NO DETECTABLE $H_3^+$ EMISSION FROM THE ATMOSPHERES OF HOT JUPITERS

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ABSTRACT

$H_3^+$ emission is the dominant cooling mechanism in Jupiter’s thermosphere and a useful probe of temperature and ion densities. The $H_3^+$ ion is predicted to form in the thermospheres of close-in “hot Jupiters,” where its emission would be a significant factor in the thermal energy budget, affecting temperature and the rate of hydrogen escape from the exosphere. Hot Jupiters are predicted to have up to $10^9$ times Jupiter’s $H_3^+$ emission because they experience extreme stellar irradiation and enhanced interactions may occur between the planetary magnetosphere and the stellar wind. Direct (but unresolved) detection of an extrasolar planet, or the establishment of useful upper limits, may be possible because a small but significant fraction of the total energy received by the planet is reradiated in a few narrow lines of $H_3^+$ within which the flux from the star is limited. We present the observing strategy and results of our search for emission from the $Q(1,0)$ transition of $H_3^+$ ($3.953 \mu m$) from extrasolar planets orbiting six late-type dwarfs using CSHELL, the high-resolution echelle spectrograph on NASA’s Infrared Telescope Facility. We exploited the time-dependent Doppler shift of the planet, which can be as large as 150 km s$^{-1}$, by differencing spectra between nights, thereby removing the stellar photospheric signal and telluric lines. We set limits on the $H_3^+$ emission from each of these systems and compare them with models in the literature. Ideal candidates for future searches are intrinsically faint stars, such as M dwarfs, at very close distances.

Key words: planetary systems — stars: individual ($\upsilon$ Andromedae, HD 46375, 55 Cancri, GJ 436, $\tau$ Bootis, HD 217101) — stars: late-type

Online material: color figures

1. INTRODUCTION

Twenty percent of the 180 known extrasolar planets orbit within 0.1 AU of their parent star and have masses comparable to Jupiter’s. The successful radial velocity technique (e.g., Mayor & Queloz 1995; Marcy & Butler 1996) provides the Keplerian parameters for these “hot Jupiters”: minimum mass ($M_p \sin i$), orbital period ($P_{\text{orb}}$), semimajor axis ($a$), and eccentricity ($e$). For the very small number of these that transit their star, the transit light curves supply the planet radius ($R_p$), orbital inclination ($i$), and true mass ($M_p$, e.g., Charbonneau et al. 2000, 2006), and in the rare case of a bright host star spectroscopy of the transit event can allow one to measure or constrain elemental and molecular abundance in the planet’s atmosphere. Our knowledge of a hot Jupiter’s atmospheric composition is limited to the case of HD 209458 b, whose parent star is bright enough ($V = 7.65$) for “transit spectrophotometry.” This method provided the first detection of an extrasolar planetary atmosphere through observations of Na I absorption by the planet’s troposphere (Charbonneau et al. 2002).

Vidal-Madjar et al. (2003, 2004), using transit spectroscopy, reported a detection of ultraviolet absorption by H i, O i, and C ii in the upper atmosphere of HD 209458 b out to several planetary radii. They inferred that the observed 15% Lyo absorption is taking place beyond the planet’s Roche limit, and thus that hydrogen was escaping at a rate of $\sim 10^{10}$ g s$^{-1}$. This observation motivated several models of the upper atmosphere of hot Jupiters that experience the influence of the parent star’s extreme ultraviolet (EUV) flux on temperature and escape rates. Rapid hydrodynamic escape of hydrogen would potentially affect the planet’s structure and evolution and shed light on the mass-radius relationship of the known transiting planets (Pont et al. 2005). The first such calculation was presented by Lammer et al. (2003), who based their model on Watson et al.’s (1981) hydrodynamic treatment, in which upper atmospheric temperature and mass loss are coupled. Lammer et al. pointed out that even though the effective temperatures of hot Jupiters are low enough for the planets to be stable against mass loss, UV-heated exosphere temperatures are much higher, promoting escape. They calculated a H escape of $\sim 10^{12}$ g s$^{-1}$, 9 orders of magnitude greater than the Jeans escape at the planet’s effective temperature (Sasselov 2003). Baraffe et al. (2004) applied this work to evolutionary calculations in which they unite irradiated planet atmospheres with interior structures.

