



Publication Year	2024
Acceptance in OA	2025-03-06T11:01:45Z
Title	A far-ultraviolet–driven photoevaporation flow observed in a protoplanetary disk
Authors	Berné, Olivier, Habart, Emilie, Peeters, Els, Schroetter, Ilane, Canin, Amélie, Sidhu, Ameet, Chown, Ryan, Bron, Emeric, Haworth, Thomas J., Klaassen, Pamela, Trahin, Boris, Lefloch, Bertrand, Le Petit, Franck, Li, Aigen, Linz, Hendrik, Mackie, Cameron J., Madden, Suzanne C., Mascetti, Joëlle, McGuire, Brett A., Merino, Pablo, Micelotta, Elisabetta R., Van De Putte, Dries, Morse, Jon A., MULAS, Giacomo, Neelamkodan, Naslim, Ohsawa, Ryou, Paladini, Roberta, PALUMBO, Maria Elisabetta, Pathak, Amit, Pendleton, Yvonne J., Petrignani, Annemieke, Pino, Thomas, Alarcón, Felipe, Puga, Elena, Rangwala, Naseem, Rapacioli, Mathias, Ricca, Alessandra, Roman-Duval, Julia, LACAS (IN ROUEFF), EVELYNE MARGUERITE LUCIE, Rouillé, Gaël, Salama, Farid, Sales, Dinalva A., Sandstrom, Karin, Zannese, Marion, Sarre, Peter, Sciamma-O'Brien, Ella, Sellgren, Kris, Shannon, Matthew J., Simonnin, Adrien, Shenoy, Sachindev S., Teyssier, David, Thomas, Richard D., Togi, Aditya, Verstraete, Laurent, Abergel, Alain, Witt, Adolf N., Wootten, Alwyn, Ysard, Nathalie, Zettergren, Henning, Zhang, Yong, Zhang, Ziwei E., Zhen, Junfeng, Bergin, Edwin A., Bernard-Salas, Jeronimo, Boersma, Christiaan, Cami, Jan, Cuadrado, Sara, Dartois, Emmanuel, Dicken, Daniel, Elyajouri, Meriem, Fuente, Asunción, Goicoechea, Javier R., Gordon, Karl D., Issa, Lina, Joblin, Christine, Kannavou, Olga, Khan, Baria, Lacinbala, Ozan, Languignon, David, Le Gal, Romane, Maragkoudakis, Alexandros, Meshaka, Raphael, Okada, Yoko, Onaka, Takashi, Pasquini, Sofia, Pound, Marc W., Robberto, Massimo, Röllig, Markus, Schefter, Bethany, Schirmer, Thiébaud, Simmer, Thomas, Tabone, Benoit, Tielens, Alexander G. G. M., Vicente, Sílvia, Wolfire, Mark G., PDRs4All Team, Aleman, Isabel, Allamandola, Louis, Auchettl, Rebecca, BARATTA, Giuseppe, Baruteau, Clément, Bejaoui, Salma, Bera, Partha P., Black, John H., Boulanger, Francois, Bouwman, Jordy, Brandl, Bernhard, Brechignac, Philippe, Brünken, Sandra, Buragohain, Mridusmita, Burkhardt, Andrew, Candian, Alessandra, CAZAUX, STEPHANIE, Cernicharo, Jose, Chabot, Marin, Chakraborty, Shubhadip, Champion, Jason, Colgan, Sean W. J., Cooke, Ilsa R., Coutens, Audrey, Cox, Nick L. J., Demyk, Karine, Meyer, Jennifer Donovan, Engrand, Cécile, Foschino, Sacha, García-Lario, Pedro, Gavilan, Lisseth, Gerin, Maryvonne, Godard, Marie, Gottlieb, Carl A., Guillard, Pierre, Gusdorf, Antoine, Hartigan, Patrick, He, Jinhua, Herbst, Eric, Hornekaer, Liv, Jäger, Cornelia, Janot-Pacheco, Eduardo, Kaufman, Michael, Kemper, Francisca, Kendrew, Sarah, Kirsanova, Maria S., Knight, Collin, Kwok, Sun, Labiano, Álvaro, Lai, Thomas S. -Y., Lee, Timothy J.
Publisher's version (DOI)	10.1126/science.adh2861

