Jumping the energetics queue: Modulation of pulsar signals by extraterrestrial civilizations

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Abstract

It has been speculated that technological civilizations evolve along an energy consumption scale first formulated by Kardashev, ranging from human-like civilizations that consume energy at a rate of \(\sim 10^{33}\) erg s\(^{-1}\) to hypothetical highly advanced civilizations that can consume \(\sim 10^{44}\) erg s\(^{-1}\). Since the transmission power of a beacon a civilization can build depends on the energy it possesses, to make it bright enough to be seen across the Galaxy would require high technological advancement. In this paper, we discuss the possibility of a civilization using naturally-occurring radio transmitters – specifically, radio pulsars – to overcome the Kardashev limit of their developmental stage and transmit super-Kardashev power. This is achieved by the use of a modulator situated around a pulsar, that modulates the pulsar signal, encoding information onto its natural emission. We discuss a simple modulation model using pulse nulling and considerations for detecting such a signal. We find that a pulsar with a nulling modulator will exhibit an excess of thermal emission peaking in the ultraviolet during its null phases, revealing the existence of a modulator.

Keywords: extraterrestrial intelligence, pulsars: general

1. Introduction

The Kardashev scale (Kardashev, 1964) classifies civilizations according to their ability to consume energy. The human civilization is the prototypical Kardashev Type-I civilization, consuming energy at the rate of \(\sim 4 \times 10^{19}\) erg s\(^{-1}\). A Kardashev Type-II civilization consumes \(\sim 4 \times 10^{23}\) erg s\(^{-1}\) – equivalent to the energy output of a Sun-like star. A Type-III civilization would be capable of consuming \(\sim 4 \times 10^{44}\) erg s\(^{-1}\), which is of the order of the luminosity of galaxies. If an extraterrestrial intelligence (ETI) decides to build a radio beacon to announce their presence in the Galaxy to prospective listeners for the purpose of eventually establishing a communication channel (Cocconi & Morrison, 1959), such a radio beacon would necessarily have a transmission power not more than that what civilization consumes. In this paper, we assume that the transmission power of an ETI beacon is of the same order of magnitude as their energy consumption. Following Kardashev (1964), we can calculate the power required to isotropically transmit a signal with a bandwidth \(\Delta f\) across the Galaxy, such that it can be received at an Arecibo-like radio telescope with a signal-to-noise ratio \(S/N\), as

\[
P \approx 6.6 \times 10^{24} \left(\frac{\Delta f}{\text{Hz}}\right) \left(\frac{S/N}{10}\right) \text{erg s}^{-1}. \tag{1}
\]

Traditional radio SETI experiments search for narrow-band (\(\sim 1\) Hz) signals. Even for such narrow-band signals, a detectable \(S/N\) would imply a transmission power that can be generated only by civilizations that are much more advanced than Type-I. The main drawback of using narrow-band signals as beacons is that the ETI is forced to choose some special frequency that may not be monitored by potential receivers. The solution to this problem is to transmit over a larger bandwidth, but since \(P \propto \Delta f\), the power requirement increases. For instance, for \(\Delta f = 1\) GHz, \(P \sim 10^{43}\) erg s\(^{-1}\), which can only be produced by civilizations that are at least Type-II. The power requirement can be reduced by trading it off with the solid angle of transmission, but barring very narrow beams, the civilization still needs to be fairly advanced to provide the necessary power. For instance, transmission with 1 GHz of bandwidth using a 1 square arcmin. beam would need \(P \sim 10^{25}\) erg s\(^{-1}\). Less advanced civilizations that wish to maximize sky coverage without incurring higher costs, however, can work around this problem by making use of

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appropriate naturally-occurring radio transmitters. In this paper, we propose that an ETI that is moderately more advanced than humans but not yet achieving a higher Kardashev type, may be able to use radio pulsars as sources of power at levels otherwise unachievable, modulating the broad-band pulsar signal for communication. The minimum requirement for such an endeavour would only be the ability to build and launch a modulating satellite to a nearby pulsar.

