Reading the Pioneer/Voyager Pulsar Map

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This interesting question came up recently: which pulsars are used in the Voyager record pulsar map? Answering this question turned into an interesting exercise in interpreting this map, which I review here.

During planning of the Pioneer 10 and 11 missions to the outer solar system, a group of astronomers proposed including a message for any intelligent extraterrestrials that might discover the probes. These two probes would be the first manmade objects to leave the solar system. While the probability of such beings discovering the probes is infinitesimally small (even assuming they exist), a message was included on a metal plaque on the outside of each probe prior to their launches in 1972 and 1973.

For Voyagers 1 and 2, outer solar system probes launched in 1977 and also destined to leave the solar system, a more extensive message was incorporated into a record containing sounds and digital pictures from Earth. The cover of the record included a message modified from the Pioneer message.

All four messages included in particular a pulsar map. This map was designed by Frank Drake to shown the location of the Earth relative to 14 pulsars. Pulsars are rapidly rotating neutron stars which emit beacons of radio waves. The precise timing of the resultant radio pulses provide markers observable in radio wavelengths across broad stretches of the galaxy.

A quick search failed to turn up a readily accessible list of the pulsars used in the map, so I decided to experiment with interpreting the map. If the map could really be interpreted to show our location, it would then be possible to identify the pulsars from the map. This would serve to test at least a few elements (only a few) involved in its potential interpretation.

The map identifies the distance and direction of the 14 pulsars relative to the direction and distance of the center of the galaxy, along with--most importantly--their periods. The periods are expressed in binary notation as multiples of the hyperfine transition period of hydrogen ($7.04024183647 \times 10^{-10}$ sec). This transition occurs in hydrogen atoms and involves a change in the relative spins of the proton and electron; the resultant radio-frequency radiation, with a wavelength of 21.1 cm, is observed in interstellar gas.

Using a diagram from p. 58 of *Murmurs of Earth* by Sagan et ali (which describes the Voyager record message), the data in table 1 is derived (listing the pulsars as on the map, clockwise from the line to the center of the galaxy). (Note: some measurements may not be accurate due to the quality of the diagram.) Pulsar period is given in the units of the hydrogen hyperfine transition (in both binary and base 10) and converted to seconds. The direction and distance information is less precisely indicated on the diagram. Distance in particular to most pulsars is poorly determined, even today.

Table 1: Pulsar data from the Pioneer/Voyager pulsar map

psr #	period (binary, H transition units)	period (base 10, H transition units)	period (seconds)	direction angle from galactic center (°)	distance (to galatic center=100)	implied distance (parsecs)
1	1000110001111100100011011101010	1178486506	0.8296830003	17	27	2300
2	10110010011000101011101101111	374101871	0.2633767643	49	2	160
3	100000110110010110001001111000	551117432	0.3880000002	58	56	4700
4	111100011011011001010100111	126726823	0.0892187481	95	15	1300
5	10101011011001101100101000011	359455043	0.2530650432	129	1	120
6	101100111011010101011110001011	753751947	0.5306595992	162	2	160
7	10110011100000101010000010	47057538	0.0331296448	174	18	1500
8	100111101000110101000100111000100	5320116676	3.7454907997	177	11	980
9	111100011111100011111000010110	1014906390	0.7145186427	145	7	570
10	101101100101101001000010110001	764842161	0.5384673780	97	10	850

11	1011110011110011100110000001101	792520205	0.5579533903	68	3	280
12	1111001011111000111010001111O	509549854	0.3587354200	52	40	3400
13	10011001011010111010010111000	321746104	0.2265170382	45	1	81
14	100000110100101010001110101100	550675372	0.3876887792	16	4	320

As an initial attempt, the derived periods were compared to a list of pulsars known as of June 1975. Using this sample of 147 would narrow down the possibilities, since it would at least include the 14 used to create the map around 1970. The list used was from Taylor and Manchester, "Observed properties of 147 pulsars," (1975), *The Astronomical Journal*, (80:794-806). Matches were found for all 14 pulsars, with data given below in table 2. Included is the difference (in parts per million) between the periods in the map and the presumed matches in Taylor and Manchester; note that most are quite good.

Table 2: Pulsars identified based on the pulsar map, 1975 data

psr #	PSR (B1950 ID)	period (seconds)	difference (ppm)	distance (parsecs)
1	B1727-47	0.829699077	19.38	5900
2	B1451-68	0.263376771	0.025	290
3	B1240-64	0.388479	1233.0	8300
4	B0833-45	0.089209301	105.9	500
5	B0950+08	0.253065037	0.024	100
6	B0823+26	0.530659803	0.384	790
7	B0531+21	0.033097565	969.2	2000
8	B0525+21	3.745493447	0.121	1900
9	B0329+54	0.714518664	0.030	1300
10	B2217+47	0.538467395	0.032	1600
11	B2016+28	0.557953407	0.030	480
12	B1933+16	0.358735431	0.031	6000
13	B1929+10	0.226517045	0.030	110
14	B1642-03	0.387688791	0.030	160

Finally, a modern pulsar listing was used to check that the pulsars can be unambiguously identified. Using the ATNF Pulsar Catalog (2002), which lists 1,480 pulsars, the data in table 3 was obtained for the above pulsars. Celestial coordinates (RA and DEC) and galactic coordinates (l and b) are given along with period, P dot (the rate of decrease of the period), the epoch (time of period measurement), and distance.