A far-ultraviolet-driven photoevaporation flow observed in a protoplanetary disk

Olivier Berné^{1,*}, Emilie Habart², Els Peeters^{3,4,5}, Ilane Schroetter¹, Amélie Canin¹, Ameet Sidhu^{3,4}, Ryan Chown^{3,4}, Emeric Bron⁶, Thomas J. Haworth⁷, Pamela Klaassen⁸, Boris Trahin², Dries Van De Putte⁹, Felipe Alarcón¹⁰, Marion Zannese², Alain Abergel², Edwin A. Bergin¹⁰, Jeronimo Bernard-Salas^{11,12}, Christiaan Boersma¹³, Jan Cami^{3,4,5}, Sara Cuadrado¹⁴, Emmanuel Dartois¹⁵, Daniel Dicken², Meriem Elyajouri², Asunción Fuente¹⁶, Javier R. Goicoechea¹⁴, Karl D. Gordon^{9,17}, Lina Issa¹, Christine Joblin¹, Olga Kannavou², Baria Khan³, Ozan Lacinbala², David Languignon⁶, Romane Le Gal^{1,18,19}, Alexandros Maragkoudakis¹³, Raphael Meshaka², Yoko Okada²⁰, Takashi Onaka^{21,22}, Sofia Pasquini³, Marc W. Pound²³, Massimo Robberto^{9,17}, Markus Röllig²⁰, Bethany Schefter³, Thiébaud Schirmer^{2,24}, Thomas Simmer², Benoit Tabone², Alexander G. G. M. Tielens^{23,25}, Sílvia Vicente²⁶, Mark G. Wolfire²³, & the PDRs4All team[†].

¹Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, Centre National de la Recherche Scientifique, Centre National d’Etudes Spatiales, 31028, Toulouse, France

²Institut d’Astrophysique Spatiale, Université Paris-Saclay, Centre National de la Recherche Scientifique, 91405 Orsay, France

³Department of Physics & Astronomy, The University of Western Ontario, London ON N6A 3K7, Canada

⁴Institute for Earth and Space Exploration, The University of Western Ontario, London ON N6A 3K7, Canada

⁵Carl Sagan Center, Search for ExtraTerrestrial Intelligence Institute, Mountain View, CA 94043, USA

⁶Laboratoire d’Etudes du Rayonnement et de la Matière, Observatoire de Paris, Université Paris Science et Lettres, Centre National de la Recherche Scientifique, Sorbonne Universités, F-92190 Meudon, France

⁷Astronomy Unit, School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, UK

⁸UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill EH9 3HJ, UK

⁹Space Telescope Science Institute, Baltimore, MD 21218, USA

¹⁰Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA

¹¹ACRI-ST, Centre d’Etudes et de Recherche de Grasse, F-06130 Grasse, France

¹²Innovative Common Laboratory for Space Spectroscopy, 06130 Grasse, France

¹³NASA Ames Research Center, Moffett Field, CA 94035-1000, USA

¹⁴Instituto de Física Fundamental (Consejo Superior de Investigación Científica), 28006, Madrid, Spain

¹⁵Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, Centre National de la Recherche Scientifique, 91405 Orsay, France

¹⁶Centro de Astrobiología, Consejo Superior de Investigación Científica-INTA, 28850, Torrejón de Ardoz, Spain

¹⁷Johns Hopkins University, Baltimore, MD, 21218, USA

¹⁸Institut de Planétologie et d'Astrophysique de Grenoble, Université Grenoble Alpes, Centre National de la Recherche Scientifique, F-38000 Grenoble, France

¹⁹Institut de Radioastronomie Millimétrique, F-38406 Saint-Martin d'Hères, France

²⁰I. Physikalisches Institut, Universität zu Köln, 50937 Köln, Germany

²¹Department of Astronomy, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan

²²Department of Physics, Faculty of Science and Engineering, Meisei University, Hino, Tokyo 191-8506, Japan

²³Astronomy Department, University of Maryland, College Park, MD 20742, USA

²⁴Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden

²⁵Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands

²⁶Instituto de Astrofísica e Ciências do Espaço, P-1349-018 Lisboa, Portugal

[†] PDRs4All team authors and affiliations are given in the supplementary materials

*To whom correspondence should be addressed; E-mail: olivier.berne@irap.omp.eu

Most low-mass stars form in stellar clusters that also contain massive stars, which are sources of far-ultraviolet (FUV) radiation. Theoretical models predict that this FUV radiation produces photo-dissociation regions (PDRs) on the surfaces of protoplanetary disks around low-mass stars, impacting planet formation within the disks. We report JWST and Atacama Large Millimeter Array observations of a FUV-irradiated protoplanetary disk in the Orion Nebula. Emission lines are detected from the PDR; modelling their kinematics and excitation allows us to constrain the physical conditions within the gas. We quantify the mass-loss rate induced by the FUV irradiation, finding it is sufficient to remove gas from the disk in less than a million years. This is rapid enough to affect giant planet formation in the disk.

