ANOMALY OF PIONEERS AND DENSITY OF SPACE

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ABSTRACT

From abnormal acceleration of Pioneers, density of Space above the Saturn's orbit was estimated at ~ 1.34×10^{-16} kg/m^3 = 8×10^{7} atoms H/dm^3. Inside of planetary system, at distances 1-5.8 au from the Sun, density of Space decreases down to ~ 0.26×10^{-16} kg/m^3.

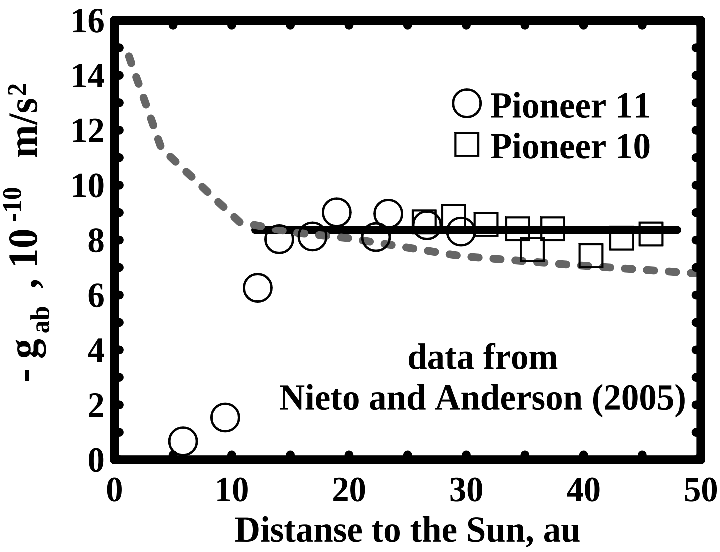

Fig. 1 Abnormal acceleration of Pioneer 11 (circles) and Pioneer 10 (squares). Data from Tab. 2 in Nieto and Anderson (2005). Solid line: average within the range 14-45.7 au from the Sun (-8.356×10^{-10} m/s^2). Dashed curve: detailed Murphy-Kats model, as calculated by Turyshev et al (2012).

Fig. 1 shows the data on abnormal acceleration of spacecrafts Pioneer 10 and 11, as obtained via numerical simulation of trajectories (data from Tab. 2 in Nieto and Anderson, 2005). Neglecting measurements at distances 5.8, 9.39, and 12.16 au from the Sun (1 au = 149597870.7 km), average value of abnormal acceleration is g_{ab} = -8.356×10^{-10} m/s^2 (see solid line in **Fig. 1**). The "unmodeled tag" was "directed towards the Sun" (Nieto and Anderson, 2005), and it caused unexpected deceleration of spacecrafts, flying outward from the Sun. Because of this, all measured values in **Fig. 1** are negative. Abnormal acceleration, obtained from numerical simulation of trajectories, was confirmed by independent measurement of red-shift of radio-emission from Pioneers (-8.74×10^{-10} m/s^2: Anderson et al, 2002).

During 20-years fly with radial velocity ~ 12 000 m/s, the "unmodeled tag", g_{ab} = -8.356×10^{-10} m/s^2, gives almost negligible lowering of spacecraft velocity by 0.5274 m/s. However, due to resulting deviation from expected coordinates by 166432 km, the interplanetary mission may miss the target.

As guessed by Murphy (1999) and Kats (1999), the anomaly of Pioneers is a result of anisotropy of heat emission from spacecrafts. Generally speaking, the "abnormal acceleration" of Pioneers is comparable with action of 60 W incandescent lamp with reflector, turned outward the Sun. Indeed, average "abnormal acceleration" of Pioneers, measured in the range 14÷45.7 au, g_{ab} = -8.356×10^{-10} m/s^2, is equivalent to forward heat emission with power:

$$P = |g_{an}\times m\times c| = 61.6 \text{ W} \quad (1)$$

Here m = 0.5×(239.73+251.883) kg is average mass of Pioneers (Anderson et al, 2002), c = 299792 km/c is speed of light. Taking into account for detailed analysis, performed by Turyshev et al (2012), Murphy-Kats hypothesis seems to be relevant (see dashed curve in **Fig 1**). However, effect of anisotropy of heat emission from Pioneers was calculated by Anderson et al (2002) at ~ 0.48×10^{-10} m/s^2. Thus, Murthy-Kats hypothesis is, at least, questionable, and there is a space for other guesses.

