The Apparent Anomalous, Weak, Long-Range Acceleration of Pioneer 10 and 11†§

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Abstract

Recently we reported that radio Doppler data generated by NASA’s Deep Space Network
(DSN) from the Pioneer 10 and 11 spacecraft indicate an apparent anomalous, constant,
spacecraft acceleration with a magnitude $\sim 8.5 \times 10^{-8}$ cm s$^{-2}$, directed towards the Sun [1]. Analysis of similar Doppler and ranging data from the Galileo and Ulysses spacecraft
yielded ambiguous results for the anomalous acceleration, but it was useful in that it ruled
out the possibility of a systematic error in the DSN Doppler system that could easily have
been mistaken as a spacecraft acceleration. Here we present some new results, including a
critique suggestions that the anomalous acceleration could be caused by collimated thermal
emission. Based partially on a further data for the Pioneer 10 orbit determination, the data
now spans January 1987 to July 1998, our best estimate of the average Pioneer 10 acceleration
directed towards the Sun is $\sim 7.5 \times 10^{-8}$ cm s$^{-2}$.

1 Introduction

Detailed analyses of radio metric data from distant spacecraft in the solar system have revealed
an anomalous acceleration acting on Pioneer 10 and 11, with supporting data from Galileo, and
Ulysses spacecraft. These data indicated existence of an apparent anomalous, constant,
acceleration acting on the spacecraft with a magnitude $\sim 8.5 \times 10^{-8}$ cm/s$^2$, directed towards the Sun [1]. Two independent codes and physical strategies were used to analyze the data. A number of potential causes have been ruled out. In this paper we report on further progress in this study.

We concentrate on the analysis of the Pioneer 10 and 11 spacecraft Doppler data. We will
discuss scenarios that involve excess power and heat generated by the Radioisotope Thermoelec-
tric Generators (RTGs). We will present our estimates for the corresponding effects in order to
demonstrate that these mechanisms can not as yet explain the reported effect.

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2 Study of the anomalous acceleration

The Pioneer spacecraft are excellent for dynamical astronomy studies. Due to their spin-stabilization and their great distances, a minimum number of Earth-attitude reorientation maneuvers are required. To obtain the S-band Doppler data from the Pioneer spacecraft, NASA used the Jet Propulsion Laboratory’s (JPL) Deep Space Network (DSN). The signals were actively reflected by a transponder on the spacecraft and calculation of the motions of the spacecraft were made based on the resulting Doppler shift in the signals. This data was used to determine the Pioneers position, velocity and the magnitudes of the orientation maneuvers.

2.1 The studies of unmodeled acceleration at JPL.

Beginning in 1980, when at 20 AU the solar radiation pressure acceleration had decreased to $< 5 \times 10^{-8}$ cm/s$^2$, JPL’s Orbit Determination Program (ODP) analysis of unmodeled accelerations (at first with the faster-moving Pioneer 10) found that the biggest systematic error in the acceleration residuals is a constant bias of $a_P \sim (8 \pm 3) \times 10^{-8}$ cm/s$^2$, directed toward the Sun (to within the accuracy of the Pioneers’ antennae).

We ultimately concluded that there is an unmodeled acceleration, $a_P$, towards the Sun of $(8.09 \pm 0.20) \times 10^{-8}$ cm/s$^2$ for Pioneer 10 and of $(8.56 \pm 0.15) \times 10^{-8}$ cm/s$^2$ for Pioneer 11. The error is determined by use of a five-day batch sequential filter with radial acceleration as a stochastic parameter subject to white Gaussian noise ($\sim 500$ independent five-day samples of radial acceleration). No magnitude variation of $a_P$ with distance was found, within a sensitivity of $2 \times 10^{-8}$ cm/s$^2$ over a range of 40 to 60 AU. All errors are from the covariance matrices associated with the least–squares analysis. The assumed data errors are larger than the standard error on the post–fit residuals.

The observed effect may be expressed by the following simple expression:

$$\nu_{\text{obs}} = \nu_{\text{model}} \times \left[ 1 - \frac{a_P \cdot t}{c} \right],$$

where $\nu_{\text{obs}}$ is the frequency of the re-transmitted signal observed by a DSN antennae, while $\nu_{\text{model}}$ is the predicted frequency of that signal. Our analyses were modeled to include the effects of planetary perturbations, radiation pressure, the interplanetary media, general relativity, and bias and drift in the Doppler signal. Planetary coordinates and the solar system masses were obtained using JPL’s Export Planetary Ephemeris DE200. The analyses calculated Earth’s polar motion and its non-uniform rotation using the International Earth Rotation Service.

