Editors' Suggestion

Search for Dark Matter Ionization on the Night Side of Jupiter with *Cassini*

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We present a new search for dark matter (DM) using planetary atmospheres. We point out that annihilating DM in planets can produce ionizing radiation, which can lead to excess production of ionospheric H_3^+. We apply this search strategy to the night side of Jupiter near the equator. The night side has zero solar irradiation, and low latitudes are sufficiently far from ionizing auroras, leading to a low-background search. We use *Cassini* data on ionospheric H_3^+ emission collected three hours either side of Jovian midnight, during its flyby in 2000, and set novel constraints on the DM-nucleon scattering cross section down to about 10^{-38} cm^2. We also highlight that DM atmospheric ionization may be detected in Jovian exoplanets using future high-precision measurements of planetary spectra.

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Early on an autumn morning of 1997, the *Cassini* spacecraft launched from Cape Canaveral aboard the Titan IV-B rocket, beginning the seven-year journey to Saturn and its majestic icy rings. To get there, *Cassini* was powered by the heat from nuclear decays of onboard plutonium-238. But that was not all; gravitational slingshot assists were also exploited from Venus (twice), Earth, and Jupiter. Equipped with instruments to record data from radio waves to the extreme ultraviolet (EUV), *Cassini* would capitalize on these flybys to extract multiwavelength data on multiple Solar System bodies [1,2].

Using *Cassini*'s visual and infrared mapping spectrometer (VIMS), one such measurement was levels of trihydrogen cations, known as H_3^+. These ions are highly abundant throughout the Universe, and are produced from H_2 interactions with cosmic rays, EUV stellar irradiation, planetary lightning, or electrons accelerated in planetary magnetic fields [3]. Planetary H_3^+ levels have been extensively studied (see, e.g., Refs. [3–15]), and they are important as they provide vital insights into atmospheric temperature, as well as a tracer of electric currents running through the atmosphere [3].

We point out that dark matter (DM) can produce an additional source of H_3^+ in planetary atmospheres. This will be produced if DM scatters and is captured by planets, and consequently annihilates, producing ionizing radiation. To produce detectable H_3^+, the DM must produce ionization in the planet's ionosphere, which occurs for the part of the captured DM distribution already thermalized toward the surface [16]. Alternatively, DM may also annihilate to mediators with lifetimes or kinematic boosts that lead to frequent decays away from where DM is thermalized [17–42], such that the sum of these scenarios covers a wide range of the parameter space.

We execute our DM ionization search using *Cassini*'s VIMS flyby data of Jovian ionospheric H_3^+ [9]. We target Jupiter as it is the most efficient DM captor compared to Saturn or other planets, and its cool core allows the lightest DM particles to be retained [43]. To optimize signal over background, we study *Cassini* data taken three hours either side of Jovian midnight, which eliminates the solar EUV irradiation background. We also focus on low-latitude data, as latitudes near the poles are subject to the intense Jovian magnetic fields, which produce ionizing auroras which are a significant source of H_3^+. At low latitudes near Jovian midnight, the background expectation is not significant, because the recombination time of H_3^+ produced by solar irradiation on the Jovian day side or the auroras near the poles is as fast as about 10–15 min [44]. This leaves insufficient time for H_3^+ to migrate from the day side to the night side, or to migrate far from the magnetic poles. These effects are schematically summarized in Fig. 1.

We will also investigate the future potential to discover DM using atmospheric ionization in Jovian exoplanets. This is most advantageous in the inner Galaxy, where the DM density is expected to be higher. However, it is impossible to spatially resolve the low-latitude emission in this case, and so auroral emission will dominate as the ionization background. We will show that the advantage of

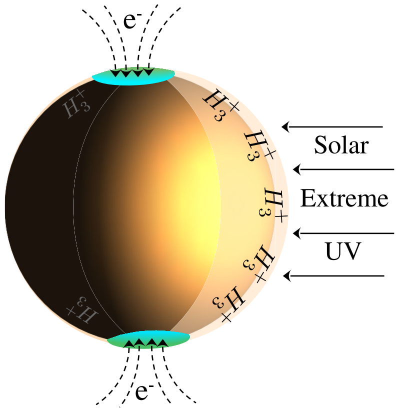

FIG. 1. Schematic of H_3^+ production in Jupiter. Auroral H_3^+ emission near the magnetic poles is sourced by precipitating electrons, and solar extreme UV irradiates the day side and dominates H_3^+ production near the equator. No significant H_3^+ is expected at low latitudes on the night side, making it an ideal DM signal region.

higher DM densities, as well as using larger exoplanets such as super-Jupiters which more readily capture DM, can overcome the significant auroral backgrounds. This can lead to potential future DM discovery space down to small scattering cross sections.

