

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

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(Received 10 June 1998)

Radio metric data from the Pioneer 10/11, Galileo, and Ulysses spacecraft indicate an apparent anomalous, constant, acceleration acting on the spacecraft with a magnitude  $\sim 8.5 \times 10^{-8} \text{ cm/s}^2$ , directed towards the Sun. Two independent codes and physical strategies have been used to analyze the data. A number of potential causes have been ruled out. We discuss future kinematic tests and possible origins of the signal. [S0031-9007(98)07300-1]

PACS numbers: 04.80.Cc, 95.10.Eg, 95.55.Pe

Exploration of the outer planets began with the launch of Pioneer 10 on 2 March 1972 [1]. (Pioneer 11 followed on 5 April 1973.) After Jupiter and (for Pioneer 11) Saturn encounters, the two spacecraft followed hyperbolic orbits near the plane of the ecliptic to opposite sides of the solar system. Although Pioneer 10 is still transmitting, its mission officially ended on 31 March 1997 when it was at the distance of 67 astronomical units (AU) from the Sun. Pioneer 11's radio system failed and coherent Doppler signals were last received on 1 October 1990, when the spacecraft was 30 AU away from the Sun.

The Pioneer spacecraft are excellent for dynamical astronomy studies. Because of their spin stabilization and their great distances, a minimum number of Earth-attitude reorientation maneuvers are required. This permits precise acceleration estimations, to the level of  $10^{-10} \text{ cm/s}^2$  (averaged over 5 days). Contrariwise, a Voyager-type spacecraft is not well suited for a precise celestial mechanics experiment as its numerous attitude-control maneuvers overwhelm any small external acceleration.

To obtain the S-band Doppler data from the Pioneer spacecraft, NASA used the Jet Propulsion Laboratory's (JPL) Deep Space Network (DSN). This data was used in the two analyses described below to determine Pioneer's initial position, velocity, and the magnitudes of the orientation maneuvers. The analyses were modeled to include the effects of planetary perturbations, radiation pressure, the interplanetary media, general relativity, and bias and drift in the range and Doppler. Planetary coordinates and the solar system masses were obtained using JPL's Export Planetary Ephemeris DE200. Both analyses calculated Earth's polar motion and its nonuniform rotation using the International Earth Rotation Service.

Beginning in 1980, when, at 20 AU from the Sun, the solar radiation pressure acceleration had decreased to  $< 5 \times 10^{-8} \text{ cm/s}^2$  [2], JPL's orbit determination program (ODP) analysis of unmodeled accelerations (at first with

the faster-moving Pioneer 10) found that the biggest systematic error in the acceleration residuals is a constant bias of  $a_P \sim (8 \pm 3) \times 10^{-8} \text{ cm/s}^2$ , directed toward the Sun [3], to within the accuracy of the Pioneers' antennas. As possible "perturbative forces" to explain this bias, we considered gravity from the Kuiper belt, gravity from the galaxy, spacecraft "gas leaks," errors in the planetary ephemeris, and errors in the accepted values of the Earth's orientation, precession, and nutation. None of these "forces" explained the apparent acceleration. Some were 3 orders of magnitude or more too small.

Nongravitational effects, such as solar radiation pressure and precessional attitude-control maneuvers, make small contributions to the apparent acceleration we have observed. The solar radiation pressure decreases as  $r^{-2}$ . As previously indicated for the Pioneers, at distances  $> 10\text{--}15 \text{ AU}$  it produces an acceleration that is much less than  $8 \times 10^{-8} \text{ cm/s}^2$ , directed away from the Sun. (The solar wind is roughly a factor of 100 smaller than this.)

A possible systematic explanation of the residuals is nonisotropic thermal radiation.  $\text{Pu}^{238}$  (half-life of 87.74 yr) radioactive thermal generators (RTGs) power the Pioneers. At launch, the RTGs delivered 160 W of electric power. Power has decreased approximately linearly ever since. By 1997 a little less than 80 W were available. The excess power and the heat generated by the plutonium has been thermally radiated into space. The power needed for this to explain  $a_P$  is  $\sim 85 \text{ W}$ . There is almost that much available, but presumably the radiation was approximately isotropic. Further, if it were not, and was the cause of  $a_P$ , this acceleration would have decreased with time. After 1980, no such (linearly decreasing) acceleration was observed. Another radiation source is the Pioneer radio beam. The power emitted from the antenna is 8 W. This implies a bias maximum of less than 9% of  $a_P$ , and in the opposite direction. (The influence of the bias is being investigated.)