The models account for a number of post-Newtonian perturbations in the dynamics of the planets, the Moon, and spacecraft: i) models for light propagation are correct to order $(v/c)^2$, ii) the equations of motion of extended celestial bodies are valid to order $(v/c)^4$. Non-gravitational effects, such as solar radiation pressure and precessional attitude-control maneuvers, make small contributions to the apparent acceleration we have observed. The solar radiation pressure decreases as $r^{-2}$. As previously indicated for the Pioneers, at distances >10-15 AU it produces an acceleration that is much less than $8 \times 10^{-8}$ cm/s$^2$, directed away from the Sun. (The solar wind is roughly a factor of 100 smaller than this.)

As possible “perturbative forces” to explain this bias, we considered gravity from the Kuiper belt, gravity from the galaxy, spacecraft “gas leaks,” errors in the planetary ephemeris, and errors in the accepted values of the Earth’s orientation, precession, and nutation. None of these “forces” could explain the apparent acceleration, and some were two orders of magnitude or more too small.
2.2 An error in the code? — The Aerospace Corporation’s result.

With no explanation of this data in hand, our attention focused on the possibility that there was some error in JPL’s ODP. To investigate this, an independent analysis of the raw data using The Aerospace Corporation’s Compact High Accuracy Satellite Motion Program (CHASMP), which was developed independently of JPL’s ODP, was performed. Although, by necessity, both programs use the same physical principles, planetary ephemeris, and timing and polar motion inputs, the algorithms are otherwise quite different. If there were an error in either program, they would not agree. (Common program elements continue to be investigated.)

The CHASMP analysis of Pioneer 10 data also showed an unmodeled acceleration in a direction along the radial toward the Sun. The value is $(8.65 \pm 0.03) \times 10^{-8}$ cm/s$^2$, agreeing with JPL’s result. The smaller error here is because the CHASMP analysis used a batch least-squares fit over the whole orbit, not looking for a variation of the magnitude of $a_P$ with distance.

Without using the apparent acceleration, CHASMP shows a steady frequency drift of about $-6 \times 10^{-9}$ Hz/s, or 1.5 Hz over 8 years (one-way only). The drift in the Doppler residuals (observed minus computed data) is clear, definite, and cannot be removed without the added acceleration, $a_P$. If there were a systematic drift in the atomic clocks of the DSN or in the time-reference standard signals, this would appear like a non-uniformity of time; i.e., all clocks would be changing with a constant acceleration. We now have been able to rule out this possibility.

In addition to our previous analysis [1], we have examined numerous “time” models (in conjunction with our studies of Galileo and Ulysses spacecraft radio metric data), searching for any (possibly radical) solution, namely: i). Drifting Clocks. This model adds a constant acceleration term to the Station Time (ST) clocks; i.e., in the ST-UTC (Universal Time Coordinates) time transformation. The model fit Doppler well for Pioneer 10, Galileo, and Ulysses but failed to model range data for Galileo and Ulysses. ii). Quadratic Time Augmentation. This model adds a quadratic-in-time augmentation to the IAT-ET (International Atomic Time-Ephemeris Time) time transformation. The model fits Doppler fairly well but range very badly. iii). Frequency Drift. This model adds a constant frequency drift to the reference frequency. The model also fits Doppler well but again fits range poorly. iv). Expanding Space. This model adds a quadratic in time term to the light time, thus mimicking a line of sight acceleration of the spacecraft. The model fits both Doppler and range very well but the coefficient of the quadratic is negative for Pioneer 10 and Galileo while positive for Ulysses. v) Speed of Gravity. This model adds a “light time” delay to the actions of the Sun and planets upon the spacecraft. The model fits Pioneer 10 and Ulysses well. But the Earth flyby of Galileo fit was terrible, with Doppler residuals as high as 20 Hz.

All these models were rejected due either to poor fits or to inconsistent solutions among spacecraft.

3 Influence of the excess power and heat from RTGs.

One might argue that a possible systematic explanation of the residuals is non-isotropic thermal radiation. Pu$^{238}$ radioactive thermal generators (RTGs) power the Pioneers.

