Appendix B

Proposal for Simultaneous Observations

Here we present the observing proposal for simultaneous observations at the Arecibo observatory and the Robert C. Byrd Green Bank Telescope. After submission, Kathryn Becker, Shami Chatterjee, and Joseph Lazio were added to the proposal.

Dual Station Observations Aimed at Developing RFI Mitigation Procedures

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B.1 Summary

We propose a modest request for time to use the Arecibo Telescope and the GBT in simultaneous observations aimed at diagnosing RFI and using the expected uncorrelated RFI between the two sites to excise RFI from several generic kinds of measurements. These include (1) identification of individual 'giant' pulses from the Crab pulsar; (2) a search for giant pulses from M33, the nearest, large galaxy in Arecibo's declination range; and (3) HI emission from weak galaxies in bands heavily contaminated by RFI at Arecibo. Our aim is to develop techniques for identification of single, dispersed pulses; to potentially confirm giant pulses from M33 possibly seen from Arecibo; and to develop RFI excision methods for spectroscopy.

Our work is motivated both scientifically and as demonstrator observations and analysis for both the LOFAR and the SKA projects.

B.2 Background

Detection of transient signals is one of the key goals of the Low-Frequency Array (LOFAR) project and most likely for the Square Kilometer Array (SKA). Compared to our knowledge of the transient sky at high energies (X-and-Gamma rays), the radio transient sky is at best poorly characterized. This is due, in part, because the combination of wide-field sampling and high gain is costly. Another difficulty is the prevalence of impulsive radio-frequency intereference (RFI) that we have found can mask even the characteristically dispersed pulses from pulsars. At Arecibo, we have made in-depth studies of the Crab pulsar's giant pulses in a multifrequency campaign. For this particular object, as is well known from the original discovery by Staelin & Reifenstein, the pulsar is more easily detectable through its occasional giant pulses than through a standard periodicity search. We have confirmed this result using observations from 0.43 to 8.8 GHz and have analyzed it in terms of the power-law distribution of giant-pulse amplitudes. Extrapolating to other galaxies, we estimate that giant-pulse emitting pulsars like the Crab are detectable to at least 1 Mpc using Arecibo for the typical giant pulse seen in a 1 hour time span.

We have searched for giant pulses from M33, the nearest large galaxy in Arecibo's declination range (McLaughlin & Cordes, in preparation). Dispersed, individual 'events' are seen in several of the beam areas (9 arcmin each) needed to cover the galaxy at 0.43 GHz. The apparent dispersion measure range $\sim 60-80$ pc cm^{-3} is about what we'd expect for M33's Galactic latitude and inclination. However, even with repeated observations of the same beam areas over a period of about two years, we have been unable to confirm the reality of these events because they are sporadic but more so because RFI contaminates much of the data. When a multibeam system becomes available at Arecibo in late 2004, we can employ reality checks that ensue from having simultaneous on-and-off source measurements. However, that multibeam system will be for L band and it is not clear that that is the best frequency range to confirm our 0.43 GHz measurements. In general terms, we expect that *multiple-site* as well as multiple-pixel observations are the key to confirming detections of this type. Most designs of the SKA, for example, will enable such observations with large-amounts of collecting area and multiple-beaming capability. Not wanting to wait for the SKA and also wanting to develop RFI mitigation schemes that may help in the design of the SKA, we propose dual-site observations using Arecibo and the GBT.

We request a small amount of time observing the Crab pulsar in order to confirm the integrity of the data and time-tagging using the data acquisition systems at the two sites. Then we request time for observing M33 at both sites to search for giant pulses. Finally, we request time to observe HI-dim galaxies whose redshifted lines fall in passbands at L band known to be contaminated with substantial RFI at Arecibo. The goal here is to investigate RFI excision for the case where the wanted signal is a frequency-domain feature rather than a temporal one. In all the observations, we will use the frequency-time plane as the fundamental data object and will investigate RFI occupancy and its cross-site correlation. Depending on the nature of the different classes of RFI, we will develop RFI excision algorithms appropriate for the particular kind of signal sought. We have substantial experience in analyzing such dynamic spectra with high time and frequency resolution in our pulsar searches and in studies of interstellar scintillation. We also have the computing resources for analyzing the large data sets expected.

