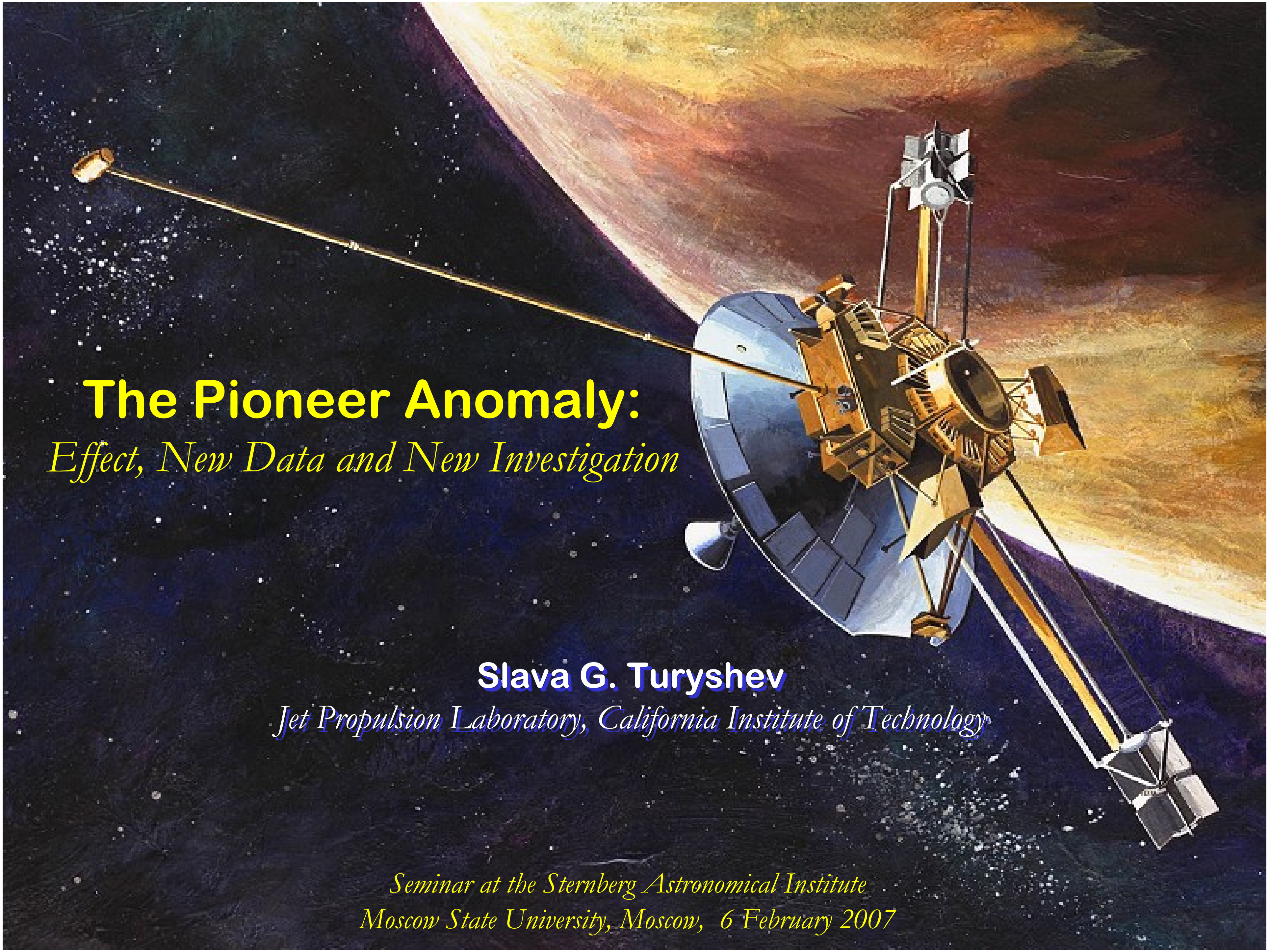


The Pioneer Anomaly:

Effect, New Data and New Investigation

Slava G. Turyshev

Jet Propulsion Laboratory, California Institute of Technology

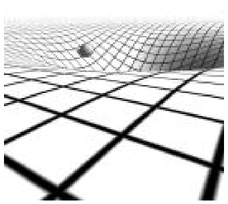
Seminar at the Sternberg Astronomical Institute

Moscow State University, Moscow, 6 February 2007

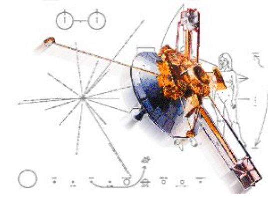
Conclusions & Outline:







- Anomalous acceleration of the Pioneers 10 and 11:

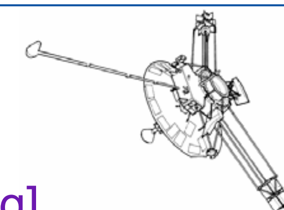


$$a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$$

- A line-of-sight constant acceleration *toward* 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, thermal mechanism, drag force, etc…
- New Physics [many proposals exist, some interesting]

- A “win-win” situation – both possibilities are important:
  - CONVENTIONAL explanation: i) confirmation of the Newton’s $1/r^2$ gravity law in the outer solar system, ii) improvement of spacecraft engineering for precise navigation & attitude control, or
  - NEW physics: would be truly remarkable…

The Pioneer 10/11 spacecraft

Agency: NASA	Pioneer 10	Pioneer 11
Launch	2 March 1972	5 April 1973
Planetary fly-bys	Jupiter: 4 Dec 1973	Jupiter: 2 Dec 1974 Saturn: 1 Sep 1979
Last data point received	27 Apr 2002 distance ~80.2 AU	1 Oct 1990 distance ~30 AU

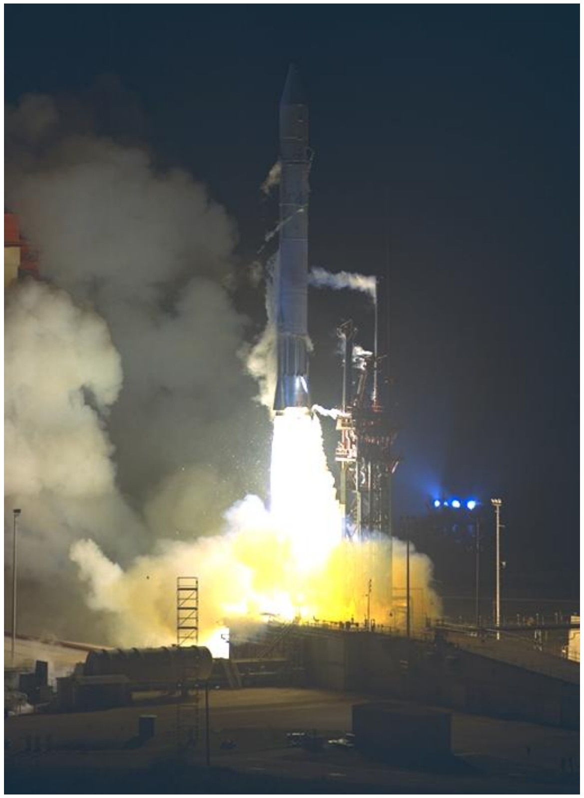
Parameters for Pioneer 10 (Pioneer 11 – identical)		
Total spacecraft mass		259 kg
SNAP-19 RTG: mass/distance		13.6 kg / 3 m
High Gain Antenna, diameter		2.74 m
Attitude control: spin-stabilized		~4.28 rpm
Communication system		Data available ($\lambda \simeq 13$ cm)
S-band, up-link	S-band, down-link	
2110 MHz	2292 MHz	Doppler
Spacecraft transmits continuously @ 8 W		