A pulsar is a neutron star that emits coherent radio radiation from its magnetic poles (see Lorimer & Kramer 2005). Pulsars are fast-rotating, and usually detected due to the fact that an offset exists between their magnetic and rotational axes, causing them to appear as periodic signals, with an observer typically receiving one pulse per one complete rotation of the pulsar. The radio luminosity of a pulsar with spin period $P$ situated at a distance $d$ from an observer is given in terms of the measured flux density as

$$L = \frac{4\pi d^2}{\delta} \sin^2 \left(\frac{\rho}{2}\right) \int_{f_1}^{f_2} S_{\text{mean}}(f) \, df,$$  

(2)

where $\delta = \frac{W_{\text{eq}}}{P}$ is the pulse duty cycle ($W_{\text{eq}}$ is the equivalent pulse width), $\rho$ is the radius of the pulsar emission cone, the integrand is the mean flux density of the pulsar as a function of frequency $f$, and $f_1$ and $f_2$ bound the spectral range of the observation. Using typical values of $\delta$ and $\rho$, a pulsar with $P = 1$ s situated at a distance of 1 kpc, with a measured 1400 MHz flux density of 1 mJy, would have a radio luminosity $\approx 7.4 \times 10^{27}$ erg s$^{-1}$. On the Kardashev scale, such a pulsar would therefore correspond to a beacon produced by a civilization between Type-I and Type-II. We speculate that a civilization with the minimum capability of sending a spacecraft to a nearby pulsar to install an orbital modulator for the sweeping pulsar beam would be able to harness the energy emission of pulsars without actually building and operating a transmitter so powerful (or being capable of doing so).

Previous works have considered extraterrestrial civilizations making use of naturally-occurring phenomena to announce their presence to any listeners. For example, Cordes (1993) has suggested that extraterrestrial civilizations may make use of astrophysical masers to amplify engineered signals, thereby transmitting more power than their position on the Kardashev scale might allow them to. A critical drawback of using a maser-based communication system is that masers are usually directional, and hence require the transmitter and receiver to be serendipitously aligned. Pulsar beams, on the other hand, albeit directional, are swept around due to the rotation of the star, thereby covering a much larger area of the sky, increasing the probability of detection. A system that makes use of pulsars, in addition to being used as beacons, can also be configured for directional communication, with say, a distant spacecraft or planetary system. Fabian (1977) and Corbel (1997) have discussed the possibility of generating X-ray pulses by dropping matter onto the surface of a neutron star, or modulating the X-ray emission of accreting neutron stars. Learned et al. (2008) has proposed that ETI may modulate the period of Cepheid variables to achieve signaling, by triggering pulsations using neutrinos beamed to the stellar core.

Cordes & Sullivan (1995) and Sullivan & Cordes (1995) postulate that ETI would employ ‘astrophysical coding’ – i.e., transmitting signals that can be detected using astrophysical signal analysis – in beacons. They argue that such a signal is more likely to be detected because astronomers would be able to easily analyse it. The idea proposed in this paper is a kind of astrophysical coding technique and enjoy the benefit of higher likelihood of detectability.

The outline of this paper is as follows: In §2 we describe our proposed modulation mechanism, and in §3 we discuss the information content of the beacon. In §4 we discuss potential observational signatures of artificial modulation, and in §5 we analyse energy considerations for this signalling scheme, before concluding in §6.

2. Modulation mechanism

Installing a modulator on a pulsar would require considerations of the emission geometry of the pulsar being engineered. If we assume an inclination angle $\alpha = 90^\circ$ (i.e., the magnetic axis orthogonal to the spin axis), the modulating satellite could orbit synchronously with the pulsar spin period to allow the signal to be transmitted over the entire area of the sky covered by the pulsar beam. In the more typical case of non-orthogonal axes, a polar orbit in which the satellite intersects the pulsar beam periodically would result in directional transmission. A scaffolding shell around the pulsar in which modulating elements are placed at locations where the pulsar beam intersects with the scaffold would result in the ability to cover the entire beaming solid angle of the pulsar.

We first consider a toy model of an orbital modulator that is synchronous with the pulsar rotation, assuming that the inclination angle of the pulsar beam, $\alpha = 90^\circ$, as shown in Figure 1(a). For a pulsar with mass $M$ and period $P$, equating centripetal acceleration to the acceleration due to gravity gives an orbital radius

$$r \approx 1.7 \times 10^3 \left(\frac{M}{1.4M_{\odot}}\right)^{1/3} \left(\frac{P}{s}\right)^{2/3} \text{km.}$$  

(3)

For a canonical $1.4M_{\odot}$ pulsar with $P = 1$ s, this gives $r \approx 1700$ km, with a tangential velocity component of approximately 4% the speed of light. To probe the structural integrity of the satellite at this distance, we model the satellite as a solid steel cylindrical bar 10 m in length and 1 m in radius, oriented in such a way that the long axis is directed radially outwards from the pulsar. The elongation of the bar due to the differential gravity on either of its ends is of the order of $10^{-5}$ m, and therefore, is inconsequential.
Instead of a satellite, a civilization capable of advanced astronomical engineering could build an equatorial ring around the pulsar that covers the entire area swept by the beam. A less desirable option would be to have a satellite in a non-synchronous orbit periodically intercepting the pulsar beam, but this would severely reduce the beaming fraction of the modulated beam, and also make message reconstruction more difficult.