Young low-mass stars are surrounded by disks of gas and dust (protoplanetary disks). These disks have lifetimes of a few million years (1–3) and are the sites of planet formation (4). Planet formation is limited by processes that remove mass from the disk such as photoevaporation (5). This occurs when the upper layers of protoplanetary disks are heated by X-ray or ultraviolet photons. Radiative heating increases the gas temperature, bringing the local sound speed above the escape velocity of the disk, causing the gas to escape. The photons could be from the central star (6) or from nearby massive stars (7). Because most low mass stars form in clusters that also contain massive stars, the majority of protoplanetary disks are exposed to radiation, so are expected to experience photoevaporation driven by ultraviolet photons during their lifetime (7–11). Theoretical models predict that far-ultraviolet (FUV) photons with energies below the Lyman limit ($E < 13.6$ eV) dominate the photoevaporation, which affects the disk mass, radius, and lifetime (7, 10, 12–18), its chemical evolution (19–21), and the growth and migration of any planet forming within the disk (22).

However, these processes have not been directly observed. Most observational constraints

on the mass loss rates associated have been obtained for “proplyds” in the Orion Nebula where the ionization of FUV driven photoevaporation flows from disks results in cometary-shaped ionization fronts (IFs) (23,24). Modelling of the observed IFs has indicated mass loss rates $\dot{M}$ in units of solar masses ($1 M_{\odot} = 1.9891 \times 10^{30}$ kg) per year of proplyds in the range $\dot{M} \approx 10^{-8}$ to $10^{-6} M_{\odot}\text{yr}^{-1}$ (25–27). However, those observations did not determine the physical conditions (radiation field, gas temperature and density) at the location where the photoevaporation flow is launched. In the regions where FUV photons penetrate the disk a photodissociation region (PDR) (28) forms at the disk surface. Most observational tracers of PDR physics (lines of H_2 , O and C^+) are in the near- and far-infrared wavelength ranges. The spatial scale of PDRs in externally illuminated disks is a few hundred astronomical units ($1 \text{ au} = 1.49 \times 10^6$ meters) corresponding to angular sizes <1 arcsecond ($''$) even for the closest star forming clusters (12, 29, 30).

Imaging of a photoevaporation flow

Fig. 1 shows optical and near-infrared images of the Orion Bar, a ridge in the Orion Nebula (31), situated about 0.25 parsec (pc, $1 \text{ pc} = 3,086 \times 10^{16} \text{ m}$) southeast of the Trapezium Cluster of massive stars. The western edge of the bar constitutes the ionization front (Fig. 1 B), which separates regions where the gas is fully ionized with $T \sim 10^4$ K (upper right part of the image) and the neutral atomic region with $T \sim 500\text{--}1000$ K (the lower left part of the image). We investigate the source “d203-506” (32, 33) with coordinates: right ascension $\text{RA} = 5^{\text{h}}35^{\text{m}}20^{\text{s}}.357$ and declination $\text{Dec} = -5^{\circ}25'05''.81$, a protoplanetary disk seen in absorption against the bright background. Previous observations of d203-506 did not show any sign of the presence of an ionization front (32–34) indicating that the radiation field reaching the disk is dominated by FUV photons.

We obtained high angular resolution ($\sim 0.1''$, corresponding to ~ 40 au at the distance to

Orion) images of d203-506 with the JWST and the Atacama Large Millimeter Array (ALMA). The JWST images were obtained in the near-infrared in multiple broad and narrow band filters using the near-infrared camera (NIRCam, (35)). The ALMA interferometric images provide observations of rotational lines of HCN and HCO^+ at a velocity resolution of 0.2 km s^{-1} (35). We also obtained spectroscopic observations in the near-infrared using the integral field unit (IFU) of the near-infrared Spectrograph (NIRSpec, (35)) on the JWST.