Pioneer 10: pre-launch testing

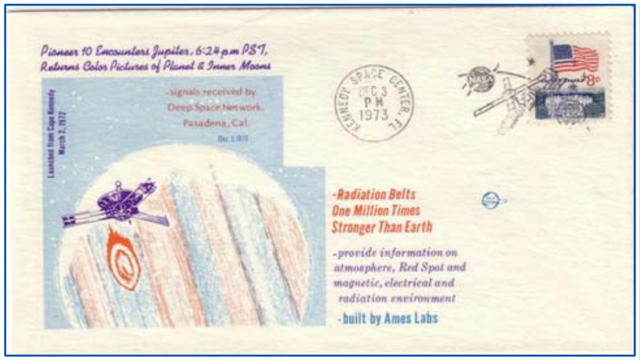
The Pioneers are still the most precisely navigated deep-space vehicles:

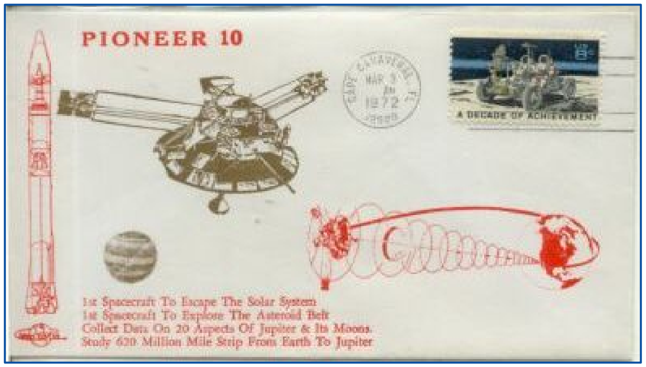
- Spin-stabilization and design permitted acceleration sensitivity $\sim 10^{-10}$ m/s^2, unlike a Voyager-type 3-axis stabilization that were almost 50 times worse;
- Precision celestial mechanics – a primary objective of the Pioneers' extended missions – search for gravitational waves, Planet X, trans-Neptunian objects, etc.