The typical case of non-orthogonal beams, however, is more complicated. A modulating satellite in a polar orbit that intercepts the pulsar beams periodically could be built, but this has the problem of low beaming fraction, which would not serve as a beacon, but could be used for directional communication. For a beacon, the last option – albeit one that would require a significant amount of astronomical engineering – would be a scaffold around a pulsar akin to a Dyson sphere (Dyson, 1960), with modulating elements placed at the points where the pulsar beam intersects the scaffold, as shown in Figure 1(b). Traditional Dyson structures around main-sequence stars provide general-purpose energy for the consumption of an advanced civilization. In the case of a Dyson sphere around a pulsar as outlined in this paper, the energy of the host star is used only for producing a beacon. The materials that make up the scaffold, and the structural engineering of the scaffold should be such that it should not interact with the particles and field lines within the pulsar magnetosphere, except at the modulating elements. The radius of the shell should be large enough such that the pulsar emission region lies within this shell. Kijak & Gil (2003) give a semi-empirical formula to calculate the heights of emission regions of pulsars, which, for a 10 km-radius pulsar, is

$$r_{em} \approx 400 \left( \frac{f}{\text{GHz}} \right)^{-0.26} \left( \frac{\dot{P}}{10^{-15}} \right)^{0.07} \left( \frac{P}{\text{s}} \right)^{0.30} \text{ km},$$

where $f$ is the frequency of radio emission at $r_{em}$, $\dot{P}$ is the period derivative, and $P$ is the period of the pulsar. Assuming that the lowest frequency of interest to the modulation is 10 MHz, a pulsar with $P = 1 \text{ s}$ and $\dot{P} = 10^{-15} \text{ s}^{-1}$ would have a maximum emission height of interest of $\sim 1300 \text{ km}$. This gives the minimum radius of the Dyson sphere.

As in any communication system, the modulation could be one of many types. It could be amplitude modulation, frequency modulation, or phase modulation, either analogue or digital. In this paper, we consider the simplest case, where an amplitude modulator toggles between 0% modulation (modulator transparent to pulsar radiation) and 100% modulation (modulator opaque to radiation) to achieve preferential nulling, resulting in single-bit data transmission. For the sake of simplicity, we also assume that the nulling is frequency-independent, that is, during a null, the entire radio emission of the pulsar is blocked. The information content of this system is discussed in §3.

We do not speculate on the nature of the modulator as it would most likely be based on technology not yet invented by humans, although it would seem that the signal-modulating mechanism could be based on confined plasma, or perhaps, electro-optic modulators (see Purvinis & Maldonado, 2010). In the case of nulling modulation, the modulating material would need to scatter, absorb or redirect the entire radiation falling on it. If the radiation is absorbed, this would manifest as an increase in the temperature of the modulator and could show up as thermal radiation when the energy is re-radiated. This is discussed in more detail in §4. The effect of radiation-induced heating of the modulator on the lifetime of the system is discussed in §5.
3. Information content

A single-bit modulation system as mentioned in the previous section would support only low bit rates. For the nulling method, the data rate, \( R = 1/P \) bits per second, where \( P \) is the spin period of the pulsar in seconds. Even utilizing the fastest pulsars, the transmission rate would be less than 1 Kbps. In this model, we have assumed that the nulling is independent of frequency. A more complex system could make use of frequency-dependent nulling, thereby increasing the data rate of the signal. Further increase in data rate using amplitude modulation would require more complex modulation mechanisms wherein the amplitude of a pulse varies over a range of modulation depths. Another possibility is using a modulating signal whose frequency is much larger than the pulsar period (but less than the ‘carrier’ frequency, or the radio frequency). This would manifest as narrow features in the time domain, within the on-pulse of the pulsar.

