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COMMENTS ON SEE:
COMPARATIVE ADVANTAGES AND EXPERIMENTAL CONSEQUENCES

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COMPARATIVE ADVANTAGES OF SEE

The Satellite Energy Exchange experiment mearsures the periodic, near-miss encounters between a *sheppard* satellite and and a small test body (satellite) in approximately the same orbit about a primary. Several important experimental requirements have been chosen to enhance capabilities: (a) The satellite be flown in a sun-synchronous orbit at an altitude of about 1350 Km, (b) *Passive* temperature system stabilized by spacecraft axial rotation with sunshade baffles at the end of the spacecraft, (c) Test bodies with different material composition be available for experiments, (d) The containment spacecraft *fly* about the sheppard mass in a zero-g environment whereas the test bodies, experience average zero-g environment over an orbital period, (e) Primary attitude and station-keeping uses magnetic field alignment plus micro-Newton thrusters such as Field Emmission Electric Propulsion, and (f) Very low power (nW) laser tracking systems minimize impulse delivered to test bodies.

With the above conditions, SEE has the capabilites: (1) Long duration (several years lifetime) flight experiment (2) Long-term, active (with historical time record), self-calibration of satelite mass distribution (capsule geodesy) over lifetime of the spacecraft. (3) Novel passive thermal stabilization systems designed to attain cryogenic temperatures around $78K$. (4) Novel spacecraft stabilization systems. (5) Ability to measure G to 1 part in 10^{6-7} depending on ultimate duration of experiment. (6) Ability to place limits on both temporal and spacial variations on G. (7) Ability to set experimental limits on the Post Newtonian parameters (PPN) α_2 and ζ_2. (8) Ability to measure (or place limits on) the non Einsteinian eccentricuty of the Earth-Sun system (and the parameter α_1) for long duration flight. (9) Ability to measure $\Delta\dot{G}/G$ to 1 part in 10^{12-13}.

The MiniSTEP, competes in a limited way with Project SEE. It is designed to improve the measurement of the equivalence principle by seven orders of magnitude using active, low temperature (1.8 K) cooling for SQUID based, differential superconducting circuits. The experiment consists of a small cylinder concentrically located within a larger cylinder at its null gravitational point. The satellite is operated in zero-g mode using four differential accelerometers consisting to two test bodies of different material composition. The SQUIDS are needed to measure test body motion to precisions of 10^{-18} over a four orbit period. The entire satellite moves in a very precise zero-g mode since the accelerometers are rigidly attached to the satellite. This limits the experiment to an aproximately six month due to limitations on helium storage used in cryogenic cooling and thrust control to maintain the zero-g operation .

PARAMETRIC ANALYSIS OF EXPERIMENTAL DATA

The extraction of experimental liimits on the PPN parameters involves the measurement of certain (postulated) effects that can occur in the satellite, test bodies, earth, moon, sun system as either measured on board the SEE satellite using laser tracking [sheppard-test body encounters] or using satellite laser-ranging experiments from Earth-based lasers to the SEE capsule [resonant earth-satellite-moon (or sun) configurations]. These experiments then give raw data that is related to various combinations of the PPN parameters. No *a priori* values of PPN parameters (with the exception of Whitehead term) will be used that might predetermine the best statistical fit of the data. These relationships are described below.

GRAVITATIONAL CONSTANT

For more than a decade, the poignant comments of the scientific correspondent and reviewer, John Maddox, Nature Magazine [**310**, 723, 30 Aug 1984] on the "Continuing doubt on gravitation" expresses even today the frustration in the usual torsional methods used to measure G. Even at the time of Maddox' editorial review, the most accurate measurement of G (and it's standard deviations) due to Luther and Towler (1982) fell entirely within the internationally accepted CODATA value of the time. There was at least some hope that more accurate experiments would steadily improve the statistical significance of future CODATA values . Recent experiments seem to have improved statistical and systematic error analysis, but these measurements differ amongst themselves by more than any of the standard deviations claimed. At least one of the mean values for G, with exceptionally good statistics due to the long, minutely detailed, and systematic ten-year experiment by the German Bureau of Standards, differs very radically from the most recent CODATA value for G. Arguably the combined value GM of about 1 part in 10^7 at the time of Maddox's comments has *improved* steadily by at least two orders of magnitude over the last decade [See the article by K. Nordtvedt on the continual improvment of data from lunar-laser ranging, "From Newton's moon to Einstein's moon," Physics Today, **49**, 26 (1996).]. The value of G has stubbornly remained at the 1 part in 10^4 range. However it is the coupling constant G (and its subsequent renormalization in a unified theory) that *contains* many of the clues that will answer some of the more fundamental questions about unification of gravity with the other forces. That is, it must contain some residual *backbone* that shows up in a partial (perhaps strong-gravity) and eventually in an ultimate unification scheme.

