A Conventional Physics Explanation for the Anomalous Acceleration of Pioneer 10/11

Louis K. Scheffel
Cadence Design Systems
555 River Oaks Parkway
San Jose, CA 95134
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Anderson, et al. find the measured trajectories of Pioneer 10 and 11 spacecraft deviate from the trajectories computed from known forces acting on them. This unmodelled acceleration can be accounted for by non-isotropic radiation of spacecraft heat. Various forms of non-isotropic radiation were proposed by Katz, Murphy, and Scheffer, but Anderson, et al. felt that none of these could explain the observed effect. This paper calculates the known effects in more detail and considers new sources of radiation, all based on spacecraft construction. These effects are then modelled over the duration of the experiment. The model provides a reasonable fit to the acceleration from its appearance at a heliocentric distance of 5 AU to the last measurement at 71 AU, but overpredicts by 9% the decrease in acceleration between intervals I and III of the Pioneer 10 observations. (For comparison, the two different measurements of the effect (SIGMA and CHASMP) themselves differ by 4% in interval III.) In any case, by accounting for the bulk of the acceleration, the proposed mechanism makes it much more likely that the entire effect can be explained without the need for new physics.

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I. INTRODUCTION

In [1], Anderson et al. compare the measured trajectory of several spacecraft against the theoretical trajectory computed from known forces. The find a small but significant discrepancy, referred to as the unmodelled or anomalous acceleration. It has an approximate magnitude of \( 8 \times 10^{-8} \text{ cm s}^{-2} \) directed approximately towards the Sun. Needless to say, any acceleration of any object that cannot be explained by conventional physics is of considerable interest. Explanations for this acceleration fall into two general categories - either new physics is needed or some conventional force has been overlooked.

One of the most likely candidates for the anomalous acceleration is non-isotropic radiation of spacecraft heat. This is an appealing explanation since the spacecraft dissipates about 2000 watts total; if only 58 watts of this total power was directed away from the sun it could account for the acceleration. Several possible mechanisms have been debated in the literature, but none are totally satisfactory.

In this paper we re-examine each proposed mechanism, explicitly including their time dependence. We propose several additional mechanisms - asymmetric RHU heat, misdirected feed radiation, and mis-modelled solar reflectivity. Finally, we compare the acceleration induced by the proposed mechanisms with the measured data, and get reasonable agreement over the whole data span.

II. THE ANOMALOUS ACCELERATION

As the Pioneer spacecraft receded from the sun, solar forces decreased and only gravitational forces, and an occasional maneuver, affected the trajectory of the spacecraft. Anderson, et al. noticed that a small additional acceleration needed to be added to the known forces to make the measured data and computations match. This is the anomalous acceleration, which started to become noticeable about 5 AU from the sun, and was roughly the same for Pioneer 10 and 11. The onset is shown in Figure 1.

Further constraints come from the ongoing study of Pioneer 10, where there are fewer confounding effects and the data span is long enough to provide significant constraints due to the radioactive decay of the heat sources. Figure 2, reproduced from [2], shows the measured acceleration 1987 to 1998. (Although they have different horizontal axes, Figure 2 largely follows Figure 1 chronologically. Pioneer 10 was at 40 AU in 1987.) The authors divide the 1987-1998 Pioneer 10 history into three intervals. Interval I is January 1987 to July 1990, interval II from July 1990 to July 1992, and interval III is from July 1992 to June 1998. The authors make this distinction by looking at the spin rate of the craft - in intervals I and III it was decreasing smoothly, but in interval II it decreased quickly and irregularly. They therefore consider the data from interval II to be less reliable than intervals I and III, since whatever affected the spin (probably gas leaks) may also have affected the acceleration.

More recent analyses have refined these results somewhat, though the main conclusions remain unchanged. Table 1 shows the most recent results from [3], which fits a constant, independent acceleration in each interval. Accelerations are in units of \( 10^{-8} \text{ cm s}^{-2} \). SIGMA and

*Electronic address: lou@cadence.com
CHASMP are two different and largely independent trajectory modelling programs; the difference between the programs is our best estimate of the real uncertainties since it is far greater than the formal errors. This data, taken at face value, shows that 57 directed watts can account for the acceleration in 1998, and that a 3% decrease was observed between interval I and interval III.

