1. INTRODUCTION

By analogy to the “magnetic planets” in the solar system (Earth, Jupiter, Saturn, Uranus, and Neptune), there have been various predictions that Jovian-mass extrasolar planets should also emit intense cyclotron maser emission at radio wavelengths (Zarka et al. 1997; Farrell et al. 1999; Zarka et al. 2001; Lazio et al. 2004; Stevens 2005; Griessmeier et al. 2005; Zarka 2006, 2007). If we extrapolate empirical relationships based on the solar system planets, it is possible to make quantitative predictions for both the characteristic emission wavelength and radio luminosity of an extrasolar planet (Farrell et al. 1999; Lazio et al. 2004; Stevens 2005; Griessmeier et al. 2005).

The star \( \tau \) Boo is an F6 IV star located 15.6 pc away (Perryman et al. 1997) that is orbited by a planet with a minimum mass of 4.14 \( M_j \) (Jovian masses) orbiting in a 3.3 day period (semimajor axis of 0.047 AU; Butler et al. 1997). For the planet orbiting \( \tau \) Boo, these predictions are that its characteristic emission wavelength should be between about 5 and 7 m (45 and 60 MHz) and that its radio luminosity would result in a flux density at the Earth of between roughly 1 and 250 mJy (Lazio et al. 2004; Stevens 2005; Griessmeier et al. 2005). The lower flux density estimates result from treating \( \tau \) Boo as effectively a solar twin, while the higher estimates take into account the (higher) level of stellar activity resulting from it being younger than the Sun (Stevens 2005; Griessmeier et al. 2005). In addition, for the solar system planets, variations within the level of solar activity can amplify the cyclotron maser emission process, producing radio luminosities (and therefore flux densities) at 1–2 orders of magnitude above the nominal level.

Indirect evidence for extrasolar planetary magnetic fields comes in the form of modulations in the \( \text{Ca} \) ii \( H \) and \( K \) lines of the stars HD 179949 and \( \nu \) And, modulations that are in phase with the orbital periods of their planets with the smallest semimajor axes (Shkolnik et al. 2005). Although they monitored \( \tau \) Boo, no similar modulations were seen. Shkolnik et al. (2005) suggest that the \( \text{Ca} \) ii line modulations result from energy transport related to the relative velocity between the planet and the stellar magnetosphere. Any such \( \text{Ca} \) ii line modulations for \( \tau \) Boo would then be suppressed, because the star’s rotation period is comparable to the planet’s orbital period (~3 days; Catala et al. 2007). Suggestively, however, the polarization observations of Catala et al. (2007) do imply a complex surface magnetic field topology for \( \tau \) Boo, consistent with a possible interaction with the planet’s magnetic field.

For the solar system planets, the cyclotron maser emission is fairly wideband, with \( \lambda / \Delta \lambda \sim 2 (\Delta \nu / \nu \sim 1/2) \). The Very Large Array (VLA) is equipped with a 4 m wavelength (74 MHz) receiving system. Images can be made with the VLA in its more extended configurations (A and B) with rms noise levels of approximately 100 mJy beam\(^{-1}\). Thus, the radio emission from the planet may extend to wavelengths of 4 m, and the planet may be detectable with current instrumentation.

This paper reports three epochs of 74 MHz observations of \( \tau \) Boo with the VLA. In \( \S \) 2 we describe the observations; in \( \S \) 3 we analyze our observations, from the standpoints of both the individual epochs and taken collectively, and we make suggestions about the methodology for observations with future radio telescopes; and in \( \S \) 4 we present our conclusions.

2. OBSERVATIONS

Our observations were conducted on three epochs with the VLA in its more extended configurations. Table 1 summarizes various observational details. The use of the extended VLA configurations provided angular resolutions comparable to or better than 1\( ' \); such resolution is required to reduce the impact of source
confusion. Dual circular polarization was recorded at all epochs, and the total bandwidth was 1.56 MHz, centered at 73.8 MHz. Figures 1–3 present 74 MHz images of the field around τ Boo at the three epochs.