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$^4$ These observations were acquired with the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope. Because STIS is no longer operational, the observations cannot be currently confirmed.
They show that for a given orbital distance there is a critical mass below which the planet will undergo rapid runaway evaporation, and although it is extremely improbable, HD 209458 b might be in such a fleeting phase.

Using a more detailed model, Yelle (2004) calculated that the energy-limited atmospheric escape rate is approximately proportional to the stellar EUV flux and for HD 209458 b is 20 times less than the Lammer et al. (2003) value. This difference is ascribed to the dependence of escape rates on the thermal structure of the upper atmosphere and the previously neglected balance between heating by EUV radiation and cooling by escape of H and radiation by molecules in the homopause at infrared wavelengths. Yelle (2004) showed that the near-IR emission by \( \text{H}_3^+ \) is an important cooling mechanism in the upper atmosphere of hot Jupiters just as it is in Jupiter’s hot thermosphere.

In § 2 we present the predictions of \( \text{H}_3^+ \) emission from a hot Jupiter that encouraged this observing program. In addition to being the first detection of \( \text{H}_3^+ \) in emission outside of the solar system,\(^5\) direct planetary detection would offer a new view into the physical properties of hot Jupiter thermospheres, applying needed constraints to models of their thermal structure. We present our search for the \( Q(1,0) \) transition of \( \text{H}_3^+ \) (\( \lambda = 3.9530 \mu \text{m} \) or 2529.72 \text{cm}^{-1} ) from the upper atmospheres of six close-in extrasolar planets. This wavelength is in the \( L' \) passband, in which the parent star, relative to optical wavelengths, is dim, making the contrast with planetary emission more favorable. We capitalized on the time-dependent Doppler shift of the planet, which can be as large as 150 km s\(^{-1} \) (or \( \Delta \lambda = 0.0020 \mu \text{m} \) at 4 \mu m) between two nights. We differentiated spectra to remove the stellar photospheric signal and telluric absorption lines, isolating any residual \( \text{H}_3^+ \) emission that would stand out as a peak and a velocity-shifted dip in the final residual. Section 3 outlines our observations and data reduction, while the analysis and resulting luminosity limits are presented in § 4. We summarize our results and discuss the requirements of future experiments in § 5.

2. \( \text{H}_3^+ \) EMISSION FROM HOT JUPITERS

Jovian \( \text{H}_3^+ \) has an equatorial column density of \( \sim 10^{15} \text{ m}^{-2} \) and is \( \sim 100 \) times more abundant at auroral latitudes (Lam et al. 1997). It has been successfully used as a diagnostic of the thermal and chemical state of Jupiter’s thermosphere and ionosphere (Stallard et al. 2002).\(^6\) \( \text{H}_3^+ \) has a strong rovibrational spectrum emitting at 3–4 \mu m, corresponding to excitation temperatures of \( \sim 1000 \) and 750 K and thereby effectively sampling the temperature range of Jupiter’s upper atmosphere (Stallard 2001). Several groups modeled the formation of \( \text{H}_3^+ \) in giant planet ionospheres (e.g., Kim et al. 1992; Achilleos et al. 1998). A chain reaction starting with the ionization of \( \text{H}_2 \) forms the molecular ion in the thermosphere. At high latitudes, this is achieved by collisions with energetic electrons funneled down along magnetic field lines,

\[
\text{H}_2 + e^- \rightarrow \text{H}_3^+ + e^- + e^- ,
\]

and more globally through stellar EUV radiation,

\[
\text{H}_2 + h\nu \rightarrow \text{H}_3^+ + e^- .
\]

An exothermic reaction quickly converts the ion to \( \text{H}_3^+ \),

\[
\text{H}_2 + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H} .
\]

\( \text{H}_3^+ \) has a minimum lifetime of about 10 s (Achilleos et al. 1998) and is destroyed by dissociative recombination:

\[
\text{H}_3^+ + e^- \rightarrow \text{H}_2^+ + \text{H} + e^- \\
\text{or } \text{H}_3^+ + e^- \rightarrow \text{H} + \text{H} + \text{H} .
\]