As guessed by Nieto et al (2005), anomaly of Pioneers is result of friction forces in the interplanetary medium. Based on this hypothesis, one may estimate density of Space, at least, its upper limit. For calculation of ballistic trajectory in atmosphere, it is necessary to account for "aerodynamic drag" (i.e. friction force of air), defined by Rayleigh formula:

$$F_d = 0.5\times C_d\times\rho\times v^2\times S \qquad (2)$$

Here F_d is aerodynamic drag (N), 0.5 is constant factor ("Rayleigh drag coefficient"), C_d is empirical "drag coefficient" (truly, correction factor to Rayleigh formula, introduced latter: C_d ~ 0.47 for cannon ball, ~ 0.82 for cylindrical bullet, etc), ρ is density of medium (kg/m^3), v is velocity (m/s) and S is cross-section area (m^2) of cannon ball or bullet. Taking into account for mass of cannon ball, m, one may calculate its "abnormal acceleration":

$$g_{ab} = -\,0.5\times C_d\times\rho\times v^2\times S/m \qquad (3)$$

It appears to be that the "atmospheric drag coefficients" are weakly applicable for the Space. For instance, collapse of air at back side of cannon ball pushes it forward, and, applying special "fish-like" profile, friction force of air may be significantly reduced (practically, down to C_d ~ 0.04). Besides, Eq. (3) is well applicable up to sound velocity (~ 340 m/s), whereas at cosmic velocities, atmospheric drag coefficient rises by tens times due to strong compression of air at forward side of, e.g., meteorite. Nevertheless, all these effects are absent in outer Space, and "space drag coefficient" may be roundly estimated from the common sense.

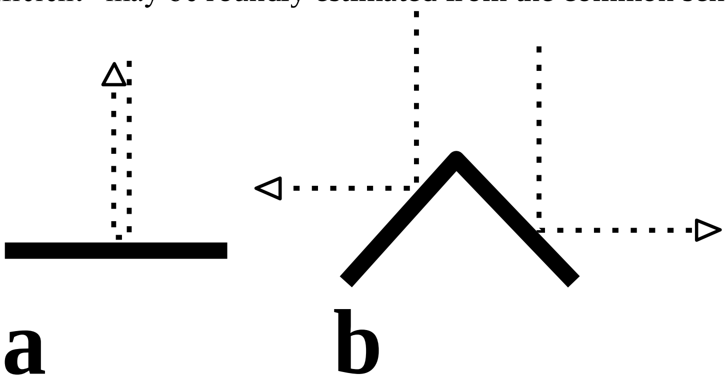

Fig. 2 Reflection of atoms at (a) 90^o angle of attack and (b) 45^o angle of attack in the coordinate system of spacecraft, which moves upward.

In the coordinate system of spacecraft (which flies with velocity v), atom of hydrogen approaches to spacecraft with velocity v, and then, upon collision, it recoils with approximately same velocity ≈ v: backward (see **Fig. 2a**) or outside (see **Fig. 2b**), depending on angle of attack. Thus, in the Solar coordinate system, velocity component of hydrogen atom in the direction of fly of spacecraft changes from 0 up to ≈ 2v at angle of attack α = 90^o (see **Fig 2a**), and up to ≈ 1v at angle of attack α = 45^o(see **Fig. 2b**). Consequently, abnormal acceleration for flat disk, orthogonal to direction of fly, may be calculated from:

$$g_{ab} \approx -\,(\rho\times v\times S)\times 2v/m = -\,0.5\times 4\times\rho\times v^2\times S/m \qquad (4)$$

Here (ρ×v×S) is total mass of atoms, accelerated from zero up to ≈ 2v during one second, and m is mass of disk. As may be seen, space drag coefficient for flat surface, orthogonal to direction of fly, is $C_d \approx 4$. Similarly, space drag coefficient for the cone with angle at the top $2\alpha = 90^o$ (see **Fig. 2b**) is $C_d \approx 2$. The same value ($C_d \approx 2$) is valid for sphere, as may be found via integration.

