



Support for Temporally Varying Behavior of the Pioneer Anomaly from the Extended Pioneer 10 and 11 Doppler Data Sets

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The Pioneer anomaly is a small sunward anomalous acceleration found in the trajectory analysis of the Pioneer 10 and 11 spacecraft. As part of the investigation of the effect, the analysis of recently recovered Doppler data for both spacecraft has been completed. The presence of a small anomalous acceleration is confirmed by using data spans more than twice as long as those that were previously analyzed. We examine the constancy and direction of the Pioneer anomaly and conclude that (i) the data favor a temporally decaying anomalous acceleration ($\sim 2 \times 10^{-11}$ m/s²/yr) with an over 10% improvement in the residuals compared to a constant acceleration model, (ii) although the direction of the acceleration remains imprecisely determined, we find no support in favor of a Sun-pointing direction over the Earth-pointing or along the spin-axis directions, and (iii) support for an early “onset” of the acceleration remains weak in the pre-Saturn Pioneer 11 tracking data. We present these new findings and discuss their implications for the nature of the Pioneer anomaly.

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Introduction.—Analysis of the navigational tracking data received from the Pioneer 10 and 11 spacecraft at large heliocentric distances of ~ 20 – 70 AU indicated the presence of a small anomalous Doppler frequency drift in their radiometric observables [1,2]. Ultimately, this drift was interpreted as an anomalous constant acceleration acting on both of these spacecraft in the sunward direction, with a magnitude of $a_P = (8.74 \pm 1.33) \times 10^{-10}$ m/s² [3]. There were also earlier reports that, in the case of Pioneer 11, the anomaly may have begun with a relatively sudden “onset” [3] shortly after the spacecraft’s encounter with Saturn. This acceleration of unknown origin is today known as the Pioneer anomaly (for a review, see [4]). In this Letter, we present an analysis of newly recovered Doppler data for both Pioneer 10 and 11 and probe the question of the constancy of the anomalous acceleration, as well as place constraints on its direction.

Data sets and analysis.—Following the 2002 study [3], an effort was initiated to collect all available Doppler data for both spacecraft [4,5]. By using standard data conditioning techniques [3], several decades-old archival data tracking files (see the discussion in [5]) were converted to modern formats, processed, edited, and filtered for corrupt data. Uplink frequency records at NASA’s Deep Space Network were reconstructed from redundant information. We summarize the newly recovered Pioneer 10 and 11 Doppler data sets in Table I, including the range of dates covered and number of two-way and three-way [3,4] coherent Doppler data points available. The largest portion of the data lies in “deep space” (“DS”) beyond planetary encounters (heliocentric distances of 18–80 AU and 9–32 AU for Pioneer 10 and 11, respectively). The data

also include planetary encounters with Jupiter (“J”) and Saturn (“S,” for Pioneer 11 only). Data for other time ranges did not survive to the present. Here, we focus on the deep space data and the portion of Pioneer 11 Saturn data which is primarily under the gravitational influence of the Sun, which we designate Saturn “approach” (“SA”). These latter data are outside of Saturn’s Roche (or Hill) radius, so Saturn and its moons can be treated only as a perturbing influence.

Compared to the 2002 data, the data arc for Pioneer 10 has doubled in length, from 11.5 to 23.1 yr, and the total number of data points increased from 20 055 to 41 054, including the Jupiter encounter. For Pioneer 11, the length of the contiguous data arc increased from 3.75 to 10.75 yr, and the number of data points increased from 10 616 to

TABLE I. Pioneer Doppler data sets.

S/C ^a	Data ^b	Date range	Points	Man. ^c
P10	J	1973-10-15–1973-12-27	5806	>6
	DS	1979-02-14–2002-03-03	35248	>83
	2002DS	1987-01-03–1998-07-22	20055	28
P11	J	1974-04-18–1974-12-26	7467	>16
	S	1977-11-01–1979-09-18	9017	>35
	SA	1977-11-01–1979-06-29	4282	...
	DS	1980-01-12–1990-10-01	65053	>92
	2002DS	1987-01-05–1990-10-01	10616	22

^a(P10) and (P11) denote Pioneer 10 and Pioneer 11, respectively.

^b(J) Jupiter; (S) Saturn; and (SA, subset of S) Saturn approach;

(DS) deep space; (2002DS) is the data used in the 2002 study [3].

^cNumber of attitude maneuvers performed.

81 537, including encounters. In terms of heliocentric distance, the Pioneer 10 and 11 arcs overlap from 18–32 AU.

