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ASTROBIOLOGY IN THE SOLAR SYSTEM: PREDICTIONS FOR THE LMT OF THE MOLECULAR CONTENT IN THE ENCELADUS ENVIRONMENT

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RESUMEN

Encelado es uno de los objetos más interesantes del Sistema Solar para estudios astrobiológicos. Para ello, hemos creado una librería de 1084 espectros sintéticos en el rango milimétrico con la finalidad de estimar, en el medioambiente de Encelado, la detectabilidad de HCN, CH_3OH, CO y PO con dos de los espectrógrafos de alta resolución del Gran Telescopio Milimétrico (GTM); SEQUOIA y MSIP1mm. Los espectros fueron creados con el sofware CASSIS. Utilizando como punto de partida los resultados de CASSINI, exploramos un amplio rango del espacio de parámetros de las propiedades físicas del ambiente rodeando Encelado. Nuestros resultados muestran, que tanto HCN como CH_3OH tienen una alta probabilidad de ser detectados, principalmente con MSIP1mm. Mientras que, CO y PO necesitarían abundancias sustancialmente más altas que las medidas por CASSINI para poder ser detectados. También encontramos que las intensidades y razones de líneas del espectro de CH_3OH puede ser una buena herramienta para diagnosticar las propiedades físicas en el ambiente de Encelado.

ABSTRACT

Enceladus is one of the most important targets for astrobiological studies in the solar system. We computed a large grid of 1084 synthetic spectra in the millimeter regime to test the detectability of HCN, CH_3OH, CO and PO in the Enceladus environment, with two high-resolution spectrometers of the Large Millimeter Telescope Alfonso Serrano (LMT); SEQUOIA and the MSIP1mm. We adopted the software CASSIS to produce the spectra and explored a large parameter space of the physical properties of the Enceladus surroundings, using the CASSINI results as a starting point. We conclude that HCN and CH_3OH have a high probability of being detected, particularly with the MSIP1mm, while, for CO and PO to be revealed, they should have a larger abundance than that measured by CASSINI. We also find that the lines intensities and ratios in the CH_3OH spectra are promising diagnostic tools for assessing the physical properties of the Enceladus environment.

Key Words: astrobiology — CASSINI — enceladus

1. INTRODUCTION

In 2005, the spacecraft CASSINI confirmed that Enceladus is an active satellite that contains a global ocean of liquid saltwater beneath its surface and that frozen particles of this ocean continually gush into space from geysers located near the south pole (Porco et al. 2006). The analysis of the molecules of these cryo-eruptions led several authors to propose that Enceladus could experience similar conditions to the hydrothermal oceanic vents of the primitive Earth (Bouquet et al. 2015; Smith et al. 2021). This finding has generated a discussion whether these properties satisfy the criteria to generate and sustain life as we know it (Barge & Rodriguez 2021).

Given that the spectral region of millimetre wavelengths is particularly rich in molecular lines, the Large Millimeter Telescope (LMT) provides an excellent opportunity to verify the presence of organic species in the material ejected from Enceladus, to study the physicochemical conditions of this satellite and to analyze the chemical networks that lead to more complex molecules. In this study, we present the results of theoretical predictions of the Enceladus emission of selected molecules for assessing their possible detection with the LMT.

2. THE COMPUTATION OF SYNTHETIC SPECTRA

Using the software CASSIS (Caux et al. 2020), we computed the synthetic emission spectra of four molecules of astrobiological interest in the Enceladus environment (HCN, CO, PO and CH_3OH) in the frequency intervals (210–280 and 85–115 GHz) covered by two LMT heterodyne high-resolution spectrometers: the MSIP1mm and SEQUOIA. For the

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TABLE 1

COLUMN DENSITY INTERVALS

Molecule	CO	CH_3OH	HCN	PO
N (10^{13}cm^{-2})	4.3–13	15–700	0.14–8.4	0.12–220

computation, we consider the local thermodynamic equilibrium (LTE) approximation, select the proper molecular parameters from the Jet Propulsion Laboratory database[3] and considered a spectral resolution of 0.1 MHz and a line width of 0.5 km s^{-1}. The instrumental noise was included in the spectra by adding a proper Gaussian noise. We explored a large range of molecular column density (N; see Table 1) and of excitation temperature ($T_{\rm exc}$; 20–200 K) of the gas ejected from Enceladus, around the values provided by CASSINI and other observations (Hansen et al. 2020). We also varied the source angular size from 1 to 6 arcsec.