We conclude, from the JPL-ODP analysis, that there is an unmodeled acceleration  $a_P$  towards the Sun of  $(8.09 \pm 0.20) \times 10^{-8} \text{ cm/s}^2$  for Pioneer 10 and of  $(8.56 \pm 0.15) \times 10^{-8} \text{ cm/s}^2$  for Pioneer 11. The error is determined by use of a five-day batch sequential filter with radial acceleration as a stochastic parameter subject to white Gaussian noise ( $\sim 500$  independent five-day samples of radial acceleration) [4,5]. *No magnitude variation of  $a_P$  with distance was found*, within a sensitivity of  $2 \times 10^{-8} \text{ cm/s}^2$  over a range of 40 to 60 AU.

Continuing our search for an explanation, we considered the possibilities: (i) that the Pioneer 10/11 spacecraft had internal systematic properties, undiscovered because they are of identical design, and (ii) that the acceleration was due to some not-understood viscous drag force (proportional to the approximately constant velocity of the Pioneers). Both of these possibilities could be investigated by studying spin-stabilized craft whose spin axes are not directed towards the Sun, and whose orbital velocity vectors are far from being radially directed.

Two candidates were Galileo in its Earth-Jupiter mission phase and Ulysses in a Jupiter-perihelion cruise out of the plane of the ecliptic. As well as Doppler data, these spacecraft also yielded a considerable quantity of range data. Ranging data are generated by cross correlating a phase modulated signal with a ground duplicate and noting the time delay. Thus, the ranging data are independent of the Doppler data, which represent a frequency shift of the radio carrier wave without modulation. (For example, solar plasma introduces a group delay in the ranging data but a phase advance in the Doppler data.) Ranging data can be used to distinguish an actual range change from a fictitious one caused by a frequency error.

A quick look at Galileo data showed it was impossible to separate the solar radiation effect from the anomalous constant acceleration with the limited data analyzed (241 days from 8 January 1994 to 6 September 1994) [6].

However, an analysis of the radiation pressure on Ulysses in its out-of-the-ecliptic journey, from 5.4 AU near Jupiter in February 1992 to the perihelion at 1.3 AU in February 1995, found a varying profile with distance [7]. The orbit solution requires a periodic updating of the solar radiation pressure. The radio Doppler and ranging data can be fit to the noise level with a time-varying solar constant in the fitting model [8]. The inferred solar constant is about 40% larger at perihelion (1.3 AU) than at Jupiter (5.2 AU), a physical impossibility. By interpreting this time variation as a true  $r^{-2}$  solar pressure plus a constant radial acceleration, we conclude that Ulysses was subjected to an unmodeled acceleration towards the Sun of  $(12 \pm 3) \times 10^{-8} \text{ cm/s}^2$ .

With no explanation of this data in hand, our attention focused on the possibility that there was some error in JPL's ODP. To investigate this, an independent analysis of the raw data using The Aerospace Corporation's Compact High Accuracy Satellite Motion Program (CHASMP), which was developed independently

of JPL's ODP, was performed. Although, by necessity, both programs use the same physical principles, planetary ephemeris, and timing and polar motion inputs, the algorithms are otherwise quite different. If there were an error in either program, they would not agree. (Common program elements continue to be investigated.)

The CHASMP analysis of Pioneer 10 data also showed an unmodeled acceleration in a direction along the radial toward the Sun [9]. The value is  $(8.65 \pm 0.03) \times 10^{-8} \text{ cm/s}^2$ , agreeing with JPL's result. The smaller error here is because the CHASMP analysis used a batch least-squares fit over the whole orbit [4], not looking for a variation of the magnitude of  $a_P$  with distance.

Without using the apparent acceleration, CHASMP shows a steady frequency drift of about  $-6 \times 10^{-9} \text{ Hz/s}$ , or 1.5 Hz over 8 yr (one way only). This equates to a clock acceleration,  $-a_t$ , of  $-2.8 \times 10^{-18} \text{ s/s}^2$ . The identity with  $a_P$  is  $a_P \equiv a_{t,c}$ . The drift in the Doppler residuals (observed minus computed data) is seen in Fig. 1. It is clear, definite, and cannot be removed without either the added acceleration,  $a_P$ , or the inclusion in the data itself of a frequency drift, i.e., a "clock acceleration"  $a_t$ .

