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Pioneer's Final Riddle *

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Abstract

Launched more than thirty years ago and now drifting in space with no further contact, the Pioneer 10 and 11 spacecraft are currently at the center of a small but developing concern: are they under the influence of an anomalous acceleration that reflects new, yet unknown physics, or merely experiencing some unexpected technical problem ? The proposals vary from basic engineering principles to extra spatial dimensions, but most probably an answer can only be obtained after a dedicated mission is underway.

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More than thirty years ago, on 2 March 1972, Pioneer 10 was launched by an Atlas/Centaur rocket from Cape Canaveral, in a voyage to the yet unchallenged far ends of the Solar System (Figure 1). About a year later, on 5 April 1973, Pioneer 11 would follow. In their epic voyage Pioneer 10 would encounter Jupiter, while Pioneer 11 would also visit Saturn, returning detailed pictures of the planets and their moons. The two spacecraft then followed hyperbolic orbits near the plane of the ecliptic to opposite sides of the Solar System (Figure 2). Initial projections gave the spacecraft a lifespan of about seven years, after which contemporary deep space scanning stations would no longer be able to determine its position and accurately receive scientific data. However, further developments in tracking capabilities extended the probes' life to an ever increasing limit. Hence, although the Pioneer 10 mission officially ended on 31 March 1997, contact was kept until 7 February, 2003, when it was at about 70 Astronomical Units from Earth (1 AU is the medium Earth-Sun distance, about 150 million kilometers). A radio failure on 1 October 1995 and the increasing exhaustion of the power source rendered the Pioneer 11 unable to contact us, when it was at approximately 40 AUs from our planet.

After flying by the outer planets they so successfully observed, both missions were scaled down. In the course of events, tracking of the spacecraft became a routine training exercise for future Lunar Prospector controllers. However, it was during this less splendorous part of their voyage that the Pioneer 10 and 11 cast their final riddle, which is currently known as the Pioneer anomaly. Analysis of radiometric data from the Pioneer 10/11 by NASA's Jet Propulsion Lab [1] has revealed the existence of an anomalous acceleration on both spacecraft, inbound to the Sun and with a (constant) magnitude of $a_A \simeq (8.5 \pm 1.3) \times 10^{-10}\ m\ s^{-2}$. This is not expected from the usual dynamics, which account solely for the gravitational pull and the outward solar wind pressure, both varying with the distance to the Sun r according to the usual inverse square law $1/r^2$. It was measured from 1980 on, when Pioneer 10 was at a distance of 20 AUs from the Sun and the solar radiation pressure acceleration on Pioneer 10 had decreased to below $5 \times 10^{-8}\ m\ s^{-2}$. This was possible because the Pioneer spacecraft were excellent for dynamical studies due to their spin-stabilization and their great distances, requiring a minimum number of Earth-attitude reorientation maneuvers for these deep space missions to go beyond the Solar System. Contrariwise, the Voyager spacecraft were not suited for precise celestial mechanics experiments, as numerous attitude-control maneuvers overwhelm any small external acceleration. This Pioneer effect seems also to have disturbed the Ulysses and Galileo spacecraft.

As a first attempt to explain this phenomena, the team who unraveled the anomaly resorted to poor accounting of thermal and mechanical effects, as well as errors in the tracking algorithms

used. However, these attempts have all failed to account for a constant acceleration. Indeed, thermal effects such as gas leaks, heat radiation due to the two nuclear generators placed on booms or to the instruments on-board all obey exponential laws. In the same way as air will quickly escape a balloon while it is full, but decrease its velocity as it is depleted, all heat radiation decreases exponentially with time, towards zero. Hence, even if a lucky combination of effects could result in an acceleration inbound the Sun, in principle it could not render a constant one (see Ref. [2] for a counter claim).

The algorithms used to calculate the acceleration of the spacecraft make use of the Doppler effect observed in the radio signal received from the spacecraft, much in the same way as one can perceive if a car is approaching or distancing from the increase or decrease of its sound pitch. A detailed analysis of the numerical conundrums of these algorithms also fails to account for an anomalous acceleration [3]. Hence, all evidence points that the Pioneer anomaly is a real effect, not a numerical contraption due to lack of precision.

There is a stronger argument against a conventional engineering explanation of the anomalous acceleration the spacecraft were subjected to. While both Pioneer 10 and 11 were completely equal in design, the Galileo spacecraft, designed to explore the Jovian system, and the joint ESA-NASA Ulysses heliosphere observatory are very different in nature. Also, the two Pioneer spacecraft follow approximate opposite hyperbolic trajectories away from the Solar System, while Galileo and Ulysses describe closed orbits.