Jupiter emits \( \sim 10^{12} \text{ W} \) in the emission lines of \( \text{H}_3^+ \) (Lam et al. 1997). At a distance of 10 pc, the resulting flux of \( 8 \times 10^{-25} \text{ W m}^{-2} \) \((=2 \times 10^{-20} \text{ W m}^{-2} \mu \text{m}^{-1} , \text{or } 0.03 \mu \text{Jy if placed in an unresolved line at spectral resolution of } 36,000 \text{) would be undetectable with today’s telescope technologies. A hot Jupiter \((a \sim 0.05 \text{ AU}) \) is 100 times closer to its parent star and experiences \( 10^4 \) times the EUV flux and enhanced magnetic interaction with the stellar magnetosphere (Shkolnik et al. 2005). Direct detection of a transiting or even nontransiting hot Jupiter atmosphere is possible because a significant fraction of this additional energy is reradiated by narrow lines of molecular coolants, including \( \text{H}_3^+ \). As predicted by Yelle (2004) for hot Jupiters and measured by Stallard et al. (2002) in our own Jupiter (see below), \( \text{H}_3^+ \) emission is the dominant coolant of the planet’s thermosphere. A measurement of \( \text{H}_3^+ \) emission would provide needed information about temperature and ion density in the thermosphere of a hot Jupiter.

Miller et al. (2000) used the Jovian ionosphere model (Achilleos et al. 1998), a three-dimensional, fully coupled model of Jupiter’s thermosphere/ionosphere, to calculate that a Jupiter orbiting the Sun at 0.05 AU would have a \( \text{H}_3^+ \) column density (due to irradiation alone) at the subsolar point of \( 10^{18} \text{ m}^{-2} \), or 1000 times that of Jupiter. The predicted emission is \( \sim 10^{17} \text{ W} \), or a few times \( 10^{-21} \text{ W m}^{-2} \) if the planet is 15 pc away. They consider this a lower limit because their model does not take into consideration an extended atmosphere as observed for HD 209458 b, a deeper atmosphere for planets that are more massive than Jupiter, any increased ionization due to the strong stellar wind, or interactions between the magnetospheres of the planet and the star.

Yelle (2004) presented a one-dimensional aeronomical calculation representing a global average of the atmospheres of hot Jupiters with \( a = 0.01, 0.05, \) and 0.1 AU. The model shows that the planets’ thermospheres are heated beyond \( 10^4 \text{ K} \) by the EUV radiation from the solar-type star. The lower thermospheres, between \( 1R_p \) and \( 1.1R_p \), are primarily cooled by \( \text{H}_3^+ \) radiative emission, despite the fact that the calculated \( \text{H}_3^+ \) densities are approximately a factor of 10 lower than in Jupiter. This is because the increased photoionization both creates \( \text{H}_3^+ \), which is quickly converted to \( \text{H}_2^+ \), and generates the electrons that destroy the \( \text{H}_3^+ \). Cooling rates vary from \( 6 \times 10^{-8} \text{ ergs cm}^{-3} \text{s}^{-1} \) at 0.1 AU to \( 3 \times 10^{-6} \text{ ergs cm}^{-3} \text{s}^{-1} \) at 0.01 AU. For the reference case, modeled after HD 209458 b \((a = 0.05 \text{ AU}, R_p = 1.4R_J) \), Yelle predicted a \( \text{H}_3^+ \) luminosity of \( 1.0 \times 10^{16} \text{ W} \), an order of magnitude less than Miller et al.’s (2000) prediction.

Neither model includes the effects of the stellar gravitational force, stellar radiation pressure, or a planetary magnetic field. The first two become important only beyond \( \sim 3R_p \), however, a magnetic field would make a direct contribution to the ionosphere. Although we do not yet know how ubiquitous magnetic fields are among extrasolar planets, Shkolnik et al. (2003, 2005) presented evidence suggesting strong fields \((B \geq B_J = 4.3 \text{ G}) \) on two hot Jupiters, HD 179949 b and \( \nu \text{ And b} \). A planetary field would trap

\(^5\) \( \text{H}_3^+ \) has been observed in absorption in the interstellar medium (e.g., Goto et al. 2002). Brittain & Rettig (2002) announced a detection of \( \text{H}_3^+ \) emission from the protoplanetary disk around HD 141569, but more detailed observations by Goto et al. (2005) failed to confirm the result.