Our Letter is organized as follows. We first discuss how H_3^+ is generally produced and detected through spectroscopic analyses, before discussing existing Jovian H_3^+ measurements and expectations without DM. We then detail how these ionization rates are calculated for Jupiter's ionosphere, and calculate the maximum ionizing power consistent with *Cassini* night-side observations. We then discuss the pathways for DM-induced H_3^+ production, and explore the relevant DM-nucleon scattering parameter space, setting new constraints based on the requirement that the DM-induced H_3^+ is larger than *Cassini*'s measurements. We conclude with a discussion of future opportunities to discover DM using planetary atmospheric ionization.

Astrophysical H_3^+ *production and emission.*—The dominant species in the high-altitude Jovian atmosphere is neutral molecular H_2. The creation of H_3^+ in the Jovian ionosphere follows from interactions of high-energy particles, ions, or ionizing photons with H_2 [3]. While there are a few H_3^+ production pathways with different ionization sources, an example of ionizing scattering is

$$H_2 + e^{-*} \to H_2^+ + 2e^-, \quad (1)$$

where high-energy electrons e can be injected by, e.g., electrons accelerated in Jovian magnetic fields, or the annihilation of DM. In any case, once H_2^+ is produced, it reacts almost instantaneously with the surrounding H_2, creating H_3^+ via [3,45]

$$H_2^+ + H_2 \to H_3^+ + H. \quad (2)$$

This H_3^+ then exists in the planetary ionosphere above a layer called the homopause, where Jovian gas decouples from convective mixing currents. This is because the relative abundance of gases above the homopause is free to evolve with altitude due to the lack of mixing, and so heavier gases that can destroy H_3^+ (such as methane) rapidly decrease in concentration [46]. Below the homopause, H_3^+ is quickly destroyed by protonating other molecules, and therefore is not relevant [44,47].

Once H_3^+ has been produced, it is expected to approach a quasithermal equilibrium, wherein the radiative deexcitation of vibrational states is slow compared to their population by collisional excitation with the surrounding H_2 [9,48]. The H_2 has characteristic temperatures between about 700 and 1000 K in the Jovian ionosphere [49], which is inherited by the H_3^+ before emitting infrared radiation efficiently through radiative vibrational deexcitation. The infrared spectrum of H_3^+ contains a large amount of substructure, and its emission lines are strongest in the spectral window between about 3 and 5 μm. Since this is also the spectral region of peak thermal emission for a blackbody of temperature between about 700 and 1000 K, H_3^+ acts as an extremely efficient thermal radiator around these temperatures [3,50].

Spectroscopic analysis of H_3^+ relies heavily on the *relative* intensities of the emission lines, since theoretical modeling is subject to significant uncertainty in the *intrinsic* intensity of each individual peak, although their frequencies and widths can be modeled to an exquisite degree of precision [3,9]. Specifically, the relative intensities of the infrared emission lines can be used to determine the temperature of the gas, assuming local thermodynamic equilibrium. In what follows, the temperatures used for H_3^+ have been calculated from the measured relative intensities of the lines.

H_3^+ plays an important role in the thermal balance of gas planets like Jupiter and Uranus, where its emission acts as the thermostatic mechanism in the high-altitude atmosphere [3,50]. While this energy equilibrium is born of a complicated dynamical atmospheric system, empirically the net effect of additional ionizing energy injection is an increased H_3^+ emission. Therefore, we will adopt the simplified but empirical model of energy balance where the total surface infrared emission of H_3^+ is proportional to the ionizing energy injected into the atmosphere [51].

Ionization data and constraints from Cassini.—The production of H_3^+ due to ionizing radiation was first confirmed spectroscopically in the auroral ionosphere of Jupiter, using the Voyager ultraviolet spectrometer experiment [4]. While the strongest H_3^+ emission (therefore greatest production) is found near the poles, in the auroral regions which are powered by infalling ions, there is a detectable smooth H_3^+ infrared signal found extending up to the equator on the day side [51]. Volcanic eruptions from Jupiter's third-largest moon Io also deposit ionizing radiation into Jupiter's atmosphere; however, this is a characterized local phenomenon.