Table 3: Same pulsars, 2002 data

psr #	PSR (J2000 ID)	R A	DEC	l (°)	b (°)	period (seconds)	P dot (10^{-15}sec/sec)	epoch (JD)	distance (parsecs)
1	J1731-4744	17h31m42.103s	-47°44'34.6"	342.57	-7.67	0.82982878524	163.626	2450939	4980
2	J1456-6843	14h56m00.11s	-68°43'38.7"	313.87	-8.54	0.263376828611	0.1013	2448409	458
3	J1243-6423	12h43m17.10s	-64°23'23.6"	302.05	-1.53	0.388481471997	4.4997	2448217	7400
4	J0835-4510	08h35m20.6761s	-45°10'35.76"	263.55	-2.79	0.08933001517	124.88	2451710	722

5	J0953+0755	09h53m09.316s	+07°55'35.60"	228.91	43.70	0.25306506819	0.22915	2441500	8440
6	J0826+2637	08h26m51.310s	+26°37'25.57"	196.96	31.74	0.53066079758	1.7094	2448383	375
7	J0534+2200	05h34m31.973s	+22°00'52.06"	184.56	-5.78	0.0335223033700234	420.5188	2452016	2490
8	J0528+2200	05h28m52.34s	+22°00'00.0"	183.86	-6.90	3.7454972494	40.046	2442057	2270
9	J0332+5434	03h32m59.35s	+54°34'43.2"	145.00	-1.22	0.71451866398	2.04959	2440621	1430
10	J2219+4754	22h19m48.136s	+47°54'53.83"	98.38	-7.60	0.5384692479485	2.76503	2448382	2450
11	J2018+2839	20h18m03.851s	+28°39'54.26"	68.10	-3.98	0.55795340728	0.14936	2440688	1100
12	J1935+1616	19h35m47.835s	+16°16'40.59"	52.44	-2.09	0.35873624827	6.00354	2442264	7940
13	J1932+1059	19h32m13.900s	+10°59'31.99"	47.38	-3.88	0.226517820862	1.15661	2448381	169
14	J1645-0317	16h45m02.045s	-03°17'58.4"	14.11	26.06	0.38768879135	1.781	2440621	2900

All 14 pulsars could be distinguished from others, although not by period alone in one or two cases. In these cases the direction made the choice clear. Table 4 compares direction and distance information from the pulsar map to that derived from the ATNF Catalog data.

Table 4: Pulsar direction and distance information

psr #	PSR (J2000 ID)	direction, angle from line to galactic center (°)		distance (parsecs)	
		from map	from ATNF data	from map	from ATNF data
1	J1731-4744	17	18.99	2300	4980
2	J1456-6843	49	46.74	160	458
3	J1243-6423	58	57.96	4700	7400
4	J0835-4510	95	96.44	1300	722
5	J0953+0755	129	118.37	120	8440
6	J0826+2637	162	144.44	160	375
7	J0534+2200	174	172.64	1500	2490
8	J0528+2200	177	172.10	980	2270
9	J0332+5434	145	144.98	570	1430
10	J2219+4754	97	98.31	850	2450
11	J2018+2839	68	68.16	280	1100
12	J1935+1616	52	52.47	3400	7940
13	J1932+1059	45	47.50	81	169
14	J1645-0317	16	29.40	320	2900

The direction information is somewhat helpful, but the distance information is not.

The precise nature of pulsar periods largely extends to the rate of decrease of these periods. If the pulsar map periods are accurate, one can in principle determine the time corresponding to those measurements of the pulsar periods. Comparing the data from the ATNF Catalog to that from the pulsar map, this is used in table 5 to estimate the date of origin of the pulsar map.

Table 5: Derived date of map origin

psr #	PSR (J2000 ID)	derived date
1	J1731-4744	1970.1
2	J1456-6843	1969.0
3	J1243-6423	1969.1
4	J0835-4510	1971.7
5	J0953+0755	1968.9
6	J0826+2637	1969.8
7	J0534+2200	1969.9
8	J0528+2200	1966.7
9	J0332+5434	1970.2
10	J2219+4754	1969.9
11	J2018+2839	1969.9
12	J1935+1616	1970.2
13	J1932+1059	1971.3
14	J1645-0317	-1399.8

Discarding the discordant value from PSR J1645-0317, this gives a date of origin of 1969.7 ± 1.2 year! This is not a bad result. (A note: I don't know whether the pulsar data was updated for the Voyager pulsar map.) Now suppose some ETI reads the map and manages to determine which pulsars we were referring to. Reading the map is not so simple in this case: the solar system is moving through space, as are the pulsars (generally with higher space velocities than main sequence stars); adjusting for the change in the pulsar periods must take into account the light travel time from the pulsars, which is hundreds to tens of thousands of years. But if these factors were successfully accounted for, the map could be used to identify the location of the solar system to within tens of light years or less.