\(^6\) The solar EUV radiation and magnetospheric charged particles that are adsorbed by Jupiter’s thermosphere dissociate or ionize the thermospheric molecules, creating a coincident ionosphere (Yelle & Miller 2004).
ions, limiting ion escape, and cause the precipitation of electrons
and ions along magnetic field lines, producing polar enhancements
of \( H_3^+ \) on the close-in planets similar to those observed on our
Jupiter. This might increase the \( H_3^+ \) emission from a hot Jupiter,
potentially by orders of magnitude beyond the predictions.

3. OBSERVATIONS AND DATA REDUCTION

Our six stellar targets have a broad range of spectral types (F7–M2.5) and \( L' \) magnitudes (2.8–7.8). Each star hosts either a hot
Jupiter-mass or a hot Neptune-mass inner planet with an orbital
period of \( \leq 7 \) days. Given the uncertainties in the predictions,
there was a possibility that detectable \( H_3^+ \) emission might have
come from planets farther away from their central star. For this
reason we included three stellar systems that have one or more
additional outer planets. Table 1 lists each planet’s minimum mass,
orbital period, and semimajor axis, while the stellar properties are
given in Table 2.

We secured two nights of \( L' \)-band spectra of the six stars on
the 3 m NASA Infrared Telescope Facility’s Cryogenic Near-IR
Facility Spectrograph (CSHELL, in its high-resolution echelle mode
during 2005 February 15–17 and August 26 and 28. (August 27
was lost due to poor weather.) A \( 0.5 \times 30'' \) slit gave a spectral
resolution of 36,000 with an average resolution element of 2.70
detector pixels (8.3 km s\(^{-1}\)). Narrowband circular variable filters
(CVF) isolate a single order within a spectral range of 1–5 \( \mu m \).

We nodded the star along the slit with a beam pattern of A-B-
clear to ensure accurate sky subtraction. The detector’s response
was displayed in Figure 2. We plot the normalized A- and B-beam
data reduction and analysis, combining only the final A- and B-beam differenced spectra (residuals, where the fringing effects are removed) for increased S/N.

We extracted a one-dimensional spectrum from each sky-subtracted, flat-fielded two-dimensional image and calibrated wavelength with a krypton arc lamp spectrum. We took exposures before and after each stellar target. Due to the very small spectral range, it is rare for an arc line to fall within this span. It was necessary to observe arc lines at the same grating position as used for the \( H_3^+ \) line, move the CVF filter to select three different grating orders, and extrapolate to the desired wavelengths using the grating law (relating orders, angles, and wavelengths; see the CSHELL manual). One-dimensional arc spectra were extracted for each of the two beams, since the curvature in the arc lines across the detector produced a small difference in the wavelength solutions. The final precision of the wavelength solution is \( 2.5 \times 10^{-5} \) \( \mu m \).

We were unable to remove the \( N_2 O \) telluric absorption lines
due to the poor S/N of our hot standard star spectra. This did not
pose a problem for most of the stellar targets when comparing two
nights of data because the atmospheric \( N_2 O \) lines were stable. How-
ever, we could not apply heliocentric velocity corrections with the
telluric lines in the spectra or “shift and add” the individual ex-
positions to accommodate for potential broadening of the \( H_3^+ \) line
due to the planet’s orbital motion within the nightly span of ob-
servations. These velocities are for the most part negligible at this
spectral resolution. The heliocentric (and barycentric) velocities
differ from night to night by less than 3 km s\(^{-1}\). The broadening
of any planetary emission due to orbital motion in a couple of
hours is usually \( \leq 8 \) km s\(^{-1}\), or one resolution element. Broad-
ening due to the planet’s rotation is also insignificant, since these
hot Jupiters are likely tidally locked to their stars, resulting in rotation rates of \( \leq 1 \) km s\(^{-1}\).

In the end, spectra of each target star on a given night were
combined to produce the final A- and B-beam spectra. The sought-
after \( H_3^+ \) emission would be greatly Doppler-shifted (150 km s\(^{-1}\))
and stand out as a peak and a velocity-shifted dip in the mean
residual (\( \pm 1/8 ([ANight1 - ANight2] + [BNight1 - BNight2]) \)).

