

A BLIND SEARCH FOR MAGNETOSPHERIC EMISSIONS FROM PLANETARY COMPANIONS TO NEARBY SOLAR-TYPE STARS

T. JOSEPH W. LAZIO^{1,2}, S. CARMICHAEL^{3,4}, J. CLARK^{3,5}, E. ELKINS^{3,6}, P. GUDMUNDSEN^{3,7}, Z. MOTT^{3,8}, M. SZWAJKOWSKI^{3,9},
AND L. A. HENNIG³

¹Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, DC 20375-5351, USA; Joseph.Lazio@nrl.navy.mil

²NASA Lunar Science Institute, NASA Ames Research Center, Moffett Field, CA, USA

³Thomas Jefferson High School for Science and Technology, 6650 Braddock Road, Alexandria, VA 22312, USA

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ABSTRACT

This paper reports a blind search for magnetospheric emissions from planets around nearby stars. Young stars are likely to have much stronger stellar winds than the Sun, and because planetary magnetospheric emissions are powered by stellar winds, stronger stellar winds may enhance the radio luminosity of any orbiting planets. Using various stellar catalogs, we selected nearby stars ($\lesssim 30$ pc) with relatively young age estimates (< 3 Gyr). We constructed different samples from the stellar catalogs, finding between 100 and several hundred stars. We stacked images from the 74 MHz (4 m wavelength) VLA Low-frequency Sky Survey, obtaining 3σ limits on planetary emission in the stacked images of between 10 and 33 mJy. These flux density limits correspond to average planetary luminosities less than $5\text{--}10 \times 10^{23}$ erg s⁻¹. Using recent models for the scaling of stellar wind velocity, density, and magnetic field with stellar age, we estimate scaling factors for the strength of stellar winds, relative to the Sun, in our samples. The typical kinetic energy carried by the stellar winds in our samples is 15–50 times larger than that of the Sun, and the typical magnetic energy is 5–10 times larger. If we assume that every star is orbited by a Jupiter-like planet with a luminosity larger than that of the Jovian decametric radiation by the above factors, our limits on planetary luminosities from the stacking analysis are likely to be a factor of 10–100 above what would be required to detect the planets in a statistical sense. Similar statistical analyses with observations by future instruments, such as the Low Frequency Array and the Long Wavelength Array, offer the promise of improvements by factors of 10–100.

Key words: planetary systems

1. INTRODUCTION

In searches for extrasolar planets, the precision to which a planetary signal can be extracted from the data can depend in part on the properties of the host star. For instance, in radial velocity surveys, one of the limiting factors in the velocity precision is intrinsic stellar “jitter,” caused by starspots or other surface inhomogeneities. Such stellar jitter is well known to be correlated with stellar activity, the level of which declines in age (Butler et al. 1996; Saar & Donahue 1997). Radial velocity surveys tend to select stars that are chromospherically quiet (Saar et al. 1998; Cumming et al. 2008), which is likely to introduce a bias toward older stars. Further, the link between chromospheric activity and age means that distinguishing planetary transits from stellar surface features will probably be easier for older, less active stars (but see Jenkins 2002). Consequently, there is a selection bias *against* planets around younger (“adolescent”) stars.

All of the solar system’s “magnetic” planets (Earth, Jupiter, Saturn, Uranus, and Neptune) generate planetary-scale magnetic fields as the result of internal dynamo currents within the planet. The solar wind incident on these planetary magnetospheres is an energy source to the planetary magnetospheres, and the magnetosphere–solar wind interaction produces energetic (keV) electrons that then propagate along magnetic field lines into auroral regions, where electron cyclotron masers are produced.

Specific details of the cyclotron maser emission vary from planet to planet, depending upon such secondary effects as the planet’s magnetic field topology. Nonetheless, applicable to all of the magnetic planets is a macroscopic relation relating the incident solar wind power P_{sw} , the planet’s magnetic field strength, and the median radio luminosity L_{rad} . Various investigators (Desch & Barrow 1984; Desch & Kaiser 1984; Desch & Rucker 1985; Barrow et al. 1986; Rucker 1987; Desch 1988; Millon & Goertz 1988) find

$$L_{rad} = \epsilon P_{sw}^x, \quad (1)$$

with ϵ the efficiency at which the solar wind power is converted to radio luminosity, and $x \approx 1$. The value for ϵ depends on whether one considers the magnetic energy or kinetic energy, respectively, carried by the stellar wind. The strong solar wind dependence is reflected in the fact that the luminosity of the Earth is larger than that of either Uranus or Neptune, even though their magnetic fields are 10–50 times stronger than that of the Earth.

