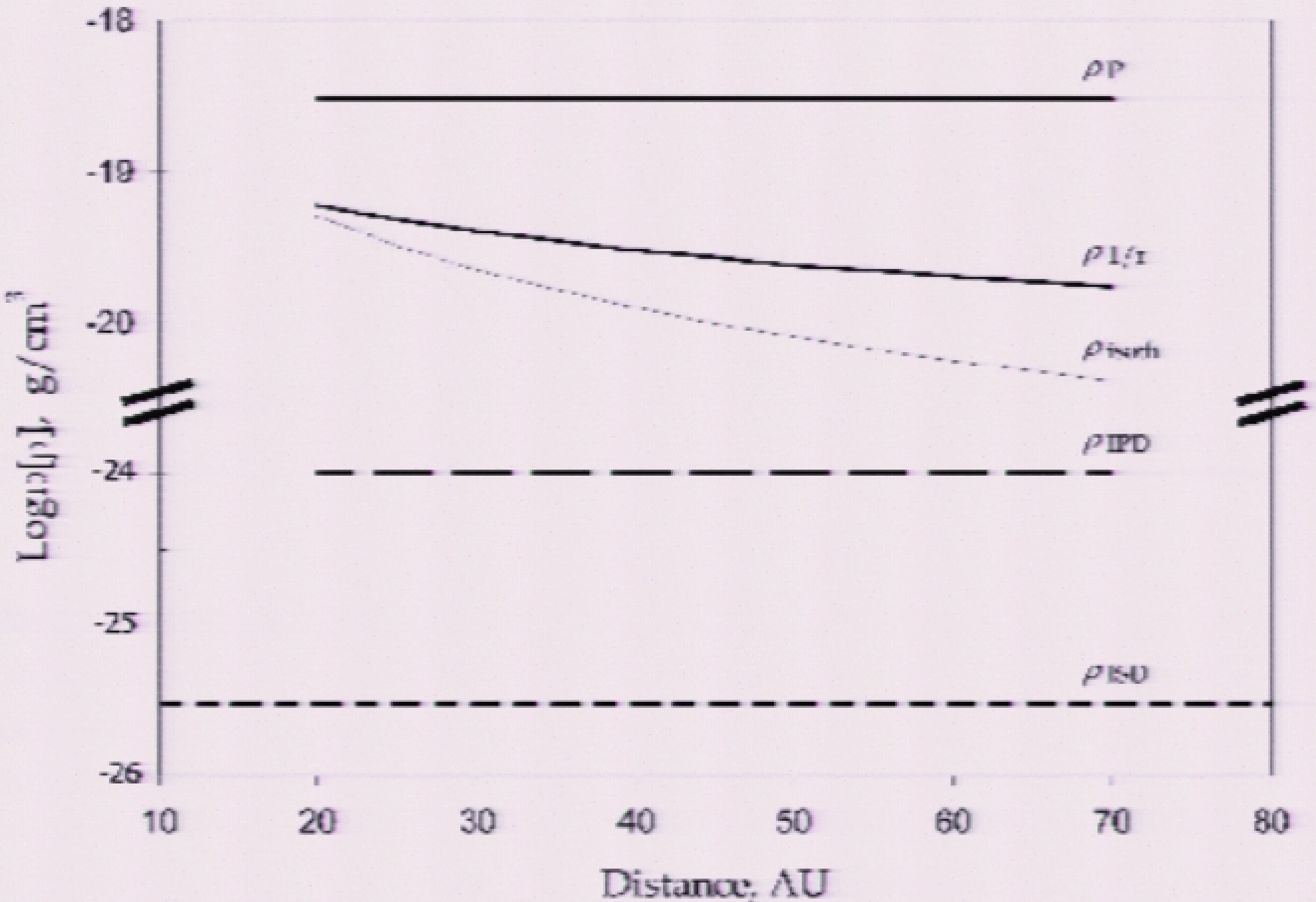
But REMEMBER, this is really a Doppler shift, that is only INTERPRETED as an acceleration.

Dust Density and Drag

$a_P \equiv$
$\rho_P \, v_P^2 \, A_P \, / m_P$

$\rho_{IPD} \leq \rho_P =$
3×10^{-19} g/cm^3

(a) Pioneer upper bound on IPD from drag
(b, c) Model-dependent upper bounds on IPD
(d) Estimate of IPD
(e) Estimate of ISD

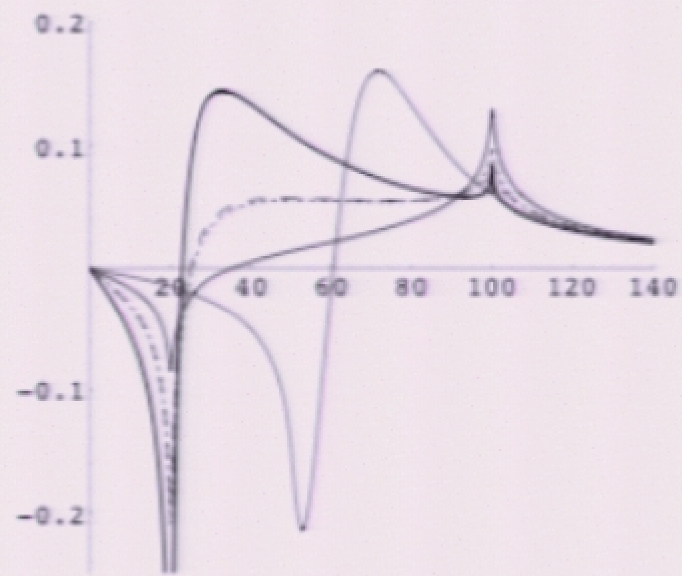


BOTTOM LINE: Any drag is DARK MATTER, not dust

KB matter and Gravity

$$\mathbf{a}_{KB}(r)\,/m_P \equiv -\,\nabla \int d^3r'\,(-G)\,\rho_{KB}(\mathbf{r'})\,/\,|\mathbf{r}-\mathbf{r'}|$$

A total spherical 1/r density yields a constant acceleration, whereas a shell does not. Further, 1/r disk with $\rho_{KB} = \rho_0/r'$; $10\text{ AU} \le r' \le 100\text{ AU}$; $1\text{ AU} \le z \le -1\text{ AU}$ does NOT yield a constant acceleration.



