Comment on "Indication, from Pioneer 10/11, Galileo, and Ulysses Data, of an Apparent Anomalous, Weak, Long-Range Acceleration"

Anderson *et al.* [1] may have underestimated the acceleration resulting from the radiation of waste heat by the Pioneer spacecraft radioactive thermal generator (RTG). These generators are not very efficient; theoretical efficiencies may be as high as 20% [2] but RTG used in spacecraft more typically have electrical efficiencies of about 6% when new [3], which decline slowly as the thermoelectric material degrades and radioactive decay reduces the Carnot efficiency. Specific parameters and detailed design information for Pioneer are difficult to obtain so I adopt an initial electrical efficiency of 6%. Then the electric power at launch of 160 W [1] implied a thermal power of 2.67 kW and a waste heat of 2.51 kW. In 1997 the thermal power, decaying with the half-life of Pu^{238} of 87.74 y, was 2.19 kW and the electrical power of 80 W [1] implied a waste heat of 2.11 kW.

The power of a collimated beam sufficient to explain the reported anomalous acceleration a_P is 85 W [1]. The same force can be obtained from the present rejected waste heat if it is radiated with $\langle \cos\theta \rangle = 0.040$, where θ is the angle between the direction of radiation and a ray from the Sun. If the 72 W of dissipated electrical power (allowing for 8 W radiated by the antenna) are radiated from the back of the spacecraft according to Lambert's law, the RTG waste heat need only give the thrust of a 37 W collimated beam, requiring $\langle \cos\theta \rangle = 0.018$. Any components of recoil force orthogonal to the spin axis are averaged to zero by the spin. This axis and the net force point towards the Earth, and at the present great distances this closely aligns them with the Sun; the solar alignment is almost exact after averaging over Earth's orbit.

The Pioneer spacecraft [4] have their RTG mounted on booms somewhat behind their high-gain antennae. Thermal radiation scattered from the back of the antenna will be preferentially directed away from the Sun, leading to a small positive $\langle \cos\theta \rangle$. Engineering drawings [5] determine the geometry sufficiently to permit a calculation of $\langle \cos\theta \rangle$ by numerical integration. Scattering by spacecraft components other than the antenna dish is ignored and the RTG are assumed to radiate as isotropic point sources at their centers. I find $\langle \cos\theta \rangle = 0.018$ if the back of the dish is assumed to be a specular reflector and $\langle \cos\theta \rangle = 0.022$ if it is assumed to scatter according to Lambert's law. These results satisfactorily explain the anomalous acceleration if most of the dissipated electrical power is radiated from the back of the spacecraft.

This argument may also be applied to the a_P measured [1] for Ulysses. Its design [6] resembles that of Pioneer, and is generic to RTG-powered outer solar system missions. There is no general reason why the Pioneer and Ulysses a_P should be approximately equal [the value $a_P = (12 \pm 3) \times 10^{-8}$ cm/s^2 for Ulysses is uncertain enough that the equality need only be to a factor of 2], but they will be similar for spacecraft of similar geometric design and power to mass ratio.

Anderson *et al.* [1] point out that the a_P they measure for Pioneer are constant to within 2×10^{-8} cm/s^2, about 24% of the mean a_P, over the range 40–60 AU (about 9 years). The accuracy of their quoted values for a_P [$(8.09 \pm 0.20) \times 10^{-8}$ cm/s^2 for Pioneer 10 and $(8.56 \pm 0.15) \times 10^{-8}$ cm/s^2 for Pioneer 11] suggests a typographical error, and that constancy may actually be known to within 2×10^{-9} cm/s^2, about 2.4%. The total thermal power decayed by about 7% over this period, but the decreasing electrical efficiency implies that the rejected waste heat declined by about 6%, a number weakly dependent on the assumed initial efficiency. This is marginally inconsistent (2.5σ) with the more stringent estimate of constancy of the acceleration (effects such as a temperature dependence of $\langle \cos\theta \rangle$ resulting from frequency-dependent radiative properties may perhaps remove any discrepancy), but is completely consistent with the 24% bound on constancy of a_P actually quoted [1].

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