In general case, assuming absolutely elastic collisions with atoms of free Space (i.e. neglecting heating of spacecraft due to friction force), "space drag coefficient" for element of surface is related to angle of attack as:

$$C_d \approx 2\{1 - \cos(2\alpha)\} = 4\times\{\sin(\alpha)\}^2 \qquad (5)$$

The most of "cosmodynamic drag" for Pioneers may be expected from antenna. In both cases, radius of antenna was 1.37 m (Anderson et al 2002). Thus, cross-section area of Pioneers may be estimated at $S \sim 5.90\ m^2$.

The depth of Pioneer's antenna was 0.46 m (Anderson et al 2002), and its concave side was turned to the Earth (i.e. approximately to the Sun), and convex side was turned outward from Sun. Thus, with angle of attack $\alpha \sim arctg(137/46) = 71.44^o$, "space drag coefficient" for Pioneers may be estimated at $C_d \approx 4\times\{\sin(71.44^o)\}^2 = 3.595$.

Initial mass of Pioneers was 259 kg, including 36 kg of fuel. Due to fuel loss on maneuvering, masses of spacecrafts were lowered down to m = 251.883 kg for Pioneer 10, and down to m = 239.73 kg for Pioneer 11 (Anderson et al, 2002).

For the gravitational stability, gas cloud should rotate around the Sun together with planets with velocity ~ $30/[R, au]^{0.5}$ km/s, where [R, au] is distance from the Sun in astronomic units (1 au = 149597870.7 km). Because of this, "cosmodynamic drag" for planets is zero. The tangential velocities of Spacecrafts were approximately equal to orbital velocities of planets (beginning from initial ~ 30 km/s before launch). Because of this, tangential "cosmodynamic drag" for Pioneers was also close to zero. Thus, observed "abnormal acceleration" of Pioneers is mostly a result of radial "cosmodynamic drag".

In **Fig. 3**, the distances of Pioneers from Sun are plotted against date (see Appendix: data from Tab 2 and Fig. 1 in Nieto and Anderson 2005). As may be seen, beginning slightly above Jupiter orbit (~ 5.2 au) for Pioneer 10, and slightly above Saturn orbit (~ 9.55 au) for Pioneer 11, radial velocities of Pioneers were approximately constant. From slopes of dashed lines in **Fig. 3**, radial velocities of Pioneers were ≈ 12 km/s (2.53 au/year).

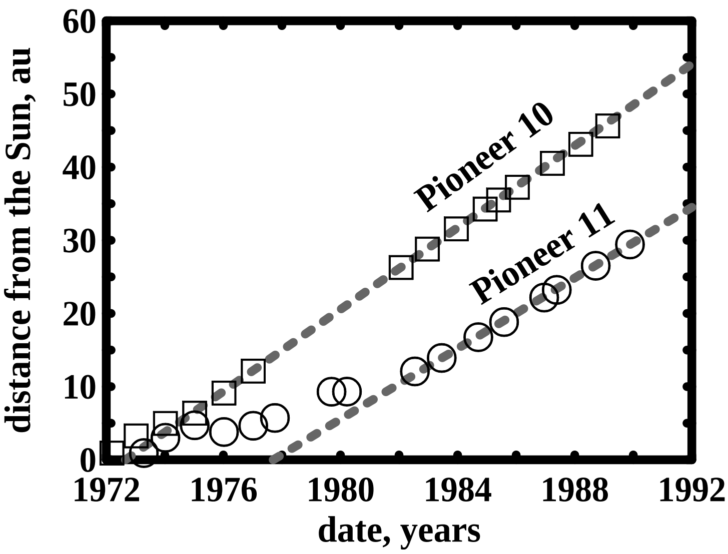

Fig. 3 Distance between the Sun and spacecrafts, Pioneer 11 (circles) and Pioneer 10 (squares) versus date (see Appendix). Data from Tab. 2 and Fig. 1 in Nieto and Anderson (2005).

Thus, with average mass of spacecraft, m = 245.8 kg, average abnormal deceleration, $g_{an} = 8.356\times10^{-10}\ m/s^2$, measured at distances >12.16 au from the Sun, C_d = 3.595, v = 12 km/s, and $S = 5.9\ m^2$, density of Space may be estimated as:

$$\rho = -\,2mg_{an}/(C_d\times v^2\times S) \approx 1.34\times10^{-16}\ kg/m^3 \approx 8\times10^7 \text{ atoms H per } dm^3 \qquad (6)$$

This value is ~ 2 times smaller than ~ 3×10^{-16} kg/m^3, estimated by Nieto et al (2005) with drag coefficient C_d = 2, mass of spacecraft m = 251 kg, velocity v = 12 km/s, cross-section area S = 5.9 m^2, and abnormal acceleration – 8.74×10^{-10} m/s^2 (from these data, $\rho = 2.58\times10^{-16}$ kg/m^3).

