Astropulse: A Search for Microsecond Transient Radio Signals Using Distributed Computing
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1. Introduction

1.1. Scientific motivation

This is an exciting time in the field of transient astronomy, both in the radio and in other parts of the spectrum. Improving technology allows astronomers to perform fast followups of transient events, store extensive digital records of observations, and run processor-intensive algorithms on data in real time. These advances make possible instruments that examine optical afterglows of gamma-ray bursts (RAPTOR, Vestrand et al. (2005)) or neutrino sources (Kowalski & Mohr 2007). In the radio, astronomers search for transients such as orphan GRB afterglows (FIRST-NVSS, Levinson et al. (2002)) or radio bursts of unknown origin (STARE, Katz et al. (2003)).

My thesis research project, called “Astropulse,” searches for brief, wideband radio pulses on timescales of microseconds to milliseconds, and surveys the entire sky visible from Arecibo Observatory. The idea of a short-timescale radio observation is not new. Other experiments are well-suited for detecting radio pulses on a microsecond timescale, or even much shorter scales. However, these observations are directed; they examine known pulsars. For instance, such an experiment might record the nanosecond structure of the signals from the Crab pulsar. And of course the idea of a radio survey is not new. Other experiments perform surveys for radio pulses over large regions of the sky. However, these observations examine 50 $\mu$s timescales or longer. Astropulse is the first undirected microsecond radio survey.

This project is made possible by Astropulse’s access to unprecedented processing power, using the distributed computing technique. We send our data to volunteers, who perform coherent dedispersion using their own computers. Then they send the results of this computation back to us, informing us whether they detected a signal, and reporting that signal’s dispersion measure, power, and other parameters. Astropulse is processor intensive because we must perform coherent dedispersion, whereas other surveys perform incoherent dedispersion. Coherent dedispersion is necessary to resolve structures below 50 $\mu$s or so, depending on the dispersion measure.

We are not committed to detecting any particular astrophysical source; rather, we are motivated by our ability to examine an unexplored region of parameter space. However, we consider that we might detect evaporating primordial black holes, millisecond (or faster) pulsars, or RRATs. I will consider each of these possibilities in turn. We could also detect communications from extraterrestrial civilizations, though we will not discuss this possibility in detail.

1.2. Black Holes

1.2.1. What is a black hole?

Astropulse searches for short radio pulses from many possible sources, including evaporating primordial black holes. A black hole is a singular solution to the equations of general relativity. In particular, it’s an aggregation of matter concentrated at a single central point. The relativistic description is given by a metric, which specifies the proper time or proper distance between any two points with an infinitesimal separation from each
other. For an uncharged, nonrotating black hole, the metric is (Frolov & Novikov 1998):

\[ ds^2 = -(1 - \frac{2GM}{c^2r})c^2dt^2 + (1 - \frac{2GM}{c^2r})^{-1}dr^2 + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \] (1)

The surface given by \( r = \frac{2GM}{c^2} \) is evidently special, because the radial spatial component of the metric blows up to infinity at that point. This is not a true singularity, as can be shown by a change of coordinates – the true singularity is at the center, \( r = 0 \). But the surface \( r = \frac{2GM}{c^2} \) is often taken to be the “radius” of the black hole, although in truth there is no mass at any point except \( r = 0 \). The radius is called the Schwarzschild radius, or the event horizon.

According to general relativity, it is not possible for matter to escape from inside the event horizon of the black hole. This is because time and space have taken one another’s functions – the coefficient of \( dt^2 \) is positive, and the coefficient of \( dr^2 \) is negative. That is, any trajectory directed out of the black hole would be analogous to a trajectory (in flat Minkowski space) that is either spacelike, or is timelike but directed backward in time.

### 1.2.2. Hawking radiation

However, it was proposed by Hawking (1974) that a black hole of mass \( M \) emits radiation like a black body whose temperature is given by the following relation:

\[ T_{BH} = \frac{\hbar c^3}{8\pi kGM} = 10^{-6} \left( \frac{M_\odot}{M} \right) \text{ K} \] (2)

This is the same temperature studied in the theory of black hole thermodynamics, which also attributes entropy to a black hole proportional to the black hole’s surface area (Raine & Thomas 2005).