### TABLE I: Weighted Least Squares (WLS) results from Anderson, et al. and equivalent directed power for a 241 kg spacecraft mass

| Interval       | SIGMA Watts | Watts | CHASMP Watts |
|----------------|-------------|-------|--------------|
| Jan 87- Jul 90 | 8.00 ± 0.01 | 57.8  | 7.84 ± 0.01  |
| Jul 92- Jul 98 | 8.25 ± 0.03 | 59.6  | 7.91 ± 0.01  |

### III. PREVIOUS WORK

Many paper and web descriptions of the Pioneer spacecraft are available. In this section we summarize the existing literature on the hypothesis that non-isotropic radiation is responsible for the unmodelled acceleration.

Murphy (and a related proposal by Scheffer) suggests 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.” Katz proposes that at least part of the acceleration is generated by radiation from the RTGs reflecting off the back of the antenna. Slusher (as credited by Anderson) proposed that the forward and backward surfaces of the RTGs may emit non-equally. Anderson, et al. argue in reply that none of these proposed sources adequately account for the acceleration.

### IV. DISCUSSION

We consider asymmetrical radiation from 4 sources - the RTG heat (direct power and reflection off the antenna), the electrical power dissipated by the spacecraft, the radioisotope heater units (RHUs) on the spacecraft, and radiation from the feed that misses the antenna. We also consider one modelling error, a mis-estimation of the reflectivity of the antenna to solar radiation. The available power from all these sources changes in time. In the following discussion, let $d$ be the date, in years. The sunward side of the spacecraft is the back, and the anti-sunward side, in the direction of motion, is the front. We calculate thrust in units of watts of directed (anti-sunward) radiation.

#### A. Radiation of spacecraft power

First, consider thermal radiation from the body of the spacecraft. A thought experiment shows that the electrical power dissipated in the spacecraft must result in thrust. The simplest model consists of the main compartment as a 60 watt isotropic radiator, and the back of the antenna a mirror. The antenna subtends 120 degrees as seen from the instrument compartment, so if the emitted radiation is isotropic, the antenna intercepts 1/4 of the total radiation, and reflects it away from the sun. Since the main compartment is centered behind the antenna, and since the sides, if anything, are worse radiators than the front, we conclude that at least 25% of spacecraft electrical power must be converted to thrust.

A more detailed analysis shows the radiation is even more anisotropic than these arguments would suggest. Assuming a uniform internal temperature and closed louvers, the power emitted from each surface is proportional to the area times the “effective” emissivity of the surface. The sides and the rear of the compartment are covered with multi-layer insulation (MLI), with an effective emissivity of 0.007 to 0.01. The lowest emissivity material on the front of the spacecraft is the surface of the louvers, with an emissivity of 0.04. Since the sides and the front have comparable surface areas, then about 80% of the total power will be radiated though the front (though hard to characterize heat leaks could reduce this value). Frontal radiation would be expected to be about 66% efficient, assuming Lambertian emission. Defining $\epsilon_{BUS}$ as the fraction of main compartment heat that is converted to thrust, we then expect $\epsilon_{BUS}$ to range between 0.25 (blockage arguments) to 0.52 (differential emissivity).

From the total electrical power is modelled

$$E(d) = (68 + 2.6 (1998.5 - d)) \text{ watts}$$

and the thrust (assuming an 8 watt radio beam) is

$$BUS(d) = \epsilon_{BUS} (E(d) - 8.0 \text{ watts})$$

#### B. Feed pattern of the radio beam

An ideal radio feed antenna would illuminate its dish uniformly, with no wasted energy missing the dish. However, the feed is physically small and cannot create such a sharp edged distribution, so some radiation always spills over the edge. This radiation is converted to thrust with an efficiency of 1.7 since it directly subtracts from the sun directed power and adds anti-sun power at a roughly 45 degree angle to the spin axis. This produces thrust

$$RADIO(d) = \epsilon_{FEED} (8 \text{ watts}) 1.7$$

where $\epsilon_{FEED}$ is the fraction of RF power that misses the antenna. Since dish area is wasted if not fully illuminated, an optimum feed (for transmission) will result in $\epsilon_{FEED} \approx 0.1$. 

