INNOVATIVE EXPLORER MISSION TO INTERSTELLAR SPACE

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A mission to interstellar space has been under discussion for over 25 years. Many fundamental scientific questions about the nature of the surrounding galactic medium and its interaction with the solar system can only be answered by in situ measurements that such a mission would provide. The technical difficulties and budgetary and programmatic realities have prevented implementation of previous studies based on the use of a near-Sun perihelion propulsive maneuver, solar sails, and large fission-reactor-powered nuclear electric propulsion systems. We present an alternative approach – the Innovative Interstellar Explorer – based on Radioisotope Electric Propulsion. A high-energy, current-technology launch of the small spacecraft is followed by long-term, lowthrust, continuous acceleration enabled by a kilowatt-class ion thruster powered by Pu-238 Stirling radioisotope generators. We describe the science, payload, and mission and spacecraft design. We also discuss the role such a mission plays in assessing heliospheric "space climate," knowledge of which is vital for human exploration to Mars and beyond.

Keywords: Interstellar space, interstellar mission, interstellar medium, RTG, electric propulsion.

1. INTRODUCTION

Our first mission into interstellar space will concentrate on exploring the distant frontier of the solar system and the galactic region immediately beyond. Although this first step toward truly interstellar flight of the future is modest, it would be an important moment in the history of the planet Earth with the human race embarking on exploration, and ultimately expansion, beyond the boundaries of its home stellar system.

Such an exploratory mission has been evaluated on practical scientific and engineering levels since the conference on "Missions Beyond the Solar System" held at NASA's Jet Propulsion Laboratory in 1976 [1]. The so called interstellar precursor mission, or Interstellar Probe, have continued to be discussed by individual authors [2-8], as well as identified as a scientific priority by consensus documents in the science community [9].

The desire to reach the unperturbed interstellar medium 300-400 AU from the sun in twenty years, a half of an professional life time of a scientist and engineer, requires spacecraft velocities approaching 100 km/s. This requirement presents a formidable challenge. Various approaches were considered for achieving high velocities: near-Sun powered perihelion maneuvers (chemical and solar thermal propulsion, or STP), solar sails, nuclear electric propulsion (NEP), and nuclear ther-

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Nomenclature

RPS (Radioisotope Power Source) – electrical power source whose energy is ultimately derived from the energy of the decay of radioisotopes.

RTG (Radioisotope Thermoelectric Generator) – RPS that relies upon the Seebeck effect to produced electrical power passively from thermal gradients.

SRG (Stirling Radioisotope Generator) – dynamic RPS that uses a mechanical Stirling cycle heat engine to convert heat produced from radioisotope decay to electrical power.

REP (Radioisotope Electric Propulsion) – electric propulsion system powered by an RPS.

NEP (Nuclear Electric Propulsion) – electric propulsion powered by a nuclear (fission) reactor.

MMRTG (Multi-mission RTG) – RTG to be used in a variety of environments including hard vacuum and planetary atmospheres, in particular that of Mars.

LISM (Local Interstellar Medium) – the interstellar medium surrounding the solar system.

AU (astronomical unit) – 1 AU = 1.49598×10^{11} m is the mean distance between the Earth and the Sun mal propulsion (NTP). Many other more exotic technologies were considered but their technology readiness levels (TRL) remain too low for a mission to be launched within the next 10-15 years.

The last major review of Interstellar Probe conducted by NASA in 1999 based the implementation on the maturing solar sail technology [9]. Changing political climate has finally allowed return to practical evaluation of nuclear power for space flight. NEP-based propulsion systems are inherently large and heavy and their launch would consequently be enormously costly. This consideration and advancement of technologies of radioisotope thermoelectric generators (RTG) point at an alternative: electric propulsion system powered by a radioisotope power source (RPS). Consequently, we concentrate on the Innovative Interstellar Explorer (IIE), a small spacecraft achieving the required velocity by high-energy launch using current launch vehicle technology followed by long-term, low-thrust continuous acceleration enabled by a kilowatt-class thruster powered by advanced Stirling radioisotope generators (SRG). Cost realities would inevitably delay a launch of an interstellar probe with an unavoidably heavy NEP-type power source until the time when significant reduction in cost of access to space will have been achieved. Our approach offers a critically important programmatic advantage of enabling the first step into interstellar space sooner rather than later.