2nd BOTTOM LINE: KB matter WILL NOT DO IT

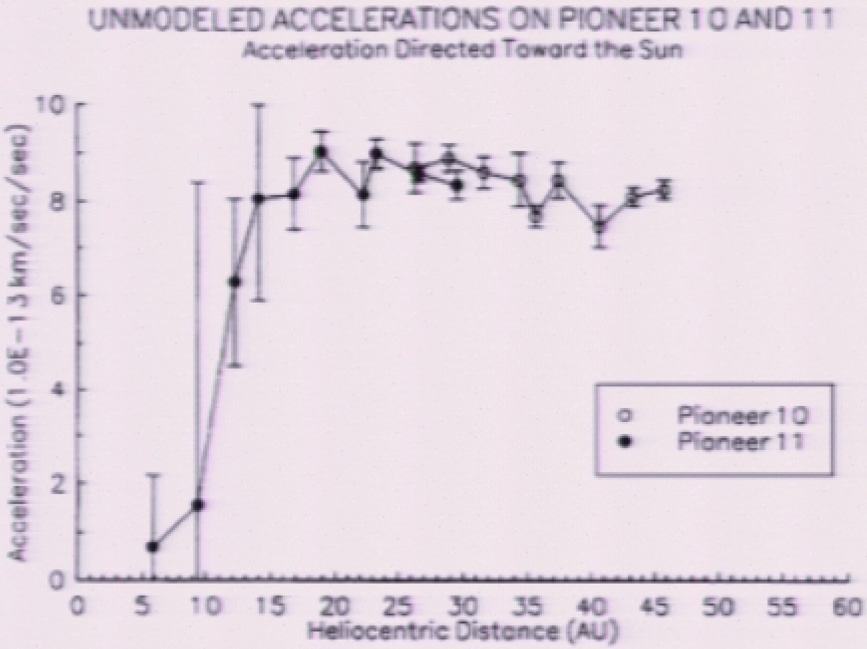
What do we only "suspect" or not know?

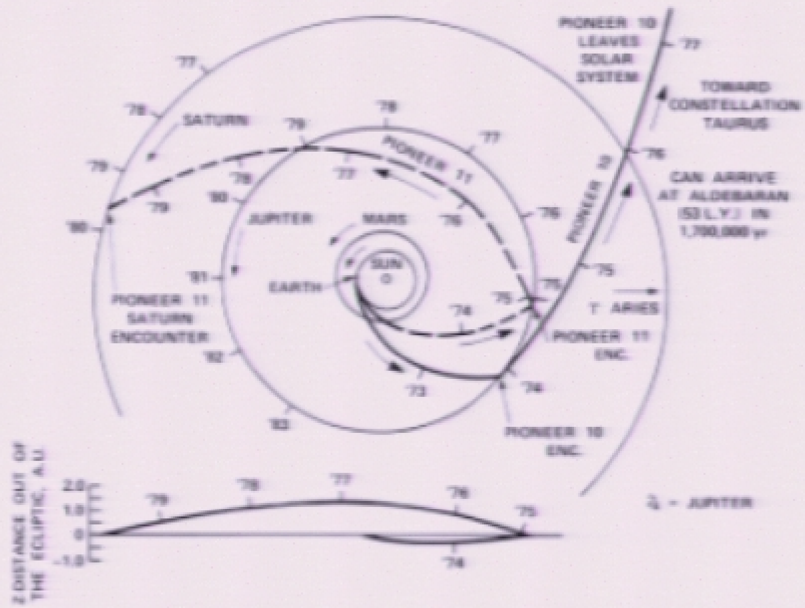
- We have no real idea how far out the anomaly goes.
- a_P continues out *roughly* as a constant from about 10 AU.

BUT:

- Before Saturn encounter (at 10 AU) and the transition to hyperbolic orbit, Pioneer 11 did not show the anomaly.
- Pioneer 10 shows an "effect" starting only at ~10 AU.

Turn-on of the Anomaly?

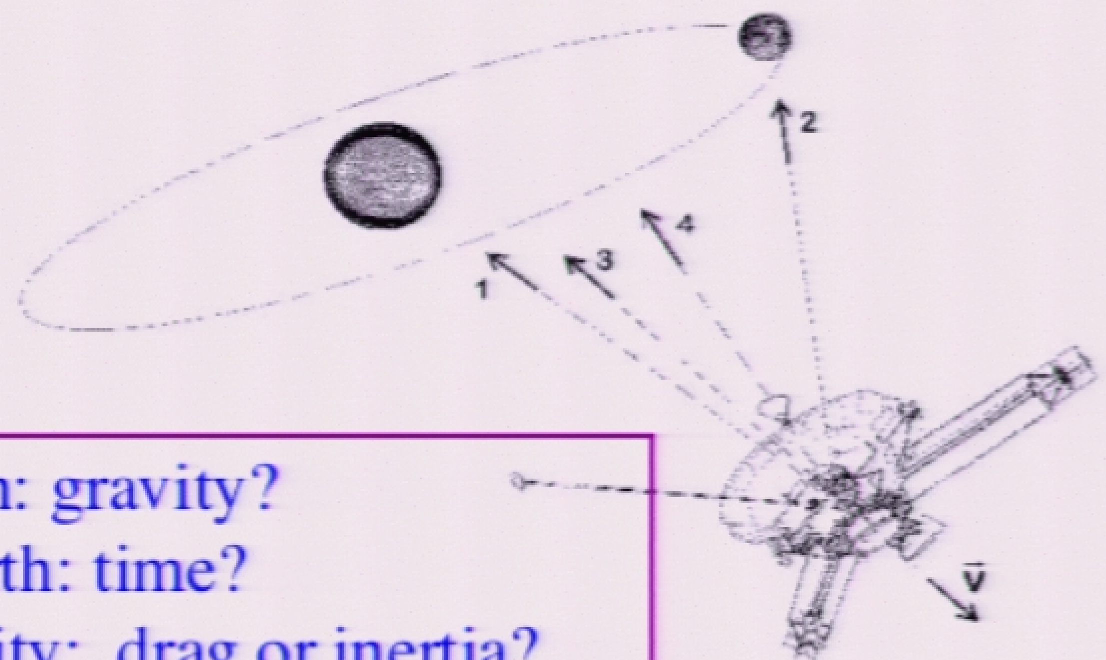




At Saturn Pioneer 11 reached escape velocity and anomaly had big error. Is it a drag turning on or the escape velocity? (Pio 10 escaped at Jupiter.)

