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# POST-NEWTONIAN EFFECTS ON SATELLITE ORBITS NEAR JUPITER AND SATURN*

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## ABSTRACT

Two approaches to measuring the parametrized post-Newtonian parameters $\beta$ and $\gamma$ using the gravitational fields of the gas giant planets are considered. First, we note that the post-Newtonian pericenter precession rates of the innermost moons of these planets are the largest in the solar system, being many times larger than that of Mercury. We review the observations of these objects to date, and suggest techniques that could well render this effect measurable. Second, we consider the post-Newtonian effects on the orbit of a spacecraft. We argue that with currently available techniques, the Doppler tracking of a spacecraft could determine the post-Newtonian effect on the orbit to the few percent level.

*Subject headings:* celestial mechanics — planets: general — relativity

## I. NATURAL SATELLITES: ORBITAL PERICENTER PRECESSION

The perihelion precession of Mercury was the first known natural phenomenon that could not be explained in terms of Newtonian gravity but could be accounted for by general relativity theory (Einstein 1961). Well before Einstein created the theory of general relativity, astronomers realized that there was an excess 43″ per century precession in the perihelion of Mercury's orbit. The measurement of this precession, and its theoretical significance, have continued to be of great scientific interest (Dicke and Goldenberg 1967; Dicke 1974; Hill and Stebbins 1975). Observations are also being made to determine the post-Newtonian perihelion precessions of Venus, the Earth, and certain asteroids (Reasenberg and Shapiro 1977). These observations are of extreme importance to experimental gravitation since of the three basic solar system tests of general relativity (perihelion precession, light bending, time delay) only the perihelion precession effect involves the parametrized post-Newtonian (PPN) parameter $\beta$.

The post-Newtonian precession of the orbit of Mercury is not, however, the largest in the solar system. The post-Newtonian (PN) contribution to the pericenter precession rate of an orbit is given by the formula:

$$\omega_{\rm PN} = \frac{G^{3/2}M^{3/2}}{c^2 a^{5/2}(1-e^2)}(2+2\gamma-\beta)\,, \qquad (1)$$

where $M$ is the mass of the central body, $a$ is the semimajor axis of the orbit, $e$ is the eccentricity of the orbit, $G$ is the gravitational constant, and $c$ is the speed of light. The PPN parameters $\beta$ and $\gamma$ have values $\beta = 1$, $\gamma = 1$ in general relativity, and we have ignored "preferred-frame" effects in the pericenter shift (Will 1974). The theoretical PPN precession rates for the innermost satellites of Jupiter, Saturn, and Uranus are all larger than that of Mercury (see Table 1). Indeed, the post-Newtonian precession of Jupiter V is about 50 times larger than that of Mercury, being more than half a degree per century. Mercury retains the distinction of having the largest post-Newtonian precession per orbit. The satellites of the gas giant planets, however, have such short orbital periods (e.g., 12 hours for Jupiter V, as compared to 88 days for Mercury) that the total precession increases rapidly with time.

Although the post-Newtonian effects are very large for these bodies, there are serious problems facing anyone who would attempt to measure and separate out the effects of post-Newtonian gravity. These difficulties are of two distinct types. The first relates to the problem of determining the orbital elements of these satellites to the desired degree of accuracy. The second type of difficulty arises because the total precession of the orbits of these satellites is governed mostly by strictly Newtonian effects. To isolate the post-Newtonian component of the precession, all larger contributions must be modeled and subtracted out.

There are essentially three observational problems which make it difficult to determine the orbital elements accurately from Earth-based observations. The first is that the complete orbits of these objects subtend a very small angle as seen from the Earth. While the orbital path of Mercury traces out an arc some 40° wide, as seen from Earth, the entire orbit of

