The data from Pioneer 10 and 11 shows an anomalous, constant, Doppler frequency drift that can be interpreted as an acceleration directed towards the Sun of \( a_P = (8.74 \pm 1.33) \times 10^{-8} \text{ cm/s}^2 \). Although one can consider a new physical origin for the anomaly, one first must investigate the contributions of the prime candidates, which are systematics generated on board. Here we expand upon previous analyses of thermal systematics. We demonstrate that thermal models put forth so far are not supported by the analyzed data. Possible ways to further investigate the nature of the anomaly are proposed.
sub-mechanisms have been made. It was found that the data and design characteristics of the craft appear to rule them out.

Nevertheless, discussion has continued. Here we investigate other, more complicated, heat mechanisms. We find that, although the data is not completely constraining, it does not provide evidence for these mechanisms. We conclude with ideas on how future work could, in principle, allow one either to rule out an onboard systematic origin to the anomaly, meaning the explanation could be unknown physics, or to determine directly that some onboard systematic is the origin of the anomaly.

2. Constant Electrical Heat Radiation as the Source

It has been recently suggested that most, if not all, of the unmodeled acceleration of Pioneer 10 and 11 is due to an essentially constant supply of heat coming from the central compartment, directed out the front of the craft through the closed louvers. This is a more subtle version of an earlier proposal calling on the total electrical power as a mechanism. That proposal was argued against because of the observed lack of decay of the acceleration with time.

But this first hypothesis does not work. The Pioneer spacecraft were not built and do not work that way. (It was known beforehand that during the extended mission there would be “dissipation of 70 to 120 W of electrical power by units within the compartment.”) The assumption of constancy is incorrect for two reasons.

One reason for the incorrectness of this proposal is that the “central compartment” consists not just of the hexagonal “equipment compartment” but also of the “experiment compartment.” These two components are openly (radiatively) connected, separated on their common side by only a half-plate wall, “partial vertical plate.” (If one wanted to one could open the top of the equipment compartment and stick one’s arm into the experiment compartment.) Indeed, to help with heat dissipation from the experiment compartment during the early stages of the flight, there are louvers placed on the front of the experiment compartment that are similar to those placed on the equipment compartment.

Another reason why a proposal of constant heat as a source is incorrect is that even the heat dissipated only from the “equipment compartment” is not a constant. The lack of constancy of heat dissipated by itself invalidates the hypothesis. This is even without showing that correctly calculating the insulation/louver properties also rules out the hypothesis.

3. Detailed Properties of the Craft and the Data

Although the hypothesis of constant heat as a source is shown in the above Section to be ruled out, it is useful to demonstrate that the spacecraft design and data give added support to this ruling. These details are presented in this Section. The details will also be useful for the discussion of a second proposal in Section 4.

3.1. Electrical power and the louvers

We begin by reviewing the total electrical power of the craft generated at the RTGs. (See Figure 1.)
After launch, when there quickly became a stable $\sim 165$ W of power, the electrical power for Pioneer 10 first decayed at a rate of $\sim 10.6$ W/yr. After Jupiter encounter the power decay rate changed to a new value of $\sim 4.4$ W/yr. Finally, after around 1987 the decay rate changed to $\sim 2.6$ W/yr. In particular, at the beginning of our run (1987.0) $\sim 97$ W was generated and at the end of our run (1998.5) $\sim 68$ W was generated. The power decay rate (which was higher for Pioneer 11) was caused by degradation of the thermistor junctions and other RTG electrical components on top of the smaller radioactive decay rate of the $^{238}$Pu thermal sources (a half-life of 87.74 yr or a decrease of $\sim 0.8\%$ each year).

What happens to this available power? We normalize to the end of our run, 1998.5. About 3 W goes into external IR cable losses. The remaining 65 W power enters the central instrument compartment. There it is approximately used as power for the Inverter Assemblies (7 W), the Central Transformer-Rectifier-Filter [CTRF] and subsystems (21.1 W), a separate TRF (2 W) the Traveling Wave Tube Amplifier [TWTA] (27.8 W), and the Power Control Unit [PCU] and battery (3 W). Other small electronic components and base shunt-current loss account for a few W. Therefore, at this late date there are at best only a few W left for the experiments or anything else. For example, in a recent July 2000 maneuver, which required enough power to run the attitude and conscan subsystems, the TWTA had to be turned off, ending its continuous activation. It was turned back on after the 2000 conscan and then off and on for the 2001 and 2 March 2002 conscans.