The locally measured gravitational constant depends (in a generic theory) on the influence of external sources through its potential U_{ext} and its local motion moving with the velocity $\mathbf{w_1}$ with respect to a preferred frame . In the PPN framework this becomes

$$\begin{aligned} G_L &= 1 - [4\beta - \gamma - 3 - \zeta_2]U_{ext} - \frac{1}{2}[\alpha_1 - \alpha_3 - \alpha_3\left(1 - \frac{I}{m_1 r_p^2}\right)]\mathbf{w_1^2} \\ &\quad + \frac{1}{2}\alpha_2\left(1 - \frac{I}{m_1 r_p^2}\right)(\mathbf{w_1} \cdot \mathbf{e}\ )^2 \end{aligned}$$

where the second term represents preferred location effects , and the last two are preferred frame effects.

NORDTVEDT EFFECT

For breakdown of the weak equivalence principle (WEP) there will be a difference between inertial and passive mass given by

$$\frac{m_p}{m_I} = 1 - [4\beta - \gamma - 3 - \alpha_1 + \frac{2}{3}\alpha_2 - \frac{2}{3}\zeta_1 - \frac{1}{3}\zeta_2]\frac{\Omega}{m_I}$$

which will then lead to a polarization of the orbits of Earth satellites due to the additional perturbations caused by the WEP breakdown.

PERIGEE SHIFTS

The perigee shift in excess of the predicted general relativistic value of a satellite orbiting the earth is

$$\dot{\varpi} = \frac{6\pi m}{p}[\frac{1}{3}(2\gamma + 2 - \beta) + \frac{1}{6}(2\alpha_1 - \alpha_2 + \alpha_3 + \zeta_2)\frac{\mu}{m} + J_2\frac{R^2}{2mp}]$$

where μ is the reduced mass of the earth-satellite system, p is the semi-latus rectum, m is is the total mass of the earth plus satellite, and R and J_2 are the radius and the quadrupole moment of the Earth respectfully. There will be additional accelerations due to preferred frame effects which will add to the above.

NON CONSERVATIVE THEORIES

Fitting experimental data to the PPN parameters is in general complicated by including the, so-called, non conservative theories. However many of these theories can be shown to have global conservation laws. Therefore the presumption of non conservation is somewhat misleading. Nevertheless, the results from two examples are worth citing:

MODIFIED BRANS-DICKIE THEORY

[See L.L.Smalley, Phys Rev D **12** ,376 (1975)] Global conservation laws are satisfied without any constraints on the PPN parameter. The only PPN parameter which differs from the usual Brans-Dicke values is

$$\zeta_2 = \frac{8\sigma}{(2\omega + 3)^3}$$

where ω is the Brans-Dicke parameter and σ is the strength parameter of the non zero divergence. The Nordtvedt parameter now becomes (assuming the usual form for the PPN parameters for a Brans-Dicke theory except for above)

$$\eta = \frac{1}{\omega + 2} - \frac{1}{3}\zeta_2$$

which says that the Nordtvedt effect is not just a test for the Brans-Dicke parameter but a test of ω and ζ_2 jointly.

MODIFIED MALIN THEORY

The Malin theory assumes that the gravitational fields take the form

$$R_{\mu\nu} = 4\pi G T_{\mu\nu}$$

This theory can be modified in such a way that the theory differs from general relativity only in the parameter

$$\zeta_4 = -\frac{1}{3}(3 + 2\tau)$$

but has global conservation laws. The parameter τ is a measure of the deviation of Euler's equation from its general relativistic form. [See L.L. Smalley & J. Prestage, Il Nuovo Cimento, $35B$, 224 (1976) for details.] Thus the Nordtvedt parameter is only a measure of the parameter τ.

