Proposal in Response to the ISSI Call for International Teams:

INVESTIGATION OF THE PIONEER ANOMALY AT THE ISSI

Abstract

To date, the Pioneer 10 and 11 spacecraft are the most precisely navigated deep-space vehicles. However, as indicated by their radio-metric data, the Pioneers' orbit reconstructions were limited by a small, anomalous, constant, blue-shifted, Doppler frequency drift. The drift can be interpreted as due to a constant sunward acceleration of $a_P = (8.74 \pm 1.33) \times 10^{-8}$ cm/s^2. This interpretation has become known as the Pioneer anomaly [1]. Although the most obvious explanation would be that there is a systematic origin to the effect, the limited set of the analyzed data does not support any of the suggested mechanisms. We assert that analysis of the entire existing Pioneer data is vital to understanding the anomaly and, hopefully, to finding its origin. Indeed, analysis of the entire existing Pioneer data record is critical in attacking the anomaly on two fronts: (i) an analysis of the early, not rigorously analyzed, data could yield a more accurate direction of the anomaly and hence might help to determine its origin; (ii) by using the entire data set, from 1972 to 2002, one could study the temporal evolution of the anomaly and determine if it is due to on-board nuclear fuel inventory and related heat radiation.

The limited data analyzed previously allowed the detection of the anomaly in the Pioneer data, but not a determination of its origin. With new knowledge of all on-board processes and a diverse team, we propose a two-step process in understanding the origin of the anomaly, namely: (i) analysis of the entire set of existing Pioneer 10 and 11 data, obtained from first launch to the last telemetry received from Pioneer 10, on 27 April 2002, when it was at a heliocentric distance of 80 AU. This data could yield critical new information about the anomaly. If the signal is confirmed and is not due to an on-board systematic, (ii) we will use our new knowledge to develop an instrumental package that will be capable to provide an independent confirmation of the anomaly. We will also study a design for a dedicated mission to explore the anomalous behavior of the Pioneer spacecraft.

This ISSI investigation could lead to a determination of the origin of the anomaly and to a characterization of its physical properties. The proposed investigation is scientifically important, it is timely, and is well situated in Europe. The investigation would be an excellent example to demonstrate the value of interdisciplinary teams in addressing complex problems in fundamental physics and in application of new technologies in spacecraft and mission designs. The results of this study could find their way into many other areas of space-exploration applications in the near future. The most important outcome of this study will be the understanding of the Pioneer anomaly.

1. Scientific Rationale

There is a strong agreement in the community that analyzing the entire existing Pioneer data set is a vital step towards understanding the anomaly and, hopefully, to finding its origin. Indeed, what is alarming is that the Pioneer 10 data within 40 AU from the Sun was never analyzed in detail. Further, at large distances the S-band Doppler observable has limited sensitivity to plane-of-sky acceleration components, thus limiting the accuracy of 3-dimensional orbit reconstruction. Even so, an approximately constant anomalous acceleration is seen as close in as 10-15 AU: Pioneer 11 shows a small anomaly during its Jupiter-Saturn cruise with a fast increase to the size of a_P as it reached its hyperbolic escape orbit after passing by Saturn.

We propose to explore the Pioneer anomaly with the entire set of available Pioneer 10 and 11 Doppler data. In this effort we propose (i) to use the entire data interval in the analysis; (ii) to recalibrate the contribution of gas leaks and any mismodeled maneuvers to the trajectory solution; (iii) to further address the issue of collimated thermal emission from the on-board power source, (iv) to characterize the anomaly in more detail, including the thermal and the distance dependencies of the effect, and (v) to test various mechanisms proposed to explain the anomaly.

There is a significant interest, among the international scientific and technology communities, in considering either a self-standing mission or an additional payload package to investigate the Pioneer anomaly. The theme of a Pioneer anomaly exploration is prominently featured in many documents presented by scientists from ESA and NASA. It was featured in the presentations and final documents of the ESA Cosmic Vision Workshops 2004-05, meetings of the ESA's Fundamental Physics Advisory Group (FPAG) in 2004-05, and also in the recommendation of the FPAG for a Roadmap in Fundamental Physics. There is also a growing number of papers published on the subject and several initiated institutional and industrial studies for a possible deep space mission both in the US and in Europe. In early 2006, there will be a major symposium where the results of several ESA-sponsored industrial studies for the Pioneer Anomaly Explorer will be presented to the scientific community and where scientists will have the opportunity to present their suggestions for possible explanations of the effect.