Next, as can be verified in any of a number of references, there are 8 W $= 10 \log_{10}[8000]$ dBm $= 39$ dBm of constant radio power being emitted in a collimated beam towards the Sun. (Actually, the beam is along the spacecraft spin...
axis which, during the time of our data set (1987-1998.5), on average points towards the Sun. This is presently our largest systematic which works against \( a_P \) and hence makes the final value larger than the experimental number. This means the total possible heat power for the spacecraft bus is about 57 W, no matter how it escapes. (And remember, a constant \( \sim 63 \) W of totally directed power are needed to explain \( a_P \).)

Now, recall that the louvers were open during the early mission to let heat escape more easily since there was much more excess electrically-generated heat. Further, in the early stages there was also much more heat to be dissipated through the shunt external regulator (called radiator) and internal regulator. When there is high shunt current, the majority of the dissipation is directed to the exterior shunt radiator. (See Figure 2.) These conditions were to keep the temperature within the central compartment from being too high. Later, when the louvers were closed, the problem was the opposite, to try to keep in as much heat as possible in order to maintain the constantly falling temperature. In this lower-power situation, the majority of the (smaller) shunt dissipation is interior to the compartment. Further, the louvers when closed are designed not to radiate heat but to retain heat. There are second surface mirrors on the insides of the louvers. (For more information see our reference.)

![Figure 2: Design shunt power distribution as a function of shunt current.](image)

This indicates that the heat from the compartment is not radiated in a strongly directional sense along the spin axis. But this appears to be in conflict with the
values for the effective emissivities of the insulation and louver outside material (0.01 and 0.27, respectively) that were used in our reference.

How can that be? Because the assumptions are off by large amounts (in opposite directions) from the real emittances (∼0.70 and 0.04, respectively). In fact saying all the 57 W goes out the louvers with an area of ∼1 m² and using the Stefan Boltzmann law would mean the exterior louver temperature was 398 K. This explains why it is difficult to understand the proposed through-the-louvers, directed-heat, emission mechanism.

3.2. Electrical power dissipation history

Further, and as we now come to, the observed approximate constancy of the anomaly over the data period is in conflict with any model that says the anomaly is from a constant compartment source. The heat in the compartment is not constant.

Consider the situation at the beginning of our analyzed data. In 1987.0, there was about 97 W total electrical power or about 29 W more than at the end of our run. Where did this go? Approximately 1 W more went to cable loss, about 5 W more went to higher Inverter Assembly/TRF losses, and ∼24 W went to run all the instruments. Of this at least 12 W went into the equipment compartment because the instruments are there. (Even a few of the external experiments also have their electronics there.) Further, the external Asteroid/Meteoroid detector (1.7 W) failed at Jupiter encounter and the external magnetometer (HVM) (3 W) failed just before our data set, so this power also would be going to the interior shunt regulator. [We note again that for low shunt current almost all of the heat loss was designed to be through the internal shunt regulator. See Figure 2.] Therefore, at the beginning of our data set the size of the effect of this thermal hypothesis should be on the order of (73/57) = 1.26 times the size of effect at the end of our run.

From the beginning to the end of our data, the ODP results (before systematic biases are included) differed by only 0.19 U out of a total final effect of 8.74 U. [We define 1 U = 1 × 10⁻⁸ cm/s².] We took this difference to be due to spin-rate change. But even if it is not (and granted uncertainties) there obviously is no measured difference on the order of 25%. (Observe that any RTG radiant-heat based systematic must also decay by 8% during our data run.)