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TABLE 1

LARGE POST-NEWTONIAN PRECESSIONS IN THE SOLAR SYSTEM

| Satellite | $\omega_{PN}$ (arcsec yr$^{-1}$) | $\omega_{quad}$ (arcsec yr$^{-1}$) | Eccentricity of Orbit | Visual Magnitude of Satellite* | Visual Magnitude of Central Body* | Quadrupole Moment of Central Body |
|---|---|---|---|---|---|---|
| Mercury......... | 0.43 | 0.015 | 0.2056† | −0.36 | −27 | $(13 \pm 8) \times 10^{-6}$‡ |
| Jupiter V......... | 22 | $3.3 \times 10^6$ | < 0.0025§ | +13.0 | −2.55 | $(14733 \pm 4) \times 10^{-6}$‖ |
| Jupiter I.......... | 2.7 | $1.7 \times 10^5$ | 0.0000† | +4.80 | −2.55 | $(14733 \pm 4) \times 10^{-6}$ |
| Jupiter II......... | 0.84 | $3.4 \times 10^4$ | 0.0003† | +5.17 | −2.55 | $(14733 \pm 4) \times 10^{-6}$ |
| Saturn I.......... | 3.4 | $1.3 \times 10^6$ | 0.0201† | +12.1 | +0.67 | $(1667 \pm 2) \times 10^{-5}$# |
| Saturn II......... | 1.8 | $5.5 \times 10^5$ | 0.0044† | +11.8 | +0.67 | $(1667 \pm 2) \times 10^{-5}$ |
| Saturn III........ | 1.1 | $2.6 \times 10^5$ | 0.0000† | +10.3 | +0.67 | $(1667 \pm 2) \times 10^{-5}$ |
| Saturn IV........ | 0.58 | $1.1 \times 10^5$ | 0.0022† | +10.4 | +0.67 | $(1667 \pm 2) \times 10^{-5}$ |
| Uranus V........ | 0.51 | $9.8 \times 10^4$ | < 0.01** | +16.5 | +5.52 | ~0.005** |

* Harris 1961.
† Alfvén and Arrhenius 1976.
‡ Hill and Stebbins 1975.
§ Sudbury 1969.
‖ Null 1976.
\# Brouwer and Clemence 1961.
** Whitaker and Greenberg 1973.

Jupiter V lies within a space of 2′. The situation is of course even worse for Saturn and Uranus. The second observational problem is the closeness of these objects to the much brighter planets which they orbit. For example, at greatest elongation Jupiter V is only about 1.5 Jupiter radii from the limb of Jupiter, yet the planet is about 15.5 mag brighter than the satellite. The glare from the much brighter planets reduces the amount of the satellite's orbit which is observable, and at the same time reduces the accuracy of the positional measurements which one can make. The third problem which makes it difficult to accurately determine the precession rate of these orbits is their rather small eccentricities. It is difficult in practice to determine the pericenter of a nearly circular orbit.

The Newtonian contributions to the precessions of the orbits of these satellites are of two types. The first type is the result of the gravitational interaction of the satellite with other objects in the solar system. About 99% of the precession of Mercury's orbit is due to this type of effect. The problem is worse for the satellites of Jupiter and Saturn. The Galilean satellites of Jupiter interact with each other so strongly that $n$-body techniques rather than perturbation theory must be used to understand their orbits. The innermost satellites of Saturn also interact strongly with one another, but the situation is much better than in the Jupiter system. The second type of Newtonian precession occurs because the gravitational potentials of the central bodies are not spherical. The largest contribution to this type of precession comes from the quadrupole moment of the central body, $J_2$. The precession of the orbit caused by this effect is given by the formula:

$$\omega_{\text{quad}} = \frac{3G^{1/2}M^{1/2}R^2J_2}{2a^{7/2}(1-e^2)^2}, \tag{2}$$

where $R$ is the radius of the central body. The magnitude of this effect for the satellites of interest is given in Table 1. We see that this effect is many orders of magnitude larger than the post-Newtonian effect because of the large oblateness of Jupiter and Saturn. To perform a successful observation of the post-Newtonian effect, therefore, the multipole moments of these planets must be determined to very high precision.

What are the prospects for overcoming these difficulties? For Jupiter V and Saturn I (the objects having the largest post-Newtonian precession rates) there is a fairly large historical data base from which to draw orbital data. Pierce (1974, 1975) has made a complete literature search on the satellite systems of Jupiter and Saturn through 1972. He found 3837 micrometer measurements and 133 photographs of Jupiter V, and 1103 micrometer measurements and six photographs of Saturn I. Even with this historical data base, the orbital elements of these satellites have not been determined to a very high degree of accuracy.