Of course, my task of reading the map was far less daunting than it would be for some ETI that finds the map. Just a sampling of issues for interpretation that did not enter this analysis:

- Correctly concluding that the map depicts pulsar periods, directions, etc.;
- Correctly interpreting the base unit of time;
- Having a substantially different sample of known pulsars;
- Accounting for space motion of pulsars;
- Accounting for light travel time in "backtracking" pulsar periods;
- Realizing that depicted distance information is unreliable.

Epilogue: After completing this page, I received a reply from the Planetary Society which referred me to a 1972 article by Carl Sagan, Linda Salzman Sagan, and Frank Drake identifying the pulsars. The article uses yet another type of pulsar identifier in a table, data from which is given below (note: this was read from a poor reproduction, so there may be errors in my table). The last column gives the pulsar identifier from a 1970 article by B. Y. Mills, giving some indication of the then non-standardized cataloguing system.

Table 6: Pulsar list from Sagan, Sagan, and Drake

psr #	ID in Sagan et ali	given period, 1970/71 epoch (sec)	period, H transition units	ID in Mills (1970)
1	1727	$8.296830000 \times 10^{-1}$	$1.178486506 \times 10^{9}$	MP 1727
2	1451	$2.633767640 \times 10^{-1}$	$3.741018705 \times 10^{8}$	PSR 1451-68
3	1240	$3.880000000 \times 10^{-1}$	$5.511174318 \times 10^{8}$	MP 1240
4	0833	$8.921874790 \times 10^{-2}$	$1.267268227 \times 10^{8}$	PSR 0833-45

5	0950	$2.530650432 \times 10^{-1}$	$3.594550429 \times 10^{8}$	CP 0950
6	0823	$5.306595990 \times 10^{-1}$	$7.537519468 \times 10^{8}$	AP 0823+26
7	0531	$3.312964500 \times 10^{-2}$	$4.705753832 \times 10^{7}$	
8	0525	3.745490800	$5.320116676 \times 10^{9}$	
9	0328	$7.145186424 \times 10^{-1}$	$1.014906390 \times 10^{9}$	CP 0328
10	2217	$5.384673780 \times 10^{-1}$	$7.648421610 \times 10^{8}$	
11	2016	$5.579533900 \times 10^{-1}$	$7.925202045 \times 10^{8}$	
12	1933	$3.587354200 \times 10^{-1}$	$5.095498540 \times 10^{8}$	JP 1933+16
13	1929	$2.265170380 \times 10^{-1}$	$3.217461037 \times 10^{8}$	PSR 1929+10
14	1642	$3.876887790 \times 10^{-1}$	$5.506753717 \times 10^{8}$	MP 1642

Some statements of interest from the Sagan et ali article:

> A time interval of only 3 weeks existed between the formulation of the idea of including a message on Pioneer 10, achieving NASA concurrence, devising the message, and delivering the draft message for engraving.

This occurred before final assembly of the Pioneer 10 spacecraft.

> The large number of digits is the key that these numbers indicate time intervals, not distances or some other quantity... There are no other conceivable quantities that we might know to ten significant figures for relatively distant cosmic objects.

Actually, angular position as well can be determined to ten significant figures.

> With 14 periods, almost all of which are accurate to nine significant figures in decimal equivalent, a society which has detailed records of past pulsar behavior should be able to reconstruct the epoch of launch to the equivalent of the year 1971. If past records of pulsar "glitches" (discontinuities in the period) are not kept or reconstructable from the physics it should still be possible to reconstruct the epoch to the nearest century or millennium... If either [of the two pulsars nearest the Earth] is correctly identified, it can be used to place the position of our solar system in the galaxy to approximately 20 pc, thereby specifying our location to approximately 1 in 10^3 stars.

This does not address the fact that light travel time from the pulsars must be taken into account. If this can be done (and, as noted above, if discontinuities in pulsar periods are not problematic), the location can be determined to within a few light years, nearly uniquely identifying the Sun.

(In 2007 Rick Nungester alerted me to a few errors, particularly my calculation of the period of pulsar #1; this is corrected above.)

References:

- ATNF, "ATNF Pulsar Catalog," March 2002, on line at *Australia Telescope National Facility* [http://www.atnf.csiro.au/research/pulsar/catalogue/psr_export.dat].
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