Postprocessing of 4 m wavelength VLA data uses procedures similar to those at shorter wavelengths, although certain details differ. The source Cygnus A served as the bandpass, flux density, and visibility phase calibrator. For two of the epochs (1999 June 8 and 2003 September 12), visibility phase calibration was performed in much the same manner as at shorter wavelengths, with the phases determined from Cygnus A transferred to the τ Boo data. Several iterations of hybrid mapping (imaging and self-calibration) then ensued. For the middle epoch, the data were acquired as part of the VLA Low-frequency Sky Survey (VLSS; Cohen et al. 2007). For these data, small “postage stamp” images of bright sources from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) within the field of view were made every 1 minute. The positions of the NVSS sources are determined at 20 cm, a wavelength at which the ionosphere should present only minor perturbations. The apparent positions at the 4 m wavelength were compared with the known positions from 20 cm. Low-order Zernicke polynomials were used to model the set of position offsets and thereby infer the phase corrections to be applied to the data. After applying these phase corrections, the full data set was imaged.

Two significant differences for the postprocessing were the impact of radio frequency interference (RFI) and the large fields of view. In order to combat RFI, the data were acquired with a much higher spectral resolution than that used for imaging. Excision of potential RFI is performed on a per baseline basis for each visibility spectrum. For two of the epochs (1999 June 8 and 2003 September 12), RFI was identified and excised manually; for the second epoch (2001 January 19), RFI was identified and excised on an automated basis by fitting a linear function to each 10 s visibility spectrum and removing outlier channels. The large field of view (11° at 74 MHz) means that the sky cannot be approximated as flat. In order to approach the thermal noise limit, we used a polyhedron algorithm (Cornwell & Perley 1992) in which the sky is approximated by many two-dimensional “facets.”

3. DISCUSSION AND ANALYSIS

We have used a number of different methods in order to assess the limits on the presence of any emission at the location of τ Boo. We begin with an assessment of the astrometric accuracy of the images.

| Epoch      | Configuration | Duration (minutes) | Beam (arcsec) | Image Noise Level (mJy beam⁻¹) |
|------------|---------------|--------------------|---------------|-------------------------------|
| 1999 Jun 8 | D→A           | 281                | 30 × 29       | 120                           |
| 2001 Jan 19| B             | 75                 | 80 × 80       | 110                           |
| 2003 Sep 12| BnA           | 66                 | 32 × 21       | 100                           |
Ionospheric phase fluctuations result in refractive shifts in the apparent positions of sources within the images. The source NVSS J1347+1720 can be seen in all of the images (Figs. 1–3). The position of this source is determined at a shorter wavelength (20 cm or 1400 MHz), at which the ionospheric-induced position shifts are unimportant. For each epoch, we have fitted an elliptical Gaussian to NVSS J1347+1720 and determined the position from that fit. Uncertainties in either right ascension or declination are between 0.3'' and 6''.

In addition, τ Boo has a measured proper motion of \( \mu \alpha = -480.34 \pm 0.66 \) mas yr\(^{-1}\) and \( \mu \delta = 54.18 \pm 0.40 \) mas yr\(^{-1}\), measured in the epoch 1991.25 (Perryman et al. 1997). Over the decade between the epoch of the proper-motion determination and the measurements reported here, we expect τ Boo to have moved by no more than about 5''. Adding these uncertainties in quadrature, we expect that the position of τ Boo in these images should be uncertain by no more than about 8''. The size of the beam (point-spread function) ranges from about 25'' (epochs 1 and 3) to 80'' (epoch 2). We conclude that our astrometry is accurate to a fraction of a beamwidth.

3.2. Single-Epoch Limits on the Planetary Radio Emission

In no epoch do we detect statistically significant emission at the location of τ Boo. Our first estimate for the upper limit to any emission from the planet orbiting τ Boo is obtained from the rms noise level in each image (Table 1). Because our astrometry is accurate to better than a beamwidth, we set an upper limit of 2.5 σ at each epoch. The resulting upper limits are 250–300 mJy.

As a second means for setting an upper limit, we use the brightest pixel within a beam centered on the position of τ Boo to estimate the flux density of any possible radio emission from its planet. This estimate takes into account the background level determined by the mean brightness in a region surrounding the central beam. Upper limits determined in this manner range from 135 to 270 mJy.