B.3 Examples of Giant Pulses

Figure 1 shows the giant pulse analysis for the Crab pulsar, where we take fast-sampled data and search for events above a threshold of 4σ as a function of time and DM. We used a matched filter approach to take into account that the pulse width is variable (for the Crab) or unknown (when searching other objects). We find, consistent with the results of Hankins and Rickett (1975), that giant pulses can exceed 10^5 Jy in a typical run of 30 minutes.

Figure 2 shows a similar analysis for one beam area on M33. RFI is evident in the DM = 0 channel in the bottom panel while a large event is seen at DM $\approx$ 80 pc cm^{-3} that may be from an object in M33 or it may be an RFI event like those often seen at Arecibo. If real, this event is strong enough to be seen with the GBT as well as Arecibo.

B.4 Proposed Observations

We propose the following:

1. **Crab pulsar:** 2 hours at 430 MHz.

2. **M33:** Three Arecibo defined sessions of 3 hours each at 430 MHz.

3. **Redshifted HI:** One 3-hour session contiguous with the M33 observations to observe a few galaxies in the velocity range corresponding to 1350-1400 MHz where RFI is common at Arecibo.

These observations are joint between Arecibo and the GBT. In addition, we request two hours at the GBT for preliminary tests because we will be using the GBT Correlator in modes that are mostly new, so we want to ensure data integrity. Ideally, these would be during a time when the Crab pulsar is visible from Green Bank.

Data acquisition at Arecibo will be done using a WAPP system for the giant pulse observations at 430 MHz with 12.5 MHz bandwidth (limited by a front-end filter) and a 50-MHz wide WAPP system for the HI observations. Gregorian systems will be used in both cases. Data acquisition using the WAPP system is very familiar to us and we have extensive software for analyzing giant-pulse features in large frequency-time data sets.

At the GBT, we will use the correlator in fast-dump mode using the new 'spigot-card' under development through a collaboration between Caltech, NRAO and Cornell. One of us (JMC) has contributed 1.6 Terabyte of disk space to the fast dump system that will be of great use for the data acquisition parameters for this proposal.

For the giant-pulse studies we will dump ~ 512 channels across 12.5 MHz with $\sim 64\,\mu$s dump times. We will sample both polarization channels. For the HI observations we will dump at a more leasurely pace ~ 1 sec, fast enough to allow editing of RFI in the frequency-time plane.

Following these successes at Parkes, NAIC will install a multibeam L-band system at the Arecibo telescope (the Arecibo L-band Feed Array, ALFA). This will consist of a 7-beam receiver now being built at the ATNF and expected to be commissioned in 2004 with a bandwidth of 300 MHz centered at 1375 MHz (see Fig. 1 *left*). NAIC will make available to users the necessary backends to enable fast-sampled, multi-spectral pulsar data collection. From the perspective of pulsar studies, one of the key goals for building this system is to allow a group of users, organized as a "consortium", to perform large-area survey(s). The detailed scientific justification for such survey(s) falls outside the limited scope of this proposal. However one clear goal will be to use the extremely large gain of the Arecibo telescope, coupled with the ability of ALFA to cover a relatively large instantaneous area, in order to search a large area of the Galactic plane with very high sensitivity. In a sense this will be an extension of PMB, but with $\sim$ 5–10 times the sensitivity to slowly rotating pulsars and even higher to fast ones, owing to the higher frequency- and time-resolution to be used. Such a survey will probe the intrinsic distribution of pulsars in the Galaxy like no other, as simulations demonstrate clearly (see Fig. 1 *right*).

Large-area surveys such as the ones to be performed using ALFA (expected to take thousands of hours of telescope time and several years to complete) require a considerable degree of planning, design, and testing for optimal efficiency and success. With this proposal we plan to begin some of this work, in particular concerning the all-important task of characterizing RFI and developing techniques for mitigating RFI at Arecibo in the relevant band (1225–1525 MHz). We propose this within the context of a consortium of researchers to be organized more formally in future: we intend to immediately make public what we learn from these tests and expect (and welcome) the list of co-investigators in this present proposal to grow in future terms. The first ALFA pulsar consortium workshop is scheduled for 1-2 Nov 2002.

B.5 Goals of Proposed Observations

Dealing with RFI in a successful manner is crucial to the ultimate success of any Arecibo multibeam survey. Combating RFI in many past surveys was done in an ad hoc manner, when at all, often after the survey started. Our experience with PMB suggests that such an approach is likely to prove unworkable in survey(s) of large scope such as the one(s) envisioned with ALFA. Also, given that RFI mitigation is a generic problem, our work will hopefully find application in other contexts.

