Spacecraft Artifacts as Physics Teaching Resources

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Have you ever felt that your students open the textbook for their introductory algebra/trig- or calculus-based physics course with the same puzzlement that an extraterrestrial would have on picking up an artifact from Earth that was covered with incomprehensible symbols?[1]

To see how one group of space scientists approached such a "communication" problem, though on a cosmic scale and with a totally alien audience, consider Fig. 1. It is a sketch of the small plaque that accompanied the *Pioneer 10* and *Pioneer 11* spacecraft[2] at their launches in 1972/1973. The artifact was designed to "... specify our position in the Galaxy, our epoch, and something of our nature."[3] What type of thinking went into the design of this attempt at interstellar communication?

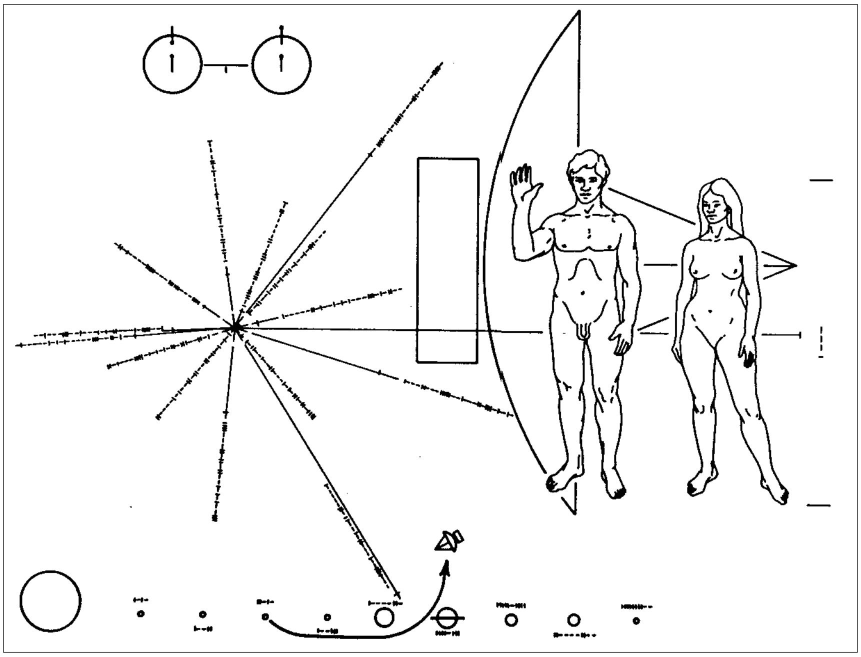

Fig. 1. Representation of engraved plaque carried on *Pioneer 10* and *11* spacecraft, the first artifact (as opposed to electromagnetic signals) produced by humans to leave the solar system. (Reprinted with permission from *Science*, ©1972, AAAS.)

Deciphering the Artifact

The small (6 x 9-in) gold-anodized aluminum plate was designed by Carl and Linda Salzman Sagan and Frank Drake in about three weeks, a "cosmic greeting card" to the universe.[4]

First of all, how does the plaque define basic dimensional quantities such as distance and time? The circular symbols in the upper left-hand corner are meant to represent the two lowest lying states of the hydrogen atom, with the proton and electron spins being either parallel or antiparallel. The corresponding energy levels of these two configurations differ by a tiny amount ($\Delta E = 5.88 \times 10^{-6}$ eV, very small compared with the famous 13.6 eV-binding energy from the ground state) due to the interaction between the magnetic moments of the proton and electron; this gives the so-called "hyperfine" (HF) splitting.[5] The frequency (f_{HF}), period (T_{HF}), and wavelength (λ_{HF}) associated with the photon emitted in the hyperfine transition between these two states are given by

$$5.88 \times 10^{-6}\text{eV} \approx \Delta E = h f_{HF} = \frac{h}{T_{HF}} = \frac{hc}{\lambda_{HF}}, \quad (1)$$

where h is Planck's constant, or numerically

$$f_{HF} \approx 1420 \text{ MHz}, \quad T_{HF} \approx 7.04 \times 10^{-10}\text{s},$$

$$\lambda_{HF} \approx 21 \text{ cm}.$$

Table I. "Name" and period (in several different forms) of the 14 pulsars illustrated on the *Pioneer 10* and *11* plaques shown in Fig. 1. The scaled periods in binary representation are taken from the plaque using the standard notation 1 = I and 0 = –.