As a final means for setting an upper limit, we have co-added ("stacked" or superposed epoch analysis) the three images, a technique that has been used with great success to find weak sources in diverse data sets (e.g., sources contributing to the hard X-ray background: Worsley et al. 2005; intergalactic stars in galaxy clusters: Zibetti et al. 2005). Experience with 74 MHz images shows that the rms noise level in an image produced from the sum of N images is \( \sqrt{N} \) lower, as is expected if the noise in the images is Gaussian random noise. Obviously, by co-adding images, we will be less sensitive to a rare, large enhancement in the planetary radio emission caused by a temporary increase in the stellar wind flux, but we will be more sensitive to the nominal flux density, particularly for the higher estimates for the planet’s flux density (e.g., Stevens 2005). The (1 σ) noise level in the co-added image is 65 mJy beam\(^{-1}\), a value consistent with that expected if the noise in all of the images is Gaussian. We do not detect any source at the position of τ Boo at the level of 165 mJy (2.5 σ).

Table 2 summarizes these limits. At any given epoch, the upper limits on radio emission at 74 MHz from the planet orbiting τ Boo range from an optimistic 134 mJy to, more conservatively, 300 mJy. On average, the planet’s flux density is not larger than 165 mJy. We convert these flux densities to luminosities, assuming that the emission is broadband (37 MHz = 1/2 of the observing frequency) and that the planet radiates into a solid angle of 1 sr (see below).

This planet does not transit its host star. While the planetary magnetosphere might be large, the typical emission altitude for an electron cyclotron maser for solar system planets is approximately 1–3 planetary radii. Thus, these limits should apply regardless of orbital phase.

3.3. Likelihood Estimates for Multiepoch Planetary Radio Observations

Earlier work by Bastian et al. (2000), Farrell et al. (2003), Ryabov et al. (2004), and Farrell et al. (2004) (and in § 3.2) reported nondetections of a single observation of a planet. (Yantis et al. [1977] and Winglee et al. [1986] also conducted blind searches for extrasolar planetary radio emission, but it is not clear that they observed any star now known to be orbited by a planet, and we believe that they observed each star for only a single epoch.) In addition, τ Boo has been observed at 150 MHz with the Giant Metrewave Radio Telescope (GMRT; Majid et al. 2006), the results from which will be reported elsewhere. Here we have reported nondetections from multiple observations of τ Boo. Both in the context of these observations, as well as from the standpoint of future observations, to what extent can multiple nondetections of a planet be used to place constraints on its radio emission?

The expected flux density for the radio emission from an extrasolar planet is (Farrell et al. 1999; Lazio et al. 2004)

\[
S = \frac{P_{\text{rad}}}{\Delta \nu \Omega D^2},
\]

where \( P_{\text{rad}} \) is the luminosity or radiated power from the planet, \( \Delta \nu \) is the emission bandwidth of the radiation, \( \Omega \) is the solid angle into which the radiation is beamed, and \( D \) is the distance of the planet (or its host star) from the Sun. In turn, the luminosity or radiated power and the emission bandwidth can be related to various planetary properties (e.g., mass and rotation rate of the planet). The standard practice has been to use empirical laws from the solar system to make predictions for \( P_{\text{rad}} \) and \( \Delta \nu \).

Planetary radio emission has a characteristic wavelength \( \lambda_c \) or frequency \( \nu_c \), which is related to the cyclotron frequency at the lowest altitude at which emission is able to escape (Farrell et al. 1999). In turn, this characteristic wavelength is related to the magnetic moment or the magnetic field strength at the planet’s surface. The emission is typically broadband, with \( \lambda_c/\Delta \lambda \sim 2 \). In making predictions, it has been assumed that extrasolar planetary radio emission is comparably broadband, and, more importantly, that any observational searches would be carried out at a wavelength near \( \lambda_c \) (frequency near \( \nu_c \)). From an observational standpoint, we incorporate a factor to take into account the possibility that a search may not have been conducted.

### Table 2

74 MHz τ Bootis Observational Limits

| Method                  | Epoch    | Limit      |
|-------------------------|----------|------------|
| rms noise level……….. | 1999 Jun 8 | 300 2.6   |
|                         | 2001 Jan 19 | 275 2.4   |
|                         | 2003 Sep 12 | 250 2.1   |
| Brightest pixel……….. | 1999 Jun 8 | 270 2.3   |
|                         | 2001 Jan 19 | 134 1.1   |
|                         | 2003 Sep 12 | 189 1.6   |
| Stacked image………..  | ……       | 165 1.4   |

Note.—Luminosity limits adopt a distance of 15.6 pc and assume an emission bandwidth of 37 MHz (=74 MHz/2).
at an optimum wavelength. Guided by the spectrum of Jupiter’s emission, we use
\[ f_0(\nu, \nu_c) = \begin{cases} 1, & \nu < 2\nu_c, \\ 0, & \nu > 2\nu_c. \end{cases} \] (2)

Although the step function nature of \( f_0(\nu, \nu_c) \) may seem artificial, Jupiter’s spectrum does cut off sharply around 40 MHz, which is approximately \( 2\nu_c \).