The equatorward (±20° latitude) H_3^+ emission signal is produced from H_3^+ originating from solar EUV [44,51], which has an ionizing power of $P_{\rm ion}^{\rm EUV} = 62\ \mu{\rm W/m^2}$ for wavelengths between Lyman-α and 10 nm. Since the dissociative recombination time of H_3^+ in the upper Jovian atmosphere is much shorter (~10–15 min at the altitude of peak H_3^+ emission) than the half-day period [44], it is expected that effectively all of the H_3^+ produced during the day will disappear during the night, and there is essentially no auroral H_3^+ contamination at low latitudes. While there are other subdominant sources of H_3^+ that may generate or destroy this molecule on the night side, it is sufficient to note that H_3^+ is not being produced by EUV, and the total emission is below the detection threshold. Therefore, by assuming that any additional source (e.g., DM) generates all of the night-side H_3^+ for its emission to be observed, we will remain conservative. Overall, the low background of H_3^+ at Jovian night time at low latitudes allows a striking potential DM-induced H_3^+ signal.

Cassini is an ideal instrument to probe a potential DM-induced H_3^+ signal, as its flyby collected data on equatorward H_3^+ on the night side of Jupiter. In this target region, *Cassini* did not detect any H_3^+ [9], consistent with standard model expectations. Therefore, we can place constraints on the homogeneous ionization of the night-side hydrogen based on the sensitivity of *Cassini*'s observation, which is taken to be the uncertainty of the reported equatorward measured (no detection) intensity:

$$I^{H_3^+} < 0.03\ {\rm mW\,m^{-2}\,\mu m^{-1}\,sr^{-1}}. \tag{3}$$

To set constraints using the night-side observations of the Jovian atmosphere, we predict what the expected H_3^+ emission signal would be as a function of the injected ionizing power. We adopt a model of the total surface H_3^+ emission $E^{H_3^+}(T)$ in which the number of H_3^+ molecules produced (and therefore the column density $CD^{H_3^+}$) is proportional to the ionizing power $P_{\rm ion}$ and the temperature-dependent molecular emission $E_{\rm mol}(T)$, which is calculated using the cooling function derived by Ref. [52]. The total surface emission is given by

$$E^{H_3^+}(T) \propto CD^{H_3^+}(P_{\rm ion}) \times E_{\rm mol}(T), \tag{4}$$

with

$$\ln[E_{\rm mol}(T)] = \sum_n c_n T^n, \tag{5}$$

where c_n are fitting coefficients. This parametrization of the cooling function is known to be accurate to less than 0.5% for temperatures between 300 and 1800 K [52]. Since the measured emission $I^{H_3^+}$ of H_3^+ is linearly related to the total surface emission up to geometric factors, we can express the measurable intensity as a function of temperature and ionizing power as

$$I^{H_3^+} = \alpha \times \beta \times P_{\rm ion} E_{\rm mol}(T), \tag{6}$$

where α and β are linear coefficients that respectively account for the geometric factors and H_3^+ production efficiency mentioned above. Since α and β are independent of night-side or day-side conditions, they cancel when taking ratios of the day-side and night-side emission in Eq. (6) to compute $P_{\rm ion}^{\rm night}$. This allows us to forego directly computing α and β and also makes our results independent of the associated systematic uncertainties. We therefore use the day-side emission data, along with night-side temperature measurements and *Cassini*'s nondetection of H_3^+ emission, to calculate the night time constraints on ionizing power,

$$P_{\rm ion}^{\rm night} < \frac{I_{\rm max}^{H_3^+}}{I_{\rm day}^{H_3^+}} \times \frac{E_{\rm mol}(T_{\rm day})}{E_{\rm mol}(T_{\rm night})} \times P_{\rm ion}^{\rm EUV} \times 1.5, \tag{7}$$

where $I_{\rm max}^{H_3^+}$ saturates the bound in Eq. (3), and $I_{\rm day}^{H_3^+} = 0.09\ {\rm mW\,m^{-2}\,\mu m^{-1}\,sr^{-1}}$ is the equatorward daytime intensity measured using ground-based observations by the Infrared Telescope Facility [51], but corrected in order to be directly compared to night-side measurements by *Cassini* [9]. The factor of 1.5 accounts for the fact that the Jovian ionospheric model finds that photons are about 1.5 times more efficient at producing H_3^+ as electrons [44,51]. We adopt a daytime (night time) equatorward temperature of 850 ± 50 K (800 ± 50 K) consistent with observations [9,53]. We therefore find the maximum night-side ionizing power to be