2. MISSION SCIENCE

The primary goal of the first interstellar mission is to reach the unperturbed, "virgin" interstellar medium and to examine its properties in situ. The physics and state of the LISM are not known in many important details [10-12]. Figure 1 shows a schematic of the sun's interstellar frontier and galactic neighborhood. The sun moves with respect to the surrounding interstellar medium with the velocity 26 km/sec, or ~5 AU/yr. This motion is described as the interstellar wind, with the wind direction close to the ecliptic plane. The heliosphere is the region where the sun controls the state and behavior of the plasma environment [13-15]. Fluxes of energetic neutral atoms disturb the interstellar medium even beyond the hypothetical bow shock [16-18], and the pristine interstellar medium is expected at the distances 300-400 AU from the Sun.

Experimental data on the heliosphere interaction with the local interstellar medium (LISM) and on the properties of the region of the heliospheric interface are scarce, mostly indirect, and often ambiguous. A selfconsistent model of the heliosphere has yet to be built and many aspects of the interaction are not understood. Therefore, the second major goal of the first interstellar mission is to explore the solar system frontier. Today, Voyager 1 and 2 spacecraft are still operational and have speeds in excess of the escape velocity from the Sun and will penetrate into interstellar space. Powered by RTGs, the spacecraft all have a finite lifetime due to the half life of the ^{238}Pu fuel (89 years) as well as degradation of the Si-Ge converters in the RTGs. The Voyagers form the Voyager Interstellar Mission with the goal of penetrating the termination shock of the solar wind, reached by Voyager 1 at 94 astronomical units (AU) from the Sun in December 2004 [19-23].

The Voyagers will unlikely reach the "undisturbed" interstellar medium prior to falling silent. In addition, the spacecraft were instrumented for planetary flybys and not for study of the heliospheric frontier. There are many fundamental science questions, however, that can only be addressed by instrumentation that actually penetrates outside of the heliosphere [3-9, 24]. The specific goals of such in situ investigation include:

Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in the Galaxy. We know amazingly little about the nature of the LISM. For example, measurements of rotation measures and dispersion measures of pulsars suggest a large scale magnetic field of ~1.4 μG, but we have no idea of the field structure or its variations within 0.1 or even 0.01 light years (LY). In addition, we do not know the direction of the magnetic field in the surrounding interstellar medium. Similarly, the properties of the nonthermal portion of the medium (including the low-energy galactic cosmic rays) remain unknown.

Explore the structure of the heliosphere and its interaction with the interstellar medium. The Voyager Interstellar Mission may establish the distance to the termination shock, but a farther-ranging probe is required to understand the dynamics of the interaction and how it is influenced by the conditions in the LISM.

Explore fundamental astrophysical processes occurring in the heliosphere and the interstellar medium. Shock acceleration of particles has profound impacts upon many branches of astrophysics. In addition, the structure of the solar wind interface with the LISM has analogs in many other astrophysical settings.