The artificially-modulated pulsar signal contains another piece of ‘information’ that is astrophysically-coded – the fact that the ETI identified the neutron star that was engineered as a pulsar indicates that their civilization may be based on at least one planet that is within the beaming solid angle of the pulsar. If the inclination angle of the pulsar beam can be determined, this helps derive a coarse constraint on the location of the civilization.

4. Observable effects

Pulse nulling (Backer, 1970) is observed in many pulsars, and is usually attributed to changes in the plasma currents in the pulsar magnetosphere (see, for example, Wang et al., 2007), although this explanation has not been conclusively established. Statistical studies of nulling and the possibly related phenomena of mode-changing and drifting sub-pulses have the potential to determine any signs of non-natural processes in action. Redman & Rankin (2009) treated the pulse-null stream for a set of pulsars as a binary sequence and performed a statistical runs test, and found that nulling is not random in many pulsars that exhibit the phenomenon. But as shown by Cordes (2013), this just indicates a different random Markov process in action. An artificially-nulled pulsar would also show up as non-random in an analysis as done by Redman & Rankin (2009), but in general, it is unclear how to distinguish between artificial and natural nulling. If we assume that the intention of the modulation is to serve as a beacon, one of the easiest ways to display an artificial nature would be to have the null runs last for prime numbers of rotations. An example histogram of null-run duration is shown in Figure 2, which is extremely unlikely to be produced due to any natural process. Another way would be to null a pulse once after every \( n \) complete rotations of the pulsar, where \( n \) is a prime number. This system might be preferable if nulling the pulsar is expensive in terms of energy, as each null run lasts for only one complete rotation of the pulsar. In this case, a histogram for the number of rotations between nulls would look similar to Figure 2. Any other information the ETI would like to transmit could additionally be imposed as amplitude modulation on the non-nulled pulses.

Irrespective of whether the modulation is due to an orbiting satellite or due to a Dysonian scaffold, during a null, if the pulsar signal is absorbed, the temperature of the absorbing medium (modulating element) should increase. To prevent heat build-up, the modulating element will need to shed this excess energy in a timescale of the duration of one complete rotation of the pulsar. Looking for excess emission with a thermal spectrum during the null phases of a pulsar would indicate such a process in action. Considering the case of an orbiting satellite as shown in Figure 1(a), assuming that the power emitted by the pulsar is given by

\[
\dot{E} = \frac{L_{\text{spin-down}}}{\Delta t} = \frac{4\pi^2 GM P^2}{3\pi^2 c^3} - \frac{4\pi^2 GM P^2}{3\pi^2 c^3} \approx \frac{4\pi^2 GM P^2}{3\pi^2 c^3} \times 10^{15} \text{ K},
\]

where \( P \) is the orbital radius. For a pulsar with \( P = 1 \text{ s} \) and \( \dot{P} = 10^{-15} \text{ s}^{-1} \), and taking \( r = 1700 \text{ km} \) as derived in (2), we get \( T \approx 2.7 \times 10^4 \text{ K} \), which corresponds to a wavelength of approximately 107 nm, in the ultraviolet. An excess of thermal emission that peaks in the ultraviolet during the null phases of this pulsar, therefore, would indicate the presence of an absorbing medium.

Pulsar signals are affected by the cold plasma that makes up the interstellar medium (ISM) in various ways (Rickett, 1996; Cordes, 2002). A challenging aspect of detecting an intelligent signal within the pulsar beam is decoupling the modulation and the effects of the ISM, particularly for pulsars in the strong scattering regime.
A simple-minded approach would be to assume that the ETI-imposed nulling covers the entire band of radio emission from the pulsar, whereas diffractive scintillation is frequency-dependent. Another factor that helps discriminate between artificial modulation and scintillation is the difference in time scales. Diffractive scintillation timescales are usually of the order of minutes to hours (Coles et al., 2010), which is significantly longer than any variation due to artificial modulation, which is of the order of the pulse period.

5. Discussion

The decision of using a conventional radio transmitter vis-à-vis a pulsar-based beacon depends on the number of pulsars required to cover the entire sky, the cost of installing modulators around those pulsars, and the lifetime of the modulating system. Assuming that the beaming solid angle of a pulsar is about 20% of the sky, it would take at least five such pulsars to cover the entire sky. If the energy requirements for sending modulating satellites to those pulsars (or building modulating Dyson shells around those pulsars) is less than that of building and operating a perpetual, omnidirectional, conventional transmitter of the same power, the former would be the optimal solution, provided the lifetime of such a system is long enough.