The magnetospheric emissions from solar system planets and the discovery of extrasolar planets have motivated both theoretical (Zarka et al. 1997, 2001; Farrell et al. 1999, 2004; Lazio et al. 2004; Stevens 2005; Griessmeier et al. 2005; Zarka 2006, 2007; Griessmeier et al. 2007a, 2007b) and observational work (Yantis et al. 1977; Winglee et al. 1986; Bastian et al. 2000; Lazio et al. 2004; Ryabov et al. 2004; George & Stevens 2007; Lazio & Farrell 2007; Smith et al. 2009) on magnetospheric emissions from extrasolar planets, including some before the confirmed discovery of any extrasolar planets.

Implicit in many of the early predictions for planetary magnetospheric emissions was that the stellar winds of other stars are comparable to the solar wind. Yet, from measurements of the sizes of astropauses (i.e., the boundary between the stellar

⁴ Current address: George Mason University.

⁵ Current address: University of Notre Dame.

⁶ Current address: University of Virginia.

⁷ Current address: Princeton University.

⁸ Current address: College of William & Mary.

⁹ Current address: Northwestern University.

wind and the local interstellar medium), Wood et al. (2002, 2005) find the mass-loss rate as a function of age, $\dot{M} \propto t^x$, with $x \approx -2$, a dependence probably linked to the decrease in surface magnetic activity with stellar age. Thus, the stellar wind around a 1 Gyr old star may be 25 times as intense as the current solar wind (from a 4.5 Gyr old star).

As a specific illustration of the possible effect of considering younger stars with more intense stellar winds, Farrell et al. (1999) and Lazio et al. (2004) predicted that the magnetospheric emission from the planet orbiting τ Boo would be of the order of 1–3 mJy at frequencies around 30 MHz (10 m wavelength), assuming that the stellar wind of the star was comparable to that of the Sun. Stevens (2005) and Griessmeier et al. (2007b), taking into account the likely stellar wind strength of τ Boo, predicted that its emission would be at a level of the order of 100–300 mJy. The former prediction (1–3 mJy) is below the sensitivity of current instrumentation, the latter is not.

This paper reports a blind search for magnetospheric emissions from nearby “adolescent” stars. In Section 2, we describe how we selected stars from existing catalogs of nearby stars, in Section 3 we present the results from our stacking analyses as well as considering the stars individually, and in Section 4 we present our conclusions.

2. STELLAR CATALOG ASSEMBLY

Three catalogs form the basis for our identification of nearby “adolescent” stars.

1. The NStars program is part of the *Space Interferometry Mission* Preparatory Science Program. Gray et al. (2003) and Gray et al. (2006) obtained spectroscopic observations of the 3600 main-sequence and giant stars within 40 pc of the Sun with spectral types earlier than M0.
2. The Spectroscopic Properties of Cool Stars (SPOCS) is a compilation of stars forming the basis of radial velocity planetary searches. From the series of observations in the SPOCS program, Takeda et al. (2007) estimated various physical parameters for the stars.
3. The Geneva–Copenhagen survey (GCS) of the solar neighborhood is an effort to assemble a complete and consistent set of observational and physical parameters for nearby F and G dwarfs (Holmberg et al. 2009).

We applied four selection criteria—spectral type, distance, age, and declination—to the published catalogs to form samples for further study. For spectral type, we selected main-sequence F, G, or K dwarfs. The electron cyclotron maser—the same process by which planets generate radio emission—has been detected from some stars. Typical detections are at frequencies of the order of 5000 MHz, from which (lower) coronal magnetic field strengths of the order of 300 G or higher are inferred (Hallinan et al. 2008). For the electron maser emission process, the quantity B/ν is approximately constant, where B is the magnetic field in the emitting region. At frequencies $\nu \approx 100$ MHz, we would expect magnetic field strengths of the order of 30 G; lower frequencies would result in even lower field strengths. A field strength of 30 G is typical of that inferred for very late M dwarfs and early L brown dwarfs (Berger 2002) and within a factor of a few of the field strength of Jupiter at the cloud tops (4 G). Moreover, while the Sun generates intense emission at these frequencies, notably Type III and IV radio bursts, even the strongest such radio bursts are far too faint to be detected over interstellar distances. Gergely (1986) has considered the detection of solar-type stars at low radio frequencies and finds