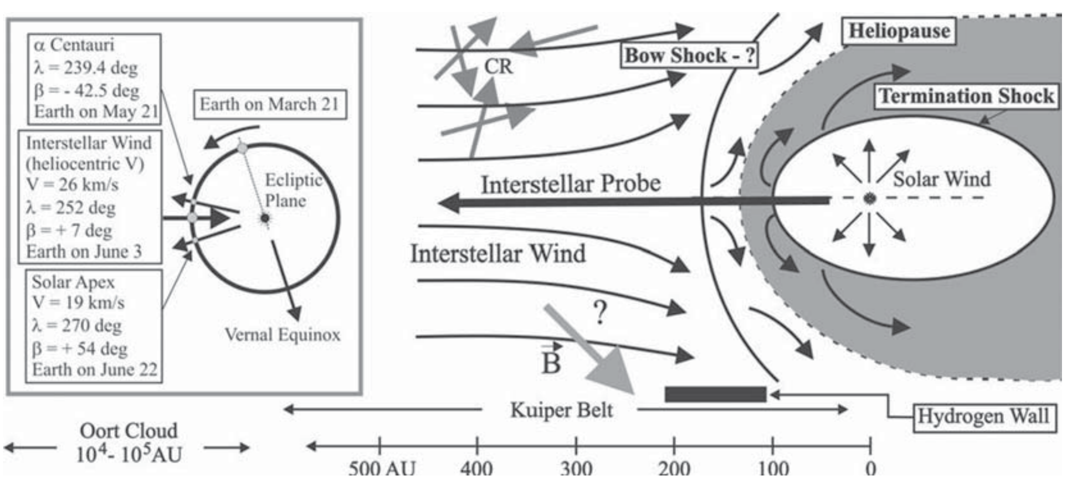

Fig. 1 Sun's galactic neighborhood (right). Box (left) shows important directions in the ecliptic plane (interstellar wind vector, apex, α-Centauri).

Determine fundamental properties of the Universe. Measurements of ^{3}He, D, and ^{7}Li would give constraints on big-bang nucleosynthesis and on how these key indicators have been processed in the interstellar medium. Extremely accurate tracking of a probe can be used to look for gravitational waves and a non-zero cosmological constant, and/or other anomalous forces such as that inferred to be acting on several deep-space missions [25]. Polarization measurements of the downlink carrier can be used to look for inherent anisotropies in the structure of space [26].

A mission into interstellar space will be complemented by the new remote techniques imaging the three-dimensional heliospheric boundary. The heliosphere is essentially asymmetric and its sheer size calls for remote probing of the heliospheric interface with the interstellar medium. One technique – imaging of the heliosphere in fluxes of energetic neutral atoms (ENA) – is mature [27-28] and it will establish the properties of the termination shock and probe the plasma in the heliospheric sheath, the region between the termination shock and the heliopause [28]. In early 2005, NASA selected a mission, the Interstellar Boundary Explorer (IBEX), to image the heliosphere in ENA fluxes [29]. The heliopause, the boundary separating solar and galactic plasmas, can be mapped in extreme ultraviolet [30-32]. Mapping of the heliopause requires enabling advances in instrumentation technology.

Several studies explored in detail the scientific payload for a mission to the interstellar space [9,24]. The instrumentation package to achieve the science goals of our Innovative Explorer Mission includes the following nine instruments: plasma analyzer, energetic particle sensor, plasma wave sensor, magnetometer, neutral atom detector, energetic neutral atom detector, Lyman-α sensor, cosmic ray detectors, and cosmic dust detector. Based on the current state of the instrumentation technology and assuming some incremental advances in instrumentation, we estimate the total mass of the science payload as 35 kg. The payload would require 30 W of power and broadcast at a 500 to 5800 bit per second data rate, depending upon the final implementation.

3. MISSION

Within the last few years, two approaches have been pursued in some detail: the use of a solar sail [9] at low thrust with a gradual build up of escape speed within a few AU from the Sun and the use of a powered solar gravity assist [6]. More massive schemes based upon nuclear electric propulsion seem to be unrealistic in the near future. Cost realities would inevitably delay a launch of an interstellar probe with an unavoidably heavy NEP-type power source until the time when significant reduction in cost of access to space will have been achieved. Our approach based on radioisotope electric propulsion offers a critically important programmatic advantage of enabling the first step into interstellar space sooner rather than later.

