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THE APPARENT ANOMALOUS, WEAK, LONG-RANGE ACCELERATION OF PIONEER 10 AND 11+

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Recently we reported that radio Doppler data generated by NASA's Deep Space Network (DSN) with the Pioneer 10 and 11 spacecraft indicate an apparent anomalous, constant, spacecraft acceleration with a magnitude $\sim 8.5 \times 10^{-8}$ cm s^{-2}, directed towards the Sun.[1] Analysis of similar Doppler and ranging data from the Galileo and Ulysses spacecraft yielded ambiguous results for the anomalous acceleration, but the analysis was useful in that it ruled out the possibility of a systematic error in the DSN Doppler system that could easily be mistaken as a spacecraft acceleration. Here we present some new results, including a critique of the suggestion that the anomalous acceleration could be caused by collimated thermal emission. Based on upgraded JPL software for the Pioneer 10 orbit determination, and on a new data interval from January 1987 to July 1998, our best estimate of the average Pioneer 10 acceleration directed towards the Sun is $7.20 \pm 0.11 \times 10^{-8}$ cm s^{-2}.

1 Introduction

Pioneer 10 was launched on 2 March 1972 to explore the outer regions of the solar system. (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. Pioneer 10 (11) is moving in the direction of Star Aldebaran (constellation of Aquila). 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.

Detailed analyses of radio metric data from the distant spacecraft in the solar system have revealed an anomalous acceleration acting on the Pioneer 10/11, with supporting data from Galileo, and Ulysses spacecraft. As indicated in our previous paper[1], the data indicate existence of an apparent anomalous, constant, acceleration acting on the spacecraft with a magnitude $\sim 8.5 \times 10^{-8}$ cm/s^2, directed towards the Sun. Two independent codes and physical strategies have been recently used to analyze the data. A number of potential causes have been ruled out. In this paper we report on further progress in this study.

We concentrate on the analysis of the Pioneer 10 and 11 spacecraft Doppler data. We will discuss scenarios that involve excess power and heat generated by the Radioisotope Thermoelectric Generators (RTGs). We will present our estimates for the corresponding effects in order to demonstrate that these mechanisms may not used to explain the reported effect.

2 Study of the anomalous acceleration

The Pioneer spacecraft are excellent for dynamical astronomy studies. Due to 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^{-9} 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). The signals were actively reflected by a transponder on the spacecraft and calculation of the motions of the spacecraft were made based on the resulting Doppler shift in the signals. This data was used in the two analyses described below to determine the Pioneers initial position, velocity and the magnitudes of the orientation maneuvers.

2.1 Unmodeled acceleration observed in JPL.

Beginning in 1980, when at 20 AU the solar radiation pressure acceleration had decreased to $< 5 \times 10^{-8}$ cm/s^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 $a_P \sim (8 \pm 3) \times 10^{-8}$ cm/s^2, directed *toward* the Sun (to within the accuracy of the Pioneers' antennae).

We ultimately concluded[1], from the JPL-ODP analysis, that there is an unmodeled acceleration, a_P, towards the Sun of $(8.09 \pm 0.20) \times 10^{-8}$ cm/s^2 for Pioneer 10 and of $(8.56 \pm 0.15) \times 10^{-8}$ 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). No magnitude variation of a_P with distance was found, within a sensitivity of 2×10^{-8} cm/s^2 over a range of 40 to 60 AU. All errors are from the covariance matrices associated with the least–squares analysis. The assumed data errors are larger than the standard error on the post–fit residuals.[1]

The observed effect may be expressed by the following simple expression:

$$\nu_{obs} = \nu_{model} \times \left[1 - \frac{a_P \cdot t}{c} \right], \qquad (1)$$

where ν_{obs} is the frequency of the re-transmitted signal observed by a DSN antennae, while ν_{model} is the predicted frequency of that signal. Our analyses were modeled ν_{model} to include the effects of planetary perturbations, radiation pressure, the interplanetary media, general relativity, and bias and drift in the Doppler signal. 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 non-uniform rotation using the International Earth Rotation Service.

The models account for a number of post-Newtonian perturbations in the dynamics of the planets, the Moon, and spacecraft: i) models for light propagation are correct to order $(v/c)^2$, ii) the equations of motion of extended celestial bodies are valid to order $(v/c)^4$. Non-gravitational 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 >10-15 AU it produces an acceleration that is much less than 8×10^{-8} cm/s^2, directed *away* from the Sun. (The solar wind is roughly a factor of 100 smaller than this.)

