

Lightning as a possible source of the radio emission on HAT-P-11b

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ABSTRACT

Lightning induced radio emission has been observed on Solar System planets. There have been many attempts to observe exoplanets in the radio wavelength, however, no unequivocal detection has been reported. Lecavelier des Etangs et al. (2013, A&A, 552, A65) carried out radio transit observations of the exoplanet HAT-P-11b, and suggested that a small part of the radio flux can be attributed to the planet. In the current letter, we assume that this signal is real, and study if this radio emission could be caused by lightning in the atmosphere of the planet. We find that a lightning storm with 530 times larger flash densities than the Earth-storms with the largest lightning activity is needed to produce the observed signal from HAT-P-11b. The optical counterpart would nevertheless be undetectable with current technology. We show that HCN produced by lightning chemistry of such thunderstorms is observable 2-3 years after the storm, which produces signatures in the L ($3.0\mu\text{m} - 4.0\mu\text{m}$) and N ($7.5\mu\text{m} - 14.5\mu\text{m}$) infrared bands. We conclude that future, combined radio and infrared observations may lead to lightning detection on planets outside the Solar System.

Key words: astrochemistry – planets and satellites: atmospheres, detection, gaseous planets – radio continuum: planetary systems – radio lines: planetary systems

1 INTRODUCTION

The discovery of the first exoplanet around a neutron star (Wolszczan & Frail 1992) and then around a Sun-like star (Mayor & Queloz 1995) opened the gates to a new astronomical field concerning extrasolar planetary systems. By March 2016, there have been 2087 exoplanets discovered (including 1297 transiting and 65 directly imaged planets, the most suitable types for lightning-hunting, Hodosán et al. 2016)¹. This large number allows us to focus on the more detailed characterisation of the different types of planets, including atmospheric chemistry and internal composition of the planetary bodies. Recently, radio observations have opened new paths to study properties of extrasolar objects, such as brown dwarfs (e.g. Williams & Berger 2015), which are only a step away from giant gas planet detections in the radio wavelengths. Electron cyclotron maser emission has been suggested to be one possible mechanism for the radio emission (Grießmeier et al. 2007). A campaign to observe this emission has been started (e.g. Lecavelier des Etangs et al. 2013, and ref. therein), however no electron cyclotron maser emission from exoplanets has been conclusively detected.

Lecavelier des Etangs et al. (2013) (hereafter L13) presented a tentative detection of a radio signal from the exoplanet HAT-P-11b. This planet is estimated to have a radius of $4.7 R_{\oplus}$ (R_{\oplus} : Earth radius), a mass of $26 M_{\oplus}$ (M_{\oplus} : Earth mass), and is at a distance of ~ 0.053 AU from its host star (Bakos et al. 2010; Lopez & Fortney 2014). In 2009, L13 observed a radio signal at 150 MHz with an average flux of 3.87 mJy that vanished when the planet passed behind its host star. They re-observed the planet with the same instruments in 2010, but no signal was detected this time. Assuming the 150 MHz signal from 2009 is real and is from the exoplanet, the non-detection in 2010 suggests that it is produced by a transient phenomenon. L13 suggested that the obtained radio signal is the result of interactions between the planetary magnetic field and stellar coronal mass ejections or stellar magnetic field. If the radio signal is real, it is unlikely to be due to cyclotron maser emission, because this type of emission is generally polarized (Weibel 1959; Vorgul & Helling 2016), and fig. 2 in L13 shows a non-detection of polarization in the data. If the mJy radio emission were caused by cyclotron maser emission, a large planetary magnetic field of 50 G would be required (L13).

Lightning is a transient phenomenon of several known cloudy atmospheres, with flash rates varying greatly. Lightning induced radio emission has been observed in the Solar System on Earth, most probably on Venus (e.g. Russell et al. 2008), and on the giant planets Jupiter (e.g.

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¹ <http://exoplanet.eu/>; 2016.03.08

Gurnett et al. 1979), Saturn (e.g. Fischer et al. 2006, 2007), Uranus (Zarka & Pedersen 1986) and Neptune (Aplin 2013). Bailey et al. (2014) suggested that present day radio observations of brown dwarfs may contain hints to the presence of lightning in these planetary-like atmospheres. Lightning emission is not polarized (Shao & Jacobson 2002). Therefore, based on the non-detection of polarization in combination with the possible transient nature of the observed radio emission, we tentatively hypothesize that the emission on HAT-P-11b is caused by lightning discharges.