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### Notes

1. Anderson, et al. (1998).
2. Katz (1998).
3. Murphy (1998).
4. Scheffer (1998).
5. Slusher (1998).
6. Katz (1999).
7. Scheffer (1999).
8. Anderson, et al. (1999).
9. Katz (1999).
C. Radiation from the RHUs

From diagram 3.8-1 in [4], 10 1-watt (in 1972) radioisotope heater units are mounted to external components (thrusters and the sun sensor) to keep them sufficiently warm. The diagram is not very specific, but the units to which they are mounted are primarily behind the main dish. Radiation from these components will contribute thrust, which we model as

\[ RHU(d) = \epsilon_{RHU} (10.0 \text{ watts}) 2^{-(d-1972)/88} \]

where \( \epsilon_{RHU} \) is the proportion of RHU heat converted to thrust. Reasonable values for \( \epsilon_{RHU} \) might range from 0.0 to 0.5, with the latter corresponding to components behind the dish radiating uniformly.

D. Radiation from the RTGs

The RTGs might contribute to the acceleration by radiating more to the front of the spacecraft than the rear, and/or by having their heat reflected asymmetrically from the spacecraft. The RTGs radiate all the thermal power that is not turned into electricity, so

\[ RTG_{HEAT}(d) = (2580 \text{ watts}) 2^{-(d-1972)/88} - E(d) \]

In [4], direct radiation asymmetry is estimated to contribute to thrust with an efficiency of at most ±0.003. RTG reflection by the antenna was proposed by Katz, but argued against by Anderson, primarily on the grounds that the RTGs are on-axis as seen by the antenna. We re-examine this argument here. From figure 3.1-2 of [4], we see that the centerline of the RTGs is behind the center of the antenna. Measurements from this diagram indicate this distance is about 23.8 cm. Figure 3.1-3 of [4] shows the far end of the RTGs is 120.5 inches (or 3.06 meters) from the centerline. From this geometrical data we can estimate the area blocked by the antenna from each RTG [4]. Numerical integration of these areas, assuming Lambertian emission by the RTGs, shows about 0.6% of the near RTG radiation and 0.4% of the far RTG radiation fall upon the dish. This energy is turned into thrust by two effects. First, the antenna shadows radiation which would otherwise go forward. An angle in the middle of the antenna is about 17 degrees forward; this corresponds to an efficiency of 0.3 (the true efficiency is probably higher since the edge is both at a greater angle and more brightly illuminated.) Next, the energy that hits the antenna must go somewhere. Some will be absorbed and re-radiated; some will bounce into space, and some will bounce and hit the instrument compartment, and be reflected or re-radiated from there. A detailed accounting seems difficult, but an overall efficiency of 0.7-0.9 seems reasonable (0.3 for shadowing and 0.4-0.6 for reflection and re-emission).

We model the total thrust from RTG heat as

\[ RTG(d) = \epsilon_{RTG} RTG_{HEAT}(d) \]

where \( \epsilon_{RTG} \) is the proportion of RTG heat converted to thrust. Combining the effects of this section, we expect \( \epsilon_{RTG} \) to range from 0.004 to 0.012.

E. Antenna solar reflectivity

The trajectory analysis programs fit the reflectivity of the spacecraft to solar radiation, \( \mathcal{K} \), as a force that falls off as \( 1/r^2 \), where \( r \) is the heliocentric distance. This fit can hide an otherwise unmodelled acceleration. Over a short time period, during which \( r \) varies little, any constant radial acceleration can be absorbed into \( \mathcal{K} \). Over a longer period of time the fitting procedure will mask any component of anomalous acceleration that varies as \( 1/r^2 \) and is less than the acceleration corresponding to the allowed variation in \( \mathcal{K} \). In particular the acceleration proposed in this paper will be partially masked since it decreases with time and hence has a \( 1/r^2 \) component.

The fitted solar reflectivity constant also provides a natural explanation for the onset of the anomalous acceleration. Consider the case where the acceleration (from any cause) exists for all \( r \). When \( r \) is small, the fitting programs absorb the extra acceleration by adjusting the value of \( \mathcal{K} \). As \( r \) increases, the power available from this source decreases, and eventually \( \mathcal{K} \) runs into the limits allowed in the fit. (Physically reasonable values perhaps range from 1.5 to about 1.9: they are certainly greater than 1.0 and less than 2.0.) Once the limit of adjustment for \( \mathcal{K} \) is reached, it becomes constant and can no longer mask the acceleration, which appears as shown in figure [4]. It might be possible to see additional signs of this process in archival data - it would show up as a decrease in the fitted value of \( \mathcal{K} \) as the spacecraft receded from the sun.