To obtain more detailed information, radial velocities of Pioneers may be estimated from differentiation of spline fit to data in **Fig. 3** (see **Appendix**).

Fig. 4 shows resulting evolution of density of Space with distance from the Sun. As may be seen, density of Space inside of Saturn orbit is small (~ 0.28×10^{-16} kg/m^3), whereas above Saturn orbit density rises to ~ 1.34×10^{-16} kg/m^3 on average (with range ~ 1.08×10^{-16} to 1.79×10^{-16} kg/m^3; see **Appendix**). Note, that the abnormal acceleration of Pioneer 11 at distance 5.8 au was measured at altitude 1.2 au above ecliptic plane. Consequently, this value may indicate just a thickness of gas cloud (i.e. about ~ 2 au). So on, there is a dilemma: which value is closer to reality inside of Saturn orbit, ~ 1.34×10^{-16} or ~ 0.28×10^{-16} kg/m^3?

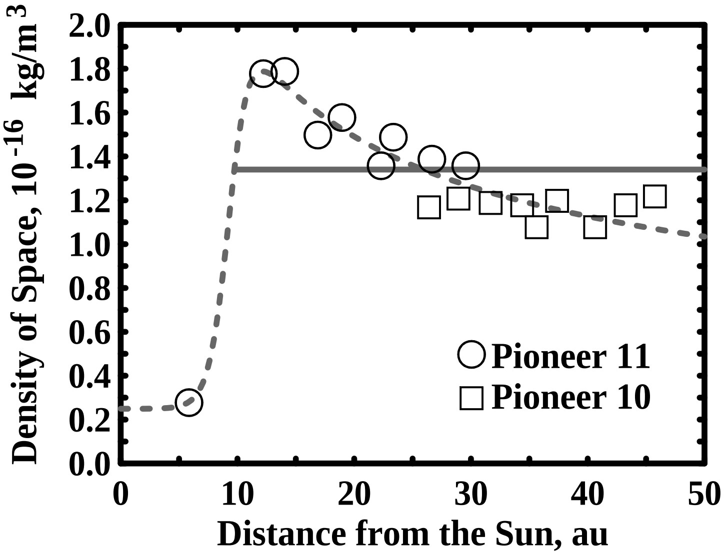

Fig. 4 Density of Space as calculated from "abnormal acceleration" of Pioneers 10 and 11 (see **Appendix**). Solid line: average density above Saturn's orbit (~1.34×10^{-16} kg/m^3). Dashed curve is given for guidance.

In **Fig. 5**, the data from Doornbos (2012) on density of upper atmosphere of the Earth are shown. These data were deduced from trajectories of special artificial satellites (so-called "accelerometers"). Scatter of data reflects "high and low tides", which arise due to gravity tags from the Sun and the Moon and action of Solar light. As may be seen, density of Space at altitude 2000 km above the Earth's surface (0.39, 1.3, 1.76, 9 $\times10^{-16}$ kg/m^3 with geometric mean 1.68×10^{-16} kg/m^3) is close to density of outer Space, 1.34×10^{-16} kg/m^3. In application to navigation of artificial satellites at altitude 2000 km, "cosmodynamic drag" is almost negligible. However, at lower orbits, "cosmodynamic drag" makes significant problems. For instance, the International Space Station, orbiting at altitudes ~ 300÷400 km, drops to the Earth with velocity ~ 100 m per day, and its orbit is corrected once per 1-3 months with use of orbital engine. However, there is no such useful device on the Moon. So, let us calculate the rest of times.