We compare the JWST and ALMA images to archival optical images from the Hubble space telescope (HST) in Fig. 2. The nearly edge-on (35) dusty disk is visible in absorption in all the HST and JWST images (Fig. 2 A-F) but in emission in the 344 GHz ($870 \text{ }\mu\text{m}$) continuum which is due to dust (Fig. 2G). It is also seen in emission with ALMA in the HCN ($v = 0, J = 4 \rightarrow 3$) line where v and J denote the vibrational and rotational quantum numbers, respectively, at a frequency of 354.505 GHz (or wavelength $\lambda = 845.664 \text{ }\mu\text{m}$, Fig. 2H), which traces cold molecular gas. ALMA HCO^+ ($v = 0, J = 4 \rightarrow 3$) at 356.734 GHz ($\lambda = 840.381 \text{ }\mu\text{m}$) and NIRCam H_2 ($v = 1 \rightarrow 0, J = 3 \rightarrow 1$) at $2.12 \text{ }\mu\text{m}$ emission maps (Figs. 2I and 2E, respectively) trace emission from the PDR surrounding the disk and absorption in the center. Both H_2 ro-vibrational and HCO^+ rotational emission lines trace warm (gas kinetic temperatures $T_{\text{gas}} = 500\text{-}1000 \text{ K}$) molecular gas in PDRs (31). The PDR is also bright in the $3.35 \text{ }\mu\text{m}$ NIRCam filter (Fig. 2F) dominated by aromatic infrared band (AIB) emission from ultraviolet-excited Polycyclic Aromatic Hydrocarbon (PAH) molecules. PAHs are known to be tracers of PDRs (36), and have been previously mapped in a proplyd in the Orion Nebula (37). The PDR in d203-506 is spatially resolved and extends south from the disk in a lobe shape. A jet is also clearly visible in the NIRCam [Fe II] filter at $1.62 \text{ }\mu\text{m}$ (Fig. 2C). A bright emission spot is present in the H_2 and HCO^+ images in the northwestern part of the PDR. This spot is also visible in the broad-band filter at $1.4 \text{ }\mu\text{m}$ (Fig. 2B) and appears to coincide with the region of interaction between the jet and the PDR, which is visible only on the side facing the

Trapezium. There is also AIB emission in the 3.35 μm NIRCcam filter at this location (Fig. 2F), indicating ultraviolet excitation. Fig. 3 shows a schematic diagram of our interpretation of the morphological features in d203-506.

Physical properties of the PDR

Fig. 4 shows the NIRSspec spectrum of d203-506 (35). Numerous ro-vibrational emission lines of CO ($v = 1 \rightarrow 0$ and $v = 2 \rightarrow 1$), OH ($v = 1 \rightarrow 0$), CH⁺ ($v = 1 \rightarrow 0$) and H₂ (up to $J = 15$) are detected. We interpret them as coming from the PDR, so trace the physical conditions of gas in the PDR. We model (35) the H₂ lines using the MEUDON PDR code (38), which calculates the H₂ excitation in PDRs (Fig. 5). We derive the Hydrogen number density n_H and temperature of the gas in the H₂ emitting layer (Fig. 2E) as $n_H = 5.5 \times 10^5 - 1.0 \times 10^7$ and $T_{\text{gas}} = 1240 - 1260$ K. We fitted a Keplerian model to the HCN emission observed with ALMA (35). This allowed to set an upper limit for the mass of the central star of d203-506 $M_\star < 0.3 M_\odot$ (35). With $T_{\text{gas}} \sim 1250$ K as determined above, the speed of sound $c_s \equiv \sqrt{\frac{7/5 k_B T_{\text{gas}}}{\mu m_H}} = 3.3 \text{ km s}^{-1}$, where k_B is the Boltzmann constant, m_H is the mass of hydrogen and μ is the ratio of total mass over hydrogen mass of interstellar gas ($\mu = 1.4$ (39)).