that current detection thresholds are at least a factor of 10^2 above what is required. If the targeted star is an F, G, or K dwarf, the presence of low radio frequency emission would be a strong indication that it is orbited by a sub-stellar companion.

Two of the catalogs, NStars and SPOCS, contain only relatively nearby stars, with distances less than 40 pc and 130 pc, respectively; for the SPOCS catalog, fully two-thirds of the stars are within 40 pc. The GCS catalog extends to much larger distances, approximately 1000 pc. We impose a distance constraint for the following reason.

In the general stacking analysis, as one stacks images from increasingly distant sources, the signal-to-noise ratio in a given image is decreasing, but is compensated by the increasing number of sources to stack. Considering stars to lie in shells at distances D with thickness ΔD , if all stars host planets, then the flux densities of planets at larger distances will be smaller by a factor of D^2 which will be exactly balanced by the increase in volume provided by going to larger distances, assuming a uniform distribution of stars. However, it is not yet known whether all stars host planets, and current limits are that the fraction of stars with planets is $f_p \approx 0.19$, for planets with semimajor axes less than about 20 AU (Marcy et al. 2008).¹⁰ Consequently, as one stacks images, an increasing fraction of the total number of images contain only noise so that the effective “signal-to-noise” ratio is decreasing. For the GCS catalog, we impose a distance constraint of 40 pc, for consistency with the other catalogs.

Two of the catalogs (SPOCS and GCS) report the ages of the stars, which we adopt. For both catalogs, ages and an estimated uncertainty are reported. Given that stellar ages often have large uncertainties associated with them, in order not to exclude stars that might be younger than their nominal ages, we construct two samples from both catalogs. One sample requires that the reported age of the star be less than 3 Gyr (samples that we denote SPOCS-age and GCS-age), while the other sample requires that the age taking its uncertainty account is less than 3 Gyr (samples that we denote SPOCS-eage and GCS-eage). The NStars catalog does not report the age of the star, but does report chromospheric flux in the Ca II H and K lines ($\log R'_{\text{HK}}$). We convert these to estimated ages following the work of Henry et al. (1996).

The final selection criterion, declination, is that we will focus on a northern hemisphere survey for which the effective declination limit is -25° (Section 3.1). More generally, we are not aware of an all-sky catalog, at a common frequency and approximately constant rms image noise level, on which to perform a similar analysis. Table 1 summarizes various properties of the sub-samples from the three catalogs.

This search is “blind” in the sense that we have made no effort to select stars already known to have planets, and even attempted to select stars whose properties are such that they might not previously have been searched for planets. Nonetheless, within our samples are small fractions of stars with known planets. We have cross-correlated our samples with the Extrasolar Planet Encyclopedia (Schneider 2009, version July 1). The SPOCS-age sample has the highest fraction of stars with known planets, 6%, with the remaining samples all having fractions below 5%. The relatively large fraction of stars with known planets in the SPOCS-age sample is consistent with the larger SPOCS

¹⁰ As magnetospheric emissions are powered by the stellar wind, for the purposes of this analysis, the presence of planets more distant from their host star is not likely to be relevant.

Table 1
Stellar Catalog Data

Catalog Name	Total Number in Catalog	Magnetospheric Subset	Median Age (Gyr)	Weighted Average Distance (pc)	Stacked Image Noise Level (mJy beam ⁻¹)	Reference
NStars	664 + 1676	252 + 249	1.3	24.4	5.7	1, 2
SPOCS-age	1074	110	1.9	19.1	11	3
SPOCS-eage	1074	176	1.4	14.3	9.3	3
GCS-age	16682	355	1.6	21.4	6.0	4
GCS-Eage	16682	656	0.7	23.0	4.8	4

Notes. The NStars catalog is published in two increments, a Northern Sample and a Southern Sample. Both the SPOCS and GCS catalogs provide age estimates and confidence intervals, from which we construct two measures of a star’s age. The “age” samples adopt the nominal stellar age while the “eage” samples use the lower limit on the age estimate. Column 3, “magnetospheric subset,” lists the number of stars from each catalog passing the four selection criteria of Section 2.