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" could explain the apparent acceleration, and were three orders of magnitude or more too small.

2.2 An error in the code? — The Aerospace Corporation's result.

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. The value is $(8.65 \pm 0.03) \times 10^{-8}$ 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, 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 -6×10^{-9} Hz/s, or 1.5 Hz over 8 years (one-way only). This equates to a clock acceleration, $-a_t$, of $-2.8 \times 10^{-18} s/s^2$. The identity with a_P is $a_P \equiv a_t c$. The drift in the Doppler residuals (observed minus computed data) is 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 non-uniformity 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 standards? Are there differences in the orbital fits when different stations' data are analyzed separately?

Also, in addition to general and special relativity theories, we did examine numerous other "time" models (in conjunction with our studies of Galileo and Ulysses spacecraft radio metric data), searching for any (possibly radical) solution, namely: i). *Drifting Clocks.* This model adds a constant acceleration term to the Station Time (ST) clocks; i.e.. in the ST-UTC (Universal Time Coordinates) time transformation. The model fit Doppler well for Pioneer 10, Galileo, and Ulysses but failed to model range data for Galileo and Ulysses. ii). *Quadratic Time*

Augmentation. This model adds a quadratic-in-time augmentation to the IAT-ET (International Atomic Time-Ephemeris Time) time transformation. The model fits Doppler fairly well but range very badly. iii). *Frequency Drift.* This model adds a constant frequency drift to the reference frequency. The model also fits Doppler well but again fits range poorly. iv). *Expanding Space.* This model adds a quadratic in time term to the light time, thus mimicking a line of sight acceleration of the spacecraft. The model fits both Doppler and range very well but the coefficient of the quadratic is negative for Pioneer 10 and Galileo while positive for Ulysses. v) *Speed of Gravity.* This model adds a "light time" delay to the actions of the Sun and planets upon the spacecraft. The model fits Pioneer 10 and Ulysses well. But the Earth flyby of Galileo fit was terrible, with Doppler residuals as high as 20 Hz.

All these models were rejected due either to poor fits or to inconsistent solutions among spacecraft.

3 Influence of the excess power and heat from RTGs.

One might argue that a possible systematic explanation of the residuals is non-isotropic thermal radiation. Pu^{238} (half life of 87.74 years) radioactive thermal generators (RTGs) power the Pioneers.

3.1 The heat coming from the RTGs.

Let us discuss the anisotropic heat reflection off of the back of the spacecraft high-gain antennae, the heat coming from the RTGs.[2] Before launch the four RTGs delivered a total electrical power of 160 W (now $\sim$ 70-75 W), from a total thermal fuel inventory of 2580 W (now $\sim$ 2090 W). Presently $\sim$ 2000 W of RTG heat must be dissipated. Only $\sim (70 - 85)$ W of directed power could explain the anomaly. Therefore, in principle there is enough power to explain the anomaly this way. However, there are two reasons that preclude such mechanism, namely:

i). The spacecraft geometry. The RTGs are located at the end of booms, and rotate about the craft in a plane that contains the approximate base of the antenna. From the RTGs the antenna is thus seen "edge on" and subtends a solid angle of $\sim$ 1.5 % of 4π steradians. This already means the proposal could provide at most $\sim$ 30 W. But there is more.

ii) The RTG's radiation pattern. The above might still come close to allowing the proposal to work if the RTGs were spherical black bodies. But they are not. The main bodies of the RTGs are cylinders and they are grouped in two packages of two. Each package has the two cylinders end to end extending away from the antenna. Every RTG has six fins that go radially out from the cylinder. Thus, the fins are "edge on" to the antenna (the fins point perpendicular to the cylinder axes). Ignoring edge effects, this means that only 2.5 % of the surface area of the RTGs is facing the antenna. Further, for better radiation from the fins, the Pioneer SNAP 19 RTGs had larger fins than the earlier test models, and the packages were insulated so that the end caps had lower temperatures and radiated less than the cylinder/fins.[3]

We conclude that this mechanism does not provide enough power to explain the Pioneer anomaly.

3.2 Non-isotropic radiative cooling of the spacecraft.

There is also the possibility that the anomalous acceleration seen in the Pioneer 10/11 spacecraft can be, "explained, at least in part, by non-isotropic radiative cooling of the spacecraft."[4] So, the question is, does "at least in part" mean this effect comes near to explaining the anomaly? We argue it does not.