$$P_{\rm ion}^{\rm night} < 40 \pm 17\ \mu{\rm W/m^2}. \tag{8}$$

This quantity should be understood to be the maximum amount of *additional* ionizing power, contributing to the energy budget of the ionosphere, that is consistent with *Cassini* data. The uncertainty in Eq. (8) is dominated by the uncertainties in the temperature measurements. Since this calculation has been independent of any DM considerations, this is the upper bound of ionizing power by any additional source. Note that limits from the day side are only a factor of a few weaker, providing an additional robustness for our bounds without substantially weakening the limits.

Dark matter induced H_3^+ *production.*—For DM to produce H_3^+ it must deposit its ionizing energy into the planet's ionosphere. This can be achieved in two ways. One scenario is that when DM is captured, it settles into an equilibrium distribution within Jupiter, with a density distribution that is usually peaked toward the core, but with a distribution tail that can still be substantial in the ionosphere [16]. The DM, which in equilibrium already sits in the ionosphere, can annihilate there into short-lived or not very kinetically boosted mediators, which immediately produce ionizing radiation, and therefore H_3^+. An alternative scenario is that DM may annihilate into longer-lived or boosted mediators, which may decay and deposit the ionizing energy at some distance from where the DM annihilated.

DM-induced ionization rates will be independent of the DM mass in our parameter space. This is because ionization will equally occur for any electrons, positrons, or photons that deposit energy above the ionization threshold of hydrogen, which is 13.6 eV. For the DM mass range we will consider (1 MeV and higher), effectively all of the energy spectrum produced is many orders of magnitude above this threshold.

The DM ionizing power $P_{\rm ion}^{\rm DM}$ can be compared to the maximum night-side ionization in Eq. (8) to obtain a limit on the DM-induced ionization. The DM ionizing power is calculated as

$$P_{\rm ion}^{\rm DM} = \frac{\Gamma_{\rm ann} \times f_{\rm iono}}{4\pi R^2}, \tag{9}$$

where $\Gamma_{\rm ann}$ is the total equilibrium mass annihilation rate in the planetary volume, $f_{\rm iono}$ is the fraction of annihilation events occurring in the ionosphere of the planet, and R is the planet radius. For the case where the annihilation occurs in the core, and the annihilation products are boosted to the ionosphere, or the mediator is sufficiently long-lived to decay in the ionosphere, $f_{\rm iono} \sim 1$ is easily achieved across a wide range of parameters. This occurs for lengths around the Jovian radius $R_{\rm Jup}$, and corresponds to a mediator decay length of $L \sim \gamma\tau$, where the boost factor is $\gamma = m_\chi/m_\phi$, with m_ϕ and τ the mediator mass and lifetime, respectively. This means that $f_{\rm iono} \sim 1$ is obtained for parameters where $m_\chi \tau/m_\phi \sim R_{\rm Jup}$. For other parameters $f_{\rm iono} < 1$, and the limits can be simply rescaled linearly from our cross section results. For the case of short-lived mediators, or mediators with small boosts, $f_{\rm iono}$ is generally less than one, and results can also be rescaled [16]. Given the orders of magnitude improvement in our bounds we will show over existing limits, we expect our setup to be sensitive to a wide range of dark sector parameters.

The equilibrium mass annihilation rate is obtained when DM annihilation and capture are in equilibrium. This is given by [43]

$$\Gamma_{\rm ann} = f_{\rm cap} \times \pi R^2 \rho_\chi v_\chi \sqrt{\frac{8}{3\pi}} \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_\chi^2}\right), \tag{10}$$

where m_χ is the DM mass, $\rho_\chi = 0.4\ {\rm GeV/cm^3}$ is the local DM density, $v_\chi = 270\ {\rm km/s}$ is the local DM velocity dispersion, $v_{\rm esc}$ is the planetary escape velocity, and $f_{\rm cap}$ is the fraction of particles passing through the planet that are captured. For the maximal geometric rate, corresponding to sufficiently large DM-nucleon scattering cross sections, $f_{\rm cap} \approx 1$. As the scattering cross section decreases, $f_{\rm cap}$ also decreases. We calculate the captured fraction of DM particles that are above our *Cassini* data's detection threshold as discussed in the previous section, and set limits by linking it to the DM-nucleon scattering cross section using the ASTERIA package [54]. For the full capture rate calculation, see Ref. [54].