References. (1) Gray et al. 2003; (2) Gray et al. 2006; (3) Takeda et al. 2007; (4) Holmberg et al. 2009.

catalog being drawn from a set of stars which are or have been the focus of radial velocity searches. The fraction of stars in our samples that are known to have planets is smaller than the estimated fraction of stars with planets (19%; Marcy et al. 2008), consistent with the notion that current planetary searches continue to be affected by selection effects.

3. MAGNETOSPHERIC EMISSION SEARCHES

3.1. Statistical Analysis

Our search is based on the VLA Low-frequency Survey (VLSS; Cohen et al. 2007). This survey imaged 95% of the sky north of a declination limit $\delta > -30^\circ$ at a frequency of 74 MHz (4 m wavelength) with a typical rms noise level of 100 mJy beam⁻¹. Our focus on this survey is twofold. First, the frequency of this survey is within a factor of 2 of the cutoff frequency of Jupiter ($\simeq 40$ MHz), so that it is plausible that other Jovian-like planets might emit at 74 MHz. Second, it is an electronically available survey covering a large fraction of the sky, so that many nearby stars are potentially accessible. There are other surveys at lower frequencies and which cover a significant fraction of the sky, to which this approach might also be applied (e.g., Rees 1990; Dwarkanath & Udaya Shankar 1990) However, the VLSS has the advantage of having images that are readily available in an electronic format combined with a high angular resolution and sensitivity.

Each individual VLSS image was obtained by combining a series of “snapshots” acquired over a range of hour angles, with the time sampling within a snapshot being 10 s. A snapshot was typically 15–25 minutes in length, with snapshots separated typically by about 1 hr. For comparison, Jovian decametric emission observed by the Nançay Decameter Array has been observed to have an average duration of about 1 hr, with a range from about 0.5 hr to a few hours, though these observations were probably dominated by the Io-controlled component of Jovian decametric emission (Aubier et al. 2000). Although it is too low in frequency to penetrate the Earth’s ionosphere, Saturnian kilometric radiation observed by the *Cassini* spacecraft shows similar temporal characteristics (Lamy et al. 2008), but is not significantly affected by the presence of a major satellite. Assuming that extrasolar planetary magnetospheric emissions are similar to those of Jupiter and Saturn, if a planet was emitting during the course of a VLSS observation, it was likely to have been emitting for at least the duration of one snapshot, and potentially all of them. Consequently, there is a factor, potentially of the order of 1/3, in the luminosities that we derive below that would account for the fact that a planet might only

be emitting for a fraction of the time that was used to acquire a VLSS observation. This factor is sufficiently small, relative to other uncertainties, that we shall not incorporate it explicitly into the analysis below.

For each of our samples (Table 1), we downloaded small images (“postage stamps,” 1° in diameter) from the VLSS image server. Although the formal declination limit of the VLSS is -30° , the lowest declination fields are the most incomplete and often have higher rms noise levels. Thus, we used an effective declination limit of -25° .

We aligned each postage stamp image so that the target star was in the central pixel. The beam (point-spread function) of the VLSS was $80''$, with an image pixel size of $25''$. The coordinates of these stars are typically determined from the *Hipparcos* astrometric mission, epoch 1991.25 (Perryman et al. 1997); the VLSS observations were conducted between 2001 and 2007, with the majority of the observations conducted between 2003 September and 2005 April. Lazio & Farrell (2007) considered the possible astrometric uncertainties between the *Hipparcos* and VLSS frames, for the relatively high proper motion star τ Boo (proper motion $\mu \simeq 0'.5$ yr⁻¹). They showed that the combination of astrometric uncertainties, uncorrected ionospheric refraction within the VLSS, and the proper motion of the star should have produced an astrometric uncertainty in alignment of no more than $8''$, a fraction of a pixel. Thus, we are confident that alignment to the central pixel in the postage stamp images is sufficient.