The most recent, and most rigorous, determination of the orbit of Jupiter V is that of Sudbury (1969). He gives a good description of the difficulties encountered in determining the orbit, particularly concerning systematic errors in the historical micrometer measurements of satellite position. He concludes that the older data yield an orbit inconsistent with his new photographic observations. Most significantly for our purposes, his range of values for the eccentricity of the orbit includes zero eccentricity, and he thus finds the precession of the pericenter to be essentially indeterminate.

The situation for Saturn I (Mimas) is far better. The eccentricity of the orbit of Mimas is at least an order of magnitude greater than that of Jupiter V, thus making it easier to determine the position and precession rate of the pericenter of its orbit. Furthermore, it is easier to observe Mimas since it is brighter than Jupiter V, while Saturn is less bright than

Jupiter. These effects also tend to make the historical data more reliable for Mimas than for Jupiter V. The historical observations of the inner satellites of Saturn were compiled and reduced up to 1928 by G. Struve (1930). Kozai (1957), analyzing those observations, was able to determine the motion of the pericenter of Mimas to an accuracy of $\pm 130''$ per year, which is only about 40 times larger than the post-Newtonian precession. It seems likely that the use of modern techniques (photography rather than micrometer measurements, satellite positions referred to background stars rather than to the limb of the planet, etc.), and a determined long range observing program, could substantially improve these data, and bring us close to the level of the post-Newtonian gravity effects. In view of the 22 hour period of Mimas, it might also be worthwhile to coordinate observations between two observatories 11 or 12 hours apart in longitude, to allow observation of both regions of greatest elongation on the same orbit. It is possible that such a program could bring the accuracy of observations to within a zero-order determination of the post-Newtonian precession of Mimas; however, to go further and actually determine the post-Newtonian precession to several digits, a way must be found to deal with the scattered light of the primary planet.

The main hope for overcoming the problem of the much brighter central planet hindering observations seems to lie in the techniques developed (and being developed) for the observation of another post-Newtonian effect: the noneclipse determination of the deflection of starlight by the Sun. This observation has been discussed by Hill *et al.* (1977) and by Handler and Matzner (1978). There, as here, the main problem is to reduce the scattered light from the nearby bright Sun or planet. The use of interferometric techniques, proposed by Hill and his collaborators, seems especially promising for Jupiter or Saturn where Mie scattering is the dominant noise source. Such techniques will not only allow one to measure the satellite positions more accurately, but should also make it possible to observe a greater portion of the orbit. It may, for example, be possible to observe up to twice as much of the orbit of Jupiter V as is now being used. The improvement in orbital accuracy because of this alone will be much more than a factor of 2, since observations made near greatest elongation, which are the easiest to make, are statistically the worst due to projection effects.

In order to separate out the precession caused by post-Newtonian gravity, the multipole moments of the central planets must be determined to very high accuracy. Perhaps the most promising method to solve this problem is the use of tracking data from spacecraft. The *Pioneer* missions to Jupiter have already given vastly improved values of the multipole moments of Jupiter (Null 1976), and future missions could give values to the needed accuracy. In the case of Saturn, which is visited by fewer spacecraft, the multipole moments can also be determined by finding the orbital elements of several of the natural satellites of the system. The moments can then be extracted, as the precession due to each multipole depends on a different power of $a$. The combination of observational and spacecraft data would yield sufficiently accurate values of the multipole moments of Saturn.

The large post-Newtonian precession rates of the orbits of the innermost satellites of Jupiter, Saturn, and Uranus are phenomena which were heretofore not fully appreciated. We hope that this paper will inspire observers to seek modern techniques which will isolate this interesting effect.

## II. SPACECRAFT MEASUREMENTS

We consider now the possibility of measuring the PPN parameters $\beta$ and $\gamma$ directly from the analysis of spacecraft tracking data. A good fundamental discussion of the methods and problems related to such measurements is given by Anderson (1974). In order to successfully measure the post-Newtonian effects on a spacecraft trajectory, we must overcome two basic difficulties. First, the effects of post-Newtonian gravity on the spacecraft must be large enough to be measured with Doppler tracking techniques. Second, any nongravitational accelerations must either be well modeled and subtracted out, or be much smaller than the post-Newtonian effects, or have a significantly different "time signature" on the orbit from that of the purely gravitational accelerations.