The ISSI opportunity is very timely for the work on the exploration of the Pioneer anomaly – a theme in the ESA Cosmic Vision 2020. We propose to initiate, develop, and coordinate the strategy of scientific and technical work to support these processes from the ISSI, as an ideal institute to harbor the core of these activities in Europe.

The Data and Needed Preparations

The earlier analyses of the Pioneer anomaly were limited by a relatively short data span of 11.5 years of Pioneer 10 data with 20,055 points from 40-70.5 AU and 3.75 years of Pioneer 11 data with 19,198 points from 22.42-37.1 AU. For this investigation we will use the early data from 1972 through the end of 1986 and add new data from 1998.5 to March 2002. An effort to retrieve the early data, existing on obsolete-format magnetic tapes, and transfer it to modern DVDs is being initiated at JPL. The transfer will be complete, making the entire data record available, as early as July 2005. We will also have extended data record describing the spacecraft events.

There will be a much larger dataset available for this analysis: for *Pioneer 10* the entire available data set will cover mission events from launch on 2 March 1972 to the last telemetry data point received from the spacecraft on 27 April 2002. This interval spanned heliocentric distances from ~1–80 AU. The total 30+ years, Pioneer 10 data set might have ~80,000 data points. For *Pioneer 11*, the entire available data set will cover the period from 5 April 1973 to 1 October 1990. This interval spanned heliocentric distances from ~1–37.1 AU. The total 17.5 year, Pioneer 11 data set might have ~50,000 data points. The new combined data record will be almost 130,000 data points or ~90,000 points larger compared to ~39,233 that were used in the previous investigation.

Since the time of our previous analysis, the physical models for the Earth's interior and the planetary ephemeris have greatly improved. This is due to the progress in GPS- and VLBI-enabling technologies, Doppler spacecraft tracking, and new radio-science data processing models and algorithms. For the proposed investigation, we will update our orbit determination programs with the latest models adopted by the IERS and will use the latest planetary ephemeris. This will improve the solutions for the DSN ground station locations by two orders of magnitude (1 cm) over that of our previous analysis. Additionally, this will allow us to better characterize not only the constant part of the anomalous acceleration, but also the annual and diurnal terms detected in the Pioneer 10/11 Doppler residuals [1].

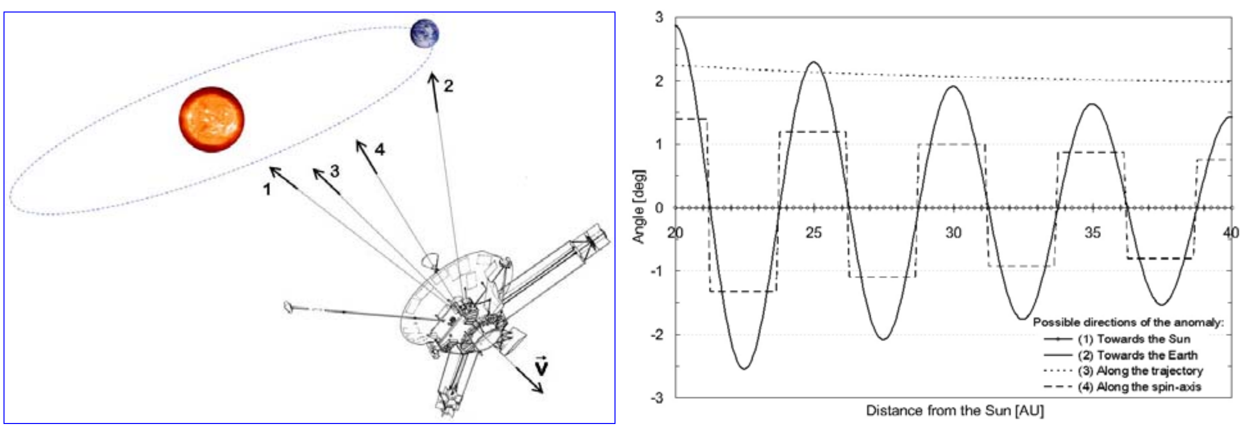

Figure 1. Left: Possible directions and thereby indicated origins for the Pioneer anomaly: 1) Towards the Sun: gravity? 2) Towards the Earth: frequency standards? 3) Along the velocity: drag or inertia? 4) Along the spin axis: internal systematics? Right: Possible directional modulation of the Pioneer anomaly. The early Pioneer data can easily discriminate between these four directions with clearly different behavior [2].