If we combine equations (1) and (2) and make the assumption that \( \Delta\nu \sim \nu_c/2 \), the expected flux density of an extrasolar planet when observed at a frequency \( \nu \) is
\[ S(P_{\text{rad}}, \nu_c, \Omega, D, \nu) = \frac{2}{\nu_c \Omega D^2} P_{\text{rad}}(\nu_c, \nu). \] (3)

We take \( P_{\text{rad}}, \nu_c (\lambda_c) \), and \( \Omega \) to be planetary parameters with the objective of constraining them from observation. The distance \( D \) to the planet (or its host star) is typically known from other means.

Our methodology for searching for radio emission from an extrasolar planet has been to utilize a radio interferometer to make images of the field surrounding the planet. In the absence of a source, the pixels in a thermal noise–limited image from a radio interferometer have a zero-mean normal distribution with a variance of \( \sigma^2 \), so the probability density function (pdf) of obtaining a pixel with a noise intensity between \( N \) and \( N + dN \) is
\[ f_0(N) = \frac{1}{\sigma\sqrt{2\pi}} e^{-N^2/2\sigma^2}. \] (4)

We adopt a signal model of \( I = S + N \) for the intensity at the location of the planet, where \( N \) is the (thermal) noise in the image and \( S \) is the flux density contributed by the planet. We assume that \( S \) is constant over the duration of the observation. If this is not the case, then the pdf of \( S \) would have to be incorporated into this analysis. In practice, perhaps the best that one could do would be to use what is known about the radio emission of the giant planets in the solar system to develop an appropriate pdf.

For the purposes of this analysis, we treat \( S \) as a constant, which has the effect that we will be placing constraints on the mean level of radio emission from a planet.

A detection occurs if the pixel intensity exceeds some threshold \( I_c \). Thus,
\[ p_S(I > I_c|S) = \int_{I_c}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-(t-S)^2/2\sigma^2} dt. \] (5)

For simplicity, we define \( x = I/\sigma \) and \( s = S/\sigma \).

Equation (3) suggests that small values of \( \Omega \) would produce large flux densities. However, small values of \( \Omega \) also imply that the radiation beam is unlikely to intersect our line of sight. We characterize the probability of interception as
\[ p_{\text{int}}(\Omega) = \frac{\Omega}{2\pi}. \] (6)

For the solar system planets, the emission is beamed from both the northern and southern auroral regions. We presume that the line of sight to a planet cannot intercept both regions simultaneously, so the appropriate denominator for this probability is a solid angle of \( 2\pi \) sr. Clearly, more complicated functions are possible, but we do not believe them to be warranted at this time. The full probability of detection is then
\[ p(P_{\text{rad}}, \Omega, \nu_c) = p_S p_{\text{int}}. \] (7)

where we have made explicit the planetary parameters that we seek to determine.

Suppose we have \( n \) observations of a planet with \( m \) detections, with \( m = 0 \) describing the current observational state. Can we place any constraints on the factors in equation (3)?

Consider first a series of trials in which the probability of detecting the planet in any single trial \( p \) is the same. This case corresponds to one in which the observations are essentially identical. Then the probability of detection in the several trials is given by the binomial probability
\[ P(p; m, n) = \binom{n}{m} p^m (1 - p)^{n-m}. \] (8)

The case of current interest would be that for which \( m = 0 \):
\[ P(p; 0, n) = (1 - p)^n. \] (9)

In any actual observational case, \( p \) will likely vary from epoch to epoch, most likely because the images will have different noise levels \( \sigma \). This will certainly be the case if the images are obtained from different instruments (e.g., the VLA vs. the GMRT). Even images from the same instrument can have different noise levels, however, depending on the prevalence of RFI during the observations, the number of antennas used, the duration of the observation, the different elevations at which the source is observed, etc. (see Table 1).