Pioneer 10 Launch: 2 March 1972

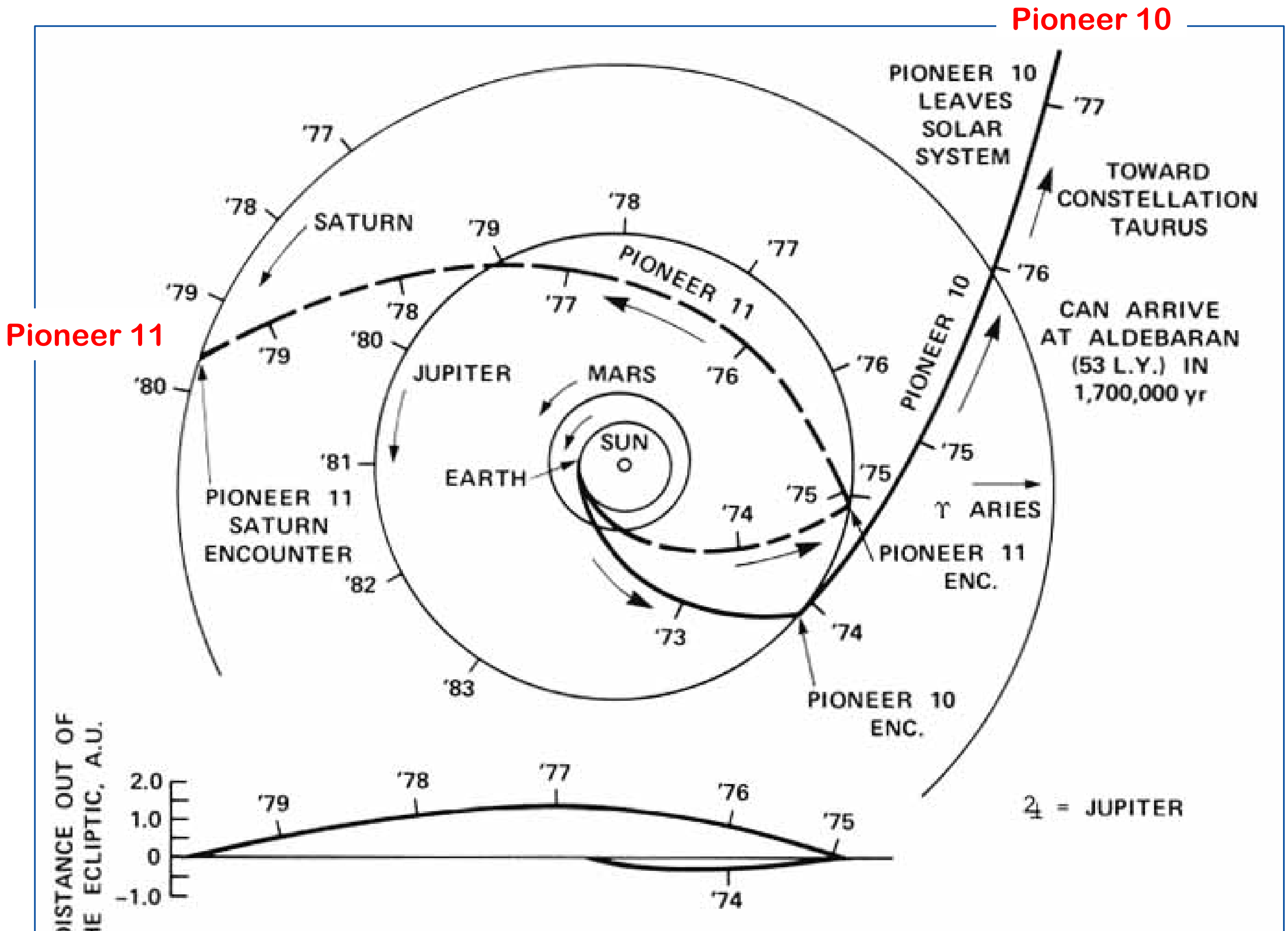


Pioneer 10 Launch: 2 March 1972





Pioneers 10 and 11: Main Missions

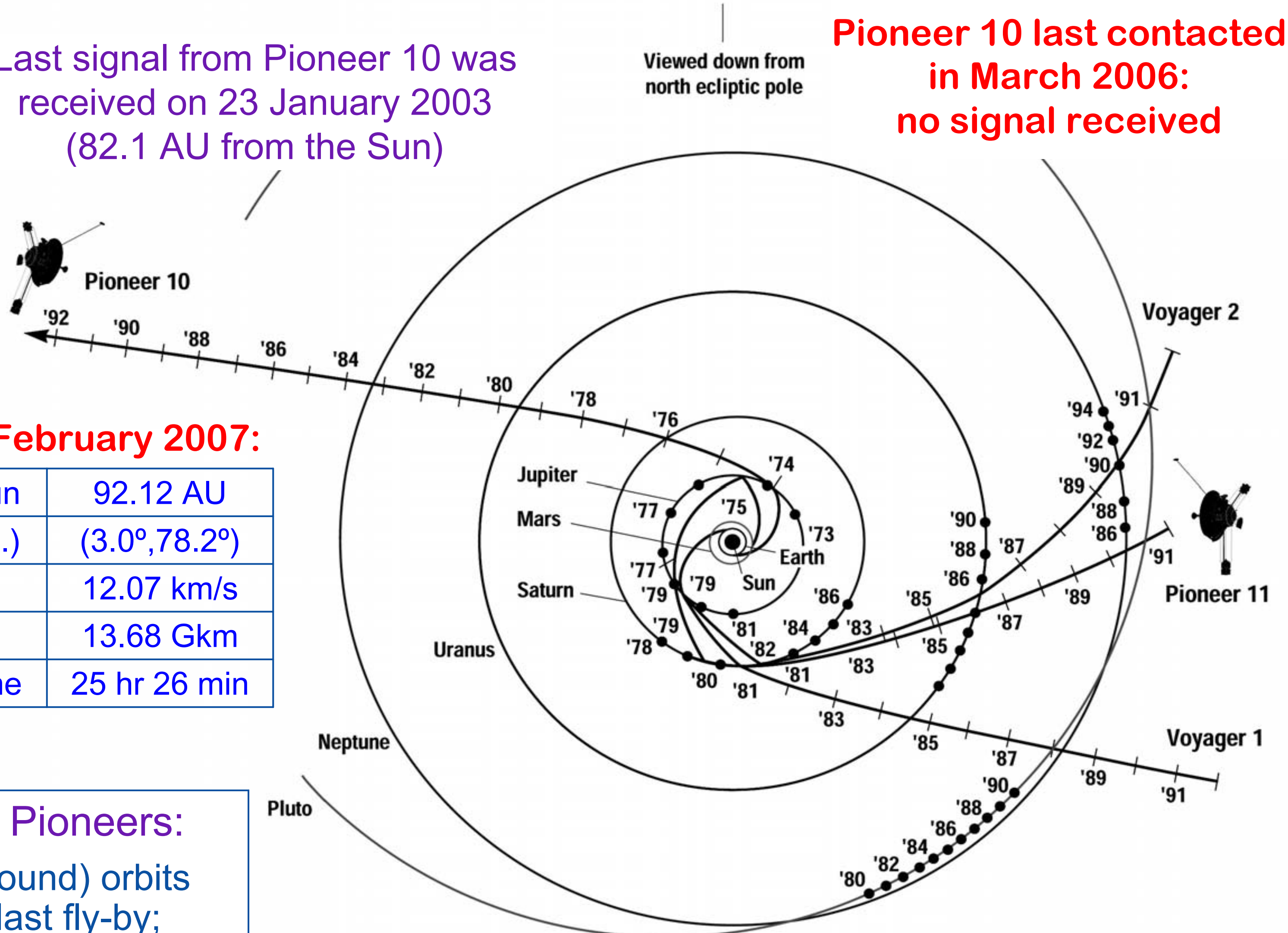


Trajectories of Pioneer 10 & 11 during the main mission phase

Trajectories of Pioneers and Voyagers

Last signal from Pioneer 10 was received on 23 January 2003 (82.1 AU from the Sun)

Pioneer 10 last contacted in March 2006: no signal received



Pioneer 10 on 6 February 2007:

Distance from the Sun	92.12 AU
Position, SE (lat., lon.)	(3.0º,78.2º)
Heliocentric velocity	12.07 km/s
Distance from Earth	13.68 Gkm
Round-Trip Light Time	25 hr 26 min

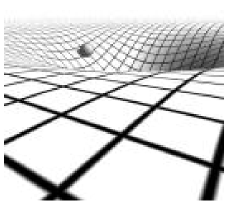
Trajectories of Pioneers:

– Elliptical (bound) orbits before the last fly-by;

– Hyperbolic (escape) orbits after the last fly-by

Trajectories of Pioneer and Voyager spacecraft, as seen from north ecliptic pole.

Detection of the Effect and Earlier Studies



- 1979: search for unmodeled accelerations w/ Pioneers began:
  - Motivation: Planet X; initiated when Pioneer 10 was at 20 AU;
  - Solar-radiation pressure away from the Sun became $< 5 \times 10^{-10}$ m/s^2
- 1980: navigational anomaly first detected at JPL:
  - The biggest systematic error in the acceleration residuals – a constant bias of **$(8 \pm 3) \times 10^{-10}$ m/s^2** directed towards the Sun

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

- Initial JPL-ODP analysis in 1990-95:
  - **$(8.09 \pm 0.20) \times 10^{-10}$ m/s^2** for Pioneer 10
  - **$(8.56 \pm 0.15) \times 10^{-10}$ m/s^2** for Pioneer 11
  - NO magnitude variation with distance over a range of 40 to 70 AU
  - The error is from a batch-sequential & filter-smoothing algorithm

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

Data used for the Analysis (1996-1998):

- **Pioneer 10**: 11.5 years; distance = 40–70.5 AU $\Rightarrow$ 20,055 data points
- **Pioneer 11**: 3.75 years; distance = 22.4–31.7 AU $\Rightarrow$ 19,198 data points