Given this, it seems unreasonable that three different designs and trajectories would all suffer different conventional effects such as heat radiation and gas leaks, but originating the same net result. Remember that the anomalous acceleration was found not only to be constant and inbound to the Sun, but also textitsimilar for all four spacecraft.

Thus, it is plausible to assume that there is no conventional explanation for the Pioneer anomaly and one must resort to new physics to account for it. From a theoretical point of view, the phenomena is puzzling: one has to device a theory which breaks the usual law of gravity in a very subtle way, so to affect only the motion of small bodies such as the referred spacecraft, for there is no analogous effect for planets. Hence, one of the very foundations of General Relativity is at stake: the Weak Principle of Equivalence, which states that all bodies fall in a gravitational field at the same rate, independently of their mass or constitution.

Physicists are, of course, happy to come across evidence of new physics. Thus, a wide range of more or less exotic hypotheses has been put forward to meet the challenge. Some propose a new interaction [3], or recover modifications of gravity suggested as alternatives to dark matter [4] (see also [5]), or seek for gravity models in which the Newtonian dynamics do

not follow in the weak-field limit [6], or consider a scalar field with a suitable potential [7]. Another suggestion considers the dependence on the momentum of the gravitational coupling, the main issue in Refs. [5, 8] and, as pointed in Ref. [7], a potential solution for the anomaly, in the context of the linear approximation of gravity and, interestingly, two potentials: the usual Newtonian one, and a second that generalizes the PPN parameter γ to a function of distance [9]. Given that the value of the anomalous acceleration can be related to those of the speed of light, $c = 3 \times 10^8\ m\ s^{-1}$, and the Hubble constant $H_0 \simeq 70\ km\ s^{-1}\ Mpc^{-1} \simeq 2.3 \times 10^{-18}\ s^{-1}$ (which allows measuring the velocity of expansion of the Universe and its age) through $a_A = cH_0$, some authors argue that the phenomena merely reflects the ongoing Universe's expansion [10]. Others claim that there exists also a connection with the cosmological constant [11], dubbed "my greatest error" by Einstein himself, but confirmed to be non-vanishing by different cosmological observations [12]. However, it seems clear that this should produce an *outgoing* acceleration, in the same way as dots on an inflating balloon's surface seem to pull away from each other. Also, this effect should be observed on all bodies, regardless of their scale, not only on the spacecraft. Finally, the computed effect due to the cosmological constant is much smaller than the anomalous acceleration felt by the spacecraft.

Another possibility involves the idea of an extra spatial dimension which is, of course, also appealing for other reasons. Extra dimensions are a crucial element in unifying models of the fundamental interactions of Nature. Imagine, for instance, an ant living on top of a sheet of paper, oblivious of the three-dimensional world around it; if one turns on a light at the center of the sheet, the ant would expect its intensity to vary with the distance to the source, r, according to $1/r$. Thus, the same flux of radiation would transverse circles of different radius, according to the energy conservation law. However, a three-dimensional observer such as ourselves would expect the dependency to be of the form $1/r^2$, since we see the flux emanating not in circles, but as spheres.

By the same token, we expect gravity to vary as $1/r^2$ because we live in a world with three spatial dimensions. However, if there is a fourth spatial dimension and we live on a three-dimensional sheet - a brane - gravity should behave as $1/r^3$ at large distances from the source, where this extra "length" becomes noticeable. Conversely, while we still expect gravity to obey the usual $1/r^2$ Newton's law at small distances, there should be some small corrections to it.

Such a general picture, which is unrelated to the problem at hand, is usually referred to as the braneworld scenario [13]. According to it, we live on a three-dimensional brane in a five-dimensional space, with a possible second brane at a distance. The tension between these branes (which keeps them at a fixed distance, like a rod between two brick walls) is perceived

by us as the cosmological constant. In the five-dimensional space away from the brane only gravity is allowed to propagate.

In a violin, vibrations are trapped between two fixed extrema, and only a certain number of notes are allowed, related to the length of each chord and the velocity of sound. By analogy, if we have two branes and gravity propagating between them, it will be constrained to exhibit certain characteristic modes, limited by the distance between those and by the speed of light. Also, small oscillations of one membrane relative to the other could lead to a change in gravity observed on each brane [14]. Such effects may be tested some day in the future, but they cannot account directly for the anomalous constant acceleration the Pioneer spacecraft are subjected to [7]. Nevertheless, a more elaborate argument involving the presence of a scalar field with an appropriate potential still allows for an explanation of the Pioneer anomaly [7].