This value of c_s exceeds the escape velocity at distances from the central star above a critical value, defined as the gravitational radius (40) $r_g \equiv \frac{G M_\star}{c_s^2}$. For $M_\star < 0.3 M_\odot$, and $T_{\text{gas}} = 1250$ K, $r_g < 26$ au. This is much smaller than the observed radial extent of the H₂ emission, which has a radius $r_{\text{H}_2} = 132 \pm 13$ au (and height $h_{\text{H}_2} = 56 \pm 13$ au, (35)). Therefore, the gas in this layer is not gravitationally bound and flows outwards of the disk, roughly at the speed of sound. The associated mass flux through the PDR is thus $j = \mu m_H n_H c_s$, and the total mass loss rate is $\dot{M} = j \times S$ where S is the surface area of the H₂ emitting layer (35). Including the uncertainties on r_{H_2} , h_{H_2} , n_H , and T_{gas} (Table S1 (35)) we calculate $\dot{M} = 1.4 \times 10^{-7}$ to $4.6 \times 10^{-6} M_\odot \text{yr}^{-1}$. We also investigated the mass loss rate using one-dimensional dynamical

models finding consistent values of $\dot{M}$.

Implication for planet formation

Gas in protoplanetary disks is the raw material from which giant planets form. Therefore, mass-loss due to photoevaporation can limit the formation of such planets. The effects of FUV radiation depend on the stellar mass, which sets the strength of the gravitational field retaining the gas. Previous theoretical models of planet growth under the influence of external FUV photoevaporation predicted that FUV radiation fields with intensity above about 500 times the standard interstellar radiation field (that is $G_0 \gtrsim 500$ using the notation of (41)), suppress giant planet formation around stars with masses $\lesssim 0.5 M_\odot$ (22). Our result for d203-506 are consistent with this prediction: it has $M_\star < 0.3 M_\odot$, $G_0 \lesssim 10^5$ (35) and the mass loss rate we calculated ($\dot{M} = 1.4 \times 10^{-7} - 4.6 \times 10^{-6} M_\odot/\text{year}$) imply a disk depletion timescale $\tau \equiv M_d/\dot{M} < 0.13 \text{ Myr}$, with M_d the disk mass (35). This is faster than even very early planet formation (42, 43). A positive correlation has been found between stellar mass and frequency of Jupiter-mass exoplanets (44, 45) which we suggest could be due to FUV radiation in stellar clusters during the planet formation process. Dynamical and compositional studies of Solar System bodies indicate that the Sun formed in a stellar cluster containing one or more massive stars (46) so might have been affected by FUV radiation.