Going further back might allow us to get an even better handle on this. In Figure 7 of reference we showed preliminary ODP results for Pioneer10 using data from approximately 1981.5 to 1989.4. These results were not spin-rate change adjusted, were not treated for systematics, used different time-evolving estimation procedures, were done by three separate JPL navigation specialists, separated and smoothed by one of us, and definitely not analyzed with the care of our recent run (1987.0 to 1998.5). The value of at the end of this earlier run is similar to the value at the beginning of our present data run, which overlaps it in time.

At the beginning of this earlier data set the total electrical power was ∼116 W. Where did this added 19 W go? About ∼1 W more went into cable losses. Of the remaining 18 W, it is expected that ∼5 W went into added internal Inverter Assembly/TRF losses, ∼11 W into the internal shunt regulator, and only of order ∼2 W into the external shunt radiator. Therefore, in 1981.5 this thermal hypothesis should have produced an effect ∼ (89/57) = 1.56 times that at the end of our run.
in 1998.5. However, there is no fractional change in size of \( a_P \) to indicate that most if not all of the anomalous acceleration is due to electric-power heat. (Also, during this total period any RTG radiant-heat based systematic would have decreased by 13%.)

One can verify these conclusions by consulting the shunt-current history. After our run started, there was basically no excess power to get rid of unless instruments were turned off and on (power-sharing). After 1992.0 the shunt-current history shows a current between 0.09 and 0.14 Amps with various spikes. (0.9 W is the base internal shunt power loss.) Before 1990.5 the situation is approximately as we have described. (See Figure 3.)

![Figure 3: The Pioneer 10 shunt-current history from 1980.0 to 1991.0. (The data is in bimodal form, with steps of \( \sim 0.05 \) Amps.)](image)

One-half year before the start (1987.0) of our data run, the external HVM shut off. This mainly external heat of 3 W then went into internal shunt heat via an additional 0.15 Amps of shunt current. In our data run, one can first see the shunt current decaying, and then the PSE (Program Storage and Execution Unit) was turned off. Before 1987.0 the shunt current is increasing. So, the agreement with our description is clear.

4. Incorrect Solar Radiation Dynamics as an Added Source

To correct the deficiencies of a constant heat source as the origin of the anomaly,
it was later proposed that the spacecraft solar radiation constant is off by a factor $+0.3$. Then it was argued that this new contribution, plus the contribution from the model of the last section, and perhaps RTG radiation could all add up to produce the anomaly. But if this new contribution (from incorrect solar-radiation modeling of the craft) were true the Pioneer Mission would have failed!

In the first place, the true solar radiation model is much more complicated than the simple model that is proposed. The true model involves many parameters describing physical quantities of different parts of the craft and the angle of orientation with respect to the Sun. This was very important during the early phase of the mission. In fact, by the second day of the mission the Pioneer 10 aim point was already several Jovian radii off and on the wrong side of Jupiter. To correct these navigation errors, a newly developed, complicated, solar radiation model (the HGA alone being like a solar sail) was implemented in POEAS (a progenitor of CHASMP). As a result, a course correction was implemented, and Pioneer 10 successfully reached its targeted aim point at Jupiter. The model was then utilized in ODP, confirming the solution.

The next time a solution for the solar radiation model parameters was required was when the Pioneer 10 spacecraft was still in the Jovian vicinity, after the successful fly-by. That solution was obtained without any complications using the same model. The solution was also stable, reliable, and within acceptable limits. Finally, a later fit to near-Earth Pioneer 10/11 data verified all the model parameters to $\pm 5\%$. This error is much smaller than the change of the parameters assumed in the “incorrect radiation dynamics” explanation of the Pioneer anomaly.

Even further, and as we already have noted, the early numbers in Figure 7 of reference were based on attempts to check the orbit accuracy. In particular, the first two Pioneer 11 points, included in the early memos, were at the distances of Jupiter and Saturn encounters. Many things, such as large maneuvers were going on; Pioneer 11 encountered Jupiter and then came back across the central solar system to encounter Saturn.

One must be careful if one assumes a measurement is wrong just to obtain the theoretical systematic result one expects. One should try to apply the same standards in obtaining a “normal explanation” as one would if one were proposing a radical one.

