PHYSICAL REVIEW D VOLUME 47, NUMBER 8 15 APRIL 1993

COMMENTS

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Perturbative forces in the proposed satellite energy exchange experiment

Paul T. Keyser
Phillips Laboratory (U.S. Air Force Systems Command), Hanscom U.S. Air Force Base, Massachusetts 01731-5000

(Received 2 September 1992)

Four possibly large sources of error in the promising proposal of Sanders and Deeds are noted. Outgassing, solar heating, magnetic force, and path-length changes will all be larger than as modeled in the proposal, and are the dominant error sources. They must be reduced if the experiment is to succeed.

PACS number(s): 04.80.+z, 04.90.+e, 06.20.Jr

Numerous proposed space tests of Newtonian gravitation exist; by far the best of these is the recent proposal by Sanders and Deeds [1]. But there are a few neglected or insufficiently adverted error sources which will significantly degrade the expected resolution $\Delta G/G$ and indeed all their tests.

First, outgassing from the shepherd and particle (avoidable only in principle) or from localized virtual leaks in the enclosure (hard to avoid) would generate gas jets [2]. Typical rates for apparatus-construction materials are sufficiently large that they amount to effective vapor pressures of 10^{-9} to 10^{-6} torr, far above the hard vacuum of space. Outgassing rates are high enough, even for carefully cleaned Al ($\approx 10^{-10}$ torr liter s cm^2) [3] and baked or electropolished stainless steel (SS) ($\approx 10^{-13}$ torr liter/s cm^2) [4] to produce significant gas evolution over the 14-m^2 surface of the enclosure during long operation.

Second, the effects of solar heating, though vastly minimized by using a continuous-sunlight orbit, would be larger than the stated 1 μm [5]. Taking their time-varying $\Delta T(\max)=5$ K (at the insulation surface) and using a more realistic linear $\alpha \approx 10^{-5}$ m/m K (larger by an order of magnitude), the length change is 50 μm twice per orbit. Although this applies to the outer insulating layer, since these layers are attached to the enclosure, their thermal expansion and contraction will shift the center of mass (c.m.) of the enclosure. This could derate their position accuracy by setting up unwanted vibrations in the enclosure-mounted tracking system, the fundamental of which would be at half the orbital frequency. Other proposed satellite experiments list this error as possibly the limiting noise for times of one day or longer [6] [each energy exchange encounter in satellite energy exchange (SEE) takes ≈ 1 d].

Third, magnetic forces may be much larger than modeled [7]. The polar magnetic field near the Earth is about 60 μT$(R_0/R)^3$, and about half that near the equatorial plane [8] (where $R=1.25R_0$ for the SEE proposal). The force due to induced magnetization on an object in a gradient is (with V the volume):

$$F_B=\mathbf{m}\cdot\partial_z\mathbf{B}=(\chi VN/\mu_0)(\partial_z B)\ . \tag{1}$$

Sanders and Deeds give a gradient of 1.2×10^{-11} T/m and a χ of 10^{-5} [9]. Two points serve to increase F_B above the values modeled by Sanders and Deeds (9×10^{-17} N on the shepherd and 2×10^{-20} N on the particle). The χ should be $\approx 2\times10^{-4}$ for typical dense materials used in apparatus construction [10], and the local gradient in the enclosure due to induction on the SS compensation rings may be as large as 6×10^{-7} T/m (with a typical approximate χ of 2×10^{-2} for SS and at a distance of ≈ 1 m). Thus the F_B on the shepherd might be about 10^{-10} N, comparable to the gravitational force $F_G=3.3\times10^{-11}$ between it and the particle at a 10-m separation [11], while the magnetic force on the particle at closest approach (3 m) might be about 5×10^{-15} N, or about 10^{-5} of the F_G at closest approach (ten times smaller if the particle is made of Al).

Fourth, various sources of position error may significantly derate the performance of the interferometer ($\Delta x \approx 0.03$ μm) [12]. Thermal-induced vibrations of the tracking system I have noted above; in addition are errors introduced by rotation of the corner-cube retroreflector on the particle [13]. The topical center of a corner cube is located D/n behind the front surface, where D is the depth from corner point to surface and n is the refractive index, and rotations (Θ) about this point shorten the optical path by $\Delta L=(D/4n)(n^2-1)\Theta^4$ (for $\Theta\approx150$ mrad and $D\approx1$ cm, the effect is ≈ 1 μm). A medium-free (i.e., $n=1$) corner cube is very hard to make precisely cubic, so the effect is essentially unavoidable. If the open-octant corner-cube design is used [14], the c.m. will be behind the corner point by some small distance z, so that rotations of the particle will introduce spurious increases in the path length, $\Delta L' = z(1-\cos\Theta)$ (for $z=2$ mm, the effect is ≈ 1 μm at $\Theta \approx 32$ mrad). This places stringent requirements on the orientation of the shepherd and particle.

Given that the other error sources will be no larger than claimed in the proposal, these four (and possibly density variations in the shepherd and particle, since the worst case should be $\pm 1\times 10^{-4}$, ten times larger [15]) will be the limiting terms. All seem solvable, though providing nontrivial experimental difficulties. These remarks are offered in the spirit of improving a good proposal before launch.

I am indebted to M.P. McHugh and R. D. Cicerone for helpful discussions.

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