The Goal for the Analysis

Before any discussion of a deep space mission can be initiated one has to fully explore the data that is already at hand [3]. Such an analysis is critical for attacking the anomaly on two fronts, namely the directional sensitivity of the earlier data and any temporal changes addressed with the entire segment, namely:

<u>Earlier data</u>: An analysis of the earlier Pioneer data could yield a more accurate direction of the anomaly and hence its origin: (i) the *sunward direction* would indicate a force originating from the Sun, (ii) the *Earth-pointing* direction would be due to an anomaly in the frequency standards, (iii) the direction of the *velocity vector* would indicate an inertial force or a drag force, or (iv) the *spin-axis direction* would indicate an on-board systematic. These directional signatures are distinct and could be extracted from the earlier data [2-3].

Therefore, the increased data span, and especially the earlier data segment, will be crucial in our ability to determine the direction of the anomaly and, thus, its true nature. Thus, if the anomaly is due to some not-yet understood systematic generated on-board, it will most likely be directed along the spin-axis of the spacecraft. As such, the solution for the anomaly will be different after each re-pointing of the spacecraft. Specifically, every re-pointing will produce a step-function discontinuity in the solution for the anomalous acceleration. Earlier in the mission, there were many of these re-pointing maneuvers; understanding their impact on the anomaly would be a very important activity of the proposed analysis of the earlier data.

From the present distance of Pioneer 10, the four possible directions of the anomaly (towards the Sun, the Earth, and along the spin-axis or velocity vectors are very close and, thus, it is quite difficult to separate one direction from another. (This is because there are a number of known forces that act along those same directions; for instance, solar radiation pressure, 8W telecommunication radio-beam, thermal radiation, gas leaks, etc.) The data we used in our previous analysis, were taken from distances between 40 AU and 70.5 AU when the spacecraft was re-pointed only once per year. We have not seen the discontinuity in our solutions for the anomalous acceleration.

<u>Entire data set:</u> One could also study the temporal evolution of the anomaly by using the entire data set. Then, if the anomaly is due to on-board nuclear fuel inventory and related heat radiation from the vehicles, one would expect a strong correlation between the decay of the anomaly's magnitude and the Plutonium half-life of 87.74 years. The available 30+ years interval of data might be able to demonstrate the effect of a ~21% reduction in the anomaly value. Any such exponential decay could not be seen with the 11.5 years of Pioneer 10 data. This behavior, although difficult to disentangle from solar radiation, would be the strongest support for a thermal origin of the anomaly. Thus, the longest possible data interval is of great importance.

Also, with the addition of the earlier data (where the spacecraft re-pointing maneuvers were performed twice per year), we expect to improve the sensitivity of our solution in the directions perpendicular to the line-of-sight by at least an order of magnitude. Therefore, the extended data set augmented by all the ancillary spacecraft data, will help us not only to precisely identify the direction of the anomaly, but also to put tighter bounds on its time and distance dependence, and, thus, to establish the true nature of the Pioneer anomaly.

This analysis is critical, requires a team with extensive expertise in navigation, spacecraft design, modeling for small forces, and, most importantly, a collaborative environment and team interaction. As such, the proposed work is ideally suited for the ISSI.

2. Expected Outcome

The objective of this proposal is twofold: First, we propose to investigate the nature of the anomalous acceleration seen in the Pioneer 10 and 11 Doppler residuals. Specifically, we propose to use a longer data span of ~30+ years to determine the 3D components of the anomaly and to put tighter bounds on the possible time variation of the effect. This analysis will determine whether the anomaly is due to some not-yet understood systematics or it is a manifestation of new physics. The second objective is to produce a complete archive of the tracking, engineering, and supporting data that will be made available to the scientific community.

Bringing our analysis programs up to date is also necessary. The models for the Earth's orientation, ephemeris, atmosphere and ionosphere have been greatly improved since our previous analysis. New station locations, crustal motions, and atmospheric and ionosphere effects will be implemented into the analysis programs at JPL. Sophisticated, detailed algorithms to describe gas leaks and heat loss of the Pioneer spacecraft will be developed and implemented in our analysis programs. The engineering, navigational and telemetry records for the craft will also be updated. By also incorporating the previously unmodeled high-rate data (1 second) we expect that we will be able to reduce the systematic uncertainties due to gas leaks and heat by an order of magnitude.