5. Possible Future Work

Of course, at present our arguments are good to only a few W. We might be able to improve upon our knowledge by studying in detail the instrument/power usage history. But this could be of no use because the data may be lost or inadequate. However, there is more one can do to provide an even more precise systematic. After all, heat in some form remains a primary candidate (perhaps the best candidate) for an explanation from onboard-generated forces. It is just that so far no explicit model has been shown to work.

The latter part of the preliminary (between 1981.5 and 1989.4) data overlaps the beginning of our later (between 1987.0 and 1998.5) analyzed data set. Therefore, we can normalize the preliminary data to our reported anomalous “experimental” value of 7.85 U, which was corrected for spin-rate change but not for other system-
atics. The limited spin-rate data we have available in our Pioneer data archives shows no dramatic or anomalous spin-rate changes before 1989 and definitely no anomalous long-term change over 1981.5 to 1987.5 (after which our archiving of all spin data is complete).

Does this therefore mean, then, that in Figure 7 of reference 1 we see a shift in $a_P$ of $\sim 0.6$ U as we go back to 1981.5? It is not clear. A shift of $\sim 0.6$ U cannot be determined on the basis of only this simple argument. The situation is much too complicated.

In addition to the problems mentioned at the end of the previous Section, the analyses used in the preliminary plot were done before an annual sinusoid was characterized. This annual term, which can be removed by an unreasonably large adjustment to the Earth’s orbital orientation (inclination and node on the J2000 Earth equator), is larger closer in to the Sun. All of the high data points on the preliminary $a_P$ curve are at boundaries of years, when the annual term is at a maximum. So, for example, the hypothesis discussed in Sec. 4 would imply that step-function changes in the heat being dissipated internally (see Figure 3) would make the sensitive annual term show abrupt deviations from its sinusoid. This is not seen in our primary data run.

The use of the shunt-current history and temperature history data would allow correlations of any $a_P$ variation with the compartment power-sharing, when (i) all systems and experiments were on with a significant shunt current, and (ii) the instruments were being turned off and there was little shunt current.

An analysis to improve the characterization of $a_P$ from the earlier data, although desirable, would be difficult. The earlier radio Doppler and spin-rate data is available in a not completely processed format. (They exist on obsolete 9-track magnetic tapes intended for a VAX.)

A precise analysis over the entire 17 years of available Pioneer data (perhaps also including later data) might reveal any changes in $a_P$ that vary slowly with time. Any changes could be correlated with the radioactive decay rate of the plutonium and the electrical power history. Then a precise heat systematic based on data rather than on ‘back-of-the-envelope’ thermal models might be found.

Further, it might be possible to do a statistically significant three-dimensional acceleration analysis, especially with the early data near 1981. If so, one could distinguish an anomalous acceleration towards the Sun from an acceleration along the spin axis.

Finally, a well-designed new craft and experiment could be undertaken to take advantage of what we have learned. This basically would be a new gravitational mission with the goal of unambiguously measuring the Pioneer anomaly to an accuracy of 10% or better.

6. Conclusion

In conclusion, we quote from ourselves: “Until more is known, we must admit that the most likely cause of this effect is an unknown systematic.” As for heat, there is no solid explanation in hand as to how a specific mechanism could work. Most importantly, the decrease in the heat supply over time should have been seen by now. It is not. To further quote from ourselves: “... we anticipate that, given our
analysis of the Pioneers, in the future precision orbital analysis may concentrate more on systematics.” This may indeed be the most important outcome of our analysis, with important implications for future deep-space missions, including the hoped for Pluto/Kuiper Belt mission.