We examined each of the images for any sources that might be confused with a target star or that would be close enough to the location of a target star to affect the stacking process. As an example, the star HD 69582, which appears in all of our samples, is approximately $75''$ (≈ 1 beam) from the radio source PKS 0814–029. This radio source is generally identified as a QSO, although no redshift has been measured. The offset between the star and radio source is significant enough that it is unlikely that the two are the same. We return to the question of individual stars below. In addition, we found a small number of stars that are located close to the boundaries of the VLSS, particularly near the southern declination limit. The noise level in the images for these stars was much higher (and it is possible that the astrometry is not as precise), so we excluded these. The total number of stars excluded on these considerations led to the sample sizes being about 10 stars smaller than a straightforward application of our initial selection criteria would suggest.

The number of stars N in each of our samples ranges from approximately 100 to several hundred. Assuming that the noise in the VLSS images is Gaussian distributed, as generally

Table 2
Magnetospheric Emission Limits

Sample	Flux Density Upper Limit (mJy)	Planetary Luminosity Limit ^a (erg s ⁻¹)	Stellar Wind Amplification Factors				K. E. Scaled Jovian Luminosity ^a (erg s ⁻¹)	M. E. Scaled Jovian Luminosity ^a (erg s ⁻¹)	
			Velocity	Density	Magnetic Field	Kinetic Energy			Magnetic Energy
NStars	17	9.0×10^{23}	1.7	9.8	2.4	48	9.5	1.2×10^{22}	2.4×10^{21}
SPOCS-age	33	1.1×10^{24}	1.4	4.9	1.8	15	4.8	3.7×10^{21}	1.2×10^{21}
SPOCS-eage	28	5.1×10^{23}	1.6	8.6	2.2	38	8.3	9.5×10^{21}	2.1×10^{21}
GCS-age	18	7.3×10^{23}	1.6	6.7	2.0	25	6.5	6.3×10^{21}	1.6×10^{21}
GCS-eage	14	6.8×10^{23}	2.2	30	3.6	319	28	8.0×10^{22}	7.1×10^{21}

Notes. The flux density upper limit and planetary luminosity limits are both 3σ . The flux density limits are converted to planetary luminosity limits using the weighted average distances for the samples (Table 1) and assuming a 74 MHz bandwidth for the planetary magnetospheric emissions. We assume a fiducial planetary distance of 1 AU and a planetary luminosity scaling with distance as d^2 , so that the kinetic and magnetic energy scaled Jovian luminosities include an additional factor of 25; if the typical magnetospheric emitting planet is more distant from (closer) its host star than 1 AU, these Jovian scaled luminosities would have to be adjusted downward (upward).

^a $1 \text{ W} = 10^7 \text{ erg s}^{-1}$.

expected for radio interferometric images,¹¹ we anticipate that the noise in a stacked image should be roughly $100N^{-1/2} \text{ mJy beam}^{-1}$, or about $5\text{--}10 \text{ mJy beam}^{-1}$. In our stacking analysis, we combined the images in a weighted sense, weighting each image's contribution to the final stacked image by its individual rms noise level. Using the NStars sample as an illustration (Table 1), and taking the rms noise levels in the images into account, we expect that the rms noise level in the stacked image should be $5.6 \text{ mJy beam}^{-1}$. The actual rms noise level is $5.7 \text{ mJy beam}^{-1}$, indicating that the assumption of Gaussian noise-dominated images for the VLSS is justified, at least to the stacked image noise levels we have obtained here. Table 1 also presents the rms noise levels in the stacked images.

In none of the stacked images do we detect statistically significant emission. In an area of approximately 1 beam in size, the strongest pixels range from approximately 1.5σ to 2.2σ . Table 2 presents 3σ limits on the average flux density of magnetospheric emissions from planets orbiting the stars in our samples from the various catalogs. Table 1 presents the weighted average distance for the stars in the various samples, with the weighted average distance for the N stars in a sample defined as

$$\frac{1}{\bar{D}^2} \equiv \sum_{i=1}^N \frac{1}{D_i^2}, \quad (2)$$

where D_i is the distance to the i th star in the sample. Using the weighted average distance, and assuming that the bandwidth of planetary magnetospheric emissions is comparable to the observation frequency, as it is in the case of Jupiter, we convert the flux density upper limits to limits on average planetary luminosities. Table 2 also presents these planetary luminosity limits.

