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

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HIGHLIGHTS

- ETI may modify the radio emission of pulsars to use them as beacons.
- We provide a few examples of modulation mechanisms.
- We provide observational signatures that astronomers can search for.

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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 $\sim 10^{19}$ 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.

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,[1] consuming energy at the rate of $\sim 4 \times 10^{19}$ erg s^{-1}. A Kardashev Type-II civilization consumes $\sim 4 \times 10^{33}$ 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 and Morrison, 1959), such a radio beacon would necessarily have a transmission power not more than what that 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 Δf across the Galaxy, such that it can be received at an Arecibo-like radio telescope with a signal-to-noise ratio S/N, as

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

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[1] The Kardashev scale has been redefined and expanded by others (see, for example, Horowitz and Sagan, 1993), but in this paper, we follow the original definition presented in Kardashev (1964), with no consequence to our treatment.

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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, $P \sim 10^{33}$ 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 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 endeavor 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 and 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

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

where $\delta = W_{\rm eq}/P$ is the pulse duty cycle ($W_{\rm eq}$ is the equivalent pulse width), ρ 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 δ and ρ, 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 Corbet (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 and Sullivan (1995) and Sullivan and 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 Section 2, we describe our proposed modulation mechanism, and in Section 3, we discuss the information content of the beacon. In Section 4, we discuss potential observational signatures of artificial modulation, and in Section 5, we analyse energy considerations for this signaling scheme, before concluding in Section 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 Fig. 1(a). For a pulsar with mass M and period P, equating centripetal acceleration to the acceleration due to gravity gives an orbital radius

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

For a canonical 1.4 $M_\odot$ 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