The radiation occurs at the event horizon of the hole, which has a radius \( r = \frac{2GM}{c^2} \), and an area \( A = 4\pi r^2 = (16\pi G^2/c^4)M^2 \). (It turns out that the Euclidean formula for the area of a sphere still holds in this case.) This gives the black hole an intrinsic luminosity of \( L = \sigma AT^4 \propto M^{-2} \).

The radiant energy comes directly from the black hole’s mass, and as a result, it is losing mass at a rate \( \dot{M} \propto -M^{-2} \). Because the black hole radiates more power as it shrinks, we expect a burst of energy in the last moments of the black hole’s life. Astropulse hopes to detect this burst of energy, so we would like to know about its duration. One can make different assumptions about the energy distribution of the radiation from a black hole evaporation (Carter et al. 1976). For a ”hard” equation of state, with an adiabatic index \( \Gamma > \frac{6}{5} \), the radiation does not reach thermal equilibrium. The standard model falls into this category, and would assume that the radiation behaves as a relativistic ideal gas, \( \Gamma = \frac{4}{3} \). In this case, the final explosion of the black hole lasts on the order of seconds. However, for a ”soft” equation of state, as proposed by Hagedorn (1965), \( \Gamma \) could be much smaller. In this case, the explosion might happen in \( 10^{-7} \) seconds or less. Astropulse is ideally suited for detecting such fast explosions.
We can integrate the radiant energy to find the total lifetime of the hole:

$$\tau_{BH} = 10^{10} \text{ year} \left( \frac{M}{10^{12} \text{ kg}} \right)^3$$

Clearly, if $\tau_{BH}$ is greater than the age of the universe, the black hole cannot be exploding now, no matter when it was created. Therefore, the black hole must have been created at a mass of $10^{12} \text{ kg}$ or less. So we should inquire about known black holes, their masses, and their origins.

1.2.3. Classes of black holes

Known (and speculated) types of black holes can be divided into solar mass, supermassive, intermediate mass, and primordial black holes.

Solar mass black holes form when a supernova forces a star’s core to implode, resulting in a neutron star or (if the progenitor star is sufficiently massive) a black hole. The Chandrasekhar limit says that a white dwarf cannot be more massive than about 1.4 solar masses, and similarly a neutron star cannot be more than $2 - 3$ solar masses depending on the assumed equation of state. The existence of neutron stars was confirmed in 1967 with the discovery of pulsars, but black holes proved harder to pin down. One method (Fre et al. 1999) for detecting a black hole is to search for an x-ray binary, where a star and a black hole orbit one another. The existence of the (invisible) black hole can be established by the redshift and blueshift of its partner, and it’s possible to detect x-ray emission as material spirals into the black hole and is absorbed.

Supermassive black holes are much larger, containing millions or billions of solar masses. The first confirmed supermassive black hole is the one at the center of our galaxy, detected via the motions of nearby stars (Raine & Thomas 2005). These stars are moving in extremely fast, tight orbits, implying a huge, dense mass at the center. Even if we assume that the source of the gravity is itself a cluster of neutron stars, it would follow that the cluster should quickly collapse into a black hole. Supermassive black holes also exist in other galaxies, and are crucial in creating the energy output of quasars and similar objects. It is not fully understood how supermassive black holes form, but they probably come from mergers of smaller black holes.

Intermediate mass black holes, for instance between $100 - 1000 M_\odot$, are even less well understood. They may be responsible for certain ultraluminous x-ray sources (Raine & Thomas 2005), or may be located at the centers of certain globular clusters. These black holes must also be formed from mergers of stellar mass black holes.

But from the above calculations, we know that black holes formed from stellar collapse ($M \sim M_\odot \sim 10^{30} \text{ kg}$) will take about $10^{34}$ years to evaporate - ridiculously long compared to the age of the universe. And in fact the black hole will grow faster than that just by absorbing the CMB and interstellar medium. At its present size, the black hole would have a temperature of about $10^{-7} \text{ K}$, so it would be completely undetectable. Intermediate mass and supermassive black holes are even less detectable, as the luminosity decreases with mass. Thus there is little hope of detecting Hawking radiation from these “conventional”
black holes. However, only one mechanism is known for producing black holes of less than solar mass. Namely, they would have to be created in the big bang (Hawking 1971).