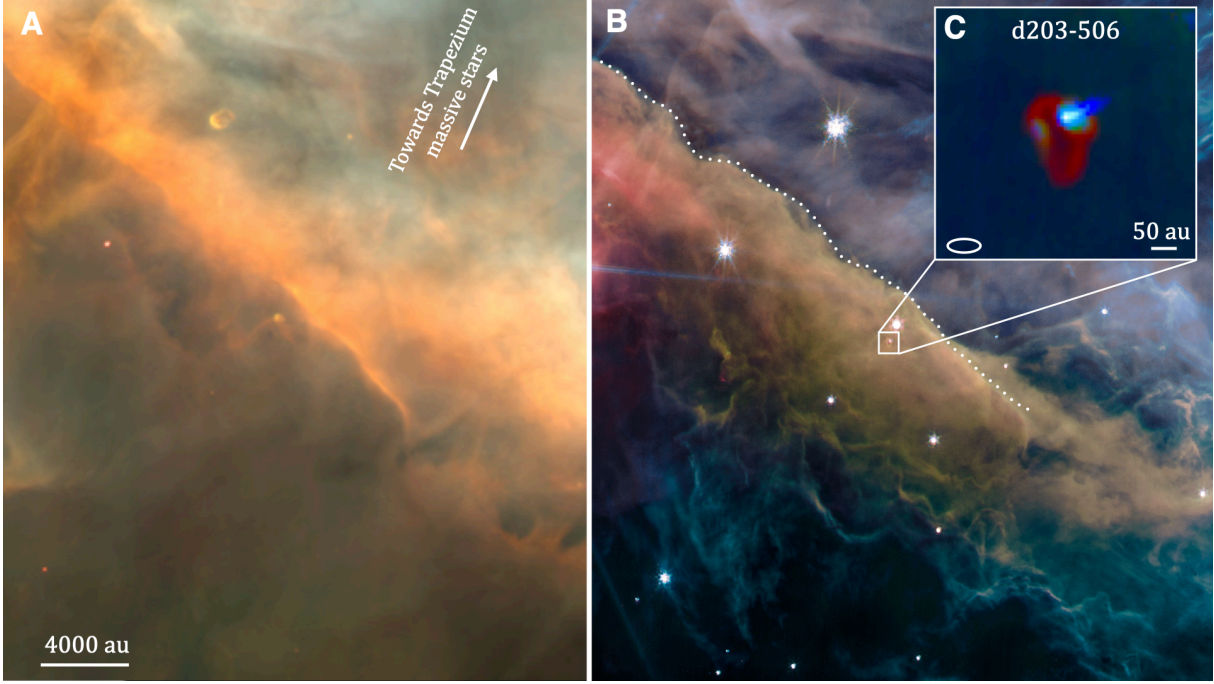


Figure 1: **Optical and near-infrared images of the Orion Bar region** (A) Hubble space telescope optical image. In blue is [OIII] at 502 nm, green $H\alpha$ at 656 nm and red [NII] at 658 nm. (B) JWST near-infrared image of the same region at the same scale. Filters centered at 1.4 and 2.0 μm are in blue; at 2.77, 3.00, 3.23, 3.35 and 3.32 μm in green; 4.05 μm in orange; and 4.44, 4.80 and 4.70 in red. The fields of view of the images in (A) and (B) are centered at coordinates $RA = 5^{\text{h}}35^{\text{m}}20^{\text{s}}.183$ and $Dec = -5^{\circ}25'06''.14$. (C) Zoom-in on the d203-506 disk. Red is the emission in the JWST-NIRCam 2.12 μm filter, tracing molecular hydrogen, blue is the 1.64 μm filter tracing the emission of [FeII], and green is the emission in the 1.40 μm broad-band filter that traces scattered light. Panel (A) credits : NASA/STScI/Rice Univ./C.O'Dell et al (47).