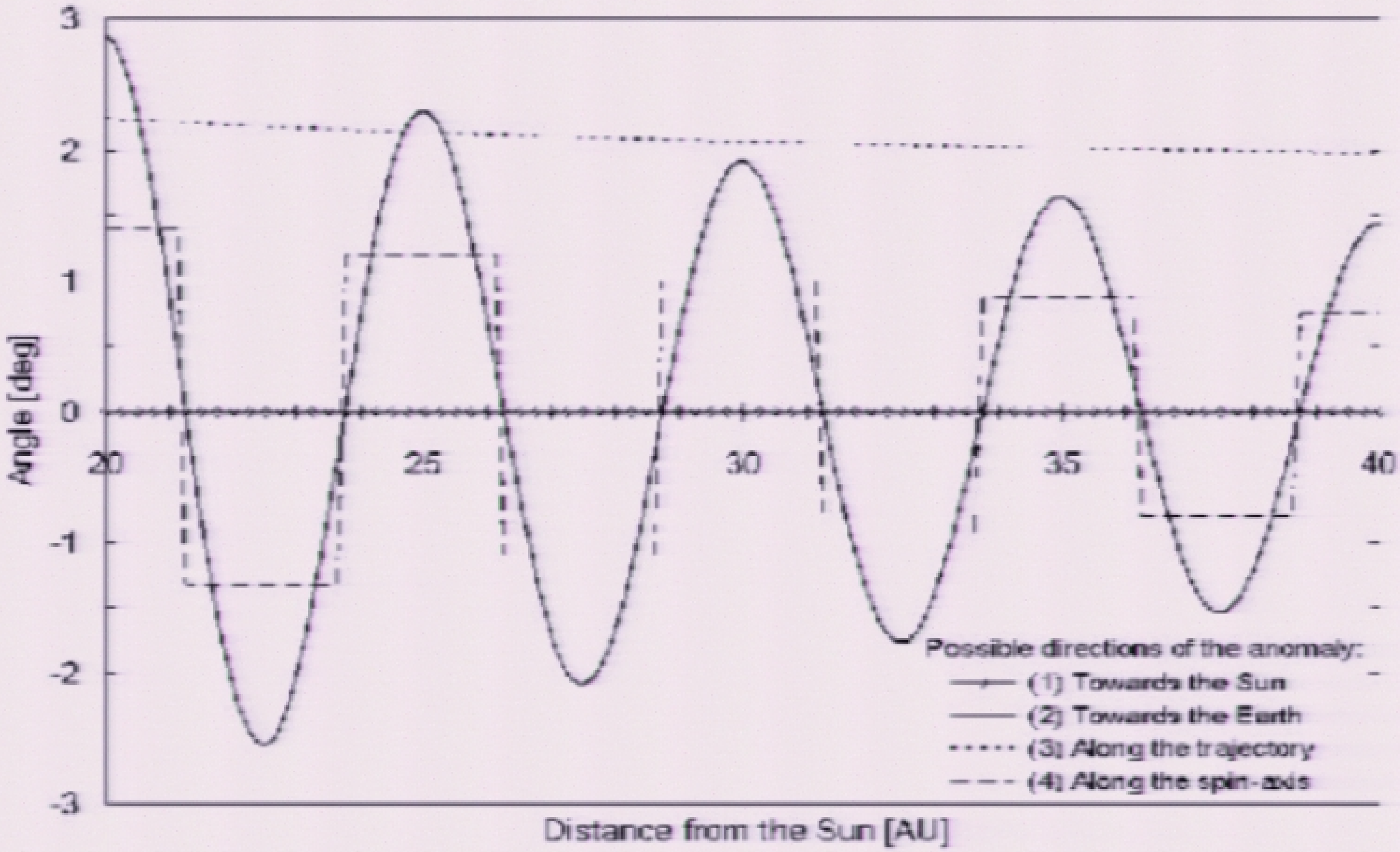
C) A FUTURE TEST

I: **The early data** from 6/78 has been retrieved and will be properly reanalyzed. Although clouded by solar radiation pressure, it will give us more information on the time-dependence and could reveal the anomaly's direction.



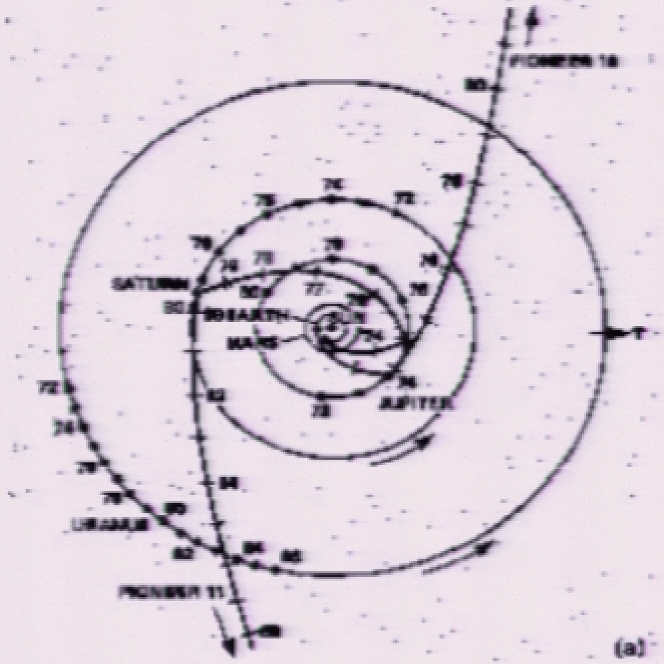
1) Towards the Sun: gravity?
2) Towards the Earth: time?
3) Along the velocity: drag or inertia?
4) On the spin axis: internal systematics?