HAT-P-11b is much closer to its host star than the Solar System planets with lightning, resulting in a stronger irradiation from the star. 3D simulations of irradiated giant gas planets have demonstrated that a very strong circulation of the atmosphere results from the high irradiation (e.g. Heng & Showman 2015) and it seems reasonable to expect similar effects for Neptune-like planets. Works like Lee et al. (2015) and Helling et al. (2016) further suggest that highly irradiated atmospheres will form clouds in very dynamic environments, which may host high lightning activity, because triboelectric charging in combination with gravitational settling allows lightning discharge processes to occur in extrasolar clouds (Helling et al. 2013). Fraime et al. (2014) took the transmission spectra of HAT-P-11b and interpreted the data with a clear atmosphere model. However, Line & Parmentier (2015) found that in the case of HAT-P-11b, patchy clouds could explain these transmission spectra. HAT-P-11b, orbiting its host star closely, likely has a dynamic atmosphere that will impact the observable cloud distribution. The resulting patchy clouds could focus potential lightning activity to a certain region, maybe at certain times covering a large fraction of the planet. These potentially large, dynamical cloud systems could support the occurrence of high lightning rates in particular regions.

2 RADIO SIGNAL STRENGTH AND LIGHTNING FREQUENCY

In this section we calculate the radiated power spectral density of lightning at 150 MHz, which allows us to estimate the radio flux of one lightning flash at this frequency. We aim to derive a lower limit for the lightning flash density, ρ_{fl} [flashes $\text{km}^{-2} \text{h}^{-1}$], that would be needed to reproduce the intermittent radio emission from HAT-P-11b.

The power spectral density, $P/\Delta f$ [W Hz^{-1}] of lightning radiated at a frequency f [Hz] follows a power-law:

$$\frac{P}{\Delta f} = \frac{P_0}{\Delta f} \left(\frac{f_0}{f} \right)^n, \quad (1)$$

where $P_0/\Delta f$ [W Hz^{-1}] is the peak power spectral density at a peak frequency of f_0 [Hz], and n is the spectral roll-off at higher frequencies (Farrell et al. 2007). The spectral irradiance of a single lightning flash, $I_{\nu, \text{fl}}$, is related to $P/\Delta f$:

$$I_{\nu, \text{fl}} = \frac{(P/\Delta f)}{4\pi d^2} \times 10^{26}, \quad (2)$$

where d is the distance to the HAT-P-11 system, and 1

$\text{W Hz}^{-1} \text{m}^{-2} = 10^{26} \text{ Jy}$. The observed spectral irradiance, $I_{\nu, \text{obs}}$:

$$I_{\nu, \text{obs}} = I_{\nu, \text{fl}} n_{\text{tot, fl}}. \quad (3)$$

$n_{\text{tot, fl}}$ is the total number of flashes, given by:

$$n_{\text{tot, fl}} = \rho_{\text{fl}} 2\pi R_p^2 \tau_{\text{obs}}, \quad (4)$$

where R_p [km] is the radius of the planet, and τ_{obs} [h] is the time over which the observations were taken. Equation 3 gives the total spectral irradiance resulted from lightning flashes from over the projected disk of the planet ($2\pi R_p^2$).

In order to estimate the flash density that would result in a radio signal like the one obtained by L13, we assume that lightning on HAT-P-11b has the same energetic properties as lightning on Saturn. *Cassini-RPWS* measured the radiated power spectral density of lightning on Saturn to be $P/\Delta f = 50 \text{ W Hz}^{-1}$ at $f = 10 \text{ MHz}$ (Fischer et al. 2006; Farrell et al. 2007). We use Eq. 1 and the values observed by the *Cassini* probe for $P/\Delta f$ and f to obtain a peak spectral power density of $P_0/\Delta f = 1.6 \times 10^{12} \text{ W Hz}^{-1}$, for $f_0 = 10 \text{ kHz}$ and $n = 3.5$, the most favourable values for minimizing flash densities in the case of HAT-P-11b.² Next, by applying $P_0/\Delta f$ to Eq. 1 we estimated the radiated power spectral density at the source of a single lightning flash at $f = 150 \text{ MHz}$, frequency at which the HAT-P-11b radio signal was observed (L13), to be $P/\Delta f = 3.9 \times 10^{-3} \text{ W Hz}^{-1}$.