The multiplicity of beams provides a unique opportunity to attack the ever-growing scourge of RFI. Correlation over beams of the myriad candidate "pulsar" periods resulting from the analysis of a relevant segment of data provides this key handle in combating RFI: depending on various parameters (e.g., the signal-to-noise ratio of a pulsar candidate; the actual position on the sky of the pulsar, if real, with respect to the location of a beam in which the candidate is discovered; the angular separation on the sky between beams) a real pulsar candidate is expected to be detected in one beam or, in a small fraction of cases, in perhaps a small number (2 or 3), but certainly not in most/all (in which case it is clearly RFI). While elegant and powerful in concept, we have found in the PMB survey that this method for removing RFI is tricky to implement in practice. In the early stages of the survey we did not have any such RFI excision method implemented at all, due to less than optimal early planning. Later on we did, and eventually found that while removing certain types of RFI, we were "zapping" a large portion of the Fourier spectrum at high frequencies (equivalent to millisecond periods) as well, and were thus obliterating many millisecond pulsars from consideration.

To deal effectively with RFI, we must first characterize it as realistically as possible for the parameters of the survey(s) to be performed at Arecibo. In particular, tests must be performed of the entire bandwidth to be used (1225–1525 MHz). Only now, with the imminent availability of 4 Wide-band Arecibo Pulsar Processor (WAPP) correlators, each capable of recording 100 MHz of bandwidth in each of two polarizations, are such tests possible. We know from the RFI monitoring program (P. Perrilat) and from recent search experience at Arecibo (e.g., **?**) that the 100 MHz-wide band at 1425–1525 MHz can sometimes be relatively devoid of RFI; and also that at lower frequencies in the range of interest it can be difficult to record a clean wide band. Beyond these qualitative statements, we know very little about the RFI environment. **We thus propose to use 3 WAPPs recording data from the L-band wide feed to investigate the RFI environment in the 1225–1525 MHz band.** We will record data with 256 lags/frequency channels in each WAPP (corresponding to a frequency resolution of 0.4 MHz, compared to 3 MHz for PMB), sampled at rates of 64 μs (250 μs for PMB), for 5 minute integrations. **The pattern of 7 beams will be mimicked by collecting data from 7 locations on the sky, separated as the ALFA beams will be, in quick succession.** We will do this repeatedly on several days, thereby acquiring several long stretches of "multibeam" data. **In addition we will collect simultaneous data from the line-feed antenna mounted on the carriage house.** The line feed provides 80 MHz bandwidth centered at 1420 MHz and we will use it primarily to identify RFI that can be removed from the data acquired with the Gregorian system.

Each feed system yields a high-resolution data set of the frequency-time plane (80 or 100 MHz $\times$ 300 sec at resolutions of 0.4 MHz $\times$ 64 μs). We will characterize the RFI according to its f-t structure, expecting some to be impulsive and broadband, some narrowband and persistent, mixtures of these two, and some (e.g. swept-frequency radar) showing complex structure. Our choices for RFI excision methods will depend on the results for our RFI characterization. We will quantify and report (1) the occupancy of RFI in the f-t plane down to the radiometer noise level; (2) those frequency bands that are persistently bad and which may require notch filtering somewhere in the frontend system; (3) the fraction of the bands that can be used *after* removing RFI.

We propose to collect data while pointing both at “virgin” sky (see ahead), and also towards relatively-faint, known pulsars. The correlator-based WAPP system is significantly different as concerns data quantization from the 1-bit digitization of square-law detected, high-pass filtered voltages from 96 polarization-summed channels per beam employed in PMB. Therefore the RFI-mitigation techniques we will develop differ from those used in PMB because of both differing RFI environments and observing hardware. In particular we will be free to clip the Arecibo data with much more flexibility, as the RFI environment allows, and retain sensitivity to the longest pulsar periods, $\gtrsim 5\,\mathrm{s}$. Building upon the experiences of the PMB survey and other survey work, we will optimize our search code and preliminary RFI excision schemes by reducing the “multibeam” data sets recorded. We expect to discover ~ 2 new pulsars, even in this preliminary pilot work, and the actual number detected will allow us to confirm or modify our simulation predictions for the Arecibo sky (which we are updating using the new electron density model of . Data will be processed using existing programs for pulsar searching that we have used with WAPP data but augmented for detailed RFI-oriented analysis and for enhanced RFI-excision procedures.