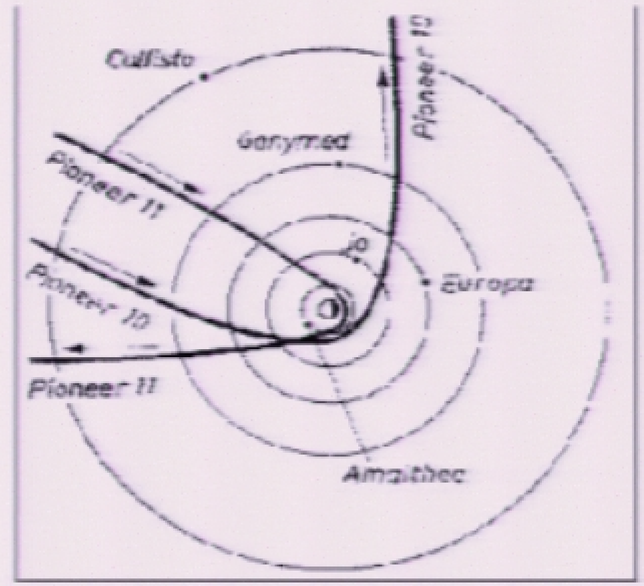
Signals of different anomaly directions

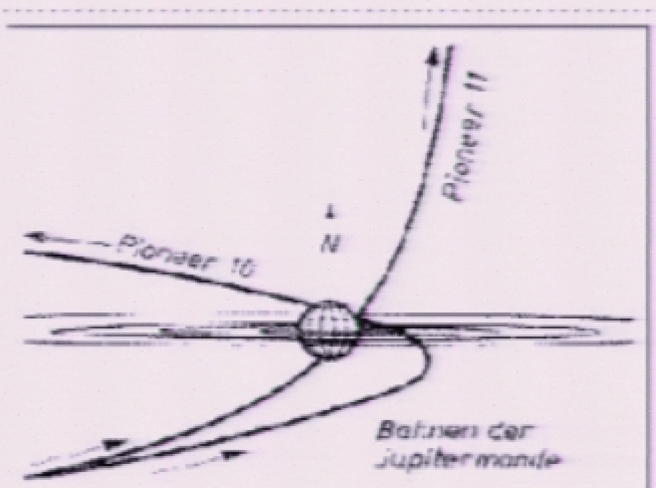


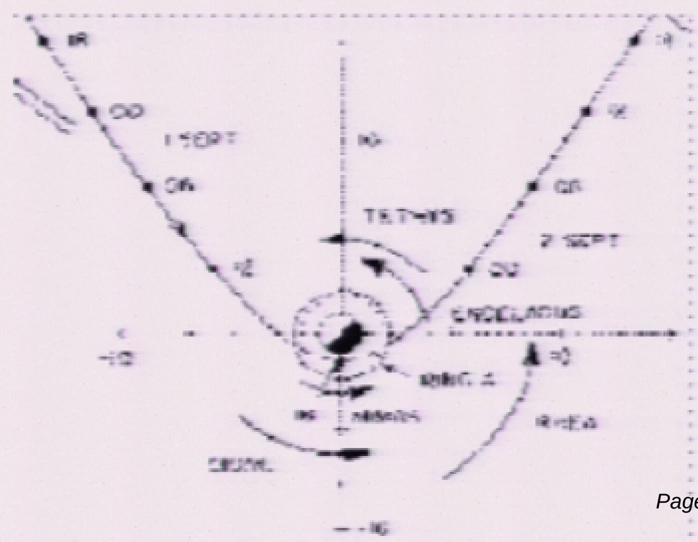
1) Towards the Sun: gravity?
2) Towards the Earth: time?
3) Along the velocity: drag or inertia?
4) On the spin axis: internal systematics?

Retrieved data contains good Saturn encounter. Also have short data artcs around earlier Jupiter encounters.