However, knowledge does not advance solely from *ad-hoc* hypotheses with the purpose of obtaining the correct figures, or even extracting yet unforeseen results from well established theories. A fundamental aspect of any scientific observation of a phenomena is its replication. Without a bulletproof confirmation by a dedicated experiment, no conclusions can be drawn. With this in mind, a mission designed solely with the purpose of accurately measuring its own motion has been proposed by two groups independently [15, 16]; in a sense, a sophisticated pebble traversing space. In one of the proposals, its shape should be as symmetric as possible, so to exclude any anisotropic effects; engines and energy sources should be as far as possible from the main body, to reduce vibrations and heat dissipation effects that might affect readings; and refined differential accelerometers should be on board, providing a direct, mechanical measurement of the probes' motion, together with the usual Doppler tracking. Such a mission has been dubbed Sputnik V, recalling the first-ever satellite and the current objective of searching for a "fifth" new interaction of Nature [15, 17, 18] (Figure 3). Alternative mission concepts have also been discussed [16, 19].

Although perhaps initially viewed with some suspicion and skewness, the study of the Pioneer anomaly has been steadily gaining momentum, as can be easily seen from the number of related peer reviewed papers published in the specialized literature. The realization of the importance of this unpredicted phenomenum as a natural testing ground for space science and gravitation has reached its climax with the first dedicated conference, held last May at Bremen's University Center for Applied Space Technology and Microgravity (ZARM). There, researchers around the world converged to discuss the subject, with backgrounds ranging from pure engineering to applied and fundamental physics.

The discussion of the abovementioned mission sketches was one of the topics of discussion,

leading to the concatenation of efforts so to supply the European Space Agency with proposals for the Cosmic Vision 2015-2025 call [20]. This effort has yielded five different mission concepts [21], among over 150 proposed in all subjects, and ongoing efforts to merge them into an unified one.

If ever approved to fly, this mission will develop new and exciting deep space navigational concepts and hopefully uncover new physics. A confirmation of the Pioneer anomaly might unfold interesting theoretical thinking, which may have an impact on the way we regard the history of the Universe as a whole.

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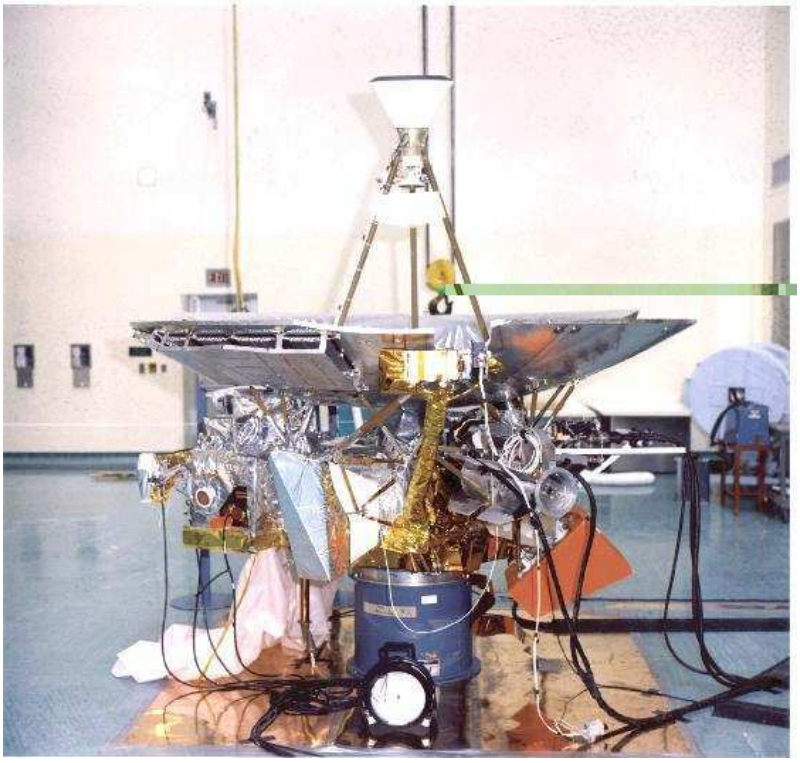