Pulsar	Period (in seconds) 1970/1971 epoch	Period (in units of τ_{HF})	Scaled period (binary representation)
0328	$7.145186424 \times 10^{-1}$	$1.014906390 \times 10^{9}$	111100011111100011111000010110
0525	3.745490800	$5.320116676 \times 10^{9}$	1001111010001101010001001110001000
0531	$3.312964500 \times 10^{-2}$	$4.705753832 \times 10^{7}$	10110011100000101010000010
0823	$5.306595990 \times 10^{-1}$	$7.537519468 \times 10^{8}$	101100111011010101011110001011
0833	$8.921874790 \times 10^{-2}$	$1.267268227 \times 10^{8}$	111100011011011001010100111
0950	$2.530650432 \times 10^{-1}$	$3.594550429 \times 10^{8}$	10101011011001101100101000011
1240	$3.880000000 \times 10^{-1}$	$5.511174318 \times 10^{8}$	100000110110010110001001111000
1451	$2.633767640 \times 10^{-1}$	$3.741018705 \times 10^{8}$	10110010011000101011101101111
1642	$3.876887790 \times 10^{-1}$	$5.506753717 \times 10^{8}$	100000110100101010001110101100
1727	$8.296830000 \times 10^{-1}$	$1.178486506 \times 10^{9}$	1000110001111100100011011101010
1929	$2.265170380 \times 10^{-1}$	$3.217461037 \times 10^{8}$	10011001011010111010010111000
1933	$3.587354200 \times 10^{-1}$	$5.095498540 \times 10^{8}$	11110010111111000111010001110
2016	$5.579533900 \times 10^{-1}$	$7.925202045 \times 10^{8}$	101111001111001110011000001101
2217	$5.384673780 \times 10^{-1}$	$7.648421610 \times 10^{8}$	101101100101101001000010110001

The idea that these time and length scales could be used as a universal set of dimensions for extraterrestrial communication arose from a suggestion made more than 40 years ago by Cocconi and Morrison who described f_{HF} as "... a unique, objective standard of frequency, which must be known to every observer in the universe: the outstanding radio emission line at 1,420 MHz (λ = 21 cm) of neutral hydrogen."[6] Astronomers have used this signature electromagnetic frequency for more than 50 years as a powerful tool to map out the distribution of cold, neutral hydrogen gas in our own galaxy.

The short mark (|) between the two circular symbols is thus meant to represent a single unit of either length or time in this new set of units (a *Système Universal*, perhaps, instead of the *Système International*). Many serious discussions of how best to communicate with extraterrestrial civilizations making use of these ideas have appeared over the last generation, both in the serious SETI literature[7,8] and in more popular formats.[9]

As an example of mathematical notation, ("powers-of-two" in this context, since the use of binary numbers is clearly more universal), estimation, and the use of significant figures using these new units, note that the right half of the plaque is dominated by a schematic representation of the *Pioneer 10/11* spacecraft, with a pair of equally schematic human beings standing alongside, drawn to scale. The size of the humans is indicated by the tick marks next to the female figure and a numerical value corresponding to this length scale is indicated, in binary notation, by the marks next to her, namely | - - -. The approximate size, of both the spacecraft and its builders, would then correspond to

| - - -	⟷	1000	⟷	$1(2^3) + 0(2^2) + 0(2^1) + 0(2^0)$	⟷	8
plaque		binary		expansion of binary		decimal

which corresponds to a height of 8(21 cm) = 1.68 m $\approx$ 5 ft, 5 in tall. In this context, an estimate of 1000 (in binary, the smallest, nontrivial base system possible) length units is the exactly appropriate order-of-magnitude calculation.

The "starburst" pattern at the left is meant to specify the positions of 14 objects (in polar projection, simple trig ideas used here) from some central position (which turns out to be Earth). There are clearly numerical values associated

Table II. Binary and decimal representations of the semi-major axes of planets in our solar system as shown on the *Pioneer 10/11* spacecraft plaque shown in Fig. 1.

Planet	Representations	
	Binary	*Decimal*
Mercury	1010	10
Venus	10011	19
Earth	11010	26
Mars	100111	39
Jupiter	10000110	134
Saturn	11110111	247
Uranus	111101111	495
Neptune	1100001100	780
Pluto	1111111100	1018

with each object. A first assumption might be that again these are binary representations of distances, but here the use of physical reasoning, and especially the idea of significant figures, come into play. These values are all given (in binary equivalent) to something like 9–10 place accuracy. If these are interpreted as lengths they would correspond to values of order $(4 \times 10^7 - 5 \times 10^9) \times (21\text{ cm})$. This gives distances of order $10^7 - 10^9$ m, typical sizes for terrestrial planets and planet-moon distances. But, how could any such distances be known to any culture to such precision, and further, how could they be assumed to be numerically stable against the proper motions of objects in our galaxy over the eons?

These values turn out instead to be the periods (measured in T_{HF} units instead of λ_{HF} units) of 14 well-known pulsars in our galaxy, whose magnitudes are indeed known to this precision. (This is another good lesson from the plaque, namely that frequency measurements in physics are often the most precise available since they can involve only the counting of large numbers of periods, which can be done very accurately. The incredible precision possible in pulsar timing can help explain, for example, the rapid strides made in this field from their initial discovery by Hewish in 1967 to their use as the first indirect evidence of gravitation radiation by Hulse and Taylor in 1974; both of these discoveries have since won the Nobel Prizes in Physics.) The periods (in seconds) of the reference pulsars from Ref. 3 are shown in Table I, along with their values scaled to the basic unit of time, T_{HF}, given by the hyperfine frequency. We also include the binary decimal equivalent as shown in the plaque.