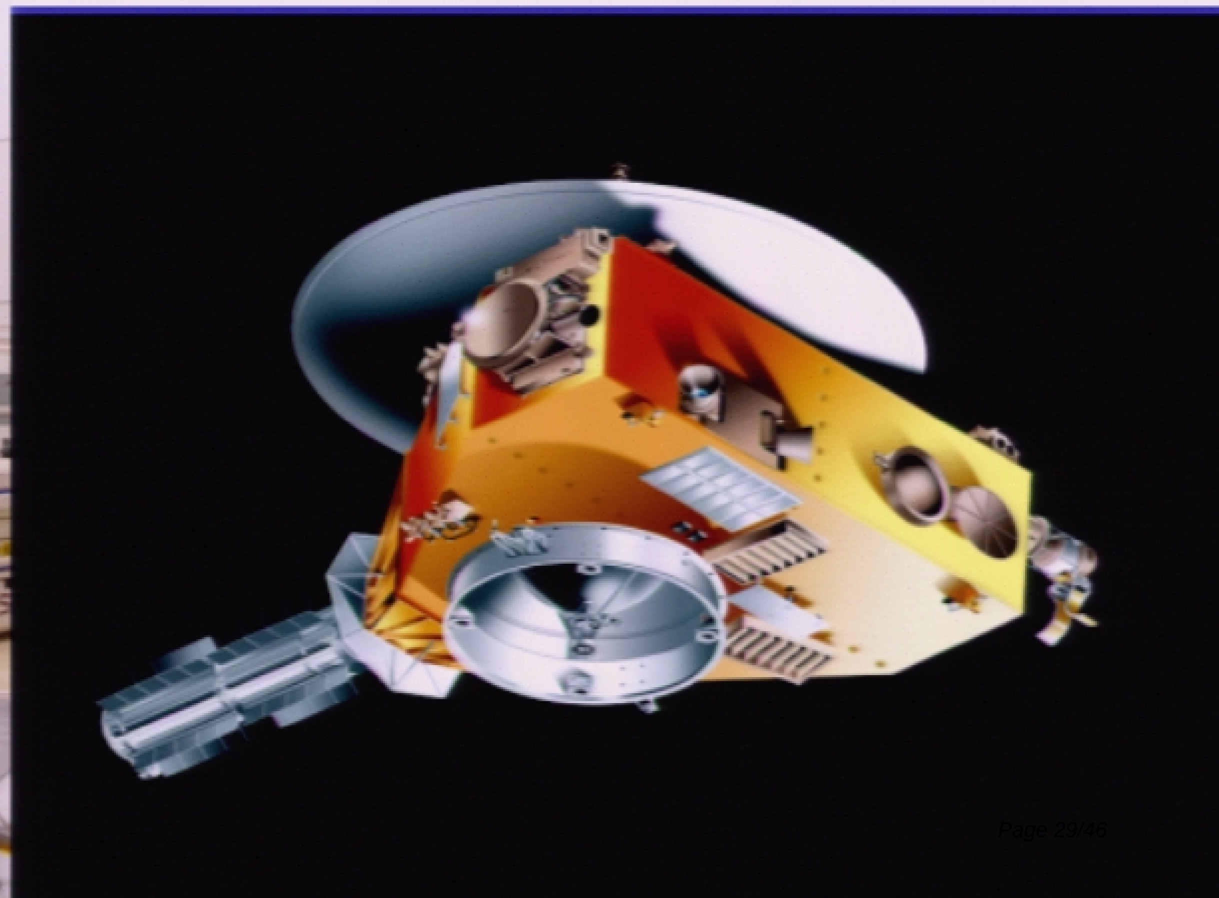


II: Possibilities for an add-on experiment

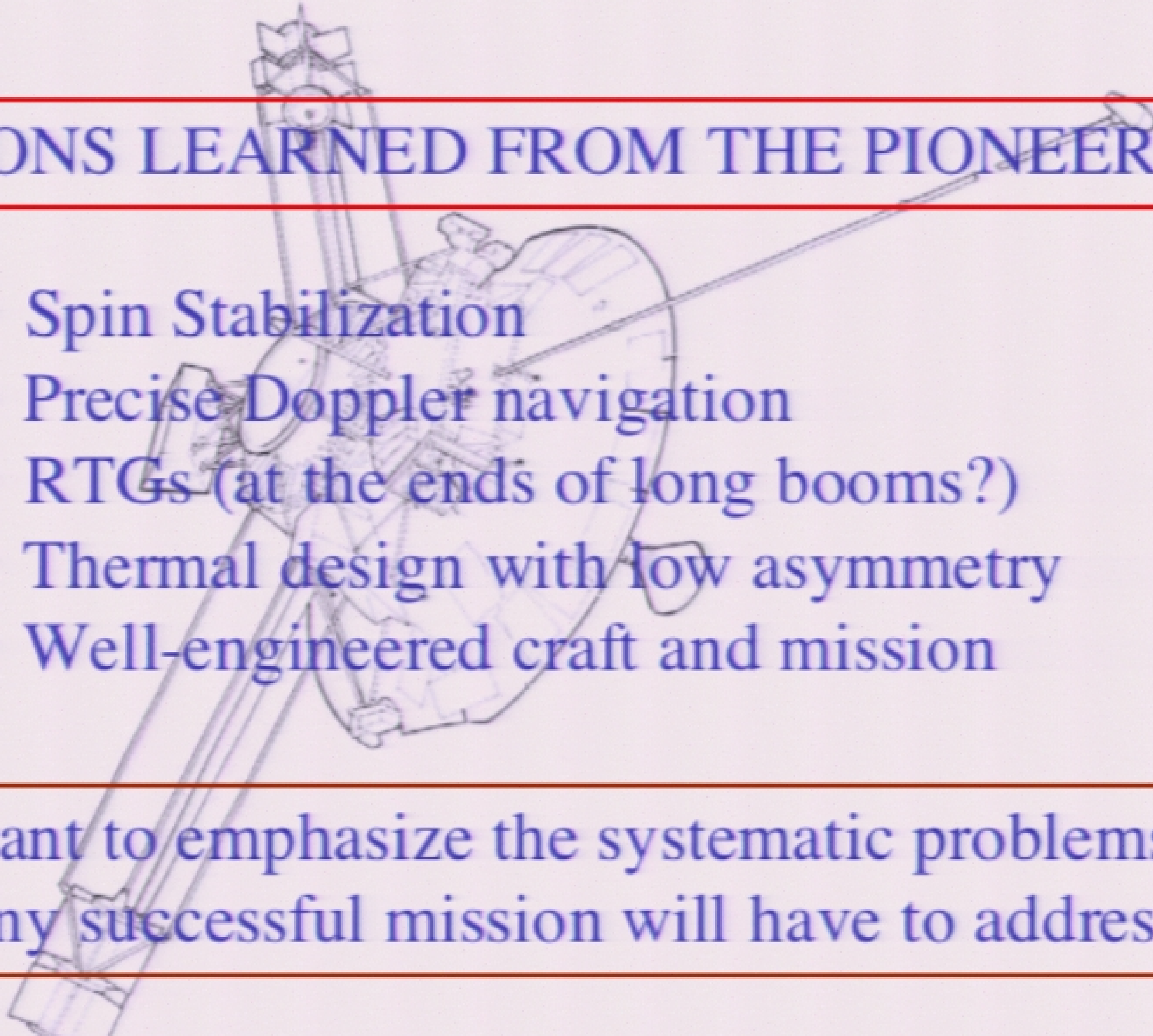
A. New Horizons mission to Pluto

B. Jettisoned package from InterStellar Probe

New Horizons/Pluto Kuiper
Jan.-Feb. 2006



III: A Dedicated Mission



LESSONS LEARNED FROM THE PIONEERS

- Spin Stabilization
- Precise Doppler navigation
- RTGs (at the ends of long booms?)
- Thermal design with low asymmetry
- Well-engineered craft and mission