If there were a systematic drift in the atomic clocks of the DSN or in the time-reference standard signals, this would appear like a nonuniformity of time; i.e., all clocks would be changing with a constant acceleration. We have not yet been able to rule out this possibility. Elements common to the Doppler and range tracking systems (e.g., DSN station clocks) need to be investigated. For example, how and to what accuracy are the clocks at different DSN stations tied to each other and to external national

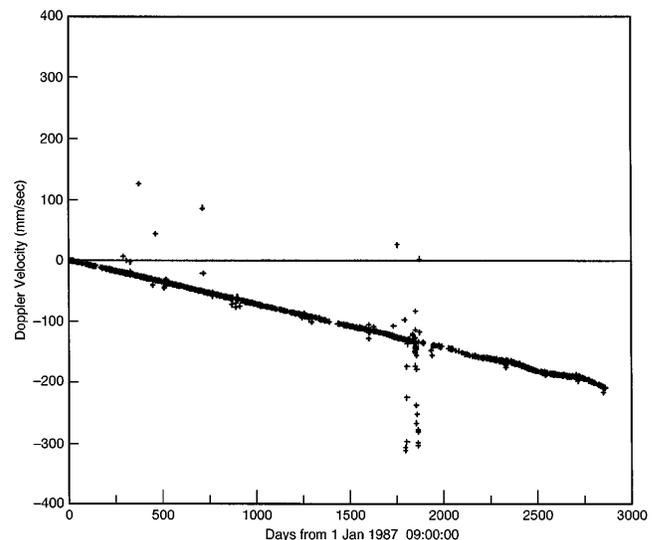


FIG. 1. Two-way Doppler residuals (observed Doppler velocity minus model Doppler velocity) for Pioneer 10 in mm/s vs time. Solar system gravity is represented by the Sun and the planetary systems [17]. [If one adds one more parameter to the model (a constant radial acceleration) the residuals are distributed about zero Doppler velocity with a systematic variation  $\sim 3.0 \text{ mm s}^{-1}$  on a time scale  $\sim 3$  months.] The outliers on the plot were rejected from the fit.

standards? Are there differences in the orbital fits when different stations' data are analyzed separately?

Aerospace's analysis of Galileo data covered the same arc as JPL and a second arc from 2 December 1992 to 24 March 1993. Doppler data from the first arc resulted in a determination for  $a_P$  of  $\sim(8 \pm 3) \times 10^{-8} \text{ cm/s}^2$ , a value similar to that from Pioneer 10. But the correlation with solar pressure was so high (0.99) that it is impossible to decide whether solar pressure is a contributing factor. (Galileo is less sensitive to both the  $a_P$ - and  $a_I$ -model effects than the Pioneers. The Pioneers have a smaller solar pressure and a longer light travel time. Sensitivity to a clock acceleration is proportional to the light travel time squared.) The second arc was 113 days long, starting 6 days prior to the second Earth encounter. This solution was also too highly correlated with solar pressure, and the data analysis was complicated by many midcourse maneuvers. The maneuver uncertainties were so great that a standard null result could not be ruled out.

However, there was an additional result from this second arc. This arc was chosen for study because there was ranging data. The two-way range change and time integrated Doppler are consistent to  $\sim 4 \text{ m}$  over a time interval of 1 day. This is strong (but not conclusive) evidence that the apparent acceleration is not the result of hardware problems at the tracking stations.

With these added discoveries, what other possible origins for the signal come to mind?

One can speculate that there is some unknown interaction of the radio signals with the solar wind. An experimental answer could be given with two different transmission frequencies. Although the main communication link on the Ulysses mission is *S*-up/*X*-down mode, a small fraction of the data is *S*-up/*S*-down. We plan to utilize this option in further analysis.

If no normal explanation for the residuals is found, further tests of the effect are needed. The weakening Pioneer 10 signal can still be reacquired for a short time. (The NASA/Ames Lunar Prospector Team has intermittently done this for training purposes, producing high-quality data.) Further Ulysses data would also help.

The Pluto Express mission could provide an excellent opportunity for high-quality data from very deep space, especially if optical tracking is used. A similar opportunity may exist, out of the plane of the ecliptic, from the proposed Solar Probe mission. Under consideration is a low-mass module to be ejected during solar fly-by.

With all of the above, it is interesting to speculate on the possibility that the origin of the anomalous signal is new physics [10]. This is true even though the probability is that some "standard physics" or some as-yet-unknown systematic will be found to explain this "acceleration." This probability is of interest in itself, given that we have found no plausible explanation so far.

The paradigm is obvious. "Is it the effects of dark matter or a modification of gravity?" Unfortunately, neither easily works.

If the cause is dark matter, it is hard to understand. The spherically symmetric distribution of matter,  $\rho \sim r^{-1}$ , produces a constant acceleration *inside* the distribution. For this to cause  $a_P$ , even only out to 50 AU, would require the total dark matter to be  $>3 \times 10^{-4} M_\odot$ . But this is in conflict with the accuracy of the ephemeris, which allows only of order a few times  $10^{-6} M_\odot$  of dark matter even within the orbit of Uranus [11]. (A 3-cloud neutrino model also did not solve the problem [12].)