4. RESULTS

The \( L' \)-band spectra of \( \upsilon \) And, one of our brightest targets, are
displayed in Figure 2. We plot the normalized A- and B-beam spectra taken on 2005 August 26 and 28 in the top two panels,
## TABLE 2
**Targets and Observations**

| STAR     | SPEC. TYPE | DIST. (pc) | K<sup>a</sup> | L<sup>b</sup> | HJD Night 1 | Total Exp. Time (s) | Total S/N (pixel<sup>-1</sup>) | HJD Night 2 | Total Exp. Time (s) | Total S/N (pixel<sup>-1</sup>) | RMS of Residual | EMISSION LIMIT (W) |
|----------|------------|------------|---------------|-------------|-------------|-------------------|-------------------------------|-------------|-------------------|-------------------------------|----------------|------------------|
| GJ 436   | M2.5       | 10.2       | 6.07          | 5.80        | 2,453,417.97| 6480              | 30                            | 2,453,418.98| 5760              | 40                            | 0.0493         | 6.3E+17          |
| π Cnc    | G8 V       | 13.4       | 4.02          | 3.96        | 2,453,417.87| 6360              | 310                           | 2,453,419.85| 960               | 100                           | 0.0098         | 1.2E+18          |
| π And    | F8 V       | 13.47      | 2.86          | 2.82        | 2,453,610.10| 7280              | 310                           | 2,453,612.06| 7520              | 370                           | 0.0038         | 1.3E+18          |
| τ Boo    | F7 V       | 15         | 3.51          | 3.47        | 2,453,418.06| 3840              | 270                           | 2,453,420.05| 2520              | 180                           | 0.0092         | 2.2E+18          |
| HD 46375 | K1 IV      | 33.4       | 7.85          | 7.79        | 2,453,417.81| 2640              | 30                            | 2,453,419.75| 7440              | 30                            | 0.0462         | 1.0E+18          |
| HD 217107| G8 IV      | 37         | 4.54          | 4.49        | 2,453,609.94| 4320              | 160                           | 2,453,611.91| 4080              | 80                            | 0.0196         | 1.1E+19          |

<sup>a</sup> K magnitudes taken from 2MASS via VizieR.

<sup>b</sup> Calculated from K magnitudes and intrinsic colors from Bessell & Brett (1988).
A Fourier analysis revealed a peak frequency of $575 \mu m^{-1}$ (0.00244 cycles pixel$^{-1}$) in both the $\upsilon$ And spectra and their residuals. We removed this frequency from the residuals as it is clearly due to small variability in telluric absorption. The final mean residual is shown in the fourth panel of Figure 2. The boxed region spans the wavelength range in which the Doppler-shifted $H_3^+$ emission would appear if detected. The rms within this region is 0.38% of the stellar photosphere signal. The residual rms is converted into an $H_3^+$ luminosity limit using the star’s $L'$ magnitude and distance. We derived the $L'$ magnitudes from the $K$ magnitudes of the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and intrinsic colors from Bessell & Brett (1988). For $\upsilon$ And, the rms translates into a luminosity limit of $1.3 \times 10^{18}$ W. The rms of the intranight residuals for the $\upsilon$ And spectra is 0.2%. This demonstrates the level of stability of the spectrograph on short timescales as well as the reliability of the data reduction and analysis.

The normalized spectra of $\tau$ Boo and 55 Cnc are presented in Figures 3 and 4. For these lower S/N spectra the rms values are 0.92% and 0.98%, respectively, corresponding to luminosity limits of $2.2 \times 10^{18}$ and $1.2 \times 10^{18}$ W. In Figure 5 we plot the rms of the night-to-night residuals for the six targets against the theoretical noise limit, $(S/N)^{-1}$. Observations of $\upsilon$ And reach this limit, but as the S/N decreases the rms deviates from the line. This is mainly due to systematic noise in the CSHELL detector, including the “noisy” pixels, which are more difficult to identify and remove with lower S/N data. The upper limits for all the targets are listed in Table 2 and plotted against absolute $L'$ magnitude in Figure 6. Clearly, higher S/N data is not the sole contributor to a more stringent $H_3^+$ luminosity limit. The lowest limit is set by the faintest and lowest S/N star because it is the closest target in our sample, GJ 436 (spectral type $M_2.5$). GJ 436, at a distance of only 10.2 pc from Earth, has a $H_3^+$ emission limit of $6.3 \times 10^{17}$ W, thus approaching Miller et al.’s (2000) estimate of $\sim 10^{17}$ W.