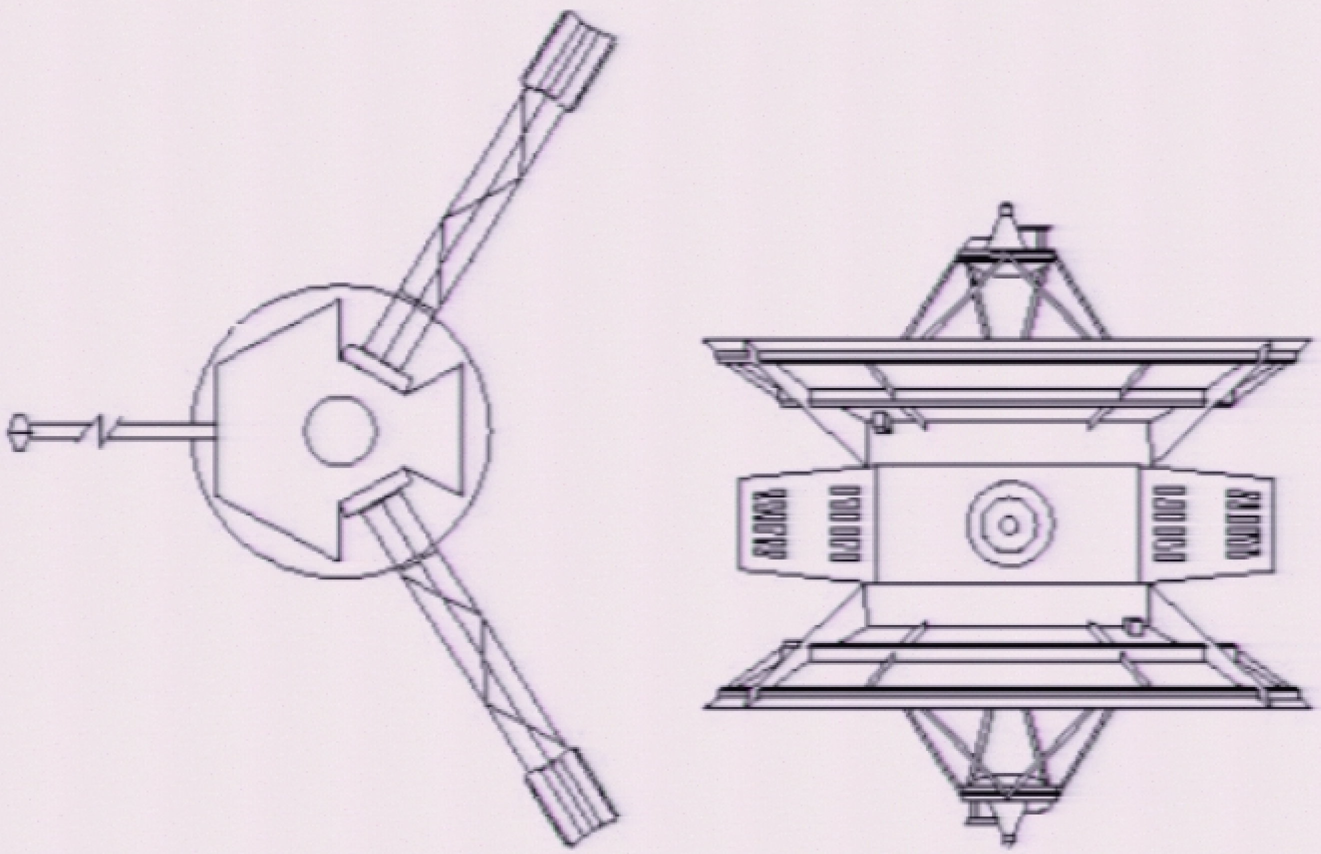
We want to emphasize the systematic problems that any successful mission will have to address.

FORE/AFT SYMMETRIC DESIGN PROPOSES UNIQUE FEATURES

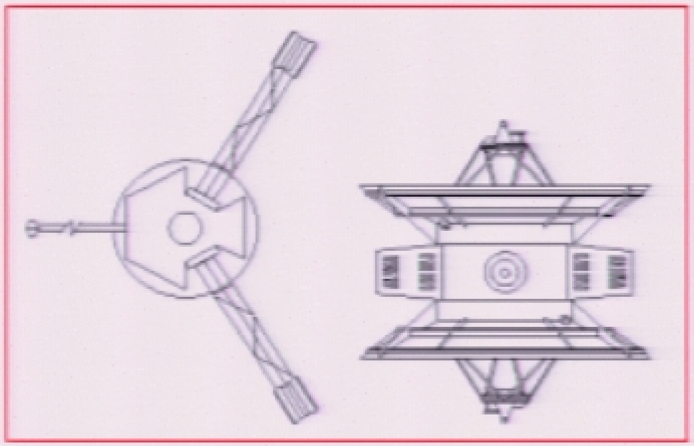
- Symmetric fore/aft thermal design, including louvers on the sides of the central bus
- Dual fore/aft antennas

- J. D, Anderson, MMN, and S. G. Turyshev,
  Mod. Phys. D **11**, 1545-1553 (2002). gr-qc/0205059
- MMN and S G. Turyshev,
  Mod. Phys. D 13, 899-906 (2004), gr-qc/0308108
- MMN and S. G. Turyshev,
  Class. Quant. Grav **21**, 4005-4023 (2004), gr-qc/0308017

Proposed mission concept



How design would kill the systematics:



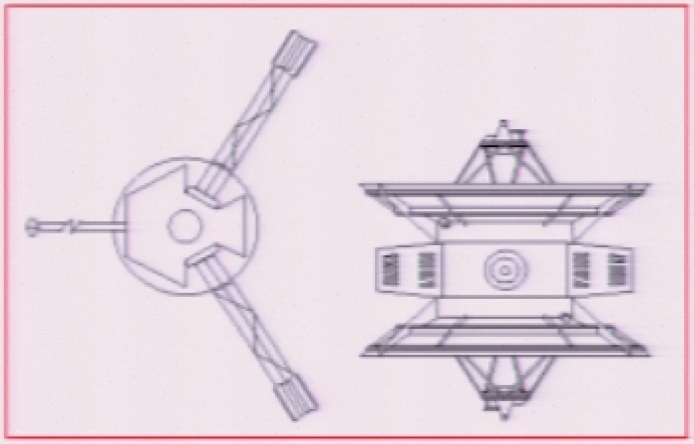
a) Broadcast in both directions so radiation force cancels.

b) Positions of RTGs and louvers, coupled with symmetric fore/aft antenna configurations and the rotation of the craft, mean heat and power are radiated axially symmetrically fore/aft, and hence have no effect.