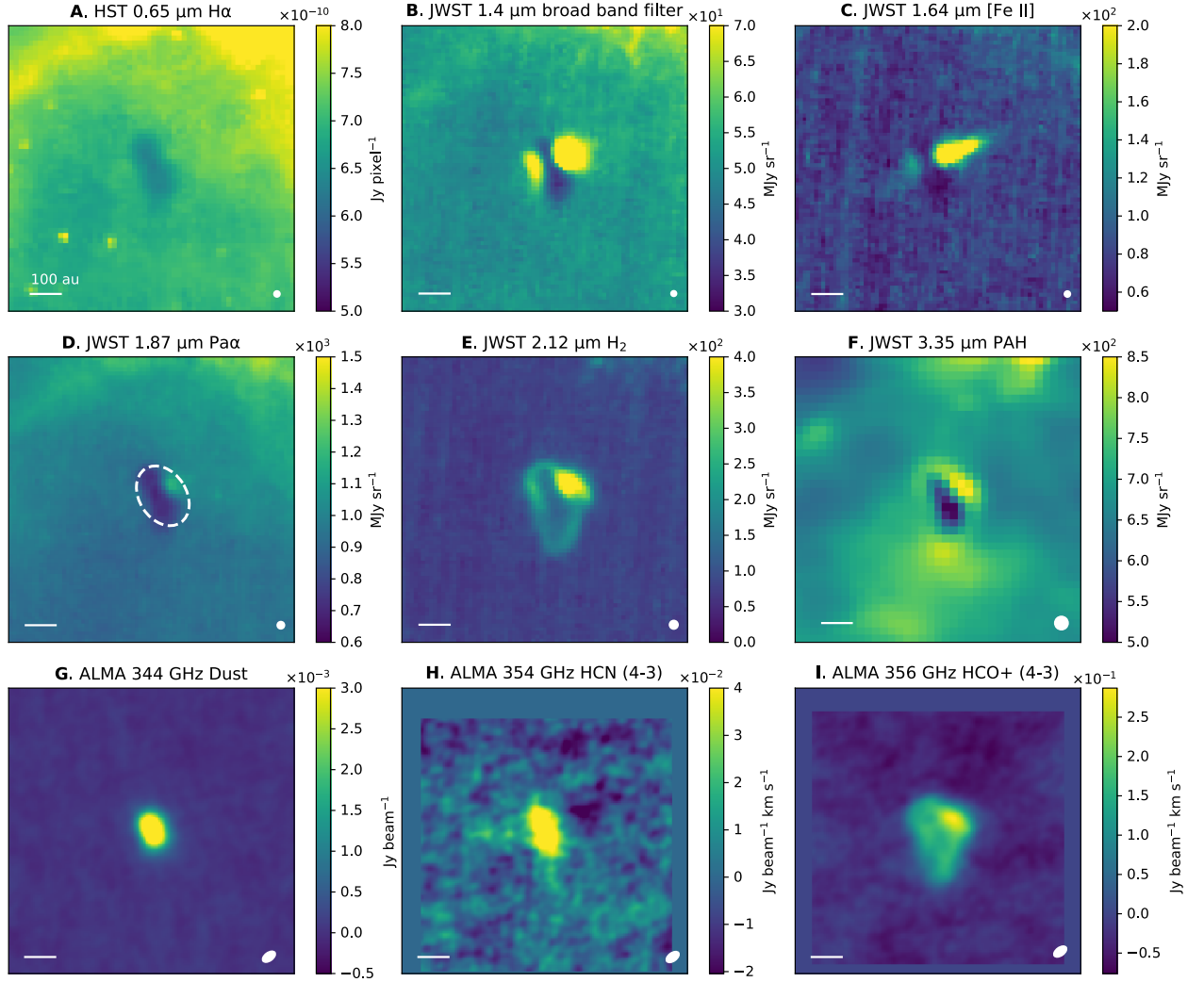


Figure 2: **Multi-wavelength images of the d203-506 disk.** (A) Optical image from HST (23), in a $H\alpha$ filter. (B-F) Near-infrared images from JWST (35). Panel E is reproduced from (33) with permission. (G-I) Sub-millimetre images from ALMA (35). In all panels the white filled ellipse indicates the size and shape of the point spread function or the reconstructed beam of the telescope and the horizontal bar is 100 au. The white dashed ellipse in panel (D) indicates the shape of the aperture used for the extraction of the NIRSpec spectrum (35). In panels (H) and (I), the notation (4-3) corresponds to the transition from quantum levels $v = 0 \rightarrow 0$, $J = 4 \rightarrow 3$. The wavelength and physical assignment of each image is labelled above each panel. $1 \text{ Jy} = 1 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$.