Using Eq. 2 and the distance of HAT-P-11, $d = 38 \text{ pc}$, we obtain the spectral irradiance for a single lightning flash to be $I_{\nu, \text{fl}} = 2.2 \times 10^{-14} \text{ Jy}$. L13 found the average observed spectral irradiance, $I_{\nu, \text{obs}}$, to be 3.87 mJy. Solving Eq. 3 for $n_{\text{tot, fl}}$, the total number of lightning flashes needed to explain the observed spectral irradiance, we obtain a value of $n_{\text{tot, fl}} \approx 1.7 \times 10^{11}$ flashes. The integration time for a single data point in L13 (fig. 2) is $\tau_{\text{obs}} = 36 \text{ min}$, and the radius of HAT-P-11b is $R_p \approx 0.4 \text{ R}_J$ (R_J : Jupiter radius; Bakos et al. 2010). Substituting these values and the derived $n_{\text{tot, fl}}$ into Eq. 4 we obtain a flash density of $\rho_{\text{fl}} \approx 53 \text{ flashes km}^{-2} \text{h}^{-1}$. Figure 1 (left) shows the flash densities that would be needed to produce a radio flux comparable to observations in L13 (their fig. 2), assuming the flux is from the planet and is entirely produced by lightning activity.

Fischer et al. (2011) analysed the SED (Saturnian Electrostatic Discharges) occurrence of a giant storm that occurred on Saturn in 2010/2011. They found an SED rate of 10 s^{-1} , which is 6000 SED h^{-1} . This is the largest rate observed on Saturn. Since no other storms were observed during this period (Dyudina et al. 2013), we apply this flash rate (assuming that one SED originates from one flash) for the whole surface of the planet. This results in a flash density of $1.4 \times 10^{-7} \text{ flashes km}^{-2} \text{h}^{-1}$ for Saturn (e.g. Hodosán et al. 2016). The observed signal on HAT-P-11b would require a storm with flash densities $\sim 3.8 \times 10^8$ times greater than observed on Saturn. However, one may argue that a planet can host multiple thunderstorms at the same time, so the SED

² The Earth value $f_0 = 10 \text{ kHz}$ (Rakov & Uman 2003) and a gentler spectral roll-off, $n = 3.5$ ($n = 4$ for Earth) were used because these values are not known for any other Solar System planet. These values are used for modelling lightning on Jupiter or Saturn (e.g. Farrell et al. 2007).

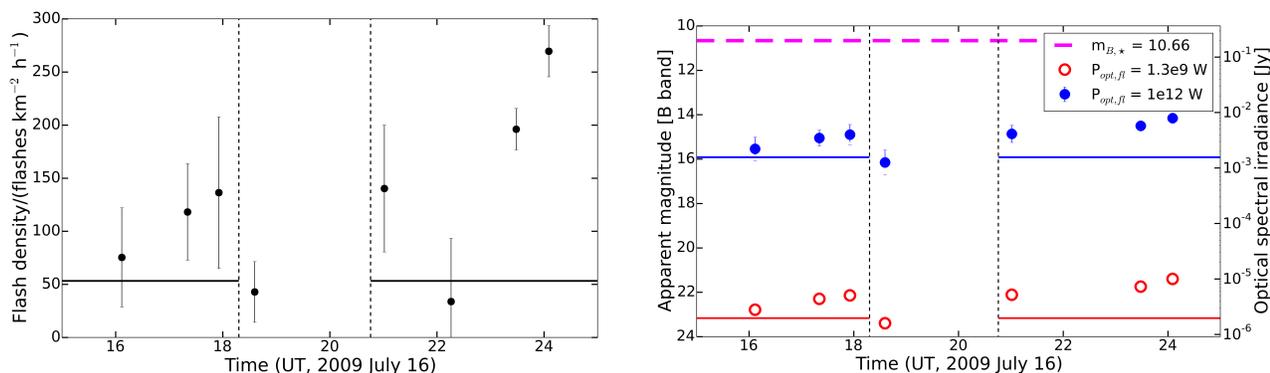


Figure 1. Lightning flash densities (left) and apparent magnitude of the lightning flashes (right) that would produce the radio fluxes observed by L13 for HAT-P-11b (their fig. 2). Horizontal solid lines: average values for the average observed radio flux of 3.87 mJy outside eclipse. Vertical dashed lines: beginning and end of the secondary eclipse of the planet. We show the mean results for the range of observed values per time from L13. **Right:** Results for two different optical powers, Saturnian (1.3×10^9 W; red) and terrestrial super-bolt (10^{12} W; blue). Magenta dashed line: apparent B magnitude of the host star HAT-P-11.