In this paper, we model the effect of any error in \( \mathcal{K} \) by introducing a fictitious force, whose value is simply the solar force on the spacecraft times the error in \( \mathcal{K} \). We assume the distance from the sun, measured in AU, increases linearly from 20 AU in 1980 to 78.5 AU in 2001:

\[ r(d) = 20 + (d - 1980)/21 \cdot (78.5 - 20) \]

The thrust, in watts, is

\[ SOLAR(d) = K_{SOLAR} \pi (1.37 \text{ m})^2 f_\odot/r^2(d) \]

where \( f_\odot = 1367 \text{ W/m}^2(\text{AU})^2 \) is the “solar radiation constant” at 1 AU, and \( K_{SOLAR} \), the amount by which the solar reflection constant is underestimated.

V. COMPARISON WITH EXPERIMENT

To compare the hypothesis with experiment, we sum the individual sources, then convert to acceleration by dividing by \( c \), the speed of light, and \( m \), the spacecraft mass.
mass (here 241 kg):

\[ acc(d) = \frac{1}{c \cdot m} [RHU(d) + RTG(d) + RADIO(d) + BUS(d) - SOLAR(d)] \]

We then compare with the plots from [2,3]. The proposed explanation has 5 adjustable parameters. In theory all are separable since they decay at different rates; in practice the data are not good enough to separate them and many fits are plausible. One reasonable fit over the entire data span has the following coefficients: \( \epsilon_{RHU} = 0.5, \epsilon_{RTG} = 0.0108, \epsilon_{FEED} = 0.1, \epsilon_{BUS} = 0.35, \) and \( K_{SOLAR} = 0.3. \)

This fit to the data is shown in Figures 1 and 2. The agreement seems reasonable in both regimes, and the proposed model provides a better fit to the early data than the constant acceleration of [3], even assuming reflectivity mismodelling to account for the onset of the acceleration. The fit from 1987 to 1998 also looks acceptable, as shown in Figure 2.

Finally, we compare with the most recent results [3] that fit a constant acceleration in each interval of the later Pioneer 10 data. The proposed model gives an average thrust of 57.8 watts in interval I, and 51.0 watts in interval III. We can normalize the result to get the correct overall average, or the right acceleration in interval I, but in either case we would expect to see an 11.8% decrease from interval I to III, where only a 3% decrease is observed. The two different measurements of the effect (SIGMA and CHASMP) themselves differ by 4% in interval III. We treat this difference as a statistical result (a procedure of dubious merit, but the best we can do) then the 9% discrepancy is 2.25 standard deviations out. This makes it unlikely at about the 2% level that this hypothesis alone accounts for all the measured result.

We can get a better fit (1.75 sigma) to the Pioneer 10 data by assigning different efficiencies to instrument heat and main compartment heat, at the cost of an extra parameter and the need to consider instrument power dissipation in detail [3].

VI. CONCLUSIONS AND FUTURE WORK

There is surely an unmodelled effect on the Pioneer spacecraft, based upon its thermal characteristics. Rough estimates show it can account for the magnitude of the unmodelled acceleration to within the errors, but overpredicts the rate of change. In any case, the proposed explanation, by accounting for the bulk of the effect, makes it more likely that conventional physics can account for the entire unmodelled acceleration. Conventional explanations for the remaining discrepancy include other unmodelled effects such as gas leaks, inaccuracies in the simple thermal model, or the effects of a complex fitting procedure applied to noisy data.

This explanation also explains some other puzzles: the values of acceleration of Pioneer 10 and 11 would be expected to be similar, but not identical, as observed. The acceleration would not have a strong effect on the spin; most of the radiation will generate little torque. Other spacecraft, built along the same general principles, would be expected to show a similar effect, but planets and other large bodies would not, as is observed.

More detailed modeling, using the Pioneer materials, construction details, and history, might confirm or refute the proposed hypothesis, and additional tracking could be useful as well. However, such improvements are limited since accurate thermal modelling is difficult [3] and the spacecraft was not designed for this purpose. Longer term, other proposed experiments such as LISA [15] are designed specifically to reduce non-gravitational systematics (by a factor of about \( 10^5 \)) and allow frequent and accurate tracking (a differential distance measurement,
each second, accurate to $10^{-9}$ cm.) Assuming the anomalous acceleration exists at all heliocentric distances, (as argued in section IV), then it should be detectable in just a few seconds of LISA data. On the other hand, if no unmodelled acceleration is detected in these more precise experiments, then almost surely the anomalous acceleration of Pioneer 10/11 is caused by overlooked prosaic sources such as those proposed here.

VII. ACKNOWLEDGEMENTS

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