We assume that the observations are independent; that is, that the probability of detecting the planet in any given observation is independent of the other observations. This assumption is certainly warranted from the observational standpoint that the noise level \( \sigma \) is independent from observational epoch to epoch. Then the joint probability of detection is
\[ \mathcal{P} = \prod_{i=1}^{N} P_i = \prod_{i=1}^{N} \binom{n_i}{m_i} p_i^{m_i} (1 - p_i)^{n_i - m_i}, \] (10)

for which the total number of trials \( n_i \) and the number of detections \( m_i \) are allowed to vary from one set of trials to another. We give the full expression here, anticipating that there may be future observations, potentially at a range of wavelengths (e.g., VLA vs. GMRT vs. Long Wavelength Array vs. Low Frequency Array; see below). For the case presented here, there is a single trial at each epoch with no detection, \( n_i = 1, m_i = 0 \), and \( N = 3 \), so
\[ \mathcal{P} = \prod_{i=1}^{3} (1 - p_i). \] (11)

For a set of observed threshold intensities \( \{x_i\} \), the likelihood function is given by equation (11):
\[ \mathcal{L}(\{x_i\}|P_{\text{rad}}, \Omega, \nu_c) = \prod_{i=1}^{3} [1 - p(x > x_i/\sigma)], \] (12)
where we have made explicit the parameter dependences entering into $S$.

For the observations reported here, because we have observations at only one wavelength, we assume that the observing frequency is sufficiently close to $\nu_c$ that $f_e(\nu, \nu_c) = 1$. In this case, the likelihood function (eq. [12]) reduces to a function of only two parameters, $P_{\text{rad}}$ and $\Omega$. Also, in practice, we compute the (base 10) logarithm of the likelihood.

Figure 4 shows the (log-)likelihood function, which we have computed with the image noise levels listed in Table 1 and the brightest pixel limits (Table 2). The peak likelihood occurs in the lower middle left of the plot, near $P_{\text{rad}} \approx 10^{15}$ W and $\Omega \approx 0.2$ sr; the first contour is at 99% of the peak, with subsequent contours at 98%, 95%, 90%, and 67%. The horizontal dashed line indicates the approximate beaming solid angle for Jupiter (Zarka & Cecconi 2004).

Two comments on the likelihood function are warranted. First, the shape of the allowed region reflects two competing effects. From equation (3), the quantities $P_{\text{rad}}$ and $\Omega$ are degenerate. The planet could radiate intensely but be beamed into a narrow solid angle, with a low probability of detection, or it could have a wide beaming angle but only modest luminosity. The competing effect is that, as the beaming angle becomes smaller, the probability of intersecting our line of sight also becomes progressively smaller.

Second, the upper limit on $P_{\text{rad}}$ in Figure 4 is motivated by predictions. A crucial element of the prediction by Stevens (2005) is that the stellar mass-loss rate was predicted on the basis of the star’s X-ray flux. It now seems that, as the beaming angle becomes smaller, the probability of detecting a burst,” which might be quite short in duration and would be “diluted” if the entire (1 hr) observation is considered. Although Bastian et al. (2000) did not observe $\nu$ Boo at the 4 m wavelength, we have considered the impact of subdividing the observation. The obvious benefit of subdividing is that the effective number of observations increases; the disadvantage is that the noise level does as well.

We assume similar observing parameters as those we obtained in our observing programs, namely, a point-source noise level of $\sigma \approx 0.3$ Jy observed in 1 hr for observations toward a star like $\nu$ Boo. We find that subdividing the observation into 10 scans (e.g., each with a duration of 5 minutes), which increases the noise level to $\sigma \approx 0.3$ Jy, leads to essentially no improvement in the constraints that can be set.

As a final comment on our likelihood method, we anticipate that future observations with either existing or future instruments (see below) might be at different wavelengths. A significant assumption in our likelihood analysis is that searches are conducted at a common wavelength and that the planet emits at that wavelength. In the case of Jupiter, for instance, its electron cyclotron emission cuts off sharply shortward of approximately 7.5 m ($\nu > 40$ MHz). If we assume that similar processes operate in the magnetospheres of extrasolar giant planets, observations at different wavelengths may not be equally constraining. Similarly, one might wish to take into account what is known about the beaming angles from the solar system planets. It would be relatively straightforward to incorporate this prior information and extend our likelihood analysis to a Bayesian formulation. In that case, appropriate priors would have to be specified for the emission wavelength, beaming angle, and radiated power.