Dark matter parameter space.—Figure 2 shows our limits on the DM-nucleon scattering cross section as a function of DM mass, using our ionization search strategy. The dark-shaded region corresponds to the Jovian night-side limits we derive from *Cassini* VIMS flyby data, labeled "Jupiter Night-Side H_3^+ (*Cassini*)," with the orange band covering the uncertainty on this limit. These bounds apply assuming DM annihilation products are deposited in Jupiter's atmosphere after being captured for the DM-nucleon cross section shown. As we will discuss, the exact shape of the bounds in Fig. 2 can vary with particle physics models. Despite this, the search strategy that we present here can be many orders of magnitude more sensitive than existing searches, especially for light DM. For example, in this figure, we have taken $f_{\rm iono} \sim 1$, which corresponds to the DM-rest mass energy being deposited fully in the ionosphere, but this can be easily rescaled depending on the DM model of interest. We have assumed here DM annihilation purely into electrons, though annihilation into any ionizing species will be efficient. If DM annihilates directly into photons, our bounds will be a factor of 1.5 stronger. These bounds will be largely unchanged if the final state is instead hadronic.

In Fig. 2 we also show projected sensitivities to the DM-nucleon scattering cross section for a DM ionization search, for benchmark inner-Galaxy Jovian exoplanets, i.e., super-Jupiters with 10 times Jupiter's mass. For these example sensitivities we have simply assumed that the DM signal matches or exceeds the ionization background. Cosmic-ray ionization is not expected to exceed 100 times the value measured near the solar position [55,56]. We therefore assume that the Jovian auroras dominate the background, with the auroral ionization intensity of these benchmarks being the same as Jupiter's, which is about a factor of 100 higher than the solar EUV [57]. This is required as the low latitudes exploited for our *Cassini* Jupiter search cannot be disentangled from the auroral emission at large distances. While the inner-Galaxy Jovian exoplanets have larger

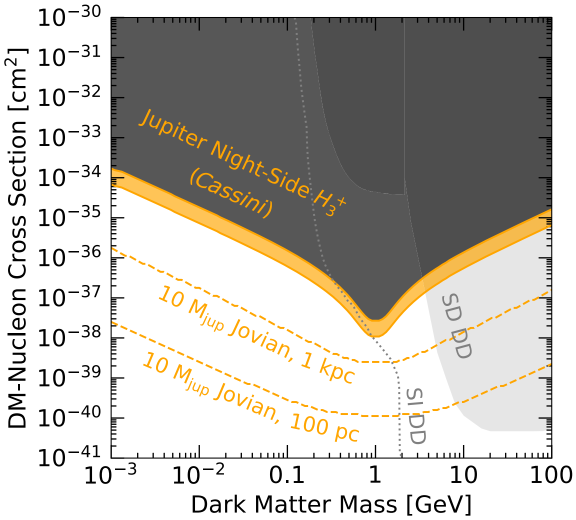

FIG. 2. New constraints on the DM-nucleon scattering cross section using planetary ionosphere measurements. The orange band covers our uncertainty in limits with night-side *Cassini* VIMS Jovian H_3^+ measurements; the dark-shaded region is excluded. We also show sensitivity projections for a benchmark Jovian exoplanet at 1 kpc or 100 pc from the Galactic Center (dashed line); see text for details and assumptions. We also show limits from direct detection, spin-independent "SI DD" and spin-dependent "SD DD" proton scattering.

ionization backgrounds, they are also embedded in larger DM densities than Jupiter, leading to larger sensitivities. Furthermore, super-Jupiters are more massive than Jupiter and have the additional bonus of larger capture rates, leading to larger expected DM signals. Our benchmark exoplanets are shown at 100 pc and 1 kpc, and in the optimistic case that further toward the Galactic Center is detectable, we show the DM parameter space sensitivity substantially increases. For the inner-Galaxy DM distribution, we have assumed a standard Navarro-Frenk-White DM profile.

