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NEW TESTS WITH OLD DATA

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The discussion of new tests of relativity must begin with a definition of the word "new." I propose to include, under that rubric, not only tests that have never been attempted before or never produced a useful result, but also those that may be repeated with significantly improved results. Thus, this paper will discuss the classical tests insofar as they have been recently refined and will give the results obtained by my colleagues and me at the Center for Astrophysics (CFA). I will also go on to describe a new test of relativity via the detection of the de Sitter precession of the Moon's orbit. These tests, when considered in the parameterized post-Newtonian (PPN) framework, have all involved determining combinations of "β" and "γ."

A further topic of consideration is that of "old" data. In attempting to improve a test of relativity, particularly when the effect to be discerned is a secular one, such as the relativistic perihelion advance of Mercury, it is important to maintain the original set of data, so that the experiment need not start all over. Even in an era of rapid advances in technology, a data set composed just of the observations made by the latest space probe (for example) will be at a disadvantage compared to one that includes earlier measurements. Still, for old data to be useful in performing new tests, they must be preserved in an accessible form, *i.e.*, not just published in scientific journals and the like, but retained along with instrument calibrations and measurement uncertainties on machine-readable media with accompanying format specifications and field descriptions. Empirically, the best way of ensuring the continued usability of old data is to continue using them.

Let us turn first to the deflection of light by massive bodies, such as the Sun. The PPN formula for the deflection (to first order in the mass of the deflecting body) has a coefficient of (1 + "γ"), where "γ" takes on a value of 0.0 in the Newtonian case and 1.0 in general relativity, and the test is to observe the deflection and thereby determine "γ." The classical experiment, of course, was to observe stars near the Sun during a solar eclipse. The results have been consistent with a value of one, but the difficulties of observing stellar positions near the Sun, even during an eclipse, have prevented a very decisive test using optical wavelengths. Still, position measurements at radio frequencies using very-long-baseline interferometry (VLBI) can greatly improve on the optical results, and preliminary analysis of such an experiment by the VLBI group at CFA indicates that a standard error of 0.002 for "γ" should be attainable.

The perihelion advance of Mercury provides another test of gravitational theories. In fact, it was the basis for the original "new" test with old data, since Einstein was able to explain the previously unexplained excess in the perihelion rate for Mercury. However, that excess represents a small residual after removing the purely Newtonian perturbations due to the other planets. The PPN coefficient of the anomalous perihelion advance is (2 + 2 "γ" − "β"), and if we assume that "γ" is known from other tests, the perihelion rate can be treated as a test of "β." Clearly, measuring the rate of advance requires observing Mercury for a long time to track the perihelion. Indeed, in order to distinguish the relativistic effect from the possibly negligible one of the solar quadrupole moment (a purely Newtonian advance of the perihelion), it is necessary to (1) track two different planets to take advantage of the different radial dependences of the two effects, or (2) determine the quadrupole

moment from other methods. This kind of test will obviously always be "renewable" in the sense that an improved external constraint on the solar quadrupole moment will immediately reduce the uncertainty in the excess (post-Newtonian) rate of perihelion advance. The results for this test are, again, consistent with general relativity, but the uncertainty in the estimate of "β" depends strongly on whether the solar quadrupole moment is also estimated or is assumed to have a value consistent with the Sun's surface rotation rate and standard models of the solar interior. From a combination of data, including ground-based radar delay and Doppler observations of Mercury and ranging to the Viking Landers on Mars, we found the "β" standard error to be 0.05 when the quadrupole moment is also estimated, and 0.02 when the latter is held fixed at the assumed value.

A third test consists of measuring the Shapiro time-delay effect in the propagation of signals passing near a massive body. The PPN formula for the delay has a geometric part and, like the first-order light deflection, a coefficient of $(1 + "\gamma")$. The simplest method is to observe the round-trip time of signals "bounced" off objects near superior conjunction with the Sun, and the most sensitive time-delay test to date followed this pattern except that the "bounces" consisted of signal returns by active transponders on the Mariner 9 and Viking spacecraft. Our combined data set covered four separate conjunctions of Mars, though with varying levels of accuracy. The resulting estimate of "γ," again, is consistent with general relativity, and the standard error of the estimate is 0.002.

A brief examination of the second and third tests reveals yet another kind of experiment (one that we have done at CFA), namely, to test "everything" at once. In this context, "everything" refers to our comprehensive model of the solar system, including not only the PPN parameters, but also the masses and orbital elements of all the significant bodies; the parameters describing the rotation of the Earth, Moon, and planets; and others too numerous to mention. The key to the method is to observe everything available (and relevant) and combine the data in a simultaneous parameter estimation procedure, taking into account the relative errors associated with each type of observation. The result is a solar-system model with "something for everyone" in it, and a means of extracting maximum information from the data. Such a global test is perpetually "renewable," and there are other advantages, as will be seen presently.

Another test of relativistic gravitation, though not of relativity *per se*, lies in the search for time variations in the gravitational coupling constant, a concept that gained wide attention with Dirac's "large number hypothesis." Indeed, the hypothesized variation can have two interpretations: either a variation of the coupling constant G, or a variation of the dynamical time scale as measured in atomic units. Such a hypothesis can be tested quite easily (and has been) in the context of our solar-system model. We have added the hypothesis parametrically to the model in each of its two forms, and thus, our "grand" solutions can be used to test either form by means of estimating the corresponding coefficient. To date, the results have been negative, that is, no variation of G can be discerned, and our estimate of the standard error in either parameter amounts to 2×10^{-11} parts per year. This represents a large factor times the formal standard deviation of the parameter estimate, partly because of limitations in our model for want of knowledge of asteroid masses. Thus, this test is especially "renewable" to the extent that asteroid masses may be determined.

A new test of relativity (and one that makes use of old data) consists of measuring the geodesic precession of the Earth-Moon system and comparing the rate

with that predicted by de Sitter in 1916. As he pointed out, a satellite orbit in a system freely falling in the Sun's gravitational field undergoes a relativistic precession proportional to the solar potential. The PPN expression for the rate has a coefficient of (1 + 2 "γ"), and a value (when "γ" = 1) of about two seconds of arc per century for the Moon. The effect was simply too small to detect until quite recently, when the increasing sensitivity and growing time coverage of the lunar laser ranging observations, in combination with the other data types used in our solar-system analysis, brought it within reach. Since this effect is simply a consequence of general relativity, and since there is no single term or small group of terms in the theory that leads to the effect, we found it necessary to add an *ad hoc* precession to our model with an adjustable coefficient to account for a possible departure from the predicted rate. We then estimated that coefficient and found no such departure. We obtained a standard error for the estimate of 0.04 arcsec per century, or 2% of de Sitter's rate.

In sum, as these tests illustrate, the ideal test of relativity makes use of the broadest possible collection of data.

DISCUSSION

HELLINGS: It appears that your uncertainty in $\dot{G}/G$ is still about twice ours. Are you planning to publish the geodetic precession results soon?

CHANDLER: Yes, soon.

TAYLOR: Could you expand on the analysis discrepancy in the $\dot{G}$ limit?

CHANDLER: Since the underlying formal standard deviation is about the same in both analyses (and much smaller than either quoted uncertainty), the discrepancy is due to differences in the choice and interpretation of numerical experiments with the data, and to differences in the details of the respective models. We (SAO and JPL) are slowly working on the comparison between the models.