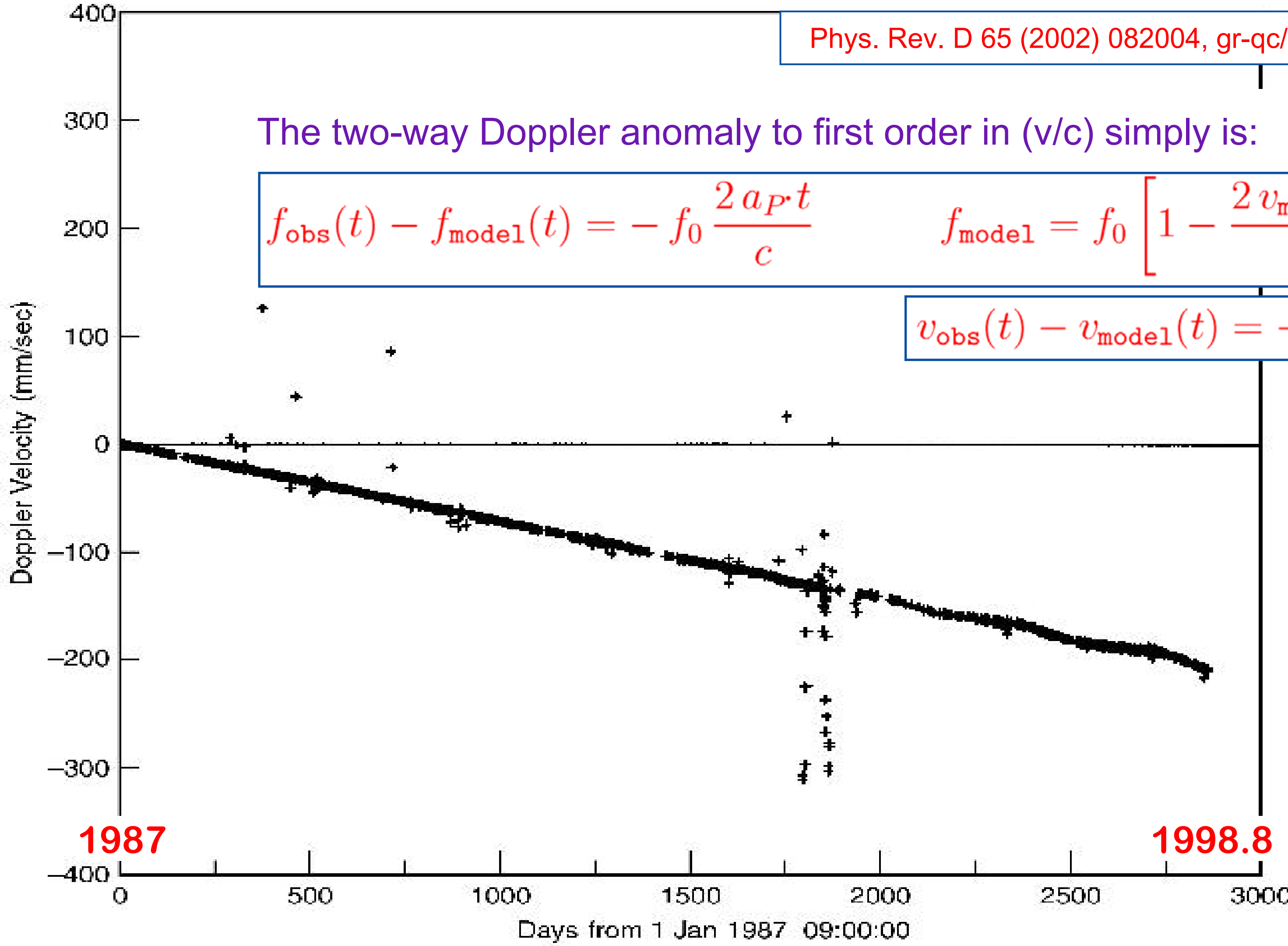
The Observed Anomalous Doppler Drift

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

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

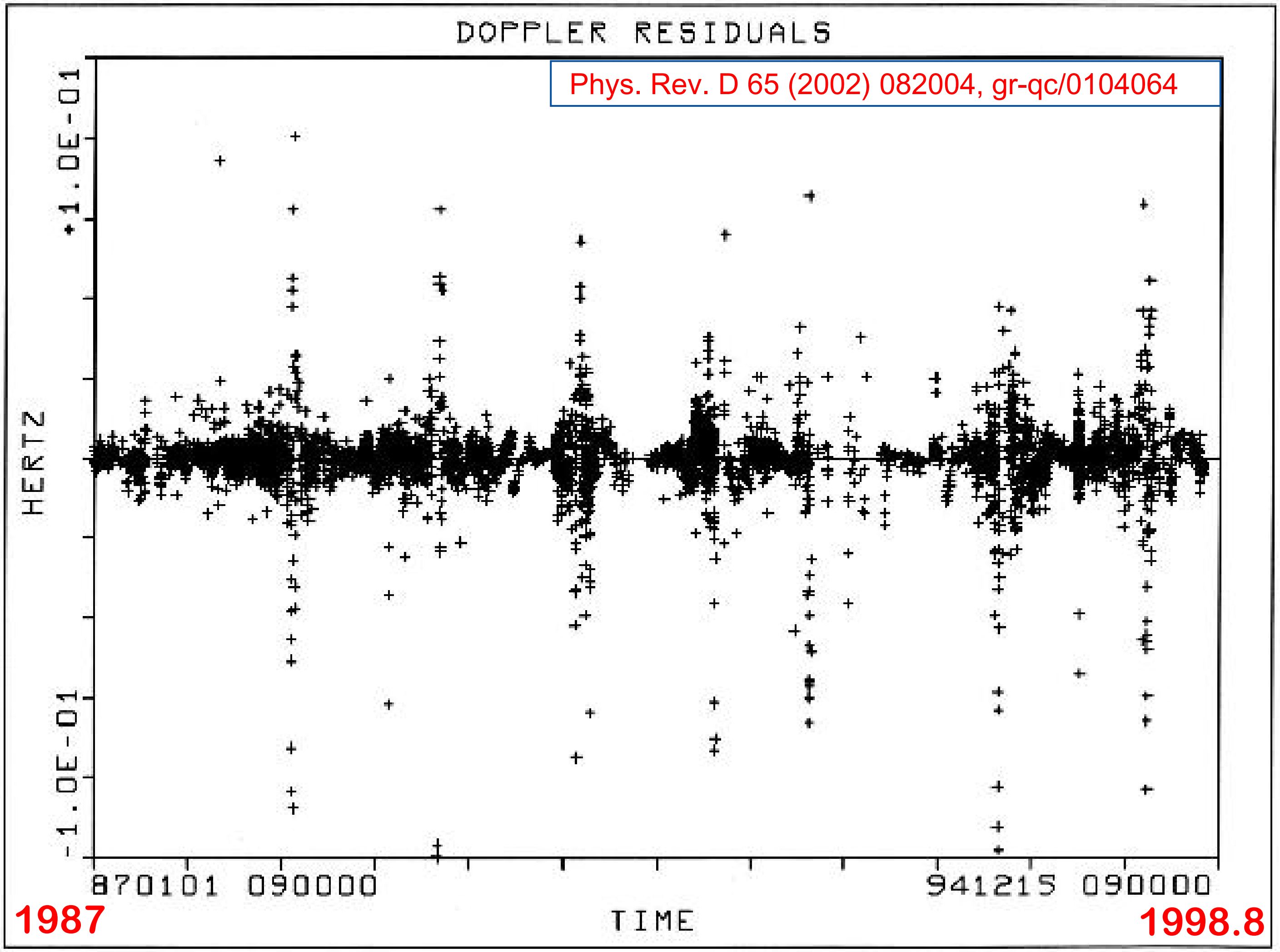
$$f_{\mathrm{obs}}(t) - f_{\mathrm{model}}(t) = -f_0 \frac{2 a_P \cdot t}{c} \qquad f_{\mathrm{model}} = f_0 \left[1 - \frac{2 v_{\mathrm{model}}(t)}{c}\right]$$