B.6 Telescope Time Request

The region of interest in the Galactic plane ($32^\circ \lesssim l \lesssim 78^\circ$; $|b| \lesssim 5^\circ$) is visible from Arecibo 4 hours each day (17:30–21:30 LST). Each set of 7×5 min pointings will take ~ 40 min, including slewing, and therefore 6 such sets of pointings are possible on each day. We request 7 such days of observations in one week-long campaign, during which we will obtain data with 3 WAPPs from the L-band wide feed at a frequency of 1225–1525 MHz. In addition, we will use a fourth WAPP along with the carriage house feed whose bandwidth is 80 MHz centered on 1420 MHz. We also request 2 hr of initial test time. We expect to direct about half of the ~ 42 sets of "7-beam" pointings at nearby known pulsars to test detectability of relatively weak pulsar signals in the presence of RFI when detected by "multiple beams", and to direct the other half of the pointings at a region of the sky where the ionized electron content is expected to be enhanced, which is thus more likely to have been particularly selected against in past surveys. The particular region will be selected using the analysis leading to the new electron-density model (NE2001, Cordes & Lazio 2002), which identified several regions of strongly enhanced scattering and electron density. One candidate direction is toward W49. In total, ~ 0.5 deg^2 will be covered. We propose a relatively small time request in order to analyze the data promptly and start considering future observations and strategies needed to ultimately implement successfully large-scale ALFA surveys — the deepest possible before the advent of the SKA.

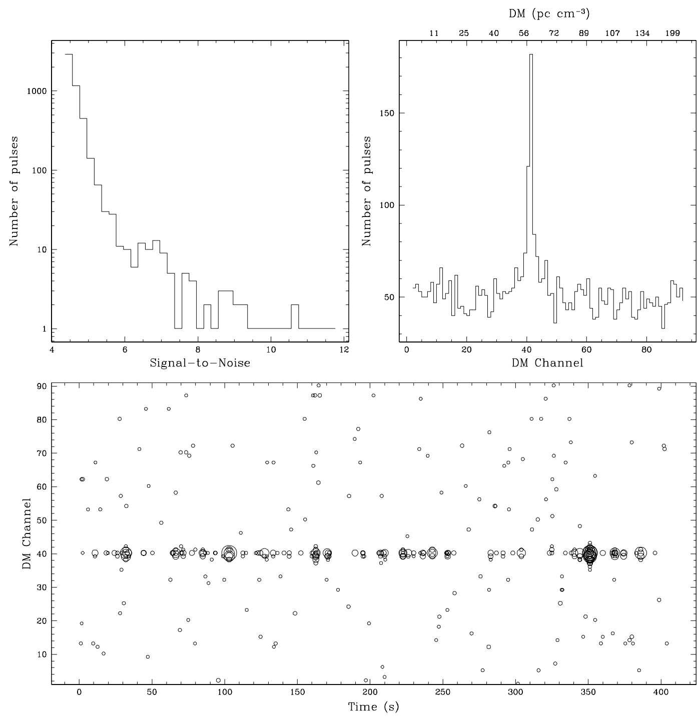

Figure B.1: Giant pulses from the Crab pulsar at 0.43 GHz using a 10-MHz bandwidth system (AOFTM). *Top Left*: Histogram of events exceeding a threshold of 4σ. *Top Right*: Histogram of events above threshold as a function of trial dispersion measure. The sharp peak corresponds to DM = 56.7 pc cm^{-3} of the Crab pulsar. *Bottom*: Events vs. time and DM channel. The total span of the data is 400 seconds. The size of the plotted symbols reflects the strength of the pulses.