Figure 1: The Pioneer 10 spacecraft before launch

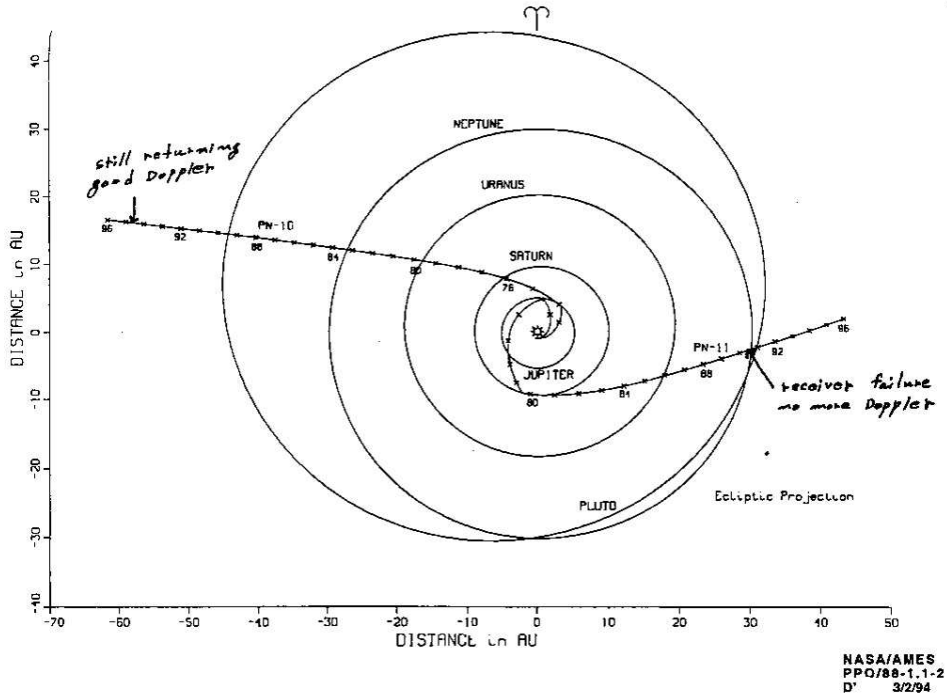

Figure 2: Trajectories of Pioneer 10 and 11

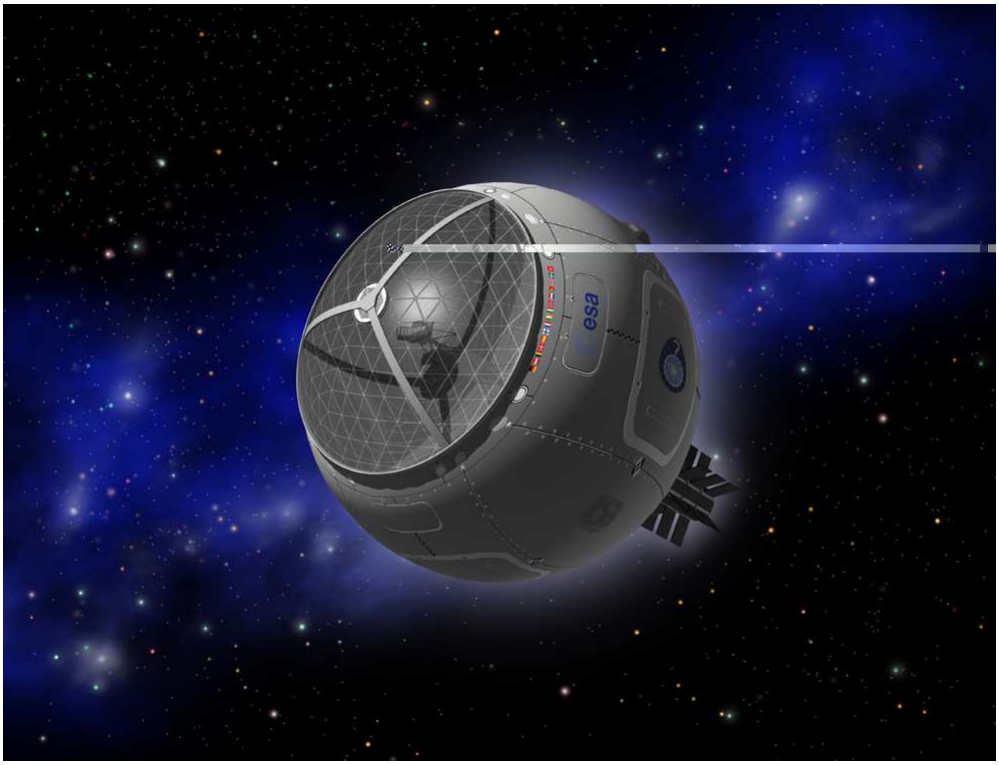

Figure 3: Artist's conception of the Sputnik V mission