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



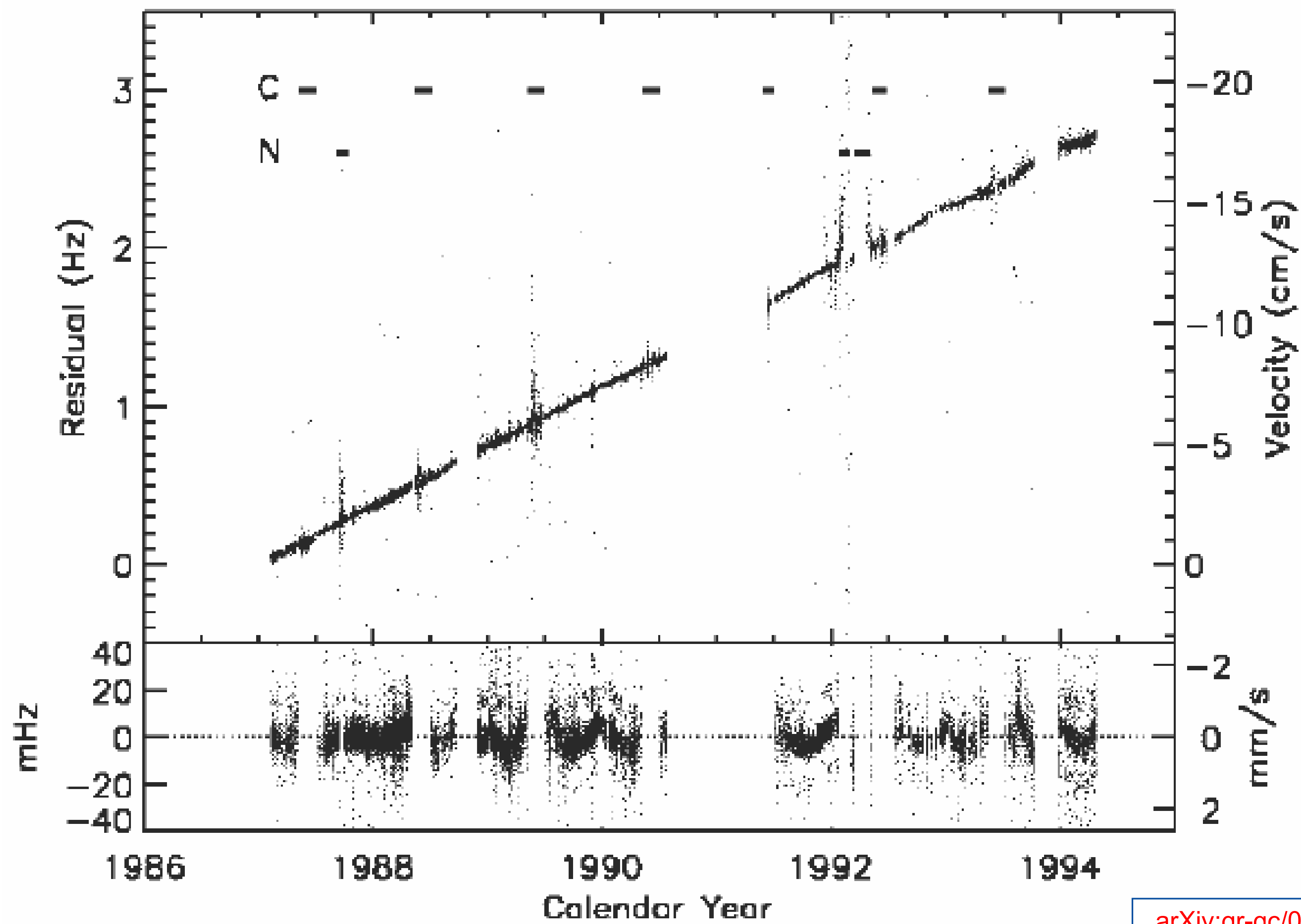
The two-way Doppler residuals (observed Doppler velocity minus modeled Doppler velocity) for Pioneer 10 vs time [1 Hz is equivalent to 65 mm/s velocity].

The Pioneer Anomaly: Quality of Data Fit



Adding only 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. Quality of the fit is determined by ratio of residuals to the downlink carrier frequency, $f_0 \approx$ 2.29 GHz.

Analysis by GSFC (Markwardt, 2002)



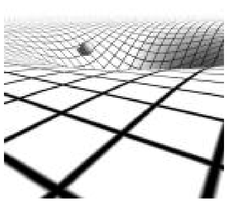
arXiv:gr-qc/0208046

Doppler residuals as a function of time of the best fit model.

Modeling of Spacecraft Motion







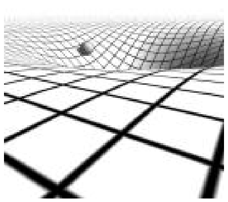
- Relativistic eq.m. for celestial bodies are correct to $(v/c)^4$:
  - Relativistic gravitational accelerations (EIH model) include: Sun, Moon, 9 planets are point masses in isotropic, PPN, N-body metric;
  - Newtonian gravity from large asteroids; terrestrial, lunar figure effects; Earth tides; lunar physical librations.
- Relativistic models for light propagation are correct to $(v/c)^2$

- Model accounts for many sources of non-grav. forces, including:
  - Solar radiation and wind pressure; the interplanetary media;
  - Attitude-control propulsive maneuvers and propellant (gas) leakage from the propulsion system;
  - Torques produced by above mentioned forces;
  - DSN antennae contributions to the spacecraft radio tracking data.
- 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).