The first phase of the proposal will be dedicated primarily to preparation of the data and the upgrade of the orbit determination and analysis programs. There were many thousands of tracking data passes from 1972 to 2002, each of which needs careful analysis, editing and processing. It is a slow and tedious process but it is a necessary step in achieving the desired results. This task will involve processing each data pass separately in order to remove corrupted data and to determine the spin rate during the pass. This process will be initiated at JPL in August-October 2005. The team input will be critical in producing the acceleration residuals needed for the further analysis. We expect a significant remote interaction prior to the first team meeting at the ISSI scheduled for November 2005. This remote interaction would make the face-to-face meeting more productive.

Most of the work in the second phase of this project is portable and can be done on laptops. This work will involve fitting various models with the acceleration residuals produced during the prior phase of the project. It will focus on the data analysis and results interpretation, and is most effective when done at face-to-face meetings. This is exactly the purpose of the proposed collaborative work at ISSI that will be vital in addressing the problem. This work will involve the entire team. The team composition and effort are adequate for the funding requested; a large existing collaboration will aid with modeling and interpretation.

The proposed analysis is difficult but relatively straightforward; it either will find support for on-board systematics or will provide evidence for an external origin of the anomaly. Both outcomes would be of major importance: (i) understanding the on-board systematics will lead to improved attitude control systems for low disturbance spacecraft design, (ii) an external origin of the anomaly might point to new physics and ultimately lead to a new mission to deep space. The ISSI as the host institution of this multidisciplinary work will be a clear winner in both situations.

The ultimate goal of the proposed research is to determine the true direction of the anomaly and its magnitude. We will also investigate the applicability of a number of suggested theories and will test them against the data. We will publish the results of our analysis in scientific journals.

References:

[1]. J. D. Anderson, P. A. Laing, E. L. Lau, A. S. Liu, M. M. Nieto, S. G. Turyshev, "Indication, from Pioneer 10/11, Galileo, and Ulysses Data, of an Apparent Anomalous, Weak, Long-Range Acceleration," *Phys. Rev. Lett*. **81**, 2858-2861 (1998). [arXiv:gr-qc/9808081]; *ibid.,* "Study of the Anomalous Acceleration of Pioneer 10 and 11."*Phys. Rev. D* **65**, 082004/1-50 (2002), [arXiv:gr-qc/0104064]

[2]. M. M. Nieto, S. G. Turyshev, "Finding the Origin of the Pioneer Anomaly," *Class. Quant. Grav.* 21 (2004) 4005-4023. [arXiv:gr-qc /0308017].

[3]. S. G. Turyshev, M. M. Nieto, and J. D. Anderson, "A Route to Understanding of the Pioneer Anomaly." [arXiv:gr-qc/0503021]

[4]. S. G. Turyshev, M. M. Nieto, and J. D. Anderson, "Lessons Learned from the Pioneers 10/11 for a Mission to Test the Pioneer Anomaly," [arXiv:gr-qc/0409117]

[5]. M. M. Nieto, S. G. Turyshev, and J. D. Anderson, "The Pioneer Anomaly: The Data, its Meaning, and a Future Test." [arXiv:gr-qc/0411077]

3. Reasons for choosing ISSI as implementation site

One of the major factors impeding progress in this field is that the scientists analyzing spacecraft navigation data and those studying on-board generated systematics are generally situated in two communities. Bringing these people together is one of the main aims of this activity. The team activity will involve theorists, experimentalists and mission designers who will exploit the data sets and spacecraft models available at ISSI during their sessions. These people work in separate institutes in Europe and the USA, and ISSI is an excellent common ground to bring them together.

ISSI is, almost by definition, the ideal environment to perform the coordinated data analysis of the various data sets obtained by Pioneers 10 and 11. The team members will compare their data modeling and analysis techniques, and will provide the reduced navigational residuals as input parameters to the participating theoreticians. The theorists will demonstrate how their models attempt to describe the measurements and show what parameters need to be measured to understand the underlying physics. The results will be a firm basis for any future space mission proposed to investigate the Pioneer anomaly.

Few individual groups have sufficient breadth for the cross fertilization that is required for this proposal to understand the origin of the Pioneer anomaly. This ISSI team will bring together specialists from around the world to enable the desired interdisciplinary sharing of ideas and methods. The ISSI study team will be a unique occasion to achieve cooperation on the needed larger scale.