One may consider radiation of the power of the main-bus electrical systems from the rear of the craft. For the Pioneers, the aft has a louver system, and "the louver system acts to control the heat rejection of the radiating platform... A bimetallic spring, thermally coupled radiatively to the platform, provides the motive force for altering the angle of each blade. In a closed position the heat rejection of the platform is minimized by virtue of the "blockage" of the blades while open louvers provide the platform with a nearly unobsructed view of space." [5]

If these louvers were open, this mechanism may would produce a comparable effect. However, by 9 AU the actuator spring temperature had already reached ~40°F. This means the louver doors were closed (i.e., the louver angle was zero) from there on out. Thus, from our quoting of the radiation properties above, the contribution of the thermal radiation to the Pioneer anomalous acceleration should be *negligibly* small. After the above time, we reach our data region. In 1984 Pioneer 10 was at about 33 AU and the power was about 105 W. (Always reduce the total power numbers by 8 W to account for the radio power.) In (1987, 1992, 1996) the craft was at ~(41, 55, 65) AU and the power was ~(95, 80, 70) W. The louvers were inactive, and no decrease in a_P was seen.

We conclude that this proposal can not explain the anomalous Pioneer acceleration.

3.3 Could the Helium pressure produced within the Pioneer RTGs be cause for the acceleration?

There exists another possible systematic from on-board the spacecraft, namely the He build-up in the RTGs from the α-decay of Pu^{238}. Is there any way that this permeating He could be causing our acceleration?

To make this mechanism work, one would need that the He leackage from the RTGs be preferentially directed away from the Sun, with a velocity large enough to cause the acceleration. The SNAP-19 Pioneer RTGs were designed in a such a way that the He pressure had not been totally contained within the Pioneer heat source over the life of RTGs. Instead, the Pioneer heat source contains a pressure relief device which allows the generated He to vent out of the heat source and into the thermoelectric converter. The strength member and the capsule clad contain small holes to permit He to escape into the thermoelectric converter. The thermoelectric converter housing-to-power output receptacle interface is sealed with a viton O-ring. This means that, due to permeation, the gas within the converter is expected to be released to the space environment throughout the life of mission, of the Pioneer RTGs. Thus, the He generated within the heat source is vented to space via the thermoelectric converter.

From the size of the fuel pucks (2" diameter 0.2" thick), 18 per RTG and 4 RTGs, the total volume of fuel is about 737 cm^3. The fuel is PMC Plutonium conglomerate. Let us over-estimate and say it is all Plutonium. Then the total mass of Plutonium is $\geq$ 14 kg, With a decay constant of 87.74 years, that means the rate of He production (from Pu decay) is about 1 gm/year. (When looking for gas leaks, 2 gr mass of hydrazine could produce our acceleration *if it came out* at nozzle speed of about 3.4 km/sec, all directed.)

So, we can rule out this helium permeating through the O-rings as the cause of our effect.

4 Recent results

Independent of the above, we continue to search for a systematic origin of the effect. A few weeks after our letter [1] was accepted, we began using new JPL software (SIGMA) to reduce the Pioneer 10 Doppler data to 50-day averages of acceleration, extending from January 1987 to July 1998, over a distance interval from 40 to 69 AU.

Before mid-1990, the spacecraft rotation rate changed (slowed) by about -0.065 rev/day/day. Between mid-1990 and mid-1992 the spin-deceleration increased to -0.4 rev/day/day. But after mid-1992 the spin rate remained ~ constant. In units of 10^{-8} cm/s^2, the mean acceleration levels obtained by SIGMA from the Doppler data in these periods are: (7.94 ± 0.11) before mid-1990, (8.39 ± 0.14) between mid-1990 and mid-1992, and (7.29 ± 0.17) after mid-1992. [Similar values

Figure 1: The Pioneer 10 Doppler data: 50-day averages of anomalous acceleration – January 1987 to July 1998.

$(8.27 \pm 0.05,\ 8.77 \pm 0.04,\ 7.76 \pm 0.08)$ were obtained using CHASMP.] We detect no long-term deceleration changes from mid-1992 to mid-1998, and only two spin-related discontinuities over the entire data period.