### 3.4. Future Observations

There are a number of next-generation, long-wavelength radio instruments under development. Notable among these are the
Low Frequency Array (LOFAR) and the Long Wavelength Array (LWA). If they are deployed as intended, both promise to provide sensitivities that are at least an order of magnitude larger than those of the 4 m wavelength VLA at comparable wavelengths ($\lambda > 3$ m or $\nu < 100$ MHz). Here we consider whether additional observations with current instrumentation would be preferable to the operation of these future facilities.

We simulated two sets of flux density measurements toward a star like $\tau$ Boo. For both measurements, the typical flux density measurement was taken to be a Gaussian random variable with a specified mean and variance, and the rms noise level was taken to be a factor of 2.5 times smaller. The first set of measurements had noise levels and flux density limits similar to those measured here, but we considered the impact of having 15 measurements rather than just 3. Not detecting planetary radio emission in such a data set would not improve significantly on the radiated power constraints (at most by a factor of a few), but would place increasingly severe constraints on the beaming angle at large power levels.

We also also considered the requirements on an instrument in order to improve the constraints significantly. Figure 5 illustrates the constraints placed by five measurements with an instrument capable of obtaining flux density measurements of approximately 25 mJy with rms noise levels of approximately 7 mJy beam$^{-1}$. Obtaining significant (an order of magnitude or better)

!!![](image)

**Fig. 5.**—Same as Fig. 4, but for a next-generation, long-wavelength instrument (e.g., the LWA or LOFAR) capable of flux density measurements in the range of 25 mJy with an rms noise level near 7 mJy beam$^{-1}$. In this case, five measurements were simulated.

improvements on the power radiated by extrasolar planetary electron cyclotron masers will require measurements at this level. One significant advantage that future long-wavelength instruments are likely to have over current instruments, however, is that future instruments are likely to have a multibeaming capability. Consequently, there is likely to be significantly more time for observation, and a much larger number of measurements (or even detections!) will thus be obtained.

4. CONCLUSIONS

We report three epochs of 4 m wavelength (74 MHz) observations of $\tau$ Boo with the VLA. Our objective was to detect the electron cyclotron maser emission from the planet orbiting this star, assuming that the planet does produce the equivalent of Jovian radio emissions. In none of our three episodic did we detect emission at the location of $\tau$ Boo. For a single epoch (Table 2), our limits on its emission range from 150 to 300 mJy, equivalent to a range of luminosities of approximately $1 - 2.5 \times 10^{16}$ W. We have also stacked ("co-added") the images to produce an average limit of 165 mJy, equivalent to a luminosity of $1.4 \times 10^{16}$ W.

We have developed a likelihood method to consider multi-epoch measurements. Our likelihood function depends on three planetary parameters: the planet’s radiated power level, $P_{\text{rad}}$, the beaming solid angle of the electron cyclotron maser, $\Omega$, and the characteristic wavelength of emission, $\lambda_{\text{rad}}$. Under the assumption that the planet does radiate at our observed wavelength, the parameters $P_{\text{rad}}$ and $\Omega$ are degenerate (Fig. 4). We find that the typical radiated power must be less than about $10^{16}$ W unless the radiated solid angle is $\Omega < 1$ sr, which would be considerably smaller than the typical value for solar system planets. Power levels of $P_{\text{rad}} < 10^{16}$ W are within the predicted range (Lazio et al. 2004; Stevens 2005; Griessmeier et al. 2005), being comparable to or below the most recent estimates that attempt to incorporate what is known about the star’s stellar wind strength.

We have also considered future long-wavelength instruments, such as the LWA and LOFAR. We find that to improve significantly upon our constraints, future instruments will have to be able to measure typical flux densities of approximately 25 mJy.

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Note added in proof.—J.-M. Griessmeier, P. Zarka, & H. Spreeuw (A&A, in press [2007]) have conducted a more recent estimation of extrasolar planetary flux density levels for the known extrasolar planets, including four emission mechanisms not considered by Lazio et al. (2004). Their predictions for τ Boo are below those of Lazio et al. (2004), so their predictions are also consistent with our nondetections.