The lesson to be learn from this section is that the analyzing data, it is necesary to leave the test theory in its most generic form with out assumptions on the existence or magnitude of certain parameters from other experiments that are not sufficiently constrained. This is strongly emphasized when it is discovered that the above theory can be further modified in such a way to add the parameter ζ_3 which represents a further modification of the local energy-momentum but which at the same time retains global conservation laws. That is to say, the Nordtvedt parameter, and other collective parameters should be analyzed statistically for a best fit to the data; otherwise it is possible to pronounce one or another theory non viable without complete justification. These considerations will be expanded in the Conclusions.

CONCLUSIONS AND DISCUSSIONS

There are a few issues that should be discussed concerning the analysis of data for gravitational experiments, and in particular for the SEE project. A primary example involves orbital dynamics and the analysis of the various contribution to the orbital motion (of the SEE capsule) in terms of the PPN parameters. Although these parameters are the eventual output of the data analysis, in some sense they effect the outcome of the experiment they are what's reported. There is a certain amount of faith in the reported data analyses of gravitational experiments. However the issues can become very confused if what is reputed to be superior statistics by independent teams do not lie within statistically significant errors of the different data sets. Such is the present status of the Earth-based measurements of the gravitational constant. The same comment must also apply to those who analyze satellite or lunar laser ranging data for experimental comparison of the generic structure of the gravitational field to the predictions of general relativity. It is important in these orbital dynamic analyses, which utilize the input of a generic (PPN) metric, that these calculations do not bias the data in a way that will not improve scientific understanding.

NORMALIZE GRAVITATIONAL CONSTANT

A typical analysis of gravitational data [Described, for example, by Will, *Experimental Gravitation*, (Freeman, San Francisco, 1985)] assumes a preferred frame for analysis. However this work does not included the contribution of the "non conserved" PPN (zeta) parameters to the Nordtvedt parameter. There **are** some indications that these parameters are very small; however this can be confusing if it can be shown that global conservation laws are not violated [See Smalley, Phys. Letts A , **57A**, 300 (1976)]. A complete analysis of the data is a necessity. It is true that small limits may be put on certain parameters by "other experiments", but it is better to error on the side of caution in analyzing the data. An extraordinary example of confusion is the large disagreement between average experimental values of the gravitational constant which significantly differ by several standard deviations over the past decade. The point to be emphasized here is that it is possible that something is small because something else is left out of the analysis. This seemingly contradictory statement is important to understand. The gist of this idea is apparent when it is realized that it is the combination of parameters that should have been there that gives the correct small results. In this case, some of the parameters may in fact be significant. For example in GR the Nordtvedt parameter vanishes. If the Nordtvedt parameter vanishes for some other theory, it does not imply that the PPN parameters α and ζ are individually zero or that the Brans-Dicke parameter ω is so large that its effect is negligible. These things should be taken in the context of many tests which provide enough independent data for verification. The possibility of systematic errors in analysis from one experimental group to another may make the analysis even more difficult to interpret especially if the other experiments have been analyzed without the verification of GR in mind. That is, an experiment designed to measure only G may not included all aspects of the gravitational field in the analysis.

MEAN ANOMALY

This is basically an experimental problem because the analysis of the data indicates that the mean anomaly effect for a satellite varies sinusoidally as measured from the time of passage of the Earth at perihelion [Thus depending on what time of the year you take data for the satellite, you must take into account this perihelion advance to get the actual value of perigee and therefore, the real advance of the perigee of the satellite. However this value depends on a combination of PPN parameters [β and γ] which may not be complete in the sense discussed above.

There is another aspect to the mean anomaly which is much more perplexing. Literally what is presented is a "time-dependent" Newtonian Lagrangian which is analyzed for perturbations of the perihelion as a function of time over a time period measured in years. Fortunately the effect of this deviation of the mean anomaly is asymetric in time and probably can be extracted from the periodic part. However, the problem with this analysis is again based upon the observation that a Lagrangian theory that is a function of time will generally not have conserved energy-momentum. Thus the existence of the non conservative PPN parameters may make interpretation of the data specious *if they are not specifically included in the theoretical analysis.* It is obvious that these terms must be there as evident from the discussion of the normalization of G due to self energies which also includes the Nordtvedt effect. Thus what is meant here is that the analysis which invokes only the γ and β parameters is probably not sufficient. [As an aside, the full PPN approximation with the generic metric has most likely been done in the analysis of $G-dot$ before, however it is not known a priori whether the effects are so small that they don't contribute at the level of 0.1 pico(1/yr), *i.e.*, $\Delta\dot{G}/G$.]