We computed a total of 1084 spectra of the four molecular species separately (Table 2). For each spectrum, using the online LMT exposure time calculators[4], we also computed the integration time needed to reach a signal-to-noise of at least 4 in the detection of the (brightest) line in the frequency interval: in 936 cases this threshold can be reached in less than an arbitrarily established exposure time (on source) limit of 18 hr.

3. RESULTS

In general, our theoretical study found that HCN and CH_3OH are easier to detect at the LMT and that the MSIP1mm spectrometer provides more chance of detection than SEQUOIA because of the higher MSIP1mm sensitivity and brightness of the lines at 1 mm.

The HCN can be detected at 1 mm even when its column density would be ∼600 times lower than the one reported by Hansen et al. (2020). SEQUOIA can also easily detect HCN in the (1-0) transition if its abundance is not lower than N=4.4 × 10^{13} cm^{-2} and the $T_{\rm exc}$ is not much higher than 20 K.

The CH_3OH transitions are also easier to detect with the MSIP1mm: if N=7 × 10^{15} cm^{-2}, a 4σ detection can be obtained in about 30 min, in all the range of $T_{\rm exc}$. Detection can also be attainable, within 18 hr of exposure time, with an abundance of CH_3OH ∼50 times lower. As for the case of HCN, also for this molecule SEQUOIA can easily detect its transitions if the abundance is the one reported by Hansen et al. (2020).

TABLE 2

NUMBER OF SYNTHETIC SPECTRA

Molecule	CO	CH_3OH	HCN	PO
SEQUOIA	0	271	220	10
MSIP1mm	21	264	288	10

PO and CO represent more impervious cases for observing with the LMT. In order to detect the PO emission lines in the SEQUOIA frequency range, its column density should be as high as 1 × 10^{15} cm^{-2}, while, in the case of the MSIP1mm, the detection might be a bit more probable, but still an abundance higher than 1 × 10^{14} cm^{-2} is required.

Due to the noise of SEQUOIA at 115 GHz, the adequate instrument to observe CO is the MSIP1mm. However, to detect the transition at 230.538 GHz, its column density should be at least 3.5 × 10^{15} cm^{-2}, about 30 times the CO abundance reported by Hansen et al. (2020).

The panels in figure 1 depict four examples of potential detection of the four molecules studied in this work. In the upper-left panel we show the synthetic spectra of the CO(2-1) transition at 230.538 GHz. The illustrated cases correspond to two column densities 1.3×10^{14} cm^{-2} (red) and 4.3×10^{13} cm^{-2} (black) for a $T_{\rm exc}$ of 20 K and 6″ in angular size. The modelled rms noise is 5.39 mK. The upper-right panel shows the HCN(3-2) emission in the 1mm band (265.886 GHz) for the parameters $T_{\rm exc}$ of 20 K and 6″ in angular size. The considered column density and noise for this spectrum are, respectively, 8.14×10^{-14} cm^{-2} and 2.36 mK. In the lower panels (left) we illustrate the synthetic 1mm spectrum of PO for the at 240.141 GHz and indicate the most prominent PO transition within a green rectangle. The panel on the lower-right provide the theoretical prediction for methanol lines in the 1mm interval. The spectrum was calculated for the parameters $T_{\rm exc}$ = 20 K, column density of 7.0×10^{15} cm^{-2} and a noise of 4.88 mK.