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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. D 65, 082004 (2002), gr-qc/0104064.
2. 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.
3. J. I. Katz, Phys. Rev. Lett. 83, 1892 (1999), gr-qc/9809070.
4. E. M. Murphy, Phys. Rev. Lett. 83, 1890 (1999), gr-qc/9810015.
5. J. D. Anderson, P. A. Laing, E. L. Lau, A. S. Liu, M. M. Nieto, and S. G. Turyshev, Phys. Rev. Lett. 83, 1893 (1999), gr-qc/9906113.
6. J. D. Anderson, P. A. Laing, E. L. Lau, A. S. Liu, M. M. Nieto, and S. G. Turyshev, Phys. Rev. Lett. 83, 1891 (1999), gr-qc/9906113.
7. L. K. Scheffer, gr-qc/0106010.
8. P. Dyal and R. O. Fimmel, Pioneer 10 and 11 Heliospheric Mission (NASA/Ames Research Center, 1982).
9. Pioneer F/G Project: Spacecraft Operational Characteristics, Pioneer Project NASA/ARC document No. PC-202.01 (NASA, Washington, D.C., 1971).
10. If this type of mechanism were the main source of $a_P$ then, since Pioneer 11 radiated less electrical heat in the extended mission, $a_P$ for Pioneer 11 should be less than that for Pioneer 10. Experimentally it is the opposite.
11. Pioneer Extended Mission Plan, Third Revision, NASA/ARC document No. PC-1001 (NASA, Washington, D.C., 1994).
12. R. O. Fimmel, J. Van Allen, and E. Burgess, Pioneer: First to Jupiter, Saturn, and beyond, NASA report NASA–SP-446 (NASA, Washington D.C., 1980).
13. The type of mirrors used can be visualized at http://www.jpl.nasa.gov/basics/bsf11-4.html “Cold internal temperatures cause the louvers to drive closed to reflect back and retain heat.”
14. Without data, thermal models of spacecraft are notoriously difficult to create. The modern Cassini spacecraft was well-modeled before launch. The Cassini RTGs are mounted on a plane directly in front of the craft instead of off to the sides on booms, like on the Pioneers. A priori models predicted a systematic of 75 U. But experiment found only
(27 ± 6) U. See M. D. Guman et al., in: *Spaceflight Mechanics 2000*, ed: C. Kluever, B. Neta, C. D. Hall, and J. M. Hanson (Univelt, San Diego), *Adv. Astronautical Sciences* **105**, 1053 (2000).

15. The insulation numbers for 2 mil aluminized kapton and mylar, agree with modern values. See, e.g., [http://www.tak2000.com](http://www.tak2000.com).

16. The 1-day batch-sequential result is discussed in our reference.

17. ODP is the Jet Propulsion Laboratory’s Orbit Determination Program.

18. J. D. Anderson, Quarterly Report to NASA/Ames Research Center, JPL Interoffice Memorandum, 8 July 1992; *Celestial Mechanics Experiment, Pioneer 10/11*, 22 July 1992. Also see the later quarterly report for the period 1 Oct. 1992 to 31 Dec. 1992, dated 17 Dec. 1992, Letter of Agreement ARC/PP017. The first and last, specifically, contain Figure 7 of our reference.

19. L. K. Scheffer, gr-qc/0107092 and gr-qc/0108054.

20. R. M. Georgevic, *Mathematical Model of the Solar Radiation Force and Torques Acting on the Components of a Spacecraft*, TM 33-494 (JPL, Pasadena, 1971).

21. P. A. Laing, *Thirty Years of CHASMP*, internal Aerospace Corporation report (2002).

22. G. W. Null, *Astron. J.* **81**, 1153 (1976). POEAS stands for Planetary Orbiter Error Analysis Study program. CHASMP is The Aerospace Corporation’s Compact High Accuracy Satellite Motion Program.

23. The ATDF’s (Archival Tracking Data Files) were processed through the STRIPPER software for input into an orbital data program. (See our reference.) The tracking data tapes themselves are in binary form in a more basic format. The observable and residual has not been calculated in the form which is used by the ODP.

24. Work in progress.

25. J. D. Anderson, M. M. Nieto, and S. G. Turyshev, Gen. Rel. and Grav. (to be submitted), Report LA-UR-02-284.

26. It was suggested one could use LISA to study the Pioneer anomaly. However, the three spacecraft of the LISA constellation will be on bound, interior elliptic orbits close to 1 AU whereas the Pioneers are on unbound, hyperbolic orbits beyond 20 AU.