During the mission, both spacecraft performed numerous maneuvers. As the Pioneers were spin-stabilized, periodic attitude maneuvers were required to realign the spin and antenna axis to the spacecraft-Earth direction to within 1.5° . While attitude maneuvers used a fore-aft pair of thrusters in tandem, small residual impulses along the spin direction may occur [4]. Information about maneuvers is available from recovered mission records and from the spacecraft telemetry [5] and is summarized in Table I. The data given are lower limits, as it is possible that a few maneuvers are not reflected in the available telemetry.

Our analysis was carried out by using the Jet Propulsion Laboratory’s (JPL) orbit determination program (ODP) that was used for earlier work on the anomaly [3,4]. As before, central to the analysis was establishing a model orbit for the spacecraft that takes into account all known forces, gravitational and nongravitational, while numerically integrating the appropriate equations of motion. The model included the effects of planetary perturbations, solar radiation pressure, propulsive maneuvers, general relativity, and bias and drift in the Doppler observable. Planetary coordinates and the Solar System masses were obtained by using JPL’s Export Planetary Ephemeris DE421. The model also included the precise positions of Earth-based stations of the Deep Space Network as well as radio propagation effects (see details in [4]).

The study of the deep space data arcs (DS; see Table I) from the extended Doppler data set was expected to improve our understanding of two key characteristics of the Pioneer anomaly: its direction and its temporal behavior. Additionally, it was expected that some of the early data, in particular, the Pioneer 11 SA data, would help us confirm whether or not the anomalous behavior began with a relatively sudden onset [3].

We considered three models for the anomalous acceleration—constant, linear, and exponential—all applied along the nominal Earth-spacecraft line. The constant model has one parameter a_P , representing a constant modeling error. The linear model

$$a_P(t) = a_P(t_0) + (t - t_0)\dot{a}_P \quad (1)$$

contains a jerk term \dot{a}_P . The exponential model

$$a_P(t) = a_P(t_0)e^{-\beta(t-t_0)\ln 2} \quad (2)$$

decays with half-life β^{-1} . This last model is physically motivated by a potential relation to the on-board power generators, which radioactively decay. The epoch is $t_0 =$ January 1, 1972.

Separately, the anomalous acceleration was estimated by using a batched stochastic model [3,4]. This method produces a smoothed acceleration for each batch [3]. As the model with the most estimated parameters, it is likely to produce the best possible fit, but, since it is purely

phenomenological, it provides the least physical insight into the anomaly.

To consider the direction of the anomaly, we separately modeled the acceleration as a constant vector in four principal directions [3,4]: that of (i) Earth, (ii) the Sun, (iii) the spin axis, and (iv) the spacecraft velocity vector. Of these, the spin and Earth-spacecraft axes are effectively degenerate as the spacecraft were maintaining an Earth orientation for continuous radio communication. We estimated an acceleration vector that was constant in a reference frame with its z axis aligned with the spacecraft-Sun line and an acceleration vector that was constant in a reference frame with its z axis aligned along the spacecraft-Earth line. The x axis in both cases lay in the plane of the ecliptic, and the y axis completed a right-handed triad. ODP solves for the components of the acceleration vector independently.

For all acceleration models, the initial state vector and the velocity impulses for each attitude maneuver were also estimated by using a least squares fit.

The estimate and formal errors for the model parameters are computed by the least squares fit assuming the Doppler measurement errors are uncorrelated. In reality, the residual still shows significant structure, perhaps due to mis-modeling (e.g., models of solar plasma, the atmosphere, etc.). The presence of such autocorrelation in the residuals is the reason why it is common for “realistic” errors to be larger than formal errors by an order of magnitude or more. In this Letter, we report formal errors, with the understanding that these values do not necessarily represent the actual uncertainty of model parameters but can be used as an indication of the overall goodness of the fit and, thus, the quality of the model.

Acceleration models are compared by computing σ_ν , the root mean square (rms) of the difference between modeled and observed Doppler frequencies. A typical “good” fit should yield rms residuals of 10 mHz or less, often under 5 mHz. An rms residual above ~ 10 mHz usually indicates that the model does not adequately describe the physics of the spacecraft’s motion, the dynamics of the Solar System, or the propagation of the radio signal. We find that the Pioneer 10 data set is noisier than that for Pioneer 11, with rms residuals differing by a factor of 2.

We evaluated the models described in the previous section by using ODP. The deep space data sets of both the Pioneer 10 and 11 spacecraft (for technical reasons, Pioneer 10 data up to 1998 and Pioneer 11 data for 1983–1990 were used) were evaluated by using the one-dimensional (1D) constant, linear, and exponential models, and the results are shown in Table II. The fit quality of the different temporal models is nearly the same. The variable models are consistent with a gradually decreasing acceleration, either at a rate of $\sim 1.7 \times 10^{-11}$ m/s²/yr or a half-life of ~ 27 yr averaged for both spacecraft.