The richness of CH_3OH spectra in the millimeter regime will allow assessing the physical conditions of the Enceladus environment from the LMT observations. In Fig. 2, we show the simulated MSIP1mm spectra of CH_3OH for different $T_{\rm exc}$; 20, 50, 80, 110, 140 and 170 K. The several emission lines present in the interval show a clear difference in their rela-

[3]https://spec.jpl.nasa.gov/ftp/pub/catalog/catdir.html

[4]https://www.lmtobservatory.org/gtm/

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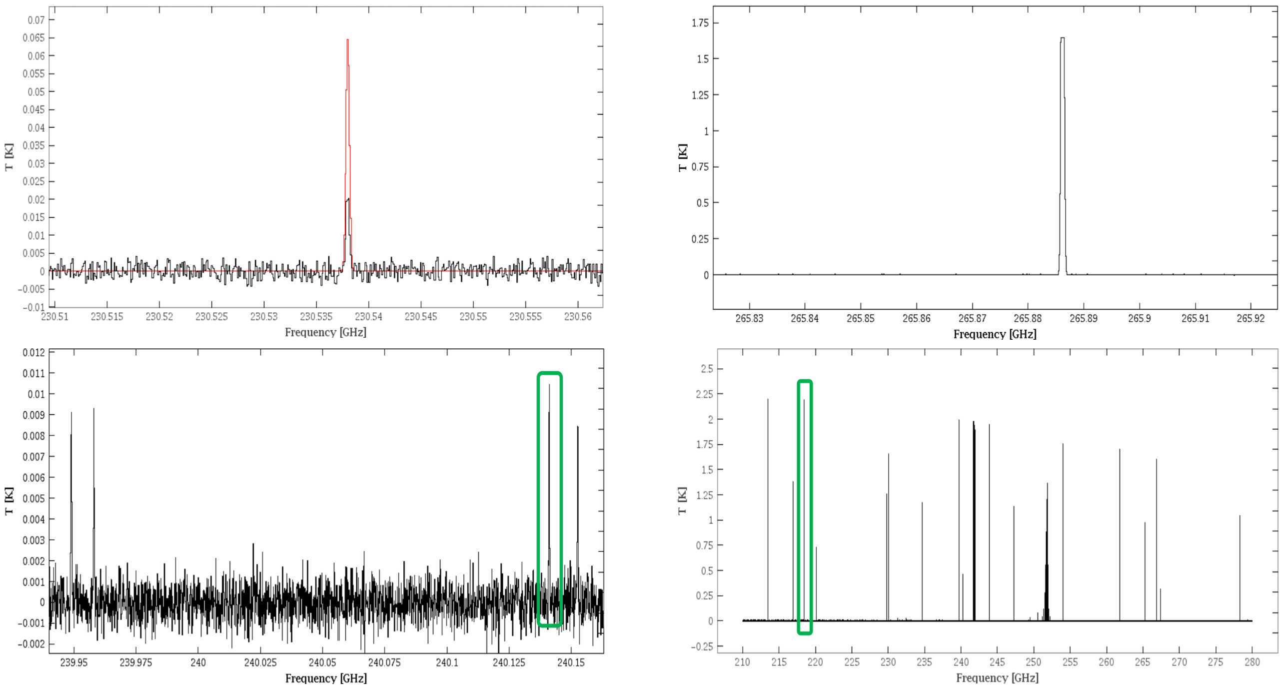

Fig. 1. Examples of possible detections with the MSIP1mm instrument of the LMT. The parameters used for calculating the synthetic spectra are given in the text. In all cases the detection is expected to be achieved in less that 18 hr.

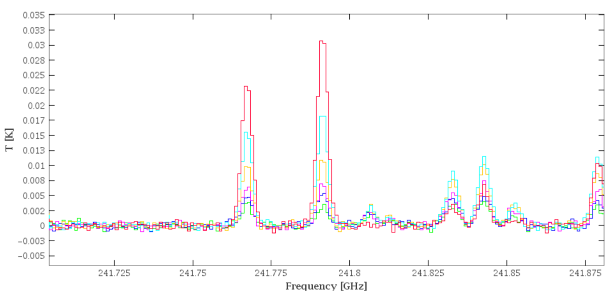

Fig. 2. Synthetic spectra of CH_3OH in the MSIP1mm interval considering a column density of 9.0×10^{13} cm^{-2}, a size of 3" and an rms of 1.0 mK. The depicted spectra correspond to six values of $T_{\rm exc}$, ranging from 20 to 170 K. An inversely proportional relationship between the excitation temperature and the emission intensity of the lines can be observed in the image.

tionship between intensity and $T_{\rm exc}$ so that appropriately chosen line ratios are a good diagnostic for the $T_{\rm exc}$ estimation, while their intensity allows measuring the abundance of the molecular species.

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