We base our mission on a launch by the existing NASA heavy launch vehicle such as Atlas V 551 – Star 48V which should place the spacecraft in Earth escape with C3 ~125 km^2/s^2. A Jupiter gravity assist adds ~25 km/s and a realistic electric propulsion system provides an equivalent of 15 km/s. The launch is optimized for a 1 kW electric thruster system (about the maximum power that can reasonably be supplied by RPSs) and generous (and likely prudent) mass margins. To reach the required large escape velocity, two stacked Star 48A solid rocket motors are used. They and the associated adaptors easily fit within the shroud of the existing heavy launch vehicles (Fig. 2). By requiring existing launch hardware, the new flight qualifications are minimized to those for this launch combination and RPSs optimized for mass-to-power output.

In a specific example of a possible mission the spacecraft is launched on 23 October 2014; it reaches a heliocentric distance of 104 AU in 17.7 years on 19 June 2032. The spacecraft bus including science, power, propulsion, and margin mass is taken as 758 kg. The power and electric propulsion system are 244 kg. Launch mass includes 453 kg of the Xe propellant. With an I_{sp} of ~3800 s and a mass flow rate of 67 mg/day, the ion engine requires 1 kW of electrical power that can be supplied by 9 SRGs, each providing 114 W at beginning of life (BOL). The engine operates for 6465 days (~155,000 hours). At 104 AU, the probe is traveling at 38 km/s (8.0 AU/yr) and requires an additional ~12 years to reach 200 AU. The numbers are based upon generous 155 kg of contingency and margin, and so represent an upper limit on the flyout time to 200 AU.

Current observations established the termination shock at 94 100 AU away [19-23], with the heliopause, the boundary separating solar and galactic plasmas, somewhere at 150-200 AU in the heliospheric nose direction. So, the minimum required distance to reach the interstellar medium is 200 AU with a preferred flyout time of 15 to 25 years. We note that the unperturbed, "virgin" interstellar medium is expected to be found only at the distances beyond 300-400 AU. Further

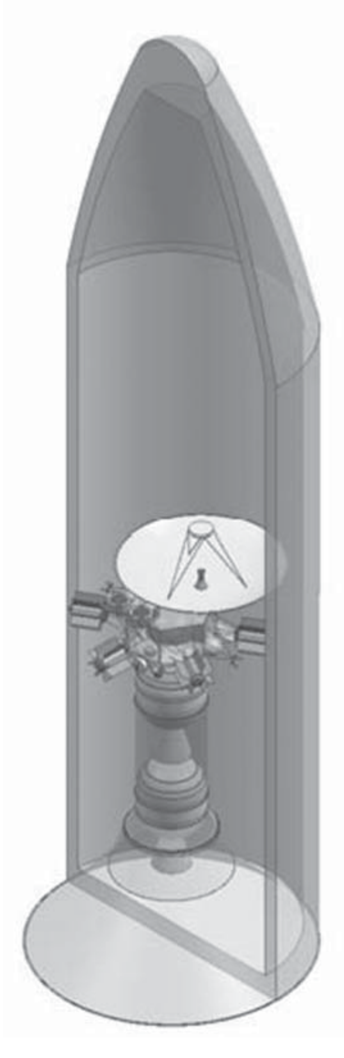

Fig. 2 Innovative Interstellar Explorer under the shroud of the launch vehicle.

distances (~1000 AU) for longer times (up to 100 years at 8 AU/yr) are preferred but pose significantly more demands on both propulsion and spacecraft.

In the mission design, all planetary gravity assists were considered from 2010 through 2050, as well as a "direct" trajectory. This confirmed that the most efficient approach was to use a Jupiter gravity assist and an aimpoint within 20° of the "heliospheric nose." We allowed for 20-day windows in a given year as well as backup launch windows (albeit at decreased performance) for three years following the "prime" window. The next prime window occurs in 2014 with backups at roughly 13-month intervals through January 2018. The pattern recurs about every 12 years, the next prime window following that of 2014 being in 2026. The required C3, Jupiter gravity assist parameters, and electric propulsion system performance were optimized across the entire trajectory from launch through a heliocentric distance of 200 AU.