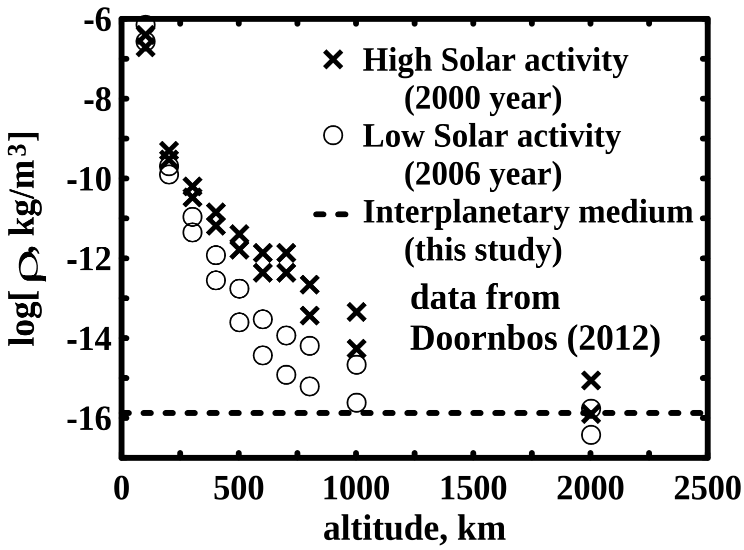

Fig. 5 Density of upper Atmosphere of the Earth at high (crosses) and low (circles) Solar activity. Data from Doornbos (2012).

The orbital velocity of the Moon is v = 1.022 km/s, its average distance from center of the Earth is r_{orb} = 384399 km, and its mass is m = 7.342×10^{22} kg. From mean radius, 1737.1 km, cross-section area of the Moon is S = 9.480×10^{6} km^2. Applying "space drag coefficient" for sphere, C_d = 2, and assuming density of Space, $\rho = 1.34\times10^{-16}$ kg/m^3, "abnormal acceleration" of the Moon may be estimated at:

$$g_{an} = -0.5\times C_d\times\rho\times v^2\times S/m = -1.817\times10^{-20} \text{ m/s}^2 \quad (7)$$

Taking into account for energy balance and condition of orbital stability, one may estimate falling velocity of the Moon:

$$dr_{orb}/dt = 2\times(r_{orb}/v)\times g_{an} = -1.367\times10^{-14} \text{ m/s} = -0.4313 \text{ km per billion of years} \quad (8)$$

From this value, expected date of Apocalypse is ~ – $r_{orb}/(dr_{orb}/dt) \approx$ 900000 billions of years, which seems to be enough for peaceful and happy life. As may be seen, due to huge ratio of mass to cross-section area, accounting for "cosmodynamic drag" for large objects is senseless. Thus, in application to the Earth's orbit, a value $\rho = 1.34\times10^{-16}$ kg/m^3 is not impossible.

Assuming constancy of temperature, domination of hydrogen atoms, density profile at altitudes >2000 km may be calculated from Boltzmann equation:

$$\log(\rho_{H,h}) = \log(\rho_{H,\infty}) + M\times g_o\times r_E/(1+h/r_E)/\ln(10)RT \quad (9)$$

Here $\rho_{H,h}$ is density at altitude h, $\rho_{H,\infty}$ is density at the Earth's orbit, M = 0.00100794 kg/mol is molar weight of hydrogen, g_o = 9.807 m/s^2 is gravity at the surface of the Earth, r_E = 6371 km is radius of the Earth, R = 8.314 J/molK is gas constant, and T is absolute temperature.

Thus, from Eq. (9), applying geometric mean density at altitude 2000 m, 1.68×10^{-16} kg/m^3 = 1×10^{8} atoms H per dm^3 from Doornbos (2012), density of Space at the Earth's orbit may be estimated from:

$$\log(\rho_{H,\infty}, \text{ atoms/dm}^3) \sim 8 - 2504/T \quad (10)$$

Temperature of Space above 2000 km from the Earth's surface may be estimated from plasma density at the Earth' orbit, ρ_{plasma} ~ 5000 proton-electron pairs per dm^3 (Axford, 1968). From thermodynamic data, dissociation of hydrogen atom is defined by (see Pivovarov, 2016):

$$H \Leftrightarrow p^+ + e^- \quad , \quad \log(K_{diss}, \text{ species/dm}^3) = \log(\rho_{plasma}{}^2/\rho_H) = 24.218 - 70385/T \quad (11)$$

Thus, temperature of Space at the Earth's orbit is

$$T = 70385/\{24.218 - \log K_{diss}\} = 70385/\{24.218 - 2\times\log(5000) + 8 - 2504/T\} = 2937 \text{ K} \quad (12)$$

Note here that the hot Space cannot warm cosmonaut, because heat emission from the cosmonaut is much more intensive than that from rarified hot gas (see Pivovarov, 2016).