We consider first the question of whether the post-Newtonian contributions to the acceleration of a spacecraft are large enough to be measured by currently viable Doppler tracking techniques. The post-Newtonian contribution to the acceleration experienced by a spacecraft in orbit about a spherical central body (assuming a "fully conservative" theory of gravity, i.e., PPN parameters $\alpha_1 = \alpha_2 = \alpha_3 = \zeta_1 = \zeta_2 = \zeta_3 = \zeta_4 = 0$ in the notation of Will 1974) is given by:

$$a_{\mathrm{PN}} = \frac{GM\boldsymbol{r}}{c^2r^3}\left[\frac{2\beta GM}{r} + \gamma\left(\frac{2GM}{r} - v^2\right)\right] + (2\gamma + 2)\frac{GM\boldsymbol{v}\cdot\boldsymbol{r}}{c^2r^3}\boldsymbol{v}\,. \tag{3}$$

Note that a direct measurement of the post-Newtonian acceleration along a spacecraft's trajectory would in principle allow one to measure both $\beta$ and $\gamma$ simultaneously because of the velocity-dependent terms in equation (3). For the nearly parabolic orbits taken by most spacecraft which encounter the gas giant planets (with the notable exception of the Jupiter orbiter) the velocity-dependent terms will be of the same size as the gravitational potential terms. A detailed covariance analysis for orbits of this type by Anderson and Lau (1978) shows that the linear combination of PPN parameters $\beta - 2\gamma$ can be well determined by Doppler tracking while the other linear combination $2\beta + \gamma$ will have an error about 10 times larger. Also note that the post-Newtonian contributions to the acceleration have different angular and radial dependence from any of the purely Newtonian multipole moment terms. This fact will allow the simultaneous determination of all sufficiently large multipole moments, and the post-Newtonian contributions, from the analysis of a single orbit.

In order to estimate the accuracy with which the PPN parameters can be measured, we adopt the following (admittedly rough and simple-minded) scheme: the maximum acceleration caused by the $\beta$-contribution to post-Newtonian gravity with a *Pioneer 11* type orbit (i.e., the acceleration at $r = 10^5$ km near Jupiter) is

$$\partial a_\beta / \partial \beta = 3.5 \times 10^{-10}\ \mathrm{km\ s^{-2}}\,. \tag{4}$$

We compare this to an acceleration noise generated by the uncertainty in the Doppler tracking system:

$$a_{\mathrm{N}} = \frac{\delta(\Delta v)}{\tau} = \frac{c}{2\tau}\,\delta\left(\frac{\Delta\nu}{\nu}\right), \tag{5}$$

where $\tau$ is the integration time of the Doppler tracking system (chosen by us to be 60 s), $\delta(\Delta v)$ is the uncertainty in the spacecraft velocity, and $\delta(\Delta\nu/\nu)$ is the size of the rms Doppler frequency shift noise. Thus, we find

$$\delta\beta \approx \frac{a_{\mathrm{N}}}{\partial a_\beta/\partial\beta} \approx 7.14 \times 10^{12}\delta\left(\frac{\Delta\nu}{\nu}\right). \tag{6}$$

This simple-minded scheme overestimates the accuracy by neglecting the problem of separating out the many different contributions to the total acceleration. At the same time it underestimates somewhat since it does not take into account the fact that measurements are made all along the orbit, not just at one point. In practice it seems to give reasonable predicted accuracies. We applied this approach to estimate the error in the measurement of $J_2$ for the *Pioneer 11* orbit. We predicted a value which was 4 times smaller than the actual error given by the detailed data analysis of Null (1976). Further, we used this technique to predict the accuracy with which $\beta$ could be determined from the proposed solar probe orbit. Our estimate agrees with the predictions of Anderson and Lau (1978) for $\beta$, based on a complete covariance analysis. Thus we conclude that equation (6) gives a reasonable estimate of the probable measurement error.

The best Doppler tracking analysis accomplished to date is that reported by Null (1976) for the *Pioneer 10* and *11* encounters with Jupiter. The NASA–JPL Doppler tracking system at that time had a data rms noise level of $\delta(\Delta\nu/\nu) = 2.3 \times 10^{-12}$ for an integration time of 1 minute. It would appear that the post-Newtonian effects on the *Pioneer 10* and *11* spacecraft trajectories are within about an order of magnitude of the noise level of the analysis which was done in 1975–1976, since, by equation (6), we find $\delta\beta \approx 16$.