4. SPACECRAFT

The Innovative Interstellar Explorer spacecraft concept is shown in fig. 3. Most critical technical challenges for spacecraft design are efficient radioisotope power sources, communication link, and spacecraft attitude control. The communications and antenna pointing become especially important with the increasing distance from the Sun. Spacecraft pointing is driven by communications requirements from deep space, taken here as 200 AU. The dry mass is driven by the power supply mass and its associated inefficiencies in turning heat into electrical power, and, finally, thrust.

With the help of JPL's Team-X, four different options were studied for the optimal launch window of 2014. We considered 1 kW and 750 W engines at varying levels of technology "aggressiveness." The Innovative Interstellar Explorer requires especially mass-efficient power sources. While the baseline design uses Stirling Radioisotope Generators (also minimizing ^{238}Pu usage) electromagnetic interference of such units with the plasma wave and magnetometer instruments are only now being assessed.

The optimal thrust direction is not in the exact direction toward Earth; in addition, a spinning spacecraft is preferred to enable scanning the sky for "field and particles" payloads with minimal instrument mass. To play data back to Earth, the spacecraft spin axis must be moved (by a monopropellant hydrazine attitude control system) to reorient the high-gain antenna toward Earth. By employing two downlink periods of 8 hours each per week, the data could be sent to the ground without overly affecting the thrust efficiency; the nominal data playback rate is 500 bps.

A particularly vexing systems problem was the desire to have the high-gain antenna as well as multiple ions engines all on the axis of symmetry. The solution, shown in fig. 3 has the spin axis on the symmetry line of the RPSs and the xenon tank. This axis intersects a perpendicular line from the high-gain antenna and centerline of the two electric thrusters. Only one thruster can be used at a time (power limitation), but both are needed due to lifetime issues. With a spin rate of several rpm, the off-center thrusting averages out to provide the required net thrust with little loss in efficiency.

While an optical downlink would offer significant advantages, it requires pointing (beyond 100 AU) with prohibitive precision of a few microradians. Hence, the communications approach is to use a 3-meter high gain antenna, high-power traveling wave tube amplifiers, Ka-band, and a downlink to fully half of the planned 11 m diameter dish "farm" now under study for implementation by the NASA's Deep Space Network (DSN). During downlinks, additional power is switched from the "idling" electric engine. Once all the xenon is used (about 105 AU), the spin axis is left permanently pointing in the downlink direction, similar to the strategy employed on Pioneer 10 and 11 and on the Ulysses spacecraft.

5. CONCLUSIONS

The proposed concept of the Innovative Interstellar Explorer can be firmed up and technology advanced, making the mission launch possible by 2015. The time is right for the first step into interstellar space.

6. ACKNOWLEDGMENTS

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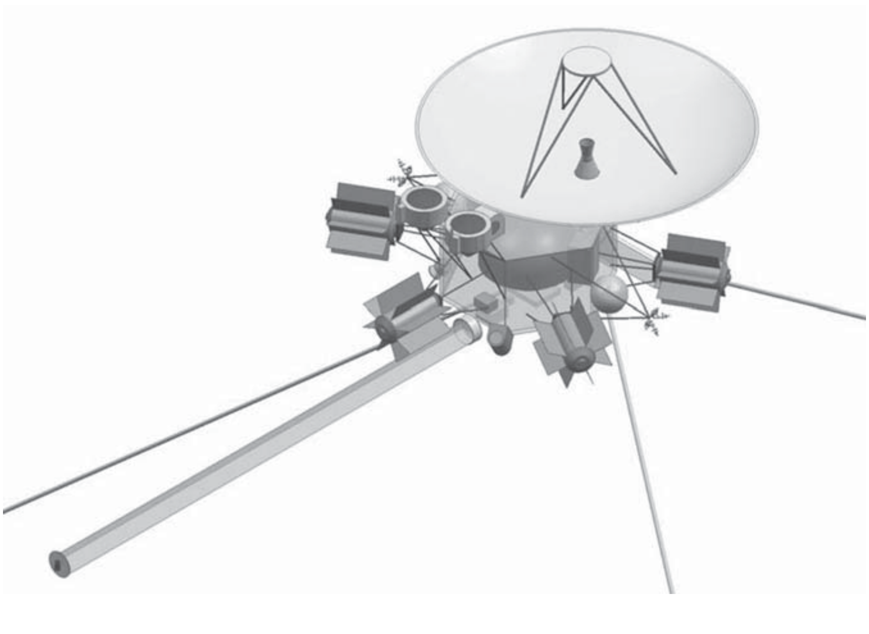