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$^1$The JPL and DSN convention for Doppler frequency shift is $\Delta \nu = \nu - \nu_0$, where $\nu$ is the measured frequency and $\nu_0$ is the reference frequency. It is positive for a spacecraft receding from the tracking station (red shift), and negative for a spacecraft approaching the station (blue shift), just the opposite of the usual convention.
3.1 The heat coming from the RTGs.

Let us discuss the anisotropic heat reflection off of the back of the spacecraft high-gain antennae, the heat coming from the RTGs [2]. Before launch the four RTGs delivered a total electrical power of 160 W (now $\sim$ 70-75 W), from a total thermal fuel inventory of 2580 W (now $\sim$ 2090 W). Presently $\sim$ 2000 W of RTG heat must be dissipated. Only $\sim$ (70 – 85) W of directed power could explain the anomaly. Therefore, in principle there is enough power to explain the anomaly this way. However, there are two reasons that preclude such a mechanism, namely:

i) The spacecraft geometry. The RTGs are located at the end of booms, and rotate about the craft in a plane that contains the approximate base of the antenna. From the RTGs the antenna is thus seen “edge on” and subtends a solid angle of $\sim$ 1.5 % of $4\pi$ steradians. This already means the proposal could provide at most $\sim$ 30 W. But there is more.

ii) The RTG’s radiation pattern. The above estimate was based on the assumption that the RTGs are spherical black bodies. But they are not. The main bodies of the RTGs are cylinders and they are grouped in two packages of two. Each package has the two cylinders end to end extending away from the antenna. Every RTG has six fins that go radially out from the cylinder. Thus, the fins are “edge on” to the antenna (the fins point perpendicular to the cylinder axes). Ignoring edge effects, this means that only 2.5 % of the surface area of the RTGs is facing the antenna. Further, for better radiation from the fins, the Pioneer SNAP 19 RTGs had larger fins than the earlier test models, and the packages were insulated so that the end caps had lower temperatures and radiated less than the cylinder/fins [3]. As a result of such a design, the vast majority of the heat radiated by the RTG’s is symmetrically directed in space unobscured by the antenna.

We conclude that this mechanism does not provide enough power to explain the Pioneer anomaly.

3.2 Non-isotropic radiative cooling of the spacecraft.

There is also the possibility that the anomalous acceleration seen in the Pioneer 10/11 spacecraft can be, “explained, at least in part, by non-isotropic radiative cooling of the spacecraft ” [4]. So, the question is, does “at least in part” mean this effect comes near to explaining the anomaly? We argue it does not.

Consider radiation of the power of the main-bus electrical systems from the rear of the craft. For the Pioneers, the aft has a louver system, and “the louver system acts to control the heat rejection of the radiating platform... A bimetallic spring, thermally coupled radiatively to the platform, provides the motive force for altering the angle of each blade. In a closed position the heat rejection of the platform is minimized by virtue of the “blockage” of the blades while open louvers provide the platform with a nearly unobstructed view of space” [5].

If these louvers were open, this mechanism could produce a comparable effect. However, by 9 AU the actuator spring temperature had already reached $\sim 40^\circ$F. This means the louver doors were closed (i.e., the louver angle was zero) from there on out. Thus, from our quoting of the radiation properties above, the contribution of the thermal radiation to the Pioneer anomalous acceleration should be negligibly small. After the above time, we reach our data region. In 1984 Pioneer 10 was at about 33 AU and the power was about 105 W. (Always reduce the total power numbers by 8 W to account for the radio beam power.) In (1987, 1992, 1996) the craft was at $\sim$ (41, 55, 65) AU and the power was $\sim$ (95, 80, 70) W. The louvers were inactive, and no decrease in $a_P$ was seen [6].

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[2] Any change of the louver angle should result in a spin change due to the thermal radiation. This is because of...
3.3 Could the Helium pressure produced within the RTGs be the cause for the acceleration?

Another possible systematic from on-board the spacecraft, is from the He build-up in the RTGs due to the α-decay of Pu$^{238}$. Is there any way that this permeating He could be causing $a_P$?