Since then, the Doppler tracking system has been improved significantly, mainly owing to the significant upgrading of the NASA–JPL Doppler tracking network in preparation for another relativistic gravity experiment: the detection of gravitational waves by Doppler tracking of distant interplanetary spacecraft (Estabrook and Wahlquist 1975; Thorne and Braginsky 1976; Wahlquist *et al.* 1977). The addition of dual-frequency tracking ("S-band" [2200 MHz] from Earth to spacecraft ["uplink"]; "S-band" and "X-band" [8600 MHz] from spacecraft to Earth ["downlink"]) and conversion to hydrogen maser clocks from the earlier rubidium clocks as master oscillators has decreased the noise level to $\delta(\Delta\nu/\nu) \approx 3 \times 10^{-14}$ for an integration time of 1 minute. This should clearly allow a determination of $\beta$ to about 20% by equation (6).

Further improvements in the Doppler tracking system (e.g., addition of X-band uplink, conversion to superconducting cavity stabilized oscillators or other improved clocks, addition of on-board spacecraft hydrogen maser clock) could push $\delta(\Delta\nu/\nu) \approx 10^{-15}$ or even $10^{-16}$ within the next decade. It seems likely that these improvements will allow the measurement of $\beta$ and $\gamma$ to at least an accuracy of $10^{-2}$, at which point the nongravitational accelerations ($\sim 10^{12}$ km s$^{-2}$) become significant. This accuracy is, for $\beta$, comparable to the best values determined from the perihelion precession of the inner planets ($\beta \approx 1.00 \pm 0.01$; Reasenberg and Shapiro 1977).

We will next consider the problem of nongravitational accelerations on the orbit of a spacecraft. From equation (4) it is clear that any nongravitational accelerations will have to be $\lesssim 10^{-12}$ km s$^{-2}$ to allow a 1% measurement of the PPN parameters. Let us review the current understanding of these sources of noise.

There are three main sources of nongravitational accelerations which can interfere with the measurement of the post-Newtonian gravitational acceleration. First, the acceleration due to radiation pressure from solar photons, which can be modeled using techniques developed by Georegevic (1971) and subtracted off. The residual solar wind and radiation pressure "noise" was found to be about $10^{-12}$ km s$^{-2}$ for the *Pioneer 10* and *11* spacecraft (Null 1976). Second, there is the acceleration caused by leakage from the attitude control jets of the spacecraft. This acceleration is also about $10^{-12}$ km s$^{-2}$ for the *Mariner-Pioneer* series of spacecraft. Third, and potentially the most serious, is the problem of electromagnetic forces on the spacecraft. Jupiter is known to possess a significant magnetic field. While there was no rigorous way to place bounds on the charges of the *Pioneer 10* and *11* spacecraft, the best estimates provide an upper limit of $10^{-7}$ Coulomb net spacecraft charge (Null 1976). This again leads one to an acceleration of about $10^{-12}$ km s$^{-2}$. For purposes of comparison, the maximum post-Newtonian acceleration experienced by a spacecraft on a *Pioneer 11* type orbit around Jupiter ($r_{\min} = 10^5$ km, $v = 50$ km s$^{-1}$) is about $4 \times 10^{-10}$ km s$^{-2}$.

Thus we conclude that the nongravitational acceleration "noise" is, for a *Mariner-Pioneer* vintage spacecraft, on the order of $10^{-2}$ times the peak post-Newtonian gravitational acceleration.

It is now clear why the gravitational fields of the gas giant planets are the best laboratories for measuring the effects of post-Newtonian gravity on spacecraft trajectories. A heliocentric spacecraft trajectory, in order to experience a post-Newtonian acceleration of the same order as *Pioneer 11*, would have to come within $10^7$ km of the Sun—about one-sixth the radius of Mercury's orbit. The nongravitational acceleration problems associated with such an orbit would be enormous because of the solar wind and radiation pressure. Clearly the gas giant planets provide a cooler and "quieter" (in terms of radiation pressure and solar wind) environment for such a measurement. The Earth, while much more accessible than the gas giant planets, does not possess as strong a gravitational field. The maximum post-Newtonian acceleration a geocentric spacecraft could experience is only about $10^{-11}$ km s$^{-2}$, which is getting fairly close to the nongravitational acceleration noise level (especially since radiation pressure and solar wind are 27 times greater at the Earth than at Jupiter). Geocentric orbital measurements may become more inviting as drag-free satellite systems are developed.