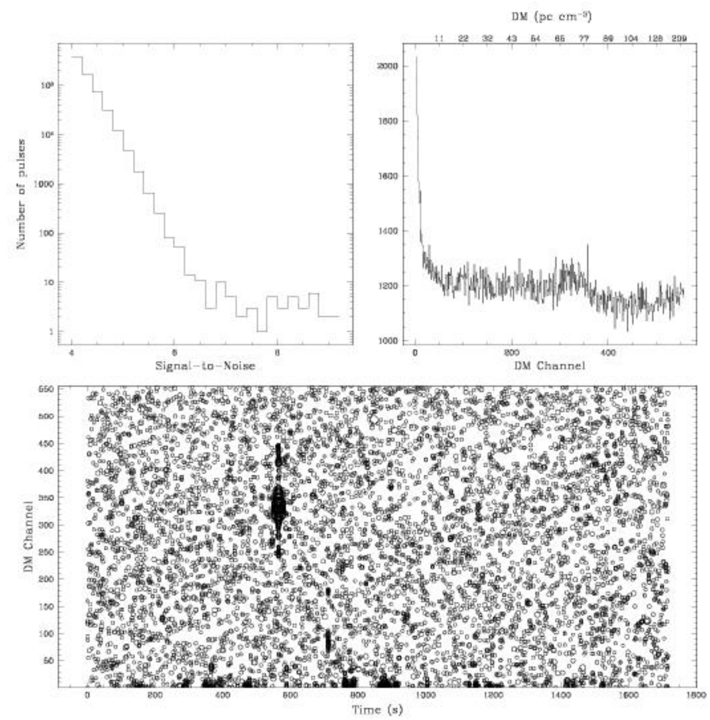

Figure B.2: Giant pulse analysis for a beam area on M33. The figure format is the same as for the Crab pulsar in Figure 1. A strong event is seen at $t \sim 500$ sec at a DM not unlike that expected for a pulsar in M33.

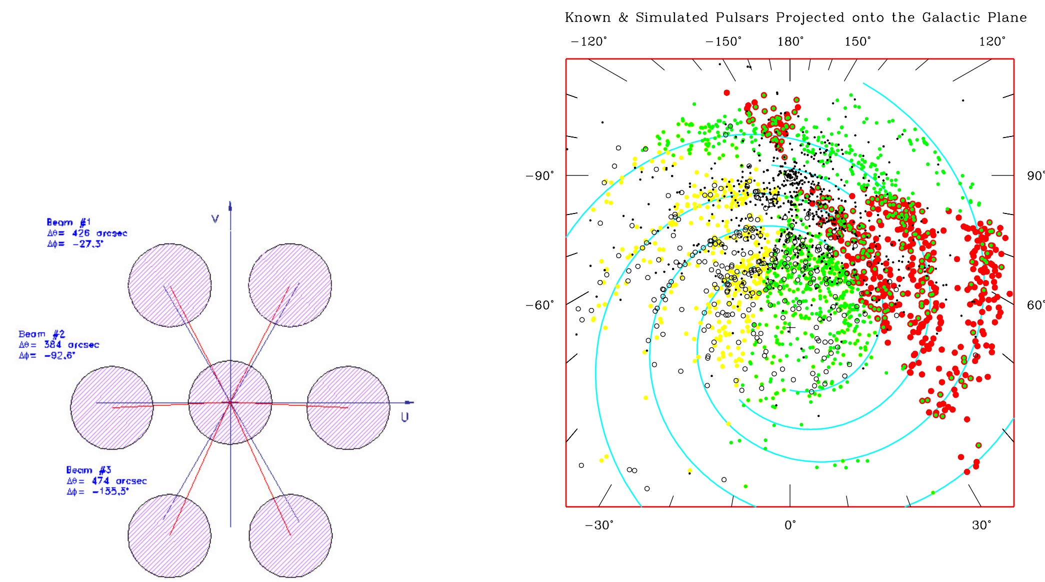

Figure B.3: *Left*: Footprint of the 7-feed system as projected onto the sky. The beams are $\sim 3'$ in diameter and their centers are separated by roughly twice this amount, making a hexagon pattern only approximately because of the nonaxial optics of the Gregorian system. Physical rotation of the feed cluster will allow us to track 7 positions for the necessary dwell times (e.g. $\lesssim 10$ minutes). *Right*: Projection of simulated and real pulsars onto the Galactic plane. Curved lines represent spiral arms from the electron density model. The simulation is a realistic model of the population and of specific surveys; it produces the correct numbers of detections in the Parkes multibeam survey. A color version is available at www.astro.cornell.edu/∼cordes.

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Appendix C

Proposal for Search for Radio Emission from Extrasolar Planets

Here we present the observing proposal for the search for cyclotron maser emission from extrasolar planets at the Arecibo Observatory, submitted October 2003 by Kathryn Becker and James Cordes.