4. List of confirmed participants [Brief CVs appended]

The team is comprised of researchers active in the fields of solar system research, gravitational physics, thermal analysis, navigation, attitude control, and solar plasma/spacecraft interaction:

1. John D. Anderson, Jet Propulsion Laboratory, Pasadena, CA, USA
2. Orfeu Bertolami, Instituto Superior Técnico, Lisboa, Portugal
3. Bernd Dachwald, DLR, Institute of Space Simulation, Köln, Germany
4. Hansjoerg Dittus, ZARM, University of Bremen, Bremen, Germany
5. Ulrich Johann, Astrium Space, Friedrichshafen, Germany
6. Dario Izzo, ESA-ESTEC, Noodrwijk, The Netherlands
7. Claus Laemmerzahl, ZARM, University of Bremen, Bremen, Germany
8. Michael Martin Nieto, Los Alamos National Laboratory, Los Alamos, NM, USA
9. Andreas Rathke, ESA-ESTEC, Noodrwijk, The Netherlands
10. Serge Reynaud, Lab. Kastler-Brossel, Paris, France
11. Wolfgang Seboldt, DLR, Institute of Space Simulation, Köln, Germany
12. Slava G. Turyshev, Jet Propulsion Laboratory, Pasadena, CA, USA – Team Leader

5. Schedule of the project [Number and duration of meetings, anticipated periods, number of participants, if different from full team, etc.]

Two initial sessions are planned, about one week long, in the late autumn of 2005 and the summer of 2006. There will be a possible final session in the autumn of 2006, if ISSI financing and planning allows. The final session may be replaced by internet conferencing. The second and/or third session formats will be decided at the first session.

A. Team Meetings at ISSI:

- First meeting: 7-11 November 2005 or 21-25 November 2005
- Second meeting (tentatively): 15-19 May 2006 or 12-16 June 2006
- Third meeting (tentatively): 9-13 October 2006 or 13-17 November 2006, to be selected by consensus among team members and in agreement with ISSI planning.

Goals for Meeting #1:

- Initial data preparation: editing, calibration, assembly of the entire dataset; establishing the spacecraft, maneuvers data file; updating standard models for small forces;
- Preliminary processing and analysis of the anomalous residuals; investigation of the suggested mechanisms; beginning of the modeling and interpretation work.

Goals for Meeting #2:

- The focus of work is same as above, but with emphasis on the modeling and interpretation of the anomalous residuals.

Goals for Meeting #3:

- Not planned yet. But should the anomaly be confirmed in the course of these investigations, we shall consider the possibility of testing for the anomaly either as an add-on instrument on a deep space mission or on a dedicated mission [3-6]. Will be determined before Meeting #2.

B. Remote Cooperation:

We will continue and strengthen our contacts and cooperation (also between the meetings). The main items for a "remote cooperation" (between the meetings) are:

1. Data preparation, modeling, and analysis; annual and diurnal terms; planetary fly-bys modeling; thermal models of spacecraft, residual generation with the JPL's orbit determination program; transition to a portable code native to a laptop computers
   - Initiative: J. D. Anderson, S.G. Turyshev, M.M. Nieto, A. Rathke, C. Laemmerzahl;
2. Modeling update, including small spacecraft-generated and environmental forces
   - Initiative: S.G. Turyshev, M.M. Nieto, B. Dachwald, W. Seboldt, H. Dittus, U. Johann;
3. Modeling update, focusing on new suggested mechanisms and scenarios:
   - Initiative: S.G. Turyshev, M.M. Nieto, O. Bertolami, S. Reynaud, C. Laemmerzahl;
4. Instrument and mission design:
   - Initiative: H. Dittus, U. Johann, A. Rathke, D. Izzo, S.G. Turyshev, M.M. Nieto, B. Dachwald, W. Seboldt, C. Laemmerzahl, O. Bertolami, S. Reynaud, J. D. Anderson.

6. Facilities required

(i) Computers for data and model handling: programs and compilers: MATLAB, IDL, other TBD, (ii) Data and model storage space, TBD, (iii) Access to several solar system data and spacecraft databases, (iv) Internet access, networked room, overhead projector and beamer.

7. Requested budget and available resources

[Financial requirements from ISSI and available alternative funding sources.]

We are an international team with 12 members and, at the moment, would only be able to pay for our travel to Bern. We request that ISSI provides accommodation for the 12 members of the team, two times a year for a duration of one week each time, and a few days of specially invited guests over a period of 12 months. At the moment we envision two sessions. But after the first session we may request an additional, third, session with partial attendance, if the financial conditions at ISSI were to allow this request. Internet conferences are also a possibility.