A spacecraft that has to be inserted into orbit around another star has to accelerate to some maximum velocity $v$ and then decelerate. To first order, the energy required for this is twice the kinetic energy of the spacecraft from launch to achieving maximum velocity, $E = mc^2(\gamma - 1)$, where $m$ is the mass of the spacecraft (including fuel mass) and $\gamma = 1/\sqrt{1 - v^2/c^2}$ is the Lorentz factor. Assuming a spacecraft mass of $10^9$ kg, travelling at a constant velocity equal to 10% of the speed of light, taking a time $t$ to travel a distance equal to the minimum Earth-pulsar distance for reported values in the ATNF Pulsar Catalogue ($\sim$160 pc; Manchester et al., 2003), the average energy consumption rate is approximately given by $E/t \sim 10^{19}$ erg s$^{-1}$. Since this is much less than the energy output of a pulsar, the cost involved in installing a few such satellites is negligible compared to the transmission power achieved. The major factor determining feasibility is then the lifetime of the system.

For a modulating satellite with no attitude stabilization, the lifetime depends on two factors: (a) the radiation pressure exerted by the pulsar beam and (b) the pressure due to particles that follow magnetic field lines impinging on the satellite. These two effects combine to push the satellite out of its orbit. For a modulating satellite with attitude control, the lifetime would depend on the amount of fuel it can carry. It is conceivable that electrical energy for attitude correction can be extracted from the pulsar beam itself, in which case, the lifetime will be considerably longer, with an upper limit given by the radio lifetime of the pulsar, which is about $10^7$ yr for normal pulsars or about $10^9$ yr for millisecond pulsars.

For a Dyson shell, the factors affecting feasibility are different. The cost incurred in installation would be much higher than that of a modulating satellite. The lifetime would depend on the structural properties of the scaffold, and also whether the surrounding environment of the pulsar contains potentially destructive asteroids or other debris.

Another factor that affects the lifetime of a satellite or a Dyson shell around a pulsar at the distances computed in §2 are radiation-induced heating and induction heating that would cause the satellite or Dyson shell to melt and evaporate. Cordes & Shannon (2008) show that an asteroid with a radius of $\sim 100$ m at a distance of $\sim 1000$ km from a pulsar will evaporate in less than a second. The materials used in the construction of such systems should therefore be able to overcome heating, and would require the development of technology not yet known to humans. For Dyson shells, another way to reduce heating would be by having a larger radius. This would incur a higher cost as more material would be needed for its construction. Another way of overcoming heating would be to have a satellite orbiting the pulsar at a safe distance and injecting material into the magnetosphere to modulate emission.

There is one major caveat to the pulsar modulation scheme discussed in this paper, namely, that we ignore the rate of increase of energy consumption of the extraterrestrial civilization. If the time it takes to advance to a higher developmental stage – one at which the ETI can afford to build a beacon matching typical pulsar luminosity – is less than that for their spacecraft to reach the target pulsars, the best choice for the civilization would be to wait. It is hard to predict rates of development, and depending on the availability of interstellar travel technology and nearby pulsars, civilizations may or may not choose to implement this scheme. For instance, in the event that intelligent, technological life evolved on a planet orbiting a companion to a pulsar in a multiple-star system, it would not only be energetically favourable, but quicker, to implement a pulsar modulation scheme.

6. Conclusion

It is reasonable to assume that energy production/consumption goes hand-in-hand with the development of technological civilizations, as seen on Earth. Technological civilizations should, therefore, sooner or later, embark on large-scale energy harvesting endeavours, such as building Dyson spheres. Even though it is unclear how inclined a civilization would be to announce their presence explicitly using beacons, if we assume that they are so inclined, modulating the signal of a nearby pulsar would be one of the most energy-efficient ways of doing it. Building a Dysonian scaffold around a pulsar would cost much less in terms of material than building a Dyson sphere at a habitable distance
around a Sun-like star, and would also be an engineering proof-of-concept for a pre-Kardashev-Type-II civilization.

Statistical studies of pulsar emission, such as those of nulling and pulse-to-pulse and intra-pulse intensity variation, have the potential to discover non-natural processes in action, thereby indicating the presence of technologically advanced civilizations in the Galaxy. Single-pulse observations of pulsars using radio telescopes with large collecting areas will provide the high-quality data required for this purpose.

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