But what if there were some imperfection (like stuck louvers or a degraded antenna)?

To take care of this, after one year rotate the craft by 180 degrees!

(The Pioneer 10 “Earth Acquisition Maneuver” took two hours and 0.5 kg fuel.)



$$a_P = (a_{foreward} + a_{backward})/2$$

With off-the-shelf technology one could obtain

$$\sigma \sim 0.06 \times 10^{-8}\ \mathrm{cm/s^2},$$

in a few years of data taking,

IF

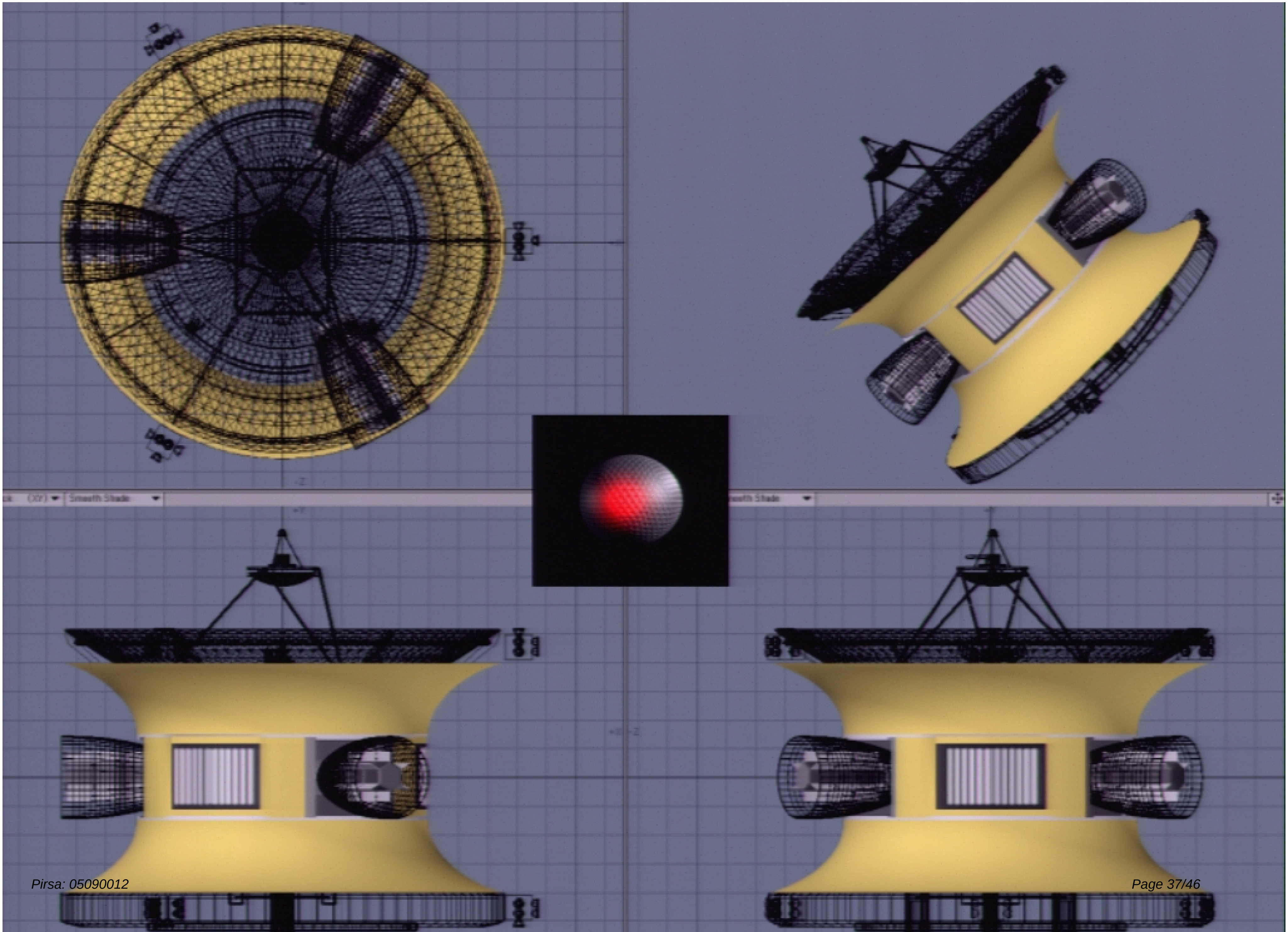
the thrusters are reliable and gas leaks can be eliminated or monitored to a high enough accuracy.

With new technology one could reach

$$\sigma \sim 0.01 \times 10^{-8}\ \mathrm{cm/s^2}$$

ESA Cosmic Vision Theme:
A NEW PIONEER COLLABORATION

- H. Dittus, C. Lämmerzahl, S. Theil (ZARM, University of Bremen)
- Bernd Dachwald, Wolfgang Seboldt (German Aerospace Center)
- W. Ertmer, E. Rasel (University of Hanover)
- U. Johann (Astrium Space, Germany)
- B. Kent, R. Bingham (Rutherford Appleton Laboratory)
- O. Bertolami (University of Lisbon)
- T. Touboul (ONERA, France)
- P. Bouyer (Orsay, France)
- S. Reynaud (ENS/LKB, France)
- C. Erd, C. de Matos, A. Rathke (ESA/ESTEC, Netherlands)
- J. D. Anderson, S. G. Turyshev (Jet Propulsion Laboratory)
- M. M. Nieto (Los Alamos National Laboratory (LANL)



Mission Summary

Objectives

- To search for any *unmodeled* small acceleration affecting the spacecraft motion at the level of ~0.1×10^{-8} cm/s^2 or less.
- Determine the physical origin of any anomaly, if found.