Contrariwise, the most commonly studied possible modification of gravity (at various scales) is an added Yukawa force [13]. Then the gravitational potential is

$$V(r) = -GMm[(1 + \alpha)r]^{-1}[1 + \alpha \exp^{-r/\lambda}], \quad (1)$$

where  $\alpha$  is the new coupling strength relative to Newtonian gravity, and  $\lambda$  is the new force's range. Since the radial force is  $F_r = -d_r V(r) = ma$ , the power series for the acceleration yields an inverse-square term, no inverse- $r$  term, then a constant term. Identifying this last term as the Pioneer acceleration yields

$$a_P = -a_1 \alpha [2(1 + \alpha)]^{-1} [r_1^2 / \lambda^2], \quad (2)$$

where  $a_1$  is the Newtonian acceleration at distance  $r_1 = 1 \text{ AU}$ . (Out to 65 AU there is no observational evidence of an  $r$  term in the acceleration.) Equation (2) is the solution curve; for example,  $\alpha = -1 \times 10^{-3}$  for  $\lambda = 200 \text{ AU}$ .

It is also of interest to consider Milgrom's proposed modification of gravity [14], where  $a \propto 1/r^2$  for some constant  $a_0 \ll a$  and  $a \propto 1/r$  for  $a_0 \gg a$ . Depending on the value of the Hubble constant, we find that  $a_0 \approx a_P$ .

Of course, there are (fundamental and deep) theoretical problems if one has a new force of the phenomenological types of those above. Even so, the deep-space data piques our curiosity. However, these and other universal-gravitational explanations for the Pioneer effect come up against a hard experimental wall.

The anomalous acceleration is too large to have gone undetected in planetary orbits, particularly for Earth and Mars. NASA's Viking mission provided radio-ranging measurements to an accuracy of about 12 m [15,16]. If a planet experiences a small, anomalous, radial acceleration,  $a_A$ , its orbital radius  $r$  is perturbed by

$$\Delta r = -l^6 a_A / (GM_\odot)^4 \rightarrow -r [a_A / a_N], \quad (3)$$

where  $l$  is the orbital angular momentum per unit mass and  $a_N$  is the Newtonian acceleration at  $r$ . [The right value in Eq. (3) holds in the circular orbit limit.]

For Earth and Mars,  $\Delta r$  is about  $-21$  and  $-76 \text{ km}$ . However, the Viking data determines the difference between the Mars and Earth orbital radii to about a 100 m accuracy, and their sum to an accuracy of about 150 m. The Pioneer effect is not seen.

Further, a perturbation in  $r$  produces a perturbation to the orbital angular frequency of

$$\Delta \omega = 2l a_A / (GM_\odot) \rightarrow 2\dot{\theta} [a_A / a_N]. \quad (4)$$

The determination of the synodic angular frequency  $\omega_E - \omega_M$  is accurate to seven parts in  $10^{11}$ , or to about 5 ms accuracy in synodic period. The only parameter that could possibly mask the spacecraft-determined  $a_R$  is  $GM_\odot$ . But a large error here would cause inconsistencies with the overall planetary ephemeris [11,17].

We conclude that the Viking ranging data limit any unmodeled radial acceleration acting on Earth and Mars to no more than  $0.1 \times 10^{-8} \text{ cm/s}^2$ . Consequently, if the anomalous radial acceleration acting on spinning spacecraft is gravitational in origin, it is *not* universal. That is, it must affect bodies in the 1000 kg range more than bodies of planetary size by a factor of 100 or more. This would be a strange violation of the principle of equivalence (PE) [18]. The fact that an anomalous signal is not seen in the analysis of the Viking Lander ranging data gives us added confidence that the anomaly is not related to DSN hardware. However, the Viking Lander data have not been analyzed by either ODP or CHASMP, so we cannot make a similar claim regarding software errors.

Similarly, the  $\Delta\omega$  results rule out the universality of the  $a_t$  time-acceleration model. In the age of the universe,  $T$ , one would have  $a_t T^2/2 \sim 0.7T$ . (Another unusual possibility is that there is some unknown nonkinematic effect causing a Doppler anomaly.)

Clearly, more analysis, observation, and theoretical work are called for. Further details will appear elsewhere.

We thank John E. Ekelund, Gene L. Goltz, William E. Kirhofer, Margaret Medina, William L. Sjogren, and S. Kuen Wong of JPL for their support in obtaining and understanding DSN tracking data. We also thank John W. Dyer, Alfred S. Goldhaber, Jack G. Hills, Irwin I. Shapiro, and Richard J. Terrile for many helpful conversations. This work was supported by the Pioneer Project, NASA/Ames Research Center, and was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. P. A. L. and A. S. L. acknowledge support by a grant from NASA through the Ultraviolet, Visible, and Gravitational Astrophysics Program. M. M. N. acknowledges support by the U.S. DOE.

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