Fig. 3 Innovative Interstellar Explorer based on radioisotope electric propulsion. The structure is dominated by six RPSs, the 3-m high-gain antenna, and the two ion engines. A 5-m magnetometer boom extends to the lower left; three mutually-orthogonal 25-m plasma wave antennas are partially visible.

REFERENCES

1. L.D. Jaffe and C. V. Ivie, "Science aspects of a mission beyond the planets", *Icarus*, **39**, pp.486-494, 1979.
2. K.T. Nock, "TAU – A mission to a thousand astronomical units", *19th AIAA/DGLR/JSASS InternationalElectric Propulsion Conference*, Colorado Springs, CO, AIAA-87-1049, May 11-13, 1987.
3. T.E. Holzer *et al.*," The Interstellar Probe: Scientific objectives for a Frontier mission to the heliospheric boundary and interstellar space", NASA Publication, 1990.
4. R.A. Mewaldt, J. Kangas, S.J. Kerridge, and M. Neugebauer, "A small interstellar probe to the heliospheric boundary and interstellar space", *Acta Astron.*, **35**, Suppl.,pp. 267-276, 1995.
5. R.L. McNutt, Jr., R. E. Gold, E. C. Roelof, L. J. Zanetti, E. L. Reynolds, R. W. Farquhar, D. A. Gurnett, and W.S. Kurth, "A sole/ad astra: From the Sun to the stars", *JBIS*, **50**, pp.463-474, 1997.
6. R.L. McNutt, Jr., G.B. Andrews, R.E. Gold, R.S. Bokulic, B.G. Boone, D.R. Haley, J.V. McAdams, B.D. Williams, M.P. Boyle, G. Starstrom, J. Riggin, D. Lester, R. Lyman, M. Ewing, R. Krishnan, D. Read, L. Naes, M. McPherson, and R. Deters, "A realistic interstellar explorer", *Adv. Space Res.,* **34**, pp.192-197, 2004.
7. M. Gruntman, R.L. McNutt, Jr., R.E. Gold, S.M. Krimigis, E.C. Roelof, G.Gloeckler, P.L. Koehn, W.S. Kurth, and S.R, Oleson, "Innovative Interstellar Explorer", 55th International Astronautical Congress, Vancouver, Canada, IAC-04-IAA.3.6.4.07, 2004.
8. G.L. Matloff, G. Vulpetti, C. Bangs, and R. Haggerty, "The Interstellar Probe (ISP): Pre-perihelion trajectories and applications of holography", NASA-CR-2002-211730, June 2003.
9. P.C. Liewer, R.A. Mewaldt, J.A. Ayon, and R.A. Wallace, "NASA's interstellar probe mission", *STAIF-2000* Proc., 2000.
10. D.P. Cox and R.J. Reynolds, "The local interstellar medium", *Annu. Rev. Astron. Astrophys.*, **25**, pp.303-344, 1987.
11. P.C. Frisch, "Characteristics of nearby interstellar medium", *Space Sci. Rev.*, **72**, pp.499-592, 1995.
12. D. Breitschwerdt, "The local bubble", *Space Sci. Rev.*, **78**, pp.173-182, 1996.
13. E.N. Parker, *Interplanetary Dynamical Processes*, Wiley-Interscience, New York, 1963.
14. A.J. Dessler,"Solar wind and interplanetary magnetic field", *Rev. Geophys.*, **5**, pp.1-41, 1967.
15. W.I. Axford,.I., "The interaction of the solar wind with the interstellar medium", in *Solar Wind*, ed. by C.P. Sonnett, P.J. Coleman, and J.M. Wilcox, NASA Spec. Publ., NASA SP-308, pp.609-660, 1972.
16. M. Gruntman, "Effect of neutral component of the solar wind on the interaction of the solar system with the interstellar gas flow", *Sov. Astron. Lett.*, **8**, pp.24-26, 1982.