1.2.4. Primordial black holes

A hole with an initial mass of \(10^{12}\) kg would be nearing the end of its life now, and may emit a detectable pulse. According to the process outlined above, this hole would have a temperature of \(10^{12}\) K, mainly visible in gamma rays. Such a small black hole could not have been created via core collapse of a star, nor by mergers of larger black holes. It would be far more dense than a stellar mass black hole, and would compress all of its mass into a region the size of a nucleon! Thus, the mini black hole would have to form from “density perturbations in the early universe” (MacGibbon et al. 1990).

1.2.5. Electromagnetic pulses

The total amount of energy released in the last second of the black hole’s life is about \(10^{23}\) J. Most previous studies have attempted to detect this energy in the cosmic gamma ray background (Raine & Thomas 2005). But Rees (1977) suggested that some of this energy could be converted into a radio pulse. The idea is that as the hole shrinks, and becomes hotter, it starts radiating not just photons, but massive particles such as electrons and positrons (due to pair production at the event horizon), and later, heavier particles as well. This forms a plasma fireball expanding around the hole. As this conducting shell expands into the ambient magnetic field, it pushes the field out of the way, creating an electromagnetic pulse. The energy imparted to the field goes like \(\gamma^2 \times \text{(initial field energy)}\), where \(\gamma\) is the Lorentz factor of the shell. If the fireball appears when the black hole has mass \(M_{\text{crit}}\), then we can derive \(T \propto (M_{\text{crit}})^{-1}\) (equation 2) and \(kT \sim m_e \gamma\). Then the duration of the pulse is the time between the passage of the initial radiation through the maximum radius of expansion \(r_{\text{max}}/c\) and the passage of the conducting shell through that radius \(r_{\text{max}}/\beta c\), where the shell’s velocity is \(\beta c\). This difference goes like \(r_{\text{max}}/\gamma^2\), so we can take the characteristic wavelength as \(\lambda \sim r_{\text{max}}/\gamma^2\).

We can derive \(r_{\text{max}}\) if we know the ambient magnetic field strength \(B\), by assuming that all of shell’s kinetic energy goes into the field, so that the field energy, which is initially \(\propto B^2 V\) for volume \(V\), becomes \(B^2 V \gamma^2 = M_{\text{crit}}\). This fixes \(V\), hence \(r_{\text{max}}\). It turns out that for a magnetic field \(B\) around \(5 \times 10^{-6}\) Gauss and a critical mass of \(\sim 2 \times 10^{11}\) g, we get \(\lambda \sim 10\) cm. So a radio pulse detectable in the 21 cm band is plausible.

An observation of these pulses would be a very significant confirmation of both Hawking radiation and the existence of primordial black holes. At the very least, we can put a much lower limit on the possible maximum density of evaporating black holes than has been done previously, contingent on the assumption that they produce radio pulses. This information would be relevant to cosmological models describing the big bang.
1.3. Pulsars

1.3.1. Origin

Another radio source we might detect with Astropulse is a pulsar. A pulsar is a rotating neutron star, whose magnetic dipole axis is aligned differently from its axis of rotation. When the magnetic axis is directed toward the Earth, we can detect a radio pulse. Since the star rotates with a regular period, the pulses have a regular period as well – although some temporary timing irregularities (glitches) are possible, especially in young pulsars (Lorimer & Kramer 2005), and the period slowly increases over time.

Neutron stars are created when a massive star runs out of nuclear fuel, so that the fusion process cannot prevent gravitational collapse. However, if the core is not too massive, neutron pressure can halt this collapse. The stellar matter bounces off the core, resulting in a supernova, and the core becomes a neutron star. If the progenitor star has some angular momentum, the neutron star may be spinning, resulting in a pulsar. Furthermore, neutron stars in binaries may accrete matter from their partners, resulting in an increased angular momentum and a “resurrection” of the pulsar.

1.3.2. Radiation mechanism

As a pulsar rotates, its magnetic dipole field rotates with it, carrying the surrounding plasma. Since the plasma cannot move faster than the speed of light, there is a critical surface (called the “light cylinder”) at a distance \( \frac{Pc}{2\pi} \) from the pulsar’s axis of rotation, where \( P \) is the period. Some of the magnetic field lines form closed loops from the north to the south pole of the pulsar. But if a magnetic field line does not close inside the light cylinder, it will not close at all. In that case, it’s called an open field line.