rates are only true for the specific storm and not for the whole planet. Considering an average storm size of 2000 km on Saturn³ (Hurley et al. 2012), the flash density based on the average SED rate of the 2010/2011-storm is 1.5×10^{-3} flashes $\text{km}^{-2} \text{h}^{-1}$. This flash density is 3.5×10^4 times smaller than the calculated 53 flashes $\text{km}^{-2} \text{h}^{-1}$ on HAT-P-11b.

On Earth, the highest flash density observed, ~ 0.1 flashes $\text{km}^{-2} \text{h}^{-1}$ (Huffines & Orville 1999), is produced in thunderstorms within the United States (USA). The 3.87 mJy signal from $\rho_{\text{fl}} \approx 53$ flashes $\text{km}^{-2} \text{h}^{-1}$ on HAT-P-11b, would require a sustained global storm with flash densities ~ 530 times greater than observed within the USA. The last two data points in fig. 2 of L13 show the highest detected radio flux, ~ 20 mJy. Assuming this signal is from the planet and only results from lightning activity, a more extreme lightning storm with 270 flashes $\text{km}^{-2} \text{h}^{-1}$ would be required on HAT-P-11b, ~ 2700 times larger than observed within the USA.

The obtained average lightning flash density of 53 flashes $\text{km}^{-2} \text{h}^{-1}$ has observational implications for direct detection of lightning and for observing its chemical effects on extrasolar planets, which are discussed in the following sections.

3 LIGHTNING DETECTION IN THE OPTICAL RANGE

The emitted power of lightning has been measured in other wavelengths on Jupiter and Saturn. In this section we apply the above-derived flash densities and estimate the emitted optical flux of the lightning storm that could produce the observed radio flux on HAT-P-11b.

Dyudina et al. (2013, table 2) lists the survey time (1.9 s), the total optical power (1.2×10^{10} W) and the optical flash rate (5 s^{-1}) of the large thunderstorm on Saturn in 2011. Based on this information the average optical power released by a single flash of this Saturnian thunderstorm is $P_{\text{opt,fl}} \approx 1.3 \times 10^9$ W. Assuming that flashes on HAT-P-11b

produce the same amount of power as Saturnian flashes and using Eq. 5 we obtain an optical irradiance from a single flash to be $I_{\text{opt,fl}} = 1.13 \times 10^{-14}$ Jy.

$$I_{\text{opt,fl}} = \frac{P_{\text{opt,fl}}/f_{\text{eff}}}{4\pi d^2} \times 10^{26}, \quad (5)$$

where $P_{\text{opt,fl}}$ is the optical power of a single flash and $f_{\text{eff}} \approx 6.47 \times 10^{14}$ Hz is the effective frequency of *Cassini's* blue filter. The total optical irradiance of flashes is obtained from $I_{\text{opt,fl}}$ and $n_{\text{tot,fl}}$, the total number of flashes hypothetically producing the same radio flux as was observed by L13. This optical irradiance is on the order of 10^{-5} Jy – 10^{-6} Jy or brightness of ~ 23 mag (B band) as shown in Fig 1, right panel (red). The star HAT-P-11 has apparent B magnitude = 10.66 (Høg et al. 2000) which is ~ 0.2 Jy in the B band, so the ratio of the planetary over the stellar flux is $\sim 10^{-6}$.

We carried out the same calculations to determine the planetary and stellar flux ratio, in case lightning on HAT-P-11b emitted a power on the order of the power of super-bolts on Earth, $P_{\text{opt,fl}} \approx 10^{12}$ W (Rakov & Uman 2003, p. 164). The produced optical flux densities and the corresponding magnitude scale are shown on Fig. 1, right panel (blue). The ratio of the planetary lightning flux and the flux of the star (with lightning flux density of 10^{-3} Jy – 10^{-2} Jy, Fig. 1, right panel) is $\sim 10^{-3}$.

The planet HAT-P-11b is on a very close orbit to the star, which suggests that current technology would not be able to distinguish the optical flux produced by lightning on the planet from the stellar optical flux.