Features

- A standard spacecraft bus that allows thermal louvers to be on the sides for symmetric fore/aft thermal rejection.

Spacecraft

- Power at launch: ~200W provided by RTGs located on booms at a distance of ~3 m from the rotational axis of the spacecraft or shielded.
- Redundancy: single-string.
- Mass: s/c dry ~300 kg; propellant ~40 kg; total at launch ~500 kg.
- Dimensions at launch: diameter ~2.5 m; height: ~3.5 m or less.
- Attitude control: spin-stabilized spacecraft.

Spacecraft (cont.)

- Navigation: Doppler, range, and possibly VLBI and/or ΔDOR.
- Pointing: control 6 μrad; knowledge 3 μrad; stability 0.1 μrad
- Telemetry: rate 1 Kbps.
- mW laser to Probe.

Lifetime

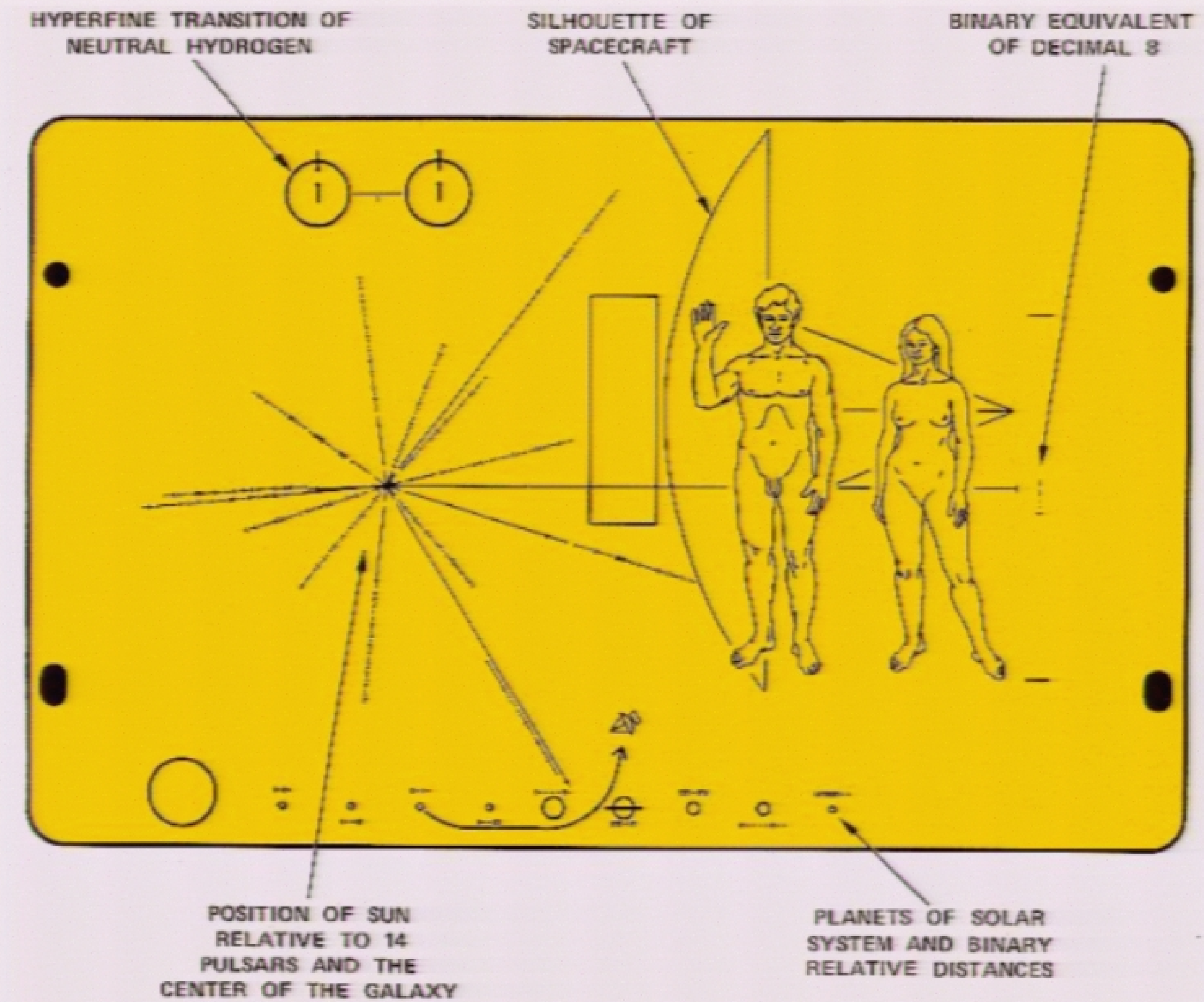
- 7 years (nominal for velocity of 5 AU/year); 12 years (extended).

We want to get there quick!

- As stated, a test could be either a stand alone mission or a probe of a large mission that is jettisoned after final propulsion is over.
- Such a mission would unambiguously determine the validity of the Pioneer anomaly.
- It would also advance the metrology of deep space navigation to unprecedented levels, something that will be needed in the future.
- Independent of the anomaly this would be very important.

- But if the anomaly exists, then …

This wide-range time exposure taken from the island of La Palma in the Canary Islands reveals an incredible view of stars, nebulae, the constellation Orion, and the Milky Way. Stretching across the image from the bottom left, faint stars compose the luminous band of the Milky Way. A group of yellowish stars at the upper right is dominated by the red giant Aldebaran, where Pioneer 10 is headed. Image: A. Vannini, C. Li Causi, A. Ricciardi, and A. Caratti


HYPERFINE TRANSITION OF NEUTRAL HYDROGEN
SILHOUETTE OF SPACECRAFT
BINARY EQUIVALENT OF DECIMAL 8
POSITION OF SUN RELATIVE TO 14 PULSARS AND THE CENTER OF THE GALAXY
PLANETS OF SOLAR SYSTEM AND BINARY RELATIVE DISTANCES