While it is easier to predict the success of the spacecraft measurements, we strongly feel that observations of the post-Newtonian effects on the natural satellites should be pursued, and the two approaches allowed to complement one another.

It is perhaps worthwhile to note that our current values for the PPN parameters $\beta$ and $\gamma$ come from the three classic *heliocentric* solar system experiments. While many groups have independently measured these effects, it is always the gravitational field of the Sun which is being measured. This is somewhat like a group of independent experimenters all using a single apparatus to measure fundamental constants. This viewpoint provides a reasonable justification, it seems to us, for expending some effort on measuring $\beta$ and $\gamma$ using a different laboratory; namely, the gravitational fields of Jupiter and Saturn, even if the values cannot be determined as accurately as the solar values.

## REFERENCES


Alfvén, H., and Arrhenius, G. 1976, *Evolution of the Solar System* (Washington: Government Printing Office).

Anderson, J. D. 1974, in *Experimental Gravitation*, ed. B. Bertotti (New York: Academic Press), pp. 163–196.

Anderson, J. D., and Lau, E. L. 1978, in *A Close-up of the Sun*, ed. M. Neugebauer and R. W. Davies (Pasadena: JPL Pub. 78–70), pp. 42–57.

Brouwer, D., and Clemence, G. M. 1961, in *Planets and Satellites*, ed. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press), pp. 31–90.

Dicke, R. H. 1974, in *Experimental Gravitation*, ed. B. Bertotti (New York: Academic Press), pp. 200–235.

Dicke, R. H., and Goldenberg, H. M. 1967, *Phys. Rev. Letters*, **18**, 313–316.

Einstein, A. 1961, *Relativity: The Special and the General Theory* (New York: Crown), pp. 124–126.

Estabrook, F. B., and Wahlquist, H. D. 1975, *Gen. Rel. Grav.*, **6**, 439.

Georegevic, R. M. 1971, *Mathematical Model of the Solar Radiation Force and Torques Acting on the Components of a Spacecraft* (Pasadena: JPL Pub. TM33–494).

Handler, F. A., and Matzner, R. A. 1978, *A.J.*, **83**, 1227.

Harris, D. L. 1961, in *Planets and Satellites*, ed. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press), pp. 272–340.

Hill, H. A., Ballard, P. T., Figoski, J. W., and Caudell, T. P. 1977, *Appl. Optics*, **16**, 195–201.

Hill, H. A., and Stebbins, R. J. 1975, *Ap. J.*, **200**, 471–483.

Kozai, Y. 1957, *Ann. Tokyo Astr. Obs.*, 2d Ser., **5**, 73.

Null, G. W. 1976, *A.J.*, **81**, 1153–1161.

Pierce, D. A. 1974, *Pub. A.S.P.*, **86**, 998–1000.

———. 1975, *Pub. A.S.P.*, **87**, 785–787.

Reasenberg, R. D., and Shapiro, I. I. 1977, in *Proceedings of the International Symposium on Experimental Gravitation*, Pavia, 1976 September (Rome: Accademia Nazionale dei Lincei).

Struve, G. 1930, *Veröff. Univ. Sternwarte, Berlin-Babelsberg*, **6**, Hefte, 4.

Sudbury, P. V. 1969, *Icarus*, **10**, 116–143.

Thorne, K. S., and Braginsky, V. B. 1976, *Ap. J.* (*Letters*), **204**, L1.

Wahlquist, H. D., Anderson, J. D., Estabrook, F. B., and Thorne, K. S. 1977, in *Proceeding of the International Symposium on Experimental Gravitation*, Pavia, 1976 September (Rome: Accademia Nazionale dei Lincei).

Whitaker, E. A., and Greenberg, R. J. 1973, *M.N.R.A.S.*, **165**, 15P–18P.

Will, C. M. 1974, in *Experimental Gravitation*, ed. B. Bertotti (New York: Academic Press), pp. 1–105.



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