A useful exercise in elementary mathematics is to "translate" the plaque's binary format of |'s and –'s into more standard ones and zeros, find the decimal equivalent, and to then identify each "leg" of the starburst pattern with one of the pulsars. For another exercise, remove entries from either the third or fourth column in Table I and ask your students to "fill in the blanks." Students may ask if these very long numbers are meant to be read by starting at the inside and going outwards or vice versa. Simply note that about half of the examples would have one or more initial zero digits if they are read in the "wrong" direction.

The bottom portion of Fig. 1 is perhaps the most obvious to us, since it shows a schematic representation of our home solar system, indicating the planet of origin and the "slingshot" orbit used by one of the *Pioneer* spacecraft. Careful examination of the binary symbols used indicates that they're slightly different from the |'s used in the hyperfine system of units (with an added serif, more like an I), indicating that a different set of units is being used: hence we must deal with unit conversions as well. (A quick calculation would also show that these solar-system distances would be implausibly small if we used the $\lambda_{HF} = 21$ cm units.) In this case we can rightly judge from the image that the distance from planet to star is being shown (in fact, the value of the semi-major axis); the pattern of binary values and their decimal equivalents in these different units are shown in Table II. In this case, the "basic" unit of length is seemingly one-tenth of the orbital radius of the innermost planet (Mercury). This "ten-ness" was designed to suggest (along with the detailed image of the human beings' appendages) something about our decimal numbering system.

Comments

Thus, the spacecraft plaque might serve as a "Chapter One" of sorts, using much of the same introductory physics and mathematics pedagogy we often assume our students know, but applied to a more "cosmic" problem. A discussion about this interesting parallel can be used as a quick "teaser" in the first week of an introductory algebra- or calculus-based physics course, or as the basis for a more serious set of homework problems designed as a refresher about generalized scientific notation. In any case, it can serve as a reminder that the results of fundamental physics (in this case, electricity, magnetism, and quantum mechanics) applied to arguably the simplest and certainly the most abundant bound-state system in the universe, namely hydrogen, might well be used to form part of the alphabet, and perhaps some of the vocabulary, of a common scientific language.

The parallels noted here could also be used (and expanded upon) in freshman seminar, "Physics for Poets," or "Science and Society" courses in discussions ranging from the SETI project to what human beings should project as their most important cultural (scientific or otherwise) achievements. In this regard, the "golden record" included with the *Voyager* program[10] is filled with images and sounds (music, language samples, etc.) that can stimulate debate on a wide variety of subjects beyond physics.

It has often been said that the most uncertain quantity in the equations used to estimate the likelihood of being able to contact other advanced extraterrestrial civilizations is the lifetime of scientific cultures. Even so, note that the *Voyager* golden record was accompanied by a stylus and included detailed instructions on the use of this archiving technology popular on this planet for roughly 100 years.[11] Now, just two decades after *Voyager* was launched, that technical process has already been largely superseded by more advanced CD, DVD, laser disc, and other data storage devices.

Acknowledgment

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References

1. For a serious review of the SETI literature, see T. Kuiper and G.D. Brin, "Resource Letter ETC-1: Extraterrestrial civilization," *Am. J. Phys*. **57**, 12 (1989).
2. For the NASA websites describing the *Pioneer* and *Voyager* missions, see http: //spaceprojects.arc.nasa.gov/Space_Projects/pioneer/PN10&11.html and http: //vraptor.jpl.nasa.gov/voyager/voyager.html.
3. C. Sagan, L.S. Sagan, and F. Drake, "A message from Earth," *Science* **175**, 881 (1972).
4. C. Sagan and F. Drake, "The search for extraterrestrial intelligence," *Sci. Am.* **232**, 80 (1975).
5. For example, see, D.J. Griffiths, *Introduction to Quantum Mechanics* (Prentice Hall, Englewood Cliffs, 1995), pp. 250–252.
6. G. Cocconi and P. Morrison, "Searching for interstellar communications," *Nature* **184**, 844 (1959).
7. C. Sagan and I. S. Shklovskii, *Intelligent Life in the Universe* (Holder-Day, San Francisco, 1966).
8. *The Search for Extraterrestrial Intelligence,* edited by P. Morrison, J. Billingham, and J. Wolfe (Dover, New York, 1979), a reprint of a 1977 NASA SP-419 technical report.
9. For example, see C. Sagan, *Contact* (Pocket Books, New York, 1997).
10. C. Sagan et al., *Murmurs of Earth: The Voyager Interstellar Record* (Random House, New York, 1978) or see the NASA website in Ref. 2.
11. The choice of a record format for the *Voyager* mission was also thought appropriate[10] because 1977 was the 100th anniversary of the invention of (tinfoil disc) recording by Thomas Edison.