17. V.B. Baranov and Yu.G. Malama, "The model of the solar wind interaction with the local interstellar medium: Numerical solution of self-consistent problem", *J. Geophys. Res.*, **98**, p.15,157-15,163, 1993.
18. G.P. Zank, Interaction of the solar wind with the local interstellar medium: A theoretical perspective, *Space Sci. Rev.*, **89**, pp.1-275, 1999.
19. L.A. Fisk, "Journey into the unknown beyond", *Science*, **309**, pp.2016-2017, 2005.
20. E.C. Stone, A.C. Cummings, F.B. McDonald, B.C. Heikkila, N. Lal, and W.R. Webber, "Voyager 1 explores the termination shock region and the heliosheath beyond", *Science*, **309**, pp.2017-2020, 2005.
21. R.B. Decker, S.M. Krimigis, E.C. Roelof, M.E. Hill, T.P. Armstrong, G. Gloeckler, D.C. Hamilton, and L.J. Lanzerotti, "Voyager 1 in the foreshock, termination shock, and heliosheath", *Science*, **309**, pp.2020-2024, 2005.
22. D.A. Gurnett and W.S. Kurth, "Ele3ctron plasma oscillations upstream of the solar wind termination shock", *Science*, **309**, pp.2025-2027, 2005.
23. L.F. Burlaga, N.F. Ness, M.H. Acuna, R.P. Lepping, J.E.P. Connerney, E.C. Stone, and F.B. McDonald, "Crossing the termination shock into the heliosheath: magnetic fields", *Science*, **309**, pp.2027-2029, 2005.
24. M. Gruntman, "Instrumentation for interstellar exploration", *Adv. Space Res.*, **34**, pp.204-212, 2004.
25. J.D. Anderson, P.A. Laing, E.L. Lau, A.S. Liu, M.M. Nieto, S.G. Turyshev, "Study of the anomalous acceleration of Pioneer 10 and 11", *Phys. Rev. D*, **65**, p.082004, 2002.
26. B. Nodland and J. P. Ralston, "Indication of anisotropy in electromagnetic propagation over cosmological distances", *Phys. Rev. Lett.*, **78**, pp.3043-3046, 1997.
27. M. Gruntman, "Energetic neutral atom imaging of space plasmas", *Rev. Sci. Instrum.*, **68**, pp.3617-3656, 1997.
28. M. Gruntman, E.C. Roelof, D.G. Mitchell, H.-J. Fahr, H.O. Funsten, and D.J. McComas, "Energetic neutral atom imaging of the heliospheric boundary region", *J. Geophys. Res.*, **106**, pp.15767-15781, 2001.
29. D. McComas *et al.*, "The Interstellar Boundary Explorer (IBEX)", in *Physics of the Outer Heliosphere*, AIP Conf. Proc., **719**, eds. V. Florinski, N.V. Pogorelov, and G.P. Zank, Melville, NY: AIP, pp.162-181, 2004.
30. M. Gruntman, "Imaging the three-dimensional solar wind", *J. Geophys. Res.*, **106**, pp.8205-8216, 2001.
31. M. Gruntman, "Mapping the heliopause in EUV", in *The Outer Heliosphere: The Next Frontiers*, Proc. COSPAR Colloq., Pergamon, pp.263-271, 2001.
32. M. Gruntman, M. Lampton, and J. Edelstein, "Imaging three-dimensional heliosphere in EUV", *Solar Physics and Space Weather Instrumentation*, eds. S. Fineschi and R.A. Viereck, Proceedings of SPIE 5901, SPIE-5901-3, 2005.(see also http://astronauticsnow.com/GalacticFrontier/)

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