3.2. Individual Stars

Prior to stacking the images in each sample, we determined the peak intensity around each star relative to the *individual* image noise level ($\approx 100 \text{ mJy beam}^{-1}$). Stars for which the peak intensity exceeded 2.5σ were then re-examined.

¹¹ In general, radio interferometric images of the sky are constructed using a fast Fourier transform, with the flux density of the visibility function at the spatial frequency origin taken to be identically zero. From Fourier transform properties, this so-called zero-spacing visibility value is equivalent to the total flux density within the field of view. In the absence of a source, the pixels in a thermal noise-limited image constructed in this manner will have a zero-mean normal distribution. The VLSS images that we analyze were constructed using this standard procedure.

One motivation for performing this check is that the VLSS catalog of sources was constructed using a threshold test, relative to the image noise level, with a relatively high signal-to-noise threshold in order to maintain a low probability for a false detection. For the VLSS, the signal-to-noise threshold was 7σ . Thus, it is possible that there is stellar (or planetary) emission that would not have been cataloged. We found no stellar position for which radio emission above 3σ ($\approx 300 \text{ mJy beam}^{-1}$) could be identified unambiguously. There were stellar positions with radio emission above this level, but they could be explained by other features, such as a sidelobe from another source.

As noted above, the positions of some stars were close to, if not coincident with, radio sources, specifically the stars HD 38392, HD 49933, HD 79555, HD 143333, and HD 202575. These stars have been detected by *ROSAT* (Huensch et al. 1998, 1999), with X-ray luminosities ranging from $6 \times 10^{20} \text{ W}$ to $3 \times 10^{22} \text{ W}$. The Benz–Güdel relation predicts that the centimeter-wavelength flux densities of these stars should be of order 0.1 mJy . Scaling these flux densities to the VLSS (74 MHz, $\lambda = 4 \text{ m}$), we expect no emission to be detectable, for any reasonable radio spectral index. We also examined the NVSS (1400 MHz, 20 cm) near the location of each star. The rms noise levels near these stars are comparable, and a 3σ upper limit to the radio emission on any of these stars is 1.9 mJy , consistent with these stars not being radio sources. Finally, we are aware of targeted radio observations of only one of these stars, HD 143333, which placed the rather unconstraining limit of 2 Jy at 5 GHz (Blair et al. 1992) on the star or any associated planet.

4. DISCUSSION AND CONCLUSIONS

What do our limits imply about potential magnetospheric emissions from planets orbiting any of the stars in our various samples? As noted in the discussion following Equation (1), the planetary luminosity can depend upon whether one is considering the kinetic energy $P_{\text{sw,kin}}$ or magnetic energy $P_{\text{sw,mag}}$ carried by the solar wind. The kinetic energy power depends upon the stellar wind density n and velocity v as $P_{\text{sw,kin}} \propto nv^3$ while the magnetic energy power depends upon the stellar wind velocity and magnetic field strength B as $P_{\text{sw,mag}} \propto vB^2$ (Zarka et al. 2001; Griessmeier et al. 2007a). The strengths of all of these quantities both depend upon distance from the host star and are expected to evolve with stellar age.

For the specific case of τ Boo, Griessmeier et al. (2007a) illustrated how one can use a stellar wind model for a star

with a known age and a planet at a known orbital distance to estimate the strength of the planetary radio emission. A straightforward extension of their approach could be applied to stars not yet known to be orbited by a planet(s) and even samples such as those we have constructed here. The additional relevant quantities that are needed would be the distribution of planetary semimajor axes and, in the case of an individual star, the distribution of its age estimate or, in the case of a sample of stars, the distribution of their age estimates. Combining these distributions, one could estimate the appropriate scaling factor by which planetary magnetospheric emission would be enhanced. However, in Section 1 we argued that the current census of extragalactic planets is likely to be biased, particularly with respect to those planets that might be most likely to be radio emitting. For that reason, we do not consider the distribution of planetary semimajor axes to be well enough constrained to incorporate it into our analysis, and we shall adopt a somewhat more simplified approach below.