Figure 2 assumes no evaporation, as the minimum DM mass that can be retained without evaporating is model dependent [58]. Given the focus of our Letter is pointing out this new search strategy, we do not focus on any detailed particle models, but provide some characteristic numbers in some benchmark models for context. For contact-interaction DM models, in our parameter range shown, the evaporation mass ranges between about ~100 MeV and 1 GeV. For long-range attractive interaction models, the DM evaporation mass can be instead sub-MeV [58]. It is also important to note that we conservatively assumed capture rates in the contact-interaction scenario; including additional captured DM from an attractive long-range model can boost our rates considerably, depending on the specific model parameters.

There are other existing search strategies that complementarily probe our parameter space in Fig. 2. The strongest Earth-based bounds are from direct detection experiments. These weaken for DM masses below about a GeV, since the DM kinetic energy falls below the threshold energy for visible ionization signals. We show the latest strongest existing bounds from spin-dependent proton-DM scattering, which are from CRESST-III [59] and PICO-60 [60], as well as spin-independent nucleon-DM scattering bounds, from CRESST [61,62], DarkSide [63], XENONnT [64], and LZ [65]. Note that our cross section, and the cross sections compared to, are all constant cross sections (i.e., independent of momentum or velocity). Different cross section classes could certainly be considered, but are not investigated here.

Other complementary astrophysical constraints include celestial-body searches with gamma rays, including with Jupiter [40], brown dwarfs [38], and white dwarfs [42]. These works derive limits assuming annihilation directly into gamma rays. Our search is instead most sensitive to annihilation into massive ionizing species such as electrons and protons, which have the best ionizing power. Models where the final state gamma-ray spectrum becomes flattened will generally be less constrained using gamma-ray observations [66,67]. Since we simply require the spectrum to be above the ionizing threshold, which is orders of magnitude smaller than the DM mass, our approach serves as a complementary way to probe the DM annihilation. We are also only sensitive to the much more precisely known local density of DM, in contrast to inner-Galaxy searches [38,42,68]. Different DM profile assumptions can wipe out the sensitivity of such searches, but would not affect our night-side Jovian search with *Cassini*. Additionally, this Letter is complementary to constraints set from electrons detected in Jupiter's radiation belt, since our results do not depend on the details of the time-varying magnetic field around Jupiter [41]. See also, e.g., Ref. [69] for complementary dark photon constraints.

Conclusions and future opportunities.—We have pointed out and shown for the first time that DM can produce ionizing radiation in planetary atmospheres, which is detectable through a smoking-gun excess of atmospheric trihydrogen cations, H_3^+. We used *Cassini* data to search for our new DM signature, exploiting flyby low-latitude H_3^+ data of Jupiter's night side, which is low background due to the lack of solar irradiation, as well as the low-latitudes being resolved sufficiently far away from the highly ionizing Jovian auroras near the poles. Night-side *Cassini* data provides new constraints on the DM-nucleon scattering cross section, unprobed by any other experiment. Improved Jovian measurements compared to *Cassini* are planned in the 2030s with the European Space Agency's Jupiter Icy Moons Explorer (JUICE) [70], which may allow increased sensitivity to DM ionization and the DM parameter space.

We also showed that exoplanets in denser DM environments such as the inner Galaxy could provide even stronger sensitivities to DM atmospheric ionization. While an inner-Galaxy search would not benefit from low-latitude searches, as auroras would not be able to be distinguished with the resolution of current telescopes, the DM ionization rate still can be significantly larger than auroral backgrounds. This is also aided by larger DM capture rates being possible with larger planets than Jupiter, such as super-Jupiters. Although optimistic, a future spectral measurement of exoplanets in the inner Galaxy with, e.g., JWST, the Roman Space Telescope, or a future more sensitive telescope could realize the exoplanetary sensitivities presented in Fig. 2.

Considering local exoplanets, H_3^+ is currently broadly searched for in the atmospheres of giant exoplanets, and is part of the target list for the European Space Agency's upcoming exoplanet mission, called the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) [71]. ARIEL will have unprecedented sensitivity to the atmospheric chemistry of transiting gas giants, and is planned to launch in 2029. Other telescopes such as JWST, or future 30-meter class telescopes, can also detect atmospheric H_3^+ through high-resolution spectroscopy [72]. We expect that these telescopes and missions may therefore provide excellent sensitivity to DM atmospheric ionization in nearby exoplanets.

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