Sources of Systematic Error: External





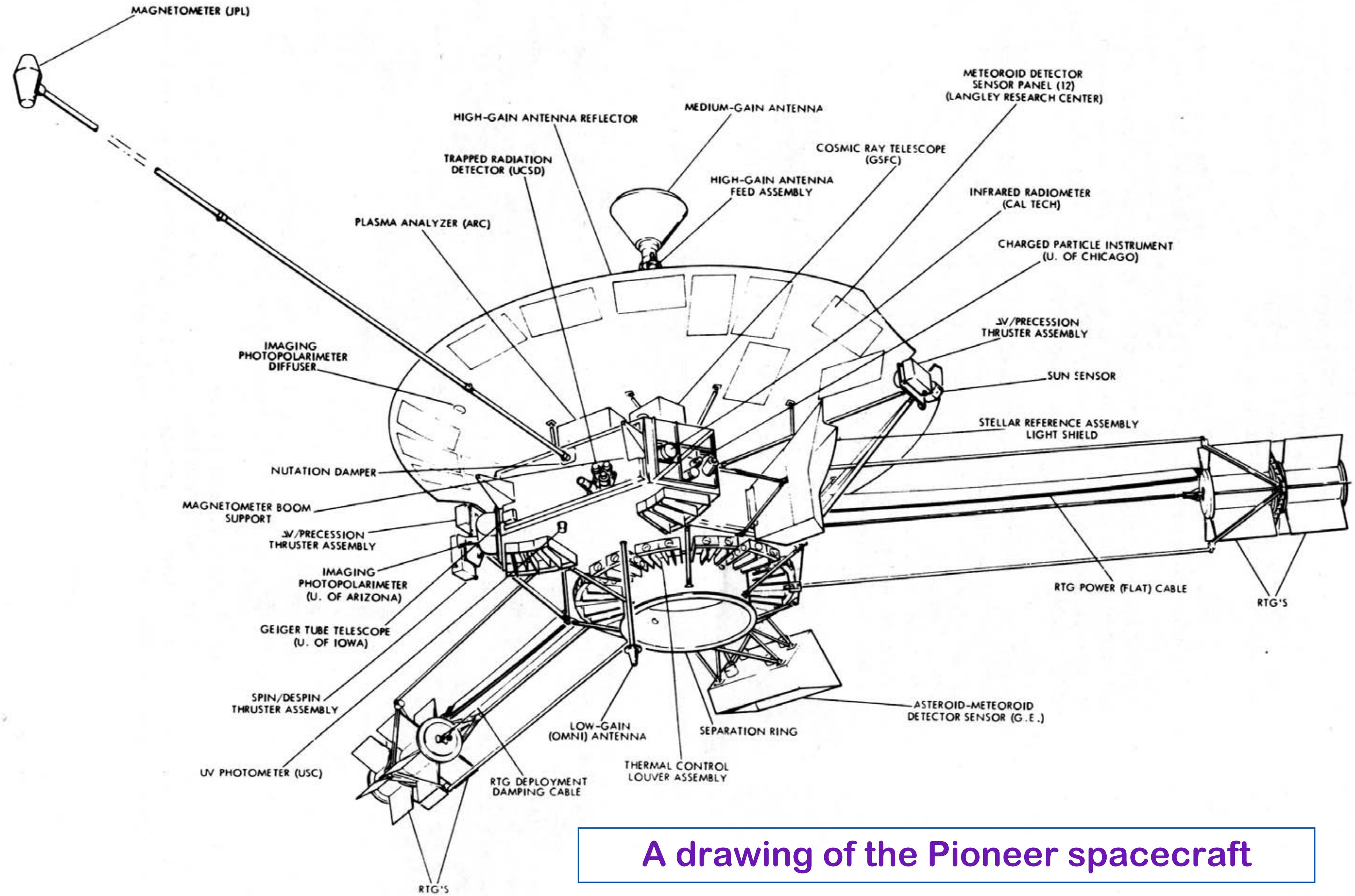


Error budget constituents	Bias 10^{-10} m/s^2	Uncertainty 10^{-10} m/s^2
1 Sources of external systematic error:		
⇛ Solar radiation pressure		± 0.001
⇛ From the mass uncertainty	$+0.03$	± 0.01
⇛ Solar wind contribution		$\pm < 10^{-5}$
⇛ Effects of the solar corona		± 0.02
⇛ Electro-magnetic Lorentz forces		$\pm < 10^{-4}$
⇛ Influence of the Kuiper belt's gravity		± 0.03
⇛ Influence of the Earth orientation		± 0.001
⇛ DSN Antannae: mechanical/phase stability		$\pm < 0.001$
⇛ Phase stability and clocks		$\pm < 0.001$
⇛ DSN station location		$\pm < 10^{-5}$
⇛ Effects of troposphere and ionosphere		$\pm < 0.001$
2 Computational systematics:		
⇛ Numerical stability of least-squares estimation		± 0.02
⇛ Accuracy of consistency/model tests		± 0.13
⇛ Mismodeling of maneuvers		± 0.01
⇛ Mismodeling of the solar corona		± 0.02
⇛ Annual/diurnal terms		± 0.32

Phys. Rev. D 65 (2002) 082004, gr-qc/0104064 IJMP A 17 (2002) 875-885, gr-qc/0107022

An interesting set of error sources, but not of a major concern!

The Pioneer 10/11 Spacecraft

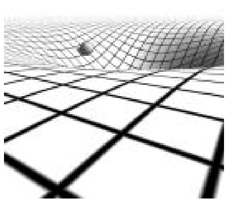


A drawing of the Pioneer spacecraft

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 $\sim$ 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 $\sim$ 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 $\Rightarrow$
- thermally radiated into space by a shunt-resistor radiator, or
- charge a battery in the equipment compartment

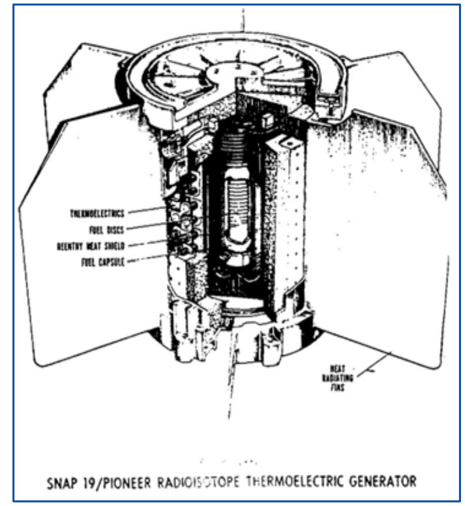
Thermal control: $\sim$ 0 - 90 F
- thermo-responsive louvers (bi-metallic springs) $\sim\downarrow$ 40 - $\uparrow$ 85 F
- insulation: multi-layered aluminized mylar and kapton blankets

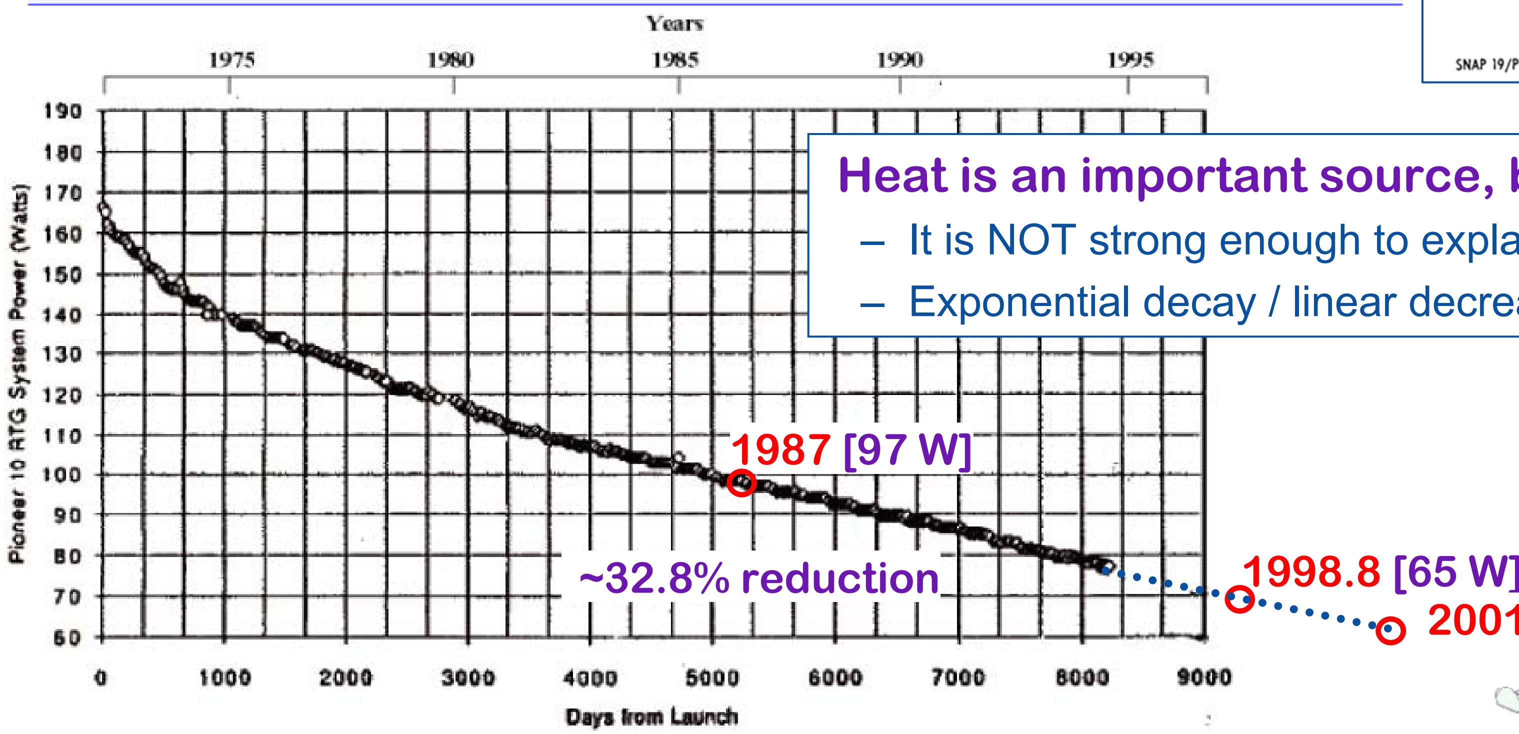
Design based on well understood process of on-board nuclear-to-electric energy conversion and heat dissipation within the craft

Sources of Systematic Error: On-board

Error budget constituents	Bias 10^{-10} m/s^2	Uncertainty 10^{-10} m/s^2
3 Sources of external systematic error:		
⇛ 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