A simplistic model for pulsar emission is that plasma moves along open field lines, radiating energy in the direction of motion due to the curvature of its trajectory. (Think of synchrotron radiation.) But no known model explains the data very well. Some theories include (Lorimer & Kramer 2005):

1. Antenna mechanisms: suppose the charged particles move in groups. If \( N \) particles with charge \( q \) are each moving, the resulting power radiation goes like \( (qN)^2 \). However, no mechanism is known to make the particles move in groups.

2. Relativistic plasma emission: energy comes from plasma turbulence. But this must be converted into another type of wave so that the energy can escape the pulsar’s magnetosphere.

3. Maser mechanisms.

1.3.3. Fastest possible pulsars

We want to know whether pulsars could produce pulses with a width on the order of microseconds. Astropulse is optimized for pulses of 200 \( \mu s \) or less, but its sensitivity relative to other surveys is best at short timescales, around 0.4 to 1.6 \( \mu s \).
So we should first ask about the minimum period of a pulsar. Most pulsars have periods on the order of 0.2 s to 2 s, but a few have millisecond periods – the period distribution is bimodal. The first millisecond pulsar to be discovered (Backer et al. 1982) was PSR 1937+214, with $P = 1.558$ ms. More recent discoveries include (Hessels 2006) PSR 1748-2446, with $P = 1.397$ ms, and (Kaaret et al. 2006) XTE J1739-285, which may have evidence of a pulsar with $P = 0.89$ ms.

We could attempt to deduce a minimum period with a classical (Newtonian) calculation. Say the pulsar has radius $R$, and is spinning such that its centripetal acceleration at the surface is equal to the acceleration of gravity, $R \omega^2 = \frac{(2\pi)^2 R}{P^2} = \frac{GM}{R^2}$. That is, its surface is in a Keplerian orbit. This results in

$$P^2 = \frac{(2\pi)^2 R^3}{GM} \tag{3}$$

$$\omega = 1.15 \times 10^4 \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{R}{10 \text{ km}}\right)^{-3/2} \text{s}^{-1} \tag{4}$$

so we can scale $P$ smaller by shrinking $R$ and/or increasing $M$. We could ask about the minimum possible value of $R$, but let’s first consider typical values $M = 1.4M_\odot$, $R = 10$ km. Then $P = 461$ $\mu$s, which is not too much smaller than known pulsar periods. Smaller pulsar radii might lead to much smaller periods due to the $3/2$ power of $R$. Yet the consensus among theorists is that it’s very difficult to devise a model that allows a period substantially below 1 ms. Why is this?

First, equation (4) is a classical equation. The Roche model is a simple model that applies general relativity, but assumes that the star’s mass is extremely centrally condensed, and distributed as if it were not rotating. This changes the factor in front of equation (4) to

$$\omega = 6.3 \times 10^3 \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{R}{10 \text{ km}}\right)^{-3/2} \text{s}^{-1} \tag{5}$$

If instead we calculate the star’s actual mass distribution according to GR (which requires knowing or guessing the equation of state), we find that the maximum mass $M_{\text{max}}$ of the nonrotating configuration differs from (and is $10\% - 20\%$ smaller than) the mass $M$ of the maximally rotating configuration. In this case, it turns out to be simplest to calculate $\omega$ in terms of $M_{\text{max}}$ and $R_{\text{max}}$, where $R_{\text{max}}$ is the radius of the nonrotating configuration with the maximum mass $M_{\text{max}}$:

$$\omega = 7.7 \times 10^3 \left(\frac{M_{\text{max}}}{M_\odot}\right)^{1/2} \left(\frac{R_{\text{max}}}{10 \text{ km}}\right)^{-3/2} \text{s}^{-1} \tag{6}$$

This equation is empirical, and to be rigorous one would have to derive it independently for every plausible equation of state. But the agreement with equation (6) is better than 4% for all equations of state considered in Lattimer et al. (1990).

We would like a pulsar with small $R$ and large $M$. In order to prevent the star from collapsing into a black hole, we require that the equation of state be very stiff at high densities, ensuring that the dense center of the star is capable of supporting itself against
gravity. On the other hand, the EOS must be soft at lower (nuclear) densities, so that the radius can be compressed to the smallest possible value. Essentially, we want a massive, self-supporting star with a relatively thin outer region of low density.

Several constraints are active. For instance, the speed of sound cannot be larger than the speed of light (causality), which prevents the EOS from becoming too stiff. And the neutron-proton ratio must be in beta equilibrium, in that the ratio with the minimum energy is realized. Mechanisms for softening the EOS at nuclear densities include pion condensation, kaon condensation, and quark stars (including strange stars).