With respect to the stellar wind powers, Griessmeier et al. (2007b) have synthesized various observations and models to determine functional dependences for stellar wind velocity, density, and magnetic field strength as a function of stellar age (their Equations (15), (16), (23), and (24)), for planets that are not too close to their host star. Applying these relations, and using the median age of the stars in the various samples (Table 1), we determine a scaling factor, relative to the current solar value at 1 AU, for each of these quantities. From the scaling factors for the individual quantities (v , n , and B), the scaling factors for the kinetic energy and magnetic energy powers are then determined. Table 2 (Columns 4–8) presents these scaling factors.

These scaling factors are clearly only approximate and somewhat model dependent. The number of stars for which stellar wind parameters have been determined is small. Nonetheless, they serve as an indication of the potential effect of stellar age. We see that powers delivered (at 1 AU) to potential planetary magnetospheres around these stars, for most of these samples, may be enhanced by factors of 10–50 for kinetic power and by factors of 5–10 for magnetic power.

The one potential exception is the GCS3-age sample, for which much larger stellar wind amplification powers appear possible. These large factors result from the relatively small median age for this sample (0.7 Gyr, Table 1). In turn, this small median age likely reflects the relative lack of precision with which stellar ages can be determined. Many stars in the GCS3-age sample have lower limits to their stellar ages around 0.1 Gyr, because their age estimates have large uncertainties (approaching 100%).

These scaling factors for the stellar wind powers are for a fiducial distance of 1 AU. As noted above, there is likely to be a strong star–planet distance dependence on the luminosity, but we do not attempt to include a distribution of planetary semimajor axes. Estimates of the star–planet distance dependence are that it is d^x , with $x \lesssim 2$ (e.g., Farrell et al. 1999; Zarka 2007), implying that Jupiter would be about 25 times more luminous were it at a distance of 1 AU instead of its current 5.2 AU distance. We therefore apply an additional scaling factor of 25.

The final columns of Table 2 present Jupiter’s luminosity scaled by these stellar wind kinetic energy and magnetic energy factors, respectively, and the distance scaling factor of 25. Even if a planet with luminosity comparable to Jupiter orbited every one of our target stars, our sensitivity limits remain approximately a factor of 10–100 above what would be needed to detect such planets. If the typical planet–star distance is larger

than our fiducial 1 AU value, the actual difference could be much larger.

We have not attempted to combine the stacked images from the various samples. While the samples themselves are homogeneous, they obtain age estimates from different methods. Further, there are many stars that are common to each sample, so that the stacked images are not independent.

There are a number of next-generation, low radio frequency instruments under development. Notable among these are the Low Frequency Array (LOFAR) and the Long Wavelength Array (LWA). If they reach their design goals, both promise to provide rms noise levels $\sigma \sim 3 \text{ mJy beam}^{-1}$, at frequencies below 100 MHz, nearly 2 orders of magnitude better than the 74 MHz VLA system which was used to conduct the VLSS. A similar statistical analysis applied to future LOFAR or LWA observations may improve significantly upon the limits presented here, or, ideally, detect extrasolar planetary emission.

Should either LOFAR or the LWA detect emission using a similar statistical analysis, identifying the stacked emission as planetary rather than stellar will be important. In targeted observations of an individual star or stars (e.g., Bastian et al. 2000; Ryabov et al. 2004; George & Stevens 2007; Lazio & Farrell 2007; Smith et al. 2009), an obvious distinguishing factor would be whether the emission is modulated with the planetary orbit. For this statistical analysis, alternate aspects of the stacked emission would have to be examined. Both LOFAR and the LWA are being designed to be broad band (over at least the 30–80 MHz frequency range), thus the radio spectrum of the stacked emission could be determined. Further, any correlation between the strength of stacked emission and the spectral type of the stars could be useful.

Building upon LOFAR and the LWA will be the Square Kilometre Array (SKA) and the Lunar Radio Array (LRA). While their designs will be influenced by the work on LOFAR, LWA, and similar low radio frequency interferometers, both the SKA and LRA currently anticipate operating at frequencies that would be relevant for the detection of planetary magnetospheres; in the case of the SKA, the design goal for its lower operational frequency limit is 70 MHz, while, for the LRA, frequencies $\nu \sim 50 \text{ MHz}$ are envisioned. Both would likely provide an order of magnitude sensitivity improvement upon LOFAR and the LWA.

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