TABLE II. Deep space acceleration parameters.

S/C ^a	Model	σ_ν mHz	a_P ^b 10^{-10} m/s ²	Additional parameter ^{b,c}
P10	Constant	4.98	8.17(2)	
	Linear	4.60	11.06(8)	$\dot{a}_P = -0.17(1)$
	Exponential	4.58	12.22(16)	$\beta^{-1} = 28.8(0.7)$
P11	Constant	3.67	9.15(7)	
	Linear	2.09	11.65(42)	$\dot{a}_P = -0.18(3)$
	Exponential	2.06	13.79(62)	$\beta^{-1} = 24.6(2.4)$

^aSee Table I for designations.

^b1- σ formal error quoted in the final digit(s).

^c \dot{a}_P in 10^{-10} m/s²/yr, β^{-1} in yr.

The results of the exponential model are shown in Fig. 1. The figure also shows the stochastic estimate, illustrating the similarity between the parameterized and stochastic models. The rms residuals of the stochastic fit show further improvement compared to other models:

$$\sigma_{P10} = 4.40 \text{ mHz}, \quad \sigma_{P11} = 2.02 \text{ mHz}. \quad (3)$$

The results of the three-dimensional (3D) models are shown in Table III. For the DS data sets, acceleration vectors that are constant in a Solar System barycentric reference frame or constant relative to the spacecraft-Earth line cannot be distinguished. The estimated vector direction is within 6° of the spacecraft spin axis.

We also investigated the possibility of an onset of the anomaly by using Pioneer 11 SA data from 1977–1979, the results of which are also shown in Table III. While we attempted to fit a simple 1D Earth-pointing constant acceleration, results were poor. (The validity of the SA results

was questioned because of the large uncertainty in the acceleration estimates, their sensitivity to solar radiation pressure parameters, the structure of the residual, and the presence of a 21 m/s maneuver. In the vicinity of this maneuver, the residual display shows residuals of 20 mHz, 5 times greater than the typical residuals outside this region.) The vector model has very large errors in the x direction, which relate to a larger solar radiation pressure effect at these distances. The acceleration magnitude for Saturn approach is $a_{P11} = (4.58 \pm 11.80) \times 10^{-10}$ m/s². This result is consistent with the acceleration estimates of the DS phase, and, thus, we cannot conclude definitively that an onset exists or not (see [3,4] for discussion).

Discussion.

Temporal behavior.—We can unambiguously confirm the presence of an anomalous acceleration in the recently recovered Pioneer 10 and 11 spacecraft tracking data, with consistent magnitudes between the two spacecraft and also consistent with previous results [1,3,6,7].

The constant acceleration models, both 1D and 3D, are essentially identical for Pioneer 10. However, for Pioneer 11, the rms residuals improve when considering an unknown constant force, perpendicular to the spacecraft-Earth direction. This may be related to the anomalous spin-up of Pioneer 11 [5].

Our estimates of a jerk term (1) are consistent with earlier studies [4]. Markwardt [6] obtained an improved fit of Pioneer 10 data when estimating a jerk of $\dot{a}_{P10} = -0.18 \times 10^{-10}$ m/s²/yr; also Toth [7] obtained $\dot{a}_{P10} = (-0.21 \pm 0.04) \times 10^{-10}$ m/s²/yr and $\dot{a}_{P11} = (-0.34 \pm 0.12)$ m/s²/yr for Pioneer 10 and 11, respectively.

The rationale for an exponential model (2) is based on the possibility that the acceleration may be due to thermal recoil forces generated on-board. Because of degradation of the radioisotope thermoelectric generator thermocouples and changes in the thermal louver system [4], the resulting thermal recoil force could have a half-life significantly shorter than the 87.74 yr half-life of the ²³⁸Pu fuel [8], with 27 yr being in the acceptable range.

The gradually decreasing linear and exponential decay models yield marginally improved fits when compared to the constant acceleration model, as does the stochastic