Lattimer et al. (1990) proposes many possible EOS’s, but none of them results in $\omega$ larger than $1.37 \cdot 10^4 \, s^{-1}$, which yields a period of $P = 459 \, \mu s$; and most models predict significantly larger periods. So in order to imagine a rotating neutron star with a significantly faster period, we would have to invent an as yet unimagined equation of state that allows the maximum mass neutron star to be even more massive and/or smaller.

1.3.4. Shortest possible duty cycles

The duty cycle of a pulsar is the fraction of time in which the pulse is visible. That is, it is determined by the opening angle of the beam, with a correction for the possibly nonzero angle between the beam and the observer’s line of sight. According to Lorimer & Kramer (2005), the opening angle scales as $\rho \sim P^{-0.5}$.

$$\rho \approx (3/2)\theta_{em} \approx \sqrt{\frac{9\pi r_{em}}{2cP}} \text{ radians} = 1.24^\circ \left(\frac{r_{em}}{10\text{km}}\right)^{1/2} \left(\frac{P}{1\text{s}}\right)^{-1/2}$$

where:

$\rho = \frac{1}{2}$ of the opening angle of the beam. That is, $\rho$ is the angle between the magnetic axis and a line tangent to the last open field line at the point of emission. This tangent line intersects the magnetic axis at a point with distance $r_{\text{intersect}} > 0$ from the center of the pulsar.

$\theta_{em}$ = the angle between the magnetic axis, and a line passing through the point of emission and the center of the pulsar. This is smaller than $\rho$.

$r_{em}$ = the radius of the emission point, i.e. its distance from the center of the pulsar

Since emission heights don’t vary too much, this can be taken as a simple $P^{-0.5}$ law. Unfortunately, this law says that smaller periods have larger duty cycles, which is counterproductive for us. (We want both small periods and short duty cycles.) However, observation shows that some millisecond pulsars have much smaller duty cycles than expected, with a beam opening angle half-width as low as $7^\circ$ for a 3 ms pulsar, seeming to imply an emission height interior to the neutron star. This means that the beam is visible for just 120 $\mu s$. And Kramer et al. (1998) suggest that if sub-millisecond pulsars exist, their emission properties would differ substantially from millisecond pulsars. So there seems to be a great deal of uncertainty about the expected pulse widths of fast pulsars; and the lower bound to the width, if any, is not known. Therefore, if we hope to see shorter pulses from pulsars, the most likely source would be a millisecond or marginally sub-millisecond pulsar with a very narrow pulse width.
1.4. Giant Pulses

In addition to regular, periodic pulses, some pulsars (such as the Crab), produce less periodic giant pulses. These pulses can have thousands of times the flux of a normal pulse (Popov & Stappers 2007) or more. There is no consensus on the origin of giant pulses, though they may come from plasma turbulence.

The Crab’s giant pulses range from a few nanoseconds at 2 Jy µs (Hankins et al. 2003) to 64 µs or more at 1000 to 10000 Jy µs, with a typical duration of a few microseconds. Popov & Stappers (2007) have measured the energies of giant pulses from the Crab, and found the proportions of pulses with durations as low as 4.1 µs. In most pulsars, the fraction of giant pulses is too low to measure statistics accurately. However, it is clear that giant pulses can have very short timescales suitable for detection by Astropulse.

1.5. RRATs

McLaughlin et al. (2006) describe a new type of pulsed radio source, believed to be a type of rotating neutron star. (Hence the name “RRATs”, for “Rotating RAdio Transients.”) The RRATs differ from previously known rotating neutron stars (i.e. pulsars) in that:

1. Their periods are very long – 5 out of 10 of them have periods longer than 4 seconds, whereas pulsars almost never have periods that long.

2. The pulses appear sporadically, averaging 4 min to 3 hours between bursts. Fourier analysis and fast folding were unable to detect a period; rather, the authors had to find the greatest common factor of the intervals between pulse arrival times. For most sources, only 3 pulses were detected.

The bursts’ durations range from 2 to 30 ms, so Astropulse is not particularly well suited for detecting them. (Astropulse is most sensitive to bursts of duration 200 µs or less.) However, RRATs are a new phenomenon, and few have been discovered. So it’s quite possible that some RRATs have much shorter burst durations.

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