Assume that the slowing of the spin rate was caused by spacecraft systems (perhaps gas leak changes) that also account for a few % systematic effect. Then, excluding other biases such as the radio beam increasing the anomaly, we should adopt the post-1992 value as the most accurate measure of the anomalous acceleration of Pioneer 10.

As stated before, we believe the most plausible explanation of the anomaly is systematics, such as radiant heat or gas leaks. But no such explanation has yet been demonstrated. Clearly, more analysis, observation, and theoretical work are called for. Further details will appear elsewhere.

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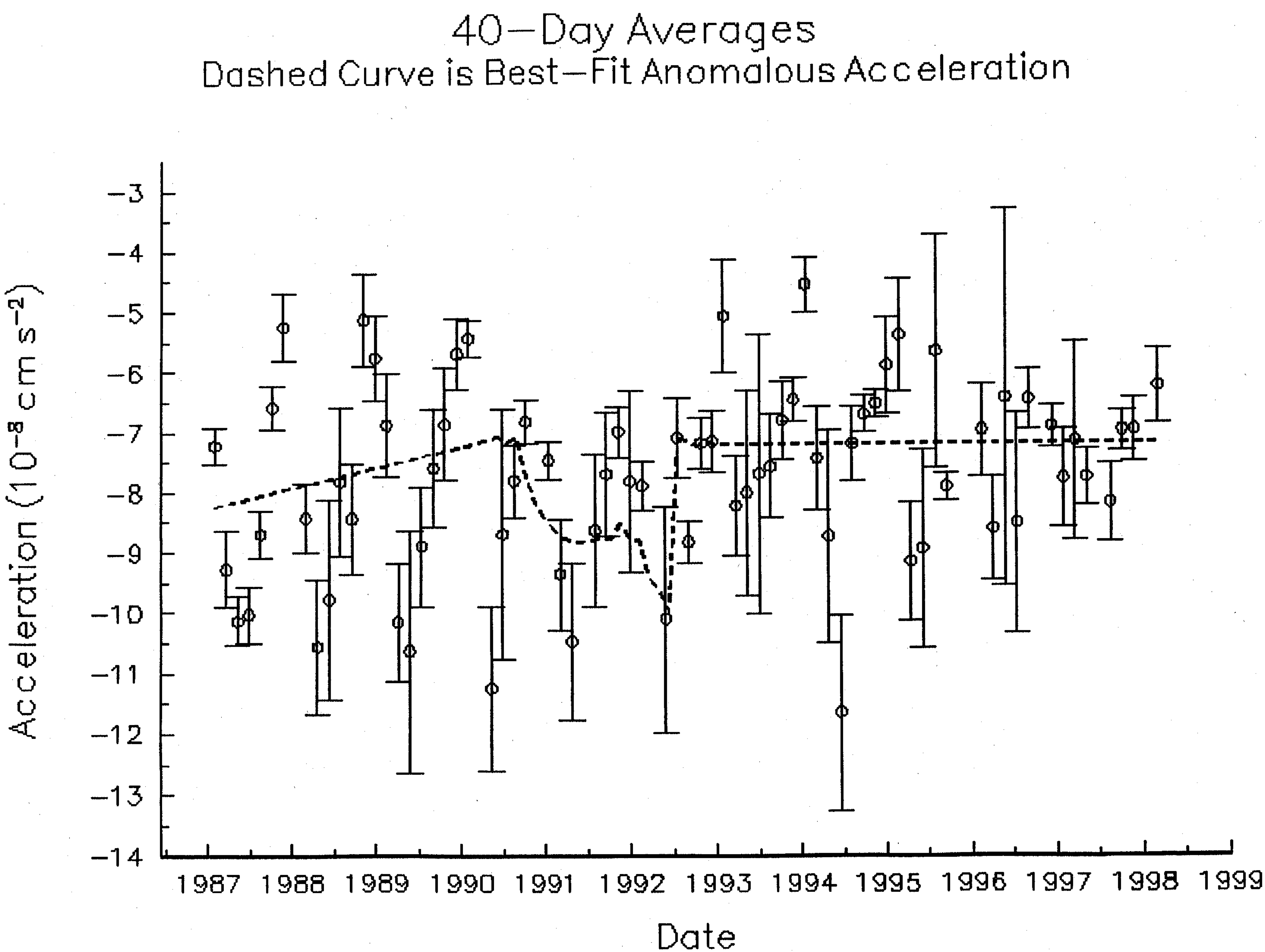
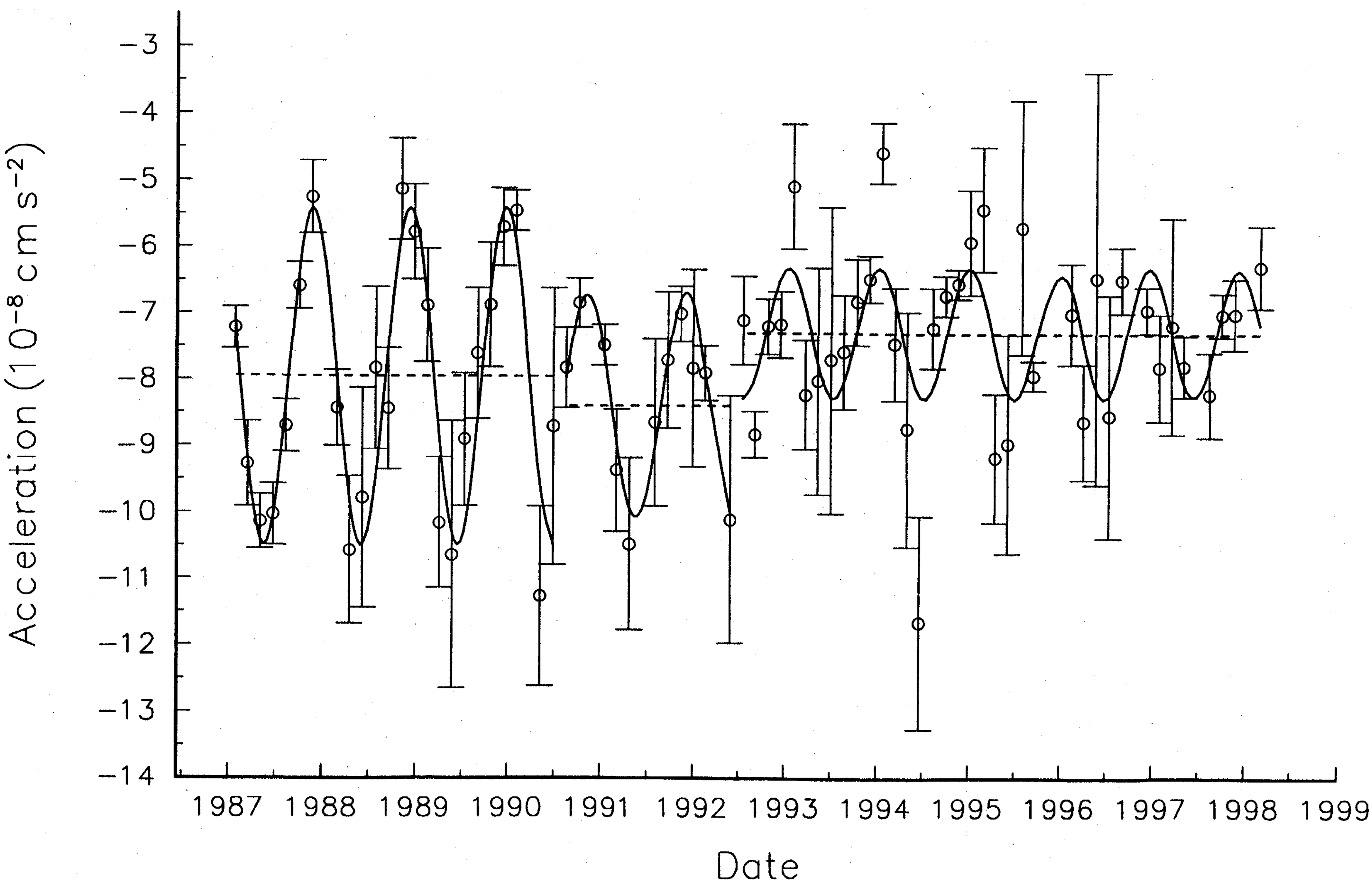

40—Day Averages
Dashed Curve is Best—Fit Anomalous Acceleration
Acceleration (10^{-8} cm s^{-2})
−3
−4
−5
−6
−7
−8
−9
−10
−11
−12
−13
−14
1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999
Date


Acceleration (10^{-8} cm s^{-2})
−3
−4
−5
−6
−7
−8
−9
−10
−11
−12
−13
−14
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
Date