So on, from Eq (10), and T = 2937 K, density of Space at the Earth's orbit is: $\rho_{H,\infty}$ = 1.404×10^{7} atoms H per dm^3 = 0.235×10^{-16} kg/m^3. As may be seen, guessed density of Space at the Earth's orbit is close to value 0.28×10^{-16} kg/m^3, deduced from "abnormal acceleration" of Pioneer 11 at distance 5.8 au from the Sun. Thus, it is likely that the major part of substance inside of planetary system is collected by planets and pushed out by Solar light, whereas problems with navigation are expected behind the orbit of Saturn.

CONCLUDING REMARKS

Abnormal acceleration of Pioneers 10 and 11 is consistent with density of Space ~ 1.34×10^{-16} kg/m^3 = 8×10^7 H atoms/dm^3 at distances >10 au from the Sun. Inside of Saturn orbit, density of Space drops down to ~ 0.26×10^{-16} kg/m^3. Taking into account for Murphy-Kats hypothesis on anisotropy of heat emission from Pioneers, these values may be considered as "upper limit" estimations. For planets and their moons, due to huge ratio of mass to cross-section area, expected effect of "cosmodynamic drag" is less than nothing. However, this factor may be significant for prediction of meteorite attacks.

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APPENDIX

Abnormal accelerations and distances from the Sun for spacecrafts Pioneer 10 and 11 versus date from Tab 2 and Fig 1 in Nieto and Anderson (2005), and estimated radial velocities of Pioneers and density of Space (present study).

Spacecraft	Date, year[a]	Distance from the Sun, au	Abnormal acceleration[b], m/s^2	Estimated radial velocity (this study)[c] km/s	Estimated space density (this study)[d] 10^{-16} kg/m^3
Pioneer 10	1972.167[e]	1	–	–	–
	1973[f]	3.34[f]	–	–	–
	1974[f]	5.05[f]	–	–	–
	1975[f]	6.45[f]	–	–	–
	1976[f]	9.19[f]	–	–	–
	1977[f]	12.19[f]	–	–	–
	1982.049	26.36	–8.68±0.50	13.28	1.17
	1982.949	28.88	–8.88±0.27	13.20	1.21
	1983.945	31.64	–8.59±0.32	13.11	1.19
	1984.922	34.34	–8.43±0.55	13.03	1.18
	1985.375	35.58	–7.67±0.23	12.99	1.08
	1986.015	37.33	–8.43±0.37	12.93	1.20
	1987.216	40.59	–7.45±0.46	12.83	1.08
	1988.186	43.20	–8.09±0.20	12.75	1.18
	1989.114	45.70	–8.24±0.20	12.67	1.22
Pioneer 11	1973.258[e]	1	–	–	–
	1974[f]	3.09[f]	–	–	–
	1975[f]	4.80[f]	–	–	–
	1976[f]	3.87[f]	–	–	–
	1977[f]	4.73[f]	–	–	–
	1977.738[g]	5.80[g]	–0.69±1.48[g]	7.51[g]	0.28[g]
	1979.665[h]	9.38[h]	–	–	–
	1980.194[h]	9.39[h]	–1.56±6.85[h]	~1.6[h]	14[h]
	1982.519	12.16	–6.28±1.77	8.92	1.78
	1983.433	14.00	–8.05±2.16	10.09	1.79
	1984.691	16.83	–8.15±0.75	11.09	1.50
	1985.564	18.90	–9.03±0.41	11.38	1.58
	1986.941	22.25	–8.13±0.69	11.64	1.36
	1987.368	23.30	–8.98±0.30	11.69	1.49
	1988.698	26.60	–8.56±0.15	11.78	1.39
	1989.864	29.50	–8.33±0.30	11.78	1.36

[a] date, e.g., 1974 is 1 January 1974; date 1974.055 is (365×0.055 + 1 =) 21 January 1974, etc.
[b] abnormal tag is "directed toward the Sun" (Nieto and Anderson, 2005)
[c] from differentiation of spline fit to data in 2nd and 3rd column
[d] "upper limit" from Eq. (6)
[e] launched at 2 March 1972 (Pioneer 10) and 5 April 1973 (Pioneer 11)
[f] data taken from Fig 1 in Nieto and Anderson (2005)
[g] at altitude ~1.2 au above ecliptic plane
[h] nearby Saturn