A Search for Cyclotron Maser Emission from Extrasolar Planets

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C.1 Abstract

Radio frequency cyclotron maser radiation is emitted by all five of our solar system's magnetized planets. Given a source of energetic (keV) electrons, such as a stellar wind, it is likely that magnetized extrasolar planets also produce this intense nonthermal radiation. We propose a search for cyclotron maser emission from known extrasolar planets, targeting those planets with the largest predicted radio fluxes at 0.327, 1.4 and 5 GHz. The detection of such radiation would be the first detection of radio emission from an extrasolar planet, and would possibly be

the first direct detection of an extrasolar planet at any wavelength. The analysis of such a detection would also provide otherwise unobtainable information about the planetary magnetosphere. The sensitivity of the Arecibo telescope and the large catalog of known extrasolar planets from which to choose appropriate candidates give the proposed search an advantage over previous searches, which produced no detections.

C.2 Introduction

In less than a decade, indirect optical techniques (specifically, radial velocity searches) have revealed more than 100 planets outside our solar system. Direct detection of planets in the optical and infrared is currently impossible, as planetary emission in these bands is overwhelmed by radiation from the parent star. Radio cyclotron maser emission, however, could provide a means for direct detection of extrasolar planets.

Produced by energetic electrons incident on a planetary magnetic field, planetary cyclotron maser emission can be distinguished from radio emission from the parent star by its polarization properties and modulation timescale. In addition to being a means for direct detection of extrasolar planets, cyclotron maser emission provides direct evidence of the magnetization of the source planet. More information about the planet's magnetosphere can be obtained from an analysis of the emission's polarization (expected to be either 100% circular or elliptical) as described in Bastian et al. (1999). Through analysis of the sense of circular polarization, the emission can be localized to one or both of the planet's hemispheres. The detection of elliptical polarization can be used to place a limit on the plasma density in the magnetosphere.

Sustained radio observations could also be used to determine the rotation period of an emitting planet, as the emission is expected to modulate on this timescale.

In addition, cyclotron maser emission provides a means by which to detect satellites orbiting extrasolar planets. In our solar system, Jupiter's radio emission is modulated by its moon Io. The energetic electrons required for the cyclotron maser come in this case not from the solar wind, but from the interaction between Io and Jupiter's magnetosphere. The detection of such a periodic modulation in the extrasolar planet's radio emission could similarly indicate the presence and revolution period of of a satellite about that planet.

Previous searches for radio emission from extrasolar planets (Bastian et al. 2000; Winglee et al. 1986), carried out at the VLA, have produced no detections. The variability of cyclotron maser emission from the planets in our solar system, however, indicates the need for continued radio monitoring of extrasolar planets even after a nondetection.

In addition, our proposed search offers several advantages over previous searches. First, Arecibo's sensitivity (close to 10 times that of the VLA) gives it a significant advantage in the detection of faint radio sources.

Second, the number of known extra solar planets has more than doubled since Bastian et al.'s search in 2000. This allows us the luxury of selecting only targets most likely to produce the measurable fluxes at Earth in the frequency bands in which we will observe.

We predict these fluxes as in Farrell et al. (1999). Since little is known about the extrasolar planets and their environments, the predictions rest on a number of assumptions. First, we assume that the magnetization of the extrasolar planets scales with mass and rotation frequency as the magnetization of our solar system's gaseous planets does (Farrell et al. 1999). We also assume that the parent stars produce stellar winds similar to our sun's and that the planetary dipole moments scale as $M \sim \omega m^{5/3}$.

Data and predictions for our five target planets are presented in Table 1. The predicted cyclotron frequency, at which cyclotron maser emission peaks, is represented by ν_c. Predicted flux densities f_I and f_{II} are also shown.

In Model I, radio power from a magnetized planet goes as

$$P_I = \left(\frac{w}{w_j}\right)^{0.58}\left(\frac{m}{m_j}\right)^{0.98}\left(\frac{d}{d_j}\right)^{-1.17} 4 \times 10^9 \text{ W} \tag{C.1}$$

where the subscript j indicates the value for Jupiter.