To make this mechanism work, one would need that the He leakage from the RTGs be preferentially directed away from the Sun, with a velocity large enough to cause the acceleration. The SNAP-19 Pioneer RTGs were designed in such a way that the He pressure has not been totally contained within the Pioneer heat source over the life of RTGs. Instead, the Pioneer heat source contains a pressure relief device which allows the generated He to vent out of the heat source and into the thermoelectric converter. (The strength member and the capsule clad contain small holes to permit He to escape into the thermoelectric converter.) The thermoelectric converter housing-to-power output receptacle interface is sealed with a viton O-ring. This means that, due to permeation, the gas within the converter is expected to be released to the space environment throughout the mission life of the Pioneer RTGs.

From the size of the fuel pucks, the total volume of fuel is about 904 cm$^3$. The fuel is PMC Pu conglomerate. The amount of Pu$^{238}$ in this fuel is about 5.8 kg. With a decay constant of 87.74 years, that means the rate of He production (from Pu decay) is about 0.8 gm/year, assuming it all leaves the cermet. Finally, $kT$ on the surface of the RTGs corresponds to less than 10$^3$ km/sec for He. (When looking for gas leaks, see below, we found that 2 gr/year mass of hydrazine could produce $a_P$ if it came out at nozzle speed of about 3.4 km/sec, all directed.)

So, we can rule out this helium permeating through the O-rings as the cause of our effect.

4 Recent results

Recently we began using new JPL software (SIGMA) to reduce the Pioneer 10 Doppler data to 50-day averages of acceleration, extending from January 1987 to July 1998, over a distance interval from 40 to 69 AU (see Figure [1]). Before mid-1990, the spacecraft rotation rate changed (slowed) by about -0.065 rev/day/day. Between mid-1990 and mid-1992 the spin-deceleration increased to -0.4 rev/day/day. But after mid-1992 the spin rate remained ~ constant. In units of 10$^{-8}$ cm/s$^2$, the mean acceleration levels obtained by SIGMA from the Doppler data in these periods are: (7.94 ± 0.11) before mid-1990, (8.39 ± 0.14) between mid-1990 and mid-1992, and (7.29 ± 0.17) after mid-1992. [Similar values (8.27 ± 0.05, 8.77 ± 0.04, 7.76 ± 0.08) were obtained using CHASMP.] We detect no long-term deceleration changes from mid-1992 to mid-1998, and only two spin-related discontinuities over the entire data period.

We have also performed a number of tests of the internal consistency of our analysis of $a_P$. Internal tests included numerous examinations of the fit results for various aspects of the theoretical model related to station coordinates, Earth orientation parameters, precession, nutation, instrumental clock stability, interplanetary plasma effects, and relativistic effects. The numerical stability of the estimation algorithm and its computer implementation are also considered. Finally, the stability of the solution was examined in detail, in terms of time-dependent changes of both the $a_P$ and the spacecraft spin-down rate.

The internal consistency tests indicate that, in addition to the formal uncertainties, there is evidence for a systematic mismodeling which results in an annual periodic term (plot B in the orientation of the lovers around the bus on the spacecraft. We detect no such a change.
Figure [1]. This term has been found in the residuals of both Pioneers and is currently being investigated. Such systematic errors lead to estimates of realistic uncertainties that are approximately two times the formal uncertainties.

Assume that the slowing of the spin rate was caused by spacecraft systems that also account for a few % systematic effect. Then, excluding other biases, such as the radio beam increasing the anomaly, we should adopt the post-1992 value as the most accurate measure of the anomalous acceleration of Pioneer 10.

As stated before, we believe the most plausible explanation of the anomaly is systematics, such as radiant heat or gas leaks. But no such explanation has yet been demonstrated. Clearly, more analysis, observation, and theoretical work are called for. Further details will appear elsewhere.

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References

[1] J. D. Anderson, P. A. Laing, E. L. Lau, A. S. Liu, M. M. Nieto, and S. G. Turyshev, Phys. Rev. Lett. 81, 2858 (1998). gr-qc/9808081.

[2] J. I. Katz, gr-qc/9809070.

[3] S. T. Christenbury, private communications, and: Teledyne report IESD 2873-172, June, 1973, tech. report no. DOE/ET/13512-T1; DE85017964, gov. doc. no. E 1.9.

[4] E. M. Murphy, gr-qc/9810015.

[5] Pioneer Project NASA/ARC document No. PC-202.
Figure 1: The Pioneer 10 Doppler data: 50-day averages of anomalous acceleration – January 1987 to July 1998.