SNAP-19 RTG





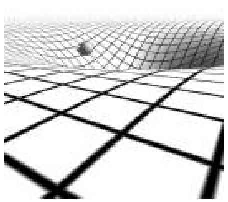
Heat is an important source, but:

- It is NOT strong enough to explain the anomaly;
- Exponential decay / linear decrease – NOT seen

Focus of the 1995-2002 Analysis







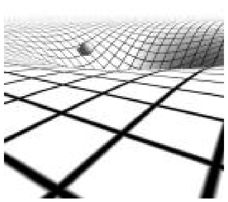
- On-board systematic & other hardware-related mechanisms:
  - Precessional attitude control maneuvers and associated "gas leaks"
  - Nominal thermal radiation due to ^{238}Pu decay [half life 87.75 years]
  - Heat rejection mechanisms from within the spacecraft
  - Hardware problems at the DSN tracking stations
- Examples of the external effects (used GLL, ULY, and Cassini):
  - Solar radiation pressure, solar wind, interplanetary medium, dust
  - Viscous drag force due to mass distribution in the outer solar system
  - Gravity from the Kuiper belt; gravity from the Galaxy
  - Gravity from Dark Matter distributed in halo around the solar system
  - Errors in the planetary ephemeris, in the Earth's Orientation, precession, polar motion, and nutation parameters
- Phenomenological time models:
  - Drifting clocks, quadratic time augmentation, uniform carrier frequency drift, effect due to finite speed of gravity, and many others
- All the above were rejected as explanations

Most of the systematics are time or/and space dependent!

The Pioneer Anomaly: Summary







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

- By 2007 the presence of the anomaly in the data (same data as in Anderson et al., 2002) confirmed by five codes:
  - JPL Orbit Determination Program [various generations for 1979-2001];
  - The Aerospace Corporation code POEAS [during period of 1995-2001];
  - Goddard Space Flight Center conducted a study in 2003 [data from NSSDC];
  - Institute for Theoretical Astronomy, Norway, Oslo [2002-2006];
  - Viktor Toth, Canada [2005-2006].
- The observed frequency drift can be interpreted as an acceleration of

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

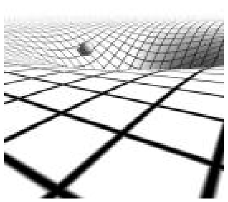
- This interpretation has become known as the Pioneer Anomaly:
  - Constant acceleration of the spacecraft toward the Sun…
- Observation $a_P \simeq cH$, stimulated many suggestions…. examples:
  - Kinematical realization of local cosmological frame; momentum-dependent gravitational coupling; modified inertia; non-uniformly-coupled scalar field(s); Brane-worlds; higher-dimensional gravitational models…
- Primary focus of newly started analysis: **“the heat or not the heat?”**

Existence of the signal is confirmed, its origin is yet unknown

Recent Pioneer Doppler Data Recovery Effort







Data used for the Analysis (1996-1998):

- Pioneer 10: 11.5 years; distance = 40–70.5 AU $\Rightarrow$ 20,055 data points
- Pioneer 11: 3.75 years; distance = 22.4–31.7 AU $\Rightarrow$ 19,198 data points

Pioneer 10/11 Doppler Data available (January 2007):

- **Pioneer 10**:
  - 1973-2002: ~30 years
  - Distance range: 4–87 AU
  - Jupiter encounter
  - ~95,000 data points, ~20GB
  - Maneuvers, spin, initial cond.
  - All telemetry is available
- **Pioneer 11**:
  - 1974-1994: ~ 20 years
  - Distance range: 1–33 AU
  - Jupiter & Saturn encounters
  - ~65,000 data points, ~15GB
  - Maneuvers, spin, initial cond.
  - All telemetry is available

- **Planning for the upcoming data analysis**:
  - After initial certification at JPL, both datasets will be made available
  - NASA supports the investigation – critical for the entire effort
  - The Planetary Society – good but insufficient for serious work
  - ZARM, Germany: received funding, started analysis of old data
  - French group funded by CNES is also planning for analysis

The on-going Pioneer data analysis is planned as an international effort

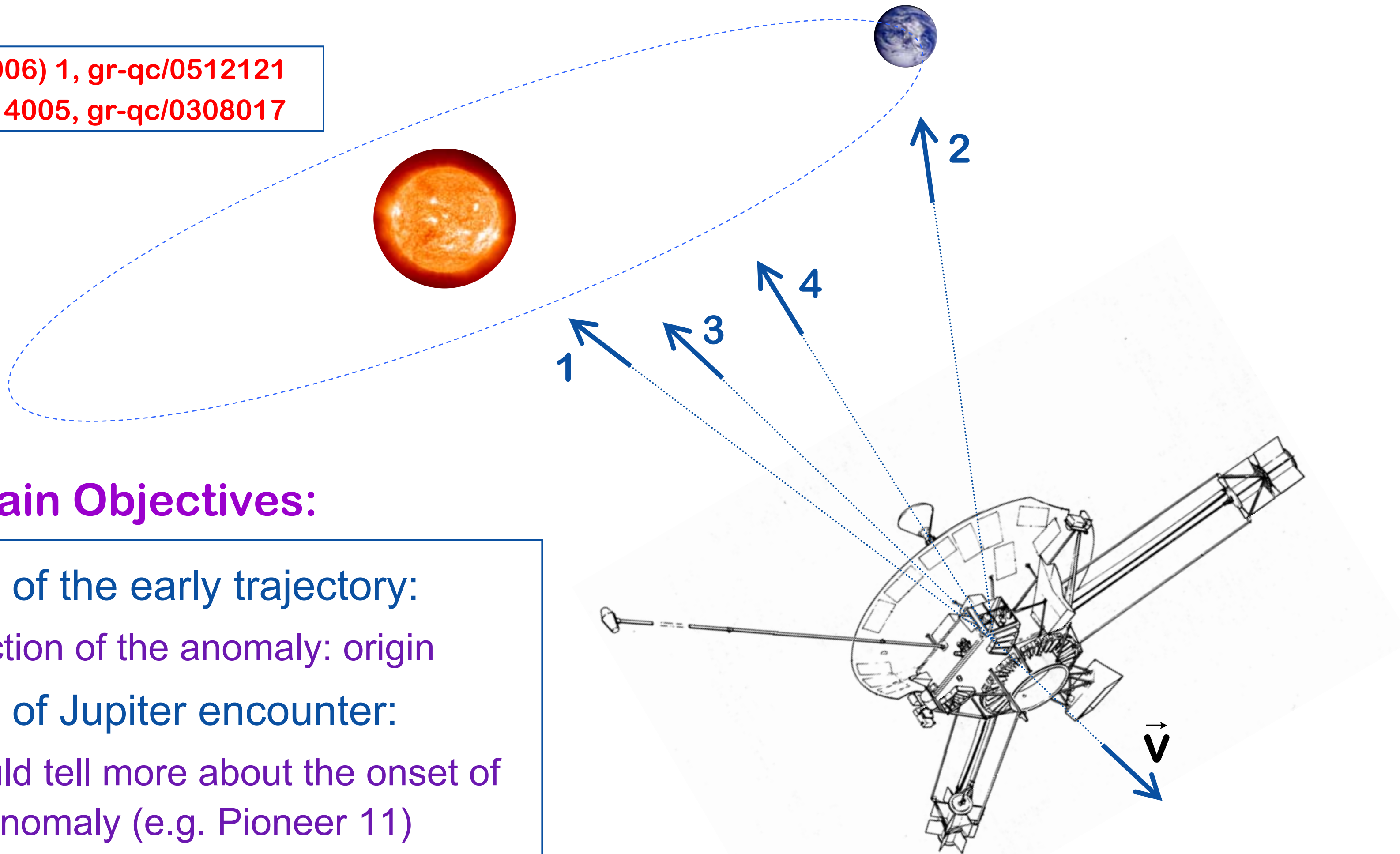
9-track Magnetic Tapes…

Somewhere in JPL…

Statistics: ~400 tapes… 90 minutes / tape

Critical Phases of the Proposed Experiment

IJMPD 16 (2006) 1, gr-qc/0512121
CQG 21 (2004) 4005, gr-qc/0308017



Four Main Objectives:

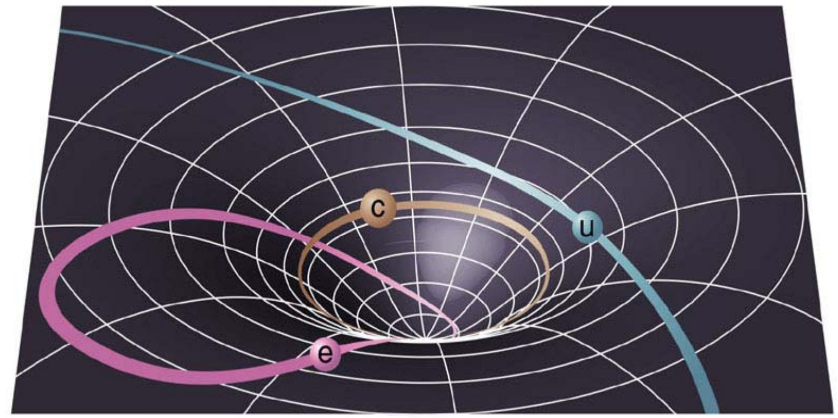
- Analysis of the early trajectory:
  - Direction of the anomaly: origin
- Analysis of Jupiter encounter:
  - Should tell more about the onset of the anomaly (e.g. Pioneer 11)
- Analysis of the entire dataset:
  - Temporal evolution of the anomaly
- Focus on on-board systematics:
  - Thermal modeling using telemetry

- Towards the Sun: gravitational models?
- Towards the Earth: frequency standards?
- Along the velocity vector: drag or inertia?
- Along the spin axis: internal systematics?

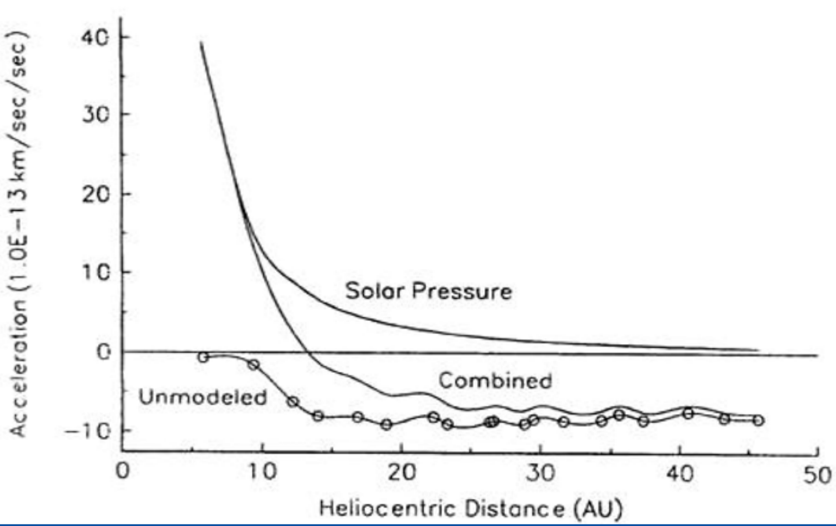
Difference Between Bound & Un-Bound Orbits?

- Navigational Anomalies during Earth fly-byes were observed with multiple spacecraft:
  - Galileo: #1 on 10/8/1990 @ altitude of ~960 km;
    #2 on 12/8/1992 @ altitude of ~305 km;
  - NEAR: 01/22/1998 @ altitude of ~550 km;
  - Cassini: 08/19/1999 @ altitude of ~1,171 km;
  - Stardust: 01/15/2001 @ altitude of ~6,000 km;
  - Rosetta: 03/04/2005 @ altitude of ~1,900 km.
- Are they relevant to the Pioneer anomaly?

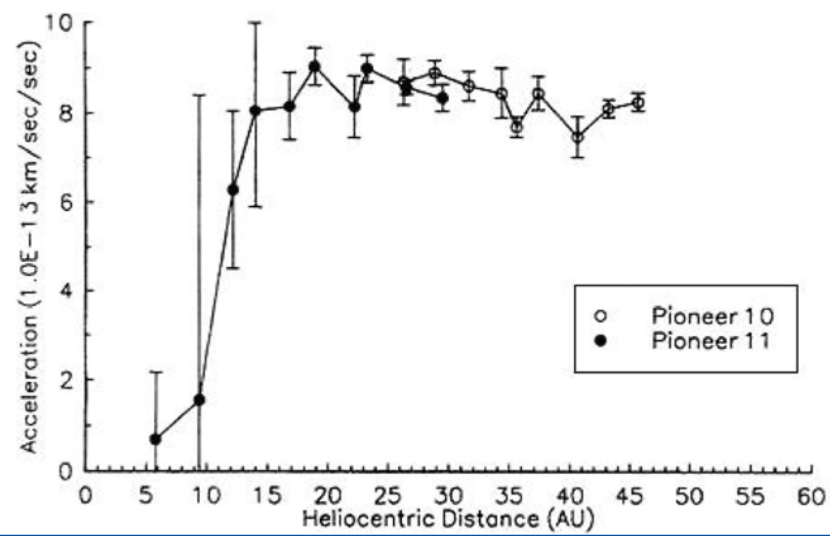
c circular orbit
e elliptical orbit
u unbound orbit



ACCELERATIONS ON PIONEER 10 AND 11
Positive Along Sun–Spacecraft Line



UNMODELED ACCELERATIONS ON PIONEER 10 AND 11
Acceleration Directed Toward the Sun



A plot of early unmodeled accelerations of Pioneer 10 (1981–1989), Pioneer 11 (1977–1989)

Conclusions and Next Steps

- As of late 2006 new data is available, both Doppler and telemetry
- Primary effort in on the analysis of the extended Doppler dataset
  - To determine true direction of the anomaly and its behavior as a function of distance from the Sun
- High fidelity Thermal Model of the Pioneers is available
  - Ideal tool for future analysis
  - Capable of examining all heliocentric distances and off-sun angles
  - Capable of identifying anisotropic thermal contributions of individual spacecraft subsystems
- Upcoming efforts in thermal analysis:
  - Quantify anisotropic contributions from individual sources such as the RTGs, louvers, and HGA.
  - Calculate anisotropic thermal emission from Pioneer spacecraft at different heliocentric distances and off-sun angles.
  - Sensitivity analysis as a function of varying optical properties
- Next Steps: focus on the anomaly:
  - Analysis of early Pioneer 11 Doppler data
  - Combined analysis of Doppler and telemetry data
- More information at:
  - http://www.issibern.ch/teams/Pioneer/


One “data point”… we need more!