5. SUMMARY AND DISCUSSION

We searched for the $Q(1,0)$ transition of the $H_3^+$ molecule at $3.953 \mu m$ from the thermospheres of close-in giant planets with their corresponding residuals in the third panel. A Fourier analysis revealed a peak frequency of $575 \mu m^{-1}$ (0.00244 cycles pixel$^{-1}$) in both the $\upsilon$ And spectra and their residuals. We removed this frequency from the residuals as it is clearly due to small variability in telluric absorption. The final mean residual is shown in the fourth panel of Figure 2. The boxed region spans the wavelength range in which the Doppler-shifted $H_3^+$ emission would appear if detected. The rms within this region is 0.38% of the stellar photosphere signal. The residual rms is converted into an $H_3^+$ luminosity limit using the star’s $L'$ magnitude and distance.

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Fig. 3.—L’ spectra of τ Boo centered on the H$^+$ 3.953 μm line. Two nights of CSHELL’s A beam and B beam are plotted in the first two panels. The y-axes are normalized intensity. The third panel shows the mean residual of the two beams as discussed in the text. The boxed region spans the wavelength range in which the Doppler-shifted H$^+$ line would be and has an rms of 0.92%. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 4.—Same as Fig. 3, but for 55 Cnc. [See the electronic edition of the Journal for a color version of this figure.]
around six stars and exploited the Doppler shift due to the planet’s orbital motion to subtract the stellar photosphere and telluric lines. The majority of our upper limits on $\text{H}_\text{2}$ luminosity are higher than predictions by Miller et al. (2000) and Yelle (2004). GJ 436, our faintest, nearest, and lowest S/N target, set the most stringent limit of $6.3 \times 10^{17}$ W, comparable to Miller et al.’s most conservative estimate but far higher than that of Yelle (2004). Our limits suggest that nonradiation effects (e.g., magnetospheric heating) do not dramatically enhance $\text{H}_\text{2}$ emission from these planets.

The brighter (but more distant) stars in our survey offer the least promise for improvement. The limit on the $\text{H}_\text{2}$ emission from the planets orbiting $\upsilon$ And, our brightest target with the highest S/N spectra, is $1.3 \times 10^{18}$ W. To achieve Miller et al.’s (2000) limit of $\sim 10^{17}$ W, a S/N of 3400 pixel$^{-1}$ is necessary, and 10 times that amount is necessary to reach Yelle’s limit. This would require a prohibitively long exposure time considering that we reached a S/N of only 300 in 2 hr of integration. We compare these requirements with the capabilities of NIRSPEC, the near-IR spectrograph mounted on the Keck II 10 m telescope: a S/N of 3400 pixel$^{-1}$ at NIRSPEC’s comparable spectral resolution requires 7 hr of integration time, but systematic effects would inhibit achieving such a high S/N.

The situation is better for less luminous but closer stars for which the contrast ratio between planetary $\text{H}_\text{2}$ emission and the stellar photosphere is higher. The only such star in our sample, GJ 436, requires a relatively low S/N of $\sim 100$ pixel$^{-1}$ to achieve a limit of $10^{17}$ W. This can be reached in 10 hr with CSHELL and in only one hour with NIRSPEC. Yelle’s limit of $\sim 10^{16}$ W remains unfeasible even with Keck, the largest optical telescope in the world.

Yelle (2004) suggested that “occultation spectroscopy,” as discussed by Richardson et al. (2003), may be the best way to observe $\text{H}_\text{2}$ in planetary atmospheres. HD 209458 b (Charbonneau et al. 2000; Henry et al. 2000), TrES-1 (Alonso et al. 2004), and HD 189733 b (Bouchy et al. 2005) are currently the only known planets for which this is practical. Given that our intranight residual rms is half that of the rms between nights, comparing spectra before, during, and after secondary eclipse is an attractive option. However, one would not get the required S/N for these stars during the $\sim 2$ hr of a single eclipse event, meaning cumulative data over several transits would be necessary. A Jupiter-sized planet transiting a nearby M dwarf would be the most promising target for a future $\text{H}_\text{2}$ search, although such a planet has yet to be discovered.

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