4 LIGHTNING CHEMISTRY

Lewis (1980) estimated that lightning produces HCN at a rate of 2×10^{-10} kg/J. Their model was set up for Jupiter, and is applicable for any hydrogen dominated atmosphere with roughly solar composition. Farrell et al. (2007) estimated the dissipative energy of a single lightning flash on

³ Also, similar storm size was observed in December 2010 (Fischer et al. 2011)

Saturn, with peak frequency, $f_0 = 10$ kHz, and spectral roll-off, $n = 3.5$, to be:

$$E_d \approx 260 \text{ Joules} \left(\frac{f_{\text{Sat}}}{f_0} \right)^n, \quad (6)$$

where $f_{\text{Sat}} = 10$ MHz is the frequency at which the lightning was observed. We can multiply the dissipative energy by the flash density obtained above to find that during the hypothetical storm on HAT-P-11b, the lightning density of 53 flashes $\text{km}^{-2} \text{h}^{-1}$ over half of the planet corresponds to an energy density on the order of $10^5 \text{ J m}^{-2} \text{ s}^{-1}$. The energy released by lightning accounts for approximately 1% of the energy from the star during the observational period.

Multiplying the lightning energy density by the production rate of HCN, we estimate that $2.4 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ of HCN is produced, on the order of 10^{11} greater than the estimate of [Lewis \(1980\)](#) for Jupiter. Accepting the energetics arguments from [Lewis \(1980\)](#), the resulting HCN will achieve a volume mixing ratio of $\sim 10^{-5}$ within the mbar regime of the atmosphere. [Moses et al. \(2013\)](#) found that similar mixing ratios (their fig. 11) should have significant observational consequences in the L ($3.0\mu\text{m} - 4.0\mu\text{m}$) and N ($7.5\mu\text{m} - 14.5\mu\text{m}$) IR bands, which they show in their fig. 16 comparing their model spectra both with and without HCN.

In order to estimate the chemical timescale⁴ for HCN on HAT-P-11b, we develop a semi-analytical pressure-temperature profile appropriate for the object using the method of [Hansen \(2008\)](#). We use for this profile the parameters for HAT-P-11b (mass, radius, distance from host star) given by [Bakos et al. \(2010\)](#) and [Lopez & Fortney \(2014\)](#), and the stellar temperature from [Bakos et al. \(2010\)](#). To determine the XUV flux impinging on the atmosphere, we take a spectrum appropriate for a K4-type star, the X-Exospheres synthetic spectrum for HD 111232 ([Sanz-Forcada et al. 2011](#)). We assume that the atmosphere is hydrogen rich, and the atmospheric gas of HAT-P-11b is at roughly solar metallicity with respect to C, N and O, i.e. that the primordial concentrations of these elements in HAT-P-11b is solar and that there is no elemental depletion into clouds. We calculate the atmospheric chemistry using our semi-analytic temperature profile and synthetic XUV flux, with the STAND2015 chemical network and the ARGO diffusion-photochemistry model ([Rimmer & Helling 2015](#)). We then examine a variety of locations in the atmosphere, injecting HCN at a mixing ratio of 10^{-6} , and evolving the atmospheric chemistry in time to determine the chemical timescale for HCN as a function of pressure, shown in Fig. 2. The dynamical timescale for vertical mixing is overlaid on the top of this plot, assuming a range of constant eddy diffusion coefficients.

The chemical timescale for HCN ranges from 100 milliseconds at the bottom of our model atmosphere (10 bar), to 2.5 years at 5 mbar (Fig. 2). At pressures less than 5 mbar, the timescale for HCN slowly drops down to about 4 months at 10 μbar , and then drops precipitously at lower pressures until at 1 μbar it achieves a timescale of about 30 minutes (Fig. 2). These results can be compared to the

⁴ The amount of time necessary for the atmospheric abundance of HCN to achieve thermochemical equilibrium.