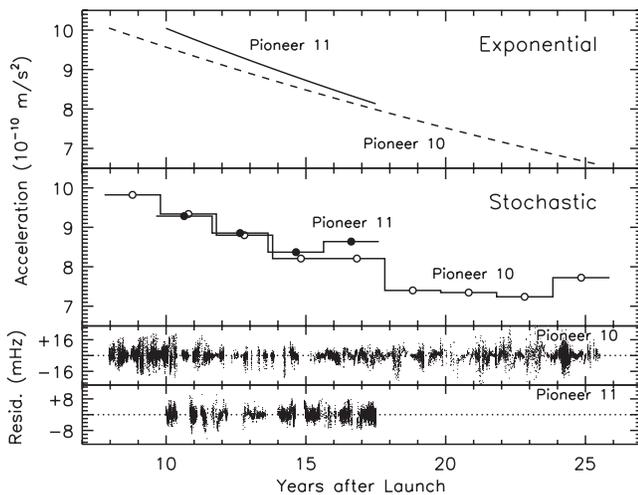


FIG. 1. Top panel: Estimates of the anomalous acceleration of Pioneer 10 (dashed line) and Pioneer 11 (solid line) using an exponential model. Second panel: Stochastic acceleration estimates for Pioneer 10 (open circles) and Pioneer 11 (filled circles), shown as step functions. Bottom two panels: Doppler residuals of the stochastic acceleration model. Note the difference in vertical scale for Pioneer 10 vs Pioneer 11.

TABLE III. Vector acceleration parameters.

S/C ^a	Data	Center	σ_ν mHz	$a_{P,z}$ ^b	$a_{P,x}$ ^b 10^{-10} m/s ²	$a_{P,y}$ ^b
P10	DS	Earth	4.98	8.17(2)	0.42(3)	0.08(1)
		Sun	4.98	8.17(2)	0.42(3)	0.08(1)
P11	DS	Earth	2.13	8.62(6)	-0.73(3)	0.97(1)
		Sun	2.21	8.64(6)	-0.76(3)	0.97(1)
P11	SA	Earth/Sun ^c	3.61	4.48 ± 0.50	-1.38 ± 11.33	-0.27 ± 1.7

^aSee Table I for designations.

^b1- σ error quoted in the final digit, except as noted.

^cResults for Earth-/Sun-pointing were similar.

model. The presence of maneuvers confounds our ability to detect such terms unambiguously. The addition of earlier data arcs, with greater occurrences of maneuvers, did not help as much as desired.

Our measure of goodness of fit, σ_ν , may allow comparison of competing models using the standard F -ratio statistic (i.e., ratio of variances), even if σ_ν itself is not a standard statistic. Preliminary results indicate that the time variable models (linear, exponential, and stochastic) are indeed better than the simple constant models, for both spacecraft trajectories. Future work will attempt to quantify this improvement more rigorously.

Direction.—For continuous communication, it was necessary to orient the spacecraft so as to keep Earth within 3° of their antenna beamwidth. The Sun-probe-Earth angle remained small and varied only from 2.6° (1980) to 0.7° (2001) for Pioneer 10 and from 6.0° (1980) to 1.7° (1990) for Pioneer 11. The solar plasma noise present in the data rendered the effort to distinguish these nearly coincident directions fruitless. There was also a possibility that Pioneer 11 data from prior to the Saturn encounter, when the Sun-probe-Earth angle was larger, would allow us to distinguish between the Earth (and spin-axis) vs Sun directions. Unfortunately, these hopes, too, were in vain because of solar plasma noise, a malfunctioning thruster, and frequent maneuvers. Although the Earth direction is marginally preferred by the solution (see Table III), the Sun, Earth, and spin-axis directions cannot be distinguished.

We can exclude an anomaly directed along the spacecraft velocity vector. In 1980, the angle between the best-fit acceleration vector and the spacecraft velocity vector is 8.5° (Pioneer 10) and 31.8° (Pioneer 11). This was sufficient to show that the anomaly is not directed along the velocity vector using Toth's orbit determination program [7] with the Pioneer 11 DS data arc.

Onset.—The Doppler data obtained by using Pioneer 11 prior to its Saturn encounter are consistent with a possible onset, but the uncertainty remains large. Some, or all, of this onset may be due to mismodeling the effects of solar pressure. However, the relative shortness of these data arcs and the large number of maneuvers performed during this period (including a significant trajectory correction maneuver) make it difficult to reach a robust conclusion.

Origin.—The most likely cause of the Pioneer anomaly is the anisotropic emission of on-board heat. This fact was recognized early on [3], leading to a detailed thermal analysis of the Pioneer 10 and 11 spacecraft. In a parallel effort, by using recovered project documentation and telemetry records, a highly detailed finite-element thermal model of the two spacecraft was constructed and used to estimate the recoil force due to anisotropically radiated on-board generated heat at various heliocentric distances [4,8]. A conclusive result can be reached only by incorporating the thermal recoil force, computed as a function of time, into the standard set of spacecraft force models that are used for Doppler analysis [4,9]. Such an analysis was initiated once the extended Pioneer 10 and 11 Doppler data sets became available. The main question is whether or not a statistically significant anomalous acceleration signal still remains in the residuals after the thermal recoil force has been properly accounted for. Results of this meticulous study will be published soon.

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