After Zarka et al. (1997), Farrell et al. (1999) include radio power from Uranus and Netpune and decametric radiation from Jupiter in their second empirical model (Model II), giving:

$$P_{II} = \left(\frac{w}{w_j}\right)^{0.79}\left(\frac{m}{m_j}\right)^{1.33}\left(\frac{d}{d_j}\right)^{-1.60} 400 \times 10^9 \text{ W}. \tag{C.2}$$

A lower limit on the flux density incident at Earth is found by assuming spherically symmetric beaming:

$$F_{I,II} = \frac{P_{I,II}}{4\pi s^2 \Delta\nu} \text{ Wm}^{-2}\text{Hz}^{-1} \tag{C.3}$$

where, as in Farrell et al. (1999), $\Delta\nu$ is the emission bandwidth, equal to half the cyclotron frequency ν_c

$$\nu_c = 2 \times M \times 2800 \text{ kHz}. \tag{C.4}$$

Table C.1. Planet Data and Predicted Parameters

Object	m (m_j)	$2\pi/\omega$ (h)	d (AU)	D (pc)	ν_c (MHz)	f_I (mJy)	f_{II} (mJy)
51 Peg	0.46	101.5	0.05	15.36	0.15	0.05	18
τ Boo	4.13	79.5	0.05	15.6	7	0.01	8
HD 195019	3.57	10	0.14	37.36	46	2×10^{-4}	0.2
70 Vir	7.44	10	0.48	18.11	157	1×10^{-4}	0.08
HD 114762	11.03	10	0.35	40.57	304	3×10^{-5}	0.02

Note. — Mass (m), star-planet distance (d) and Earth-star distance (D) from the California and Carnegie Planet Search Team: http://exoplanets.org. In cases where $d < 0.1$ AU, it is assumed that the planet is tidally locked to its parent star; hence, its rotation period is equal to its revolution period. In all other cases, we estimate the rotation period to be 10 hours, after Farrell et al. (1999). HD 114762 has been provisionally classified as a brown dwarf by Schneider in the Extra-Solar Planets Encyclopedia: http://www.obspm.fr/encycl/encycl.html.

C.3 Proposed Observations

We propose 36 hours of observations divided among five target planets, as in Table 2. Each planet will be observed for two hours at each of three frequencies (327 MHz, 1.4 GHZ and 5 GHz). Observations at 1.4 and 5 GHz will use the 4 WAPP backends with 100 MHz bandwidth across 512 channels and a 0.1 second dump time. The 327 MHz observations will be made using a single WAPP with 32 MHz bandwidth.

We propose observations at frequencies significantly higher than ν_c both out of observational pragmatism and in recognition of the limited information available about the planets and their environments. In addition, magnetically activated radiation has occassionally been found to defy the predictions of empirical models. See, for example, the brown dwarf LP944-20, for which flaring and quiescent emission was observed several orders of magnitude above the predicted luminosity (Berger, Ball, Becker et al. 2001).

In particular, our limited knowledge of the target planets' magnetization means that ν_c could deviate substantially from predictions: if a planet is significantly more magnetized than assumed in the model, the peak frequency of its cyclotron maser emission will be raised accordingly. Of course, it is also possible a target object is less magnetized than we have assumed.

We propose to use the remaining six hours for extended ($\sim$ 3 h) observations of 70 Vir and HD 114762, the objects with ν_c closest to 327 MHz. Though these sources are predicted to be too faint for detection, the sensitive dependence of radiated power on stellar wind speed means that a small, temporary change in the activity of the parent star could bring the cyclotron maser emission up to detectable levels (Farrell et al. 1999).

Table C.2. Proposed Observations

Object	327 MHz	1.4 GHz	5 GHz	RA	Dec
51 Peg	2h	2h	2h	22:57:27.9	20:46:7
τ Boo	2h	2h	2h	13:47:16.0	17:27:24
HD 195019	2h	2h	2h	20:28:18.6	18:46:10
70 Vir	5h	2h	2h	13:28:26.0	13:46:49
HD 114762	5h	2h	2h	13:12:20.1	17:31:2

We propose somewhat longer observations than those conducted by Bastian et al. As they note, the time spent on each source in their search (1-2 hours) may have been insufficient for detection. Spending a minimum of 2 hours on each object increases the probability of observing this highly variable emission.

Once collected, data will be reduced into dynamic spectra. This format readily reveals both time and frequency structure and allows for easy extraction of interesting (or RFI-corrupted) data in either dimension.

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