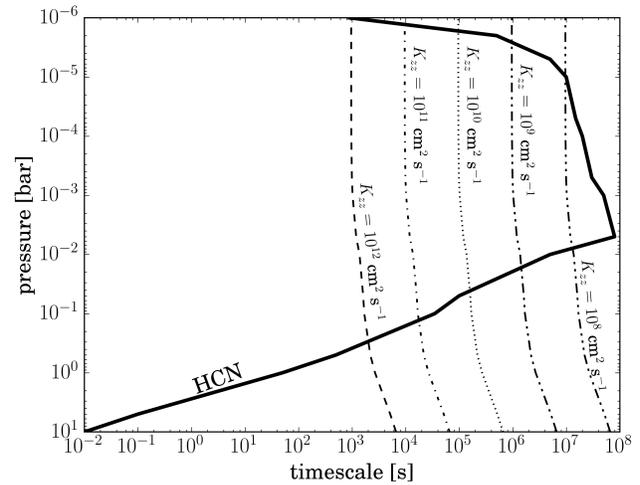


Figure 2. The chemical lifetime of HCN [s] plotted vs. pressure [bar], along with various dynamical timescales with eddy diffusion coefficients ranging $K_{zz} = 10^8 \dots 10^{12} \text{ cm}^2 \text{ s}^{-1}$.

dynamical timescale of the atmosphere, represented approximately by the eddy diffusion coefficient (see [Lee et al. 2015](#), for details). If the chemical timescale for HCN is smaller than the dynamical timescale, then the HCN would be destroyed before it is transported higher into the atmosphere. If the chemical timescale for HCN is larger than the dynamical timescale, then the HCN will survive long enough to reach other parts of the atmosphere, where it will survive longer. Assuming lightning takes place on HAT-P-11b at pressures of $\lesssim 0.1$ bar, the HCN will survive long enough to be transported into the mbar regime, where it will survive for 2-3 years before being chemically destroyed. If, on the other hand, HCN is formed much below the 0.1 bar level, at pressures of $\gtrsim 1$ bar, the chemical timescale is too short for the HCN to escape, and it will be rapidly destroyed before it could be observed.

It is informative to examine how HCN is destroyed. In the lower atmosphere, HCN is primarily destroyed by reacting with atomic hydrogen: $\text{HCN} + \text{H} \rightarrow \text{CN} + \text{H}_2$. The CN will quickly react with H_2 to reform HCN, but at the same time, the thermally dissociated products of water, the hydroxyl radical, enters into a rapid three-body reaction with CN to form HCNO, which reacts with H to form NO and CH_2 . This process quickly becomes inefficient higher in the atmosphere, both because the termolecular reaction to form HCNO becomes less efficient and because less atomic hydrogen is available. However, in the upper atmosphere, photochemistry begins to set the chemical time-scale for HCN, primarily via the reaction: $\text{HCN} + \text{O} \rightarrow \text{NCO} + \text{H}$. The atomic oxygen is liberated by photolysis of the hydroxyl radical, which itself results from reactions between water and the photochemical products of methane.

5 SUMMARY

We present an interpretation of the radio observations of HAT-P-11b made by [L13](#) under the assumption that these transient radio signals are real and were caused by lightning on HAT-P-11b. We determined that the flash density

of 53 flashes $\text{km}^{-2} \text{h}^{-1}$ over the hemisphere of the planet would be necessary to explain the average radio signal, 530 times greater than the rate of lightning storms observed in dense storms within the United States and several orders of magnitude beyond the storms observed on Saturn. We also examine the optical emission such a storm would generate, as well as the impact of this storm on the atmospheric chemistry, assuming a hydrogen-rich atmosphere.

In summary, we find that:

- The storms that can be observed using present-day radio instruments are likely to cover large fraction of the planetary surface with larger flash densities than storms thus far observed within our Solar System.
- Radio detections of lightning would be difficult to confirm by present-day optical technology for extrasolar planets. This is especially the case for planets close to their host star.
- The amount of HCN produced by lightning at pressures ≤ 0.1 bar, in a hydrogen-rich atmosphere of an irradiated exoplanet with strong winds, is predicted to yield detectable quantities that linger in the atmosphere for 2-3 years after the advent of the lightning storm. If the lightning occurs much deeper in the atmosphere, the HCN will react away before it can diffuse into the upper atmosphere, and will probably not be observable.

Our calculations can be applied to determine the minimum storm size detectable within an exoplanetary atmosphere using current or future radio instruments. Our recommendation to observers who detect radio emission, especially if it is unpolarized, from an exoplanet would be to follow up these observations with infrared observations made in the L and N bands when possible, in order to look for HCN emission, which should be observable for 2-3 years if lightning occurs around the 0.1 bar level of an atmosphere with reasonably large vertical convective velocities. If HCN is detected at that time, and if both the radio emission and the HCN turn out to be transient, this would be strong evidence for lightning on an exoplanet.

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