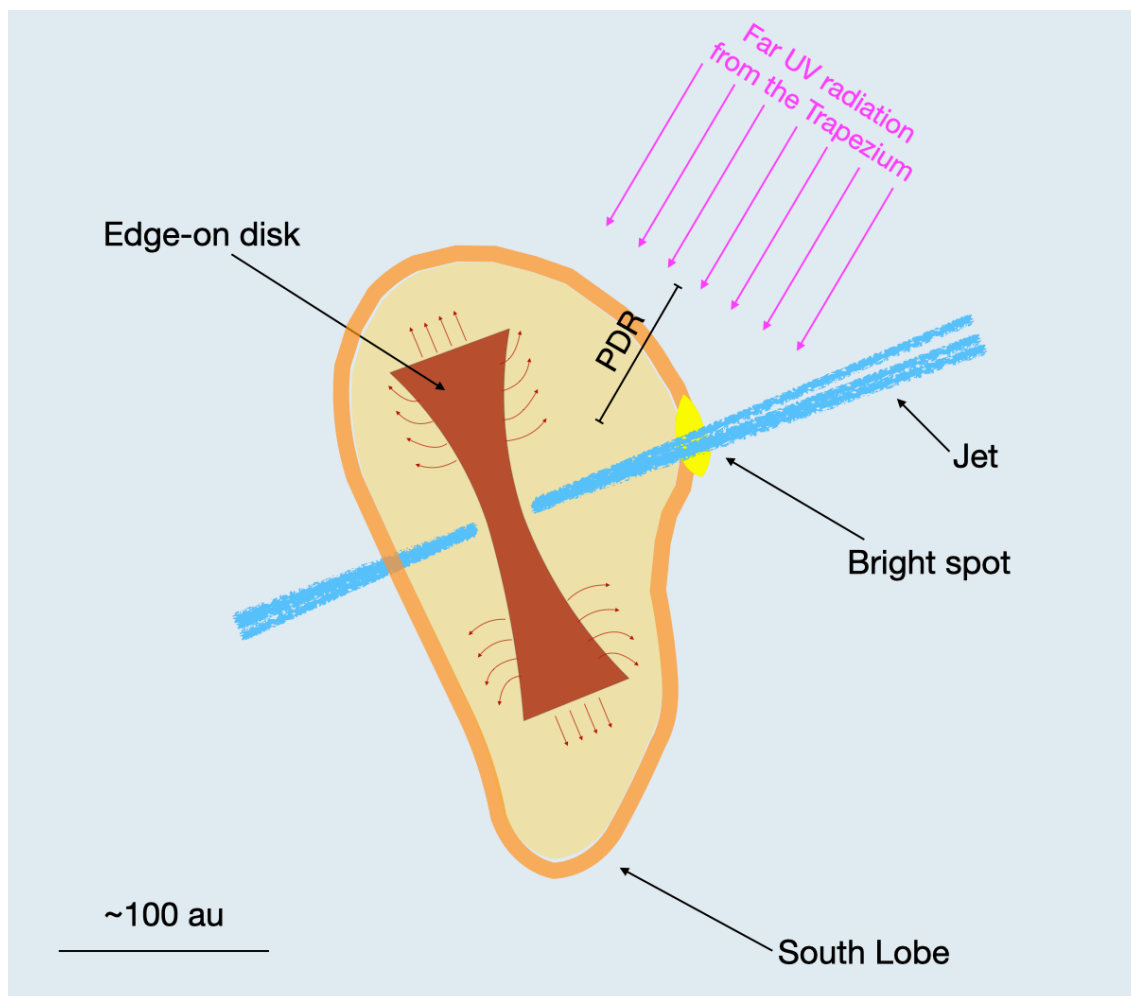


Figure 3: **Schematic diagram of our interpretation of d203-506.** The edge-on disk consisting of cold molecular gas, corresponding to absorption in the NIRcam images and HCN and dust emission in ALMA images (Fig. 2), is shown in dark brown. Molecular gas escapes from this disk (brown arrows), feeding the photo-evaporation flow which creates an envelope around the disk (light brown). This envelope is delimited by the dissociation front, in orange, where molecular hydrogen is dissociated into hydrogen atoms by the far ultraviolet photons from the trapezium star (pink arrows). This transition from molecular gas of the disk to atomic gas under ultraviolet irradiation constitutes the photodissociation region (PDR). A jet from the central star, shown in blue and corresponding to [FeII] emission interacts with the envelope creating a bright emission spot, shown in yellow. The surroundings of d203-506 (in gray in this diagram) consist of diffuse atomic gas.

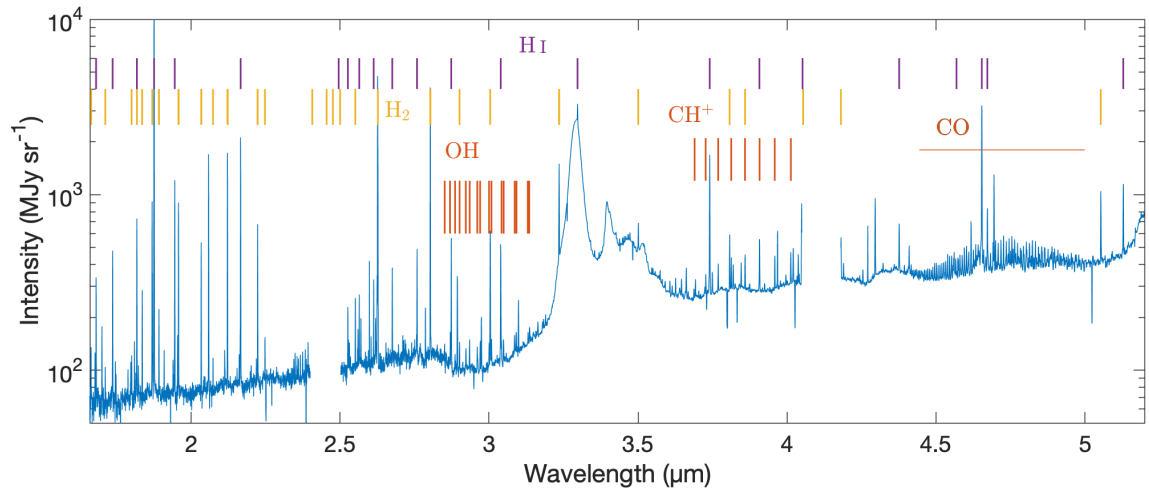


Figure 4: **JWST NIRSpec spectrum of d203-506.** Wavelength positions of the detected species are indicated. The broad emission bands at 3.3 and 3.4 μm are from the C-H vibrational emission of polycyclic aromatic hydrocarbon (PAH) molecules. Unlabeled lines are, in most cases, atomic lines (e.g., [OI] or [FeII]). There are no data between wavelengths 2.40-2.50 μm and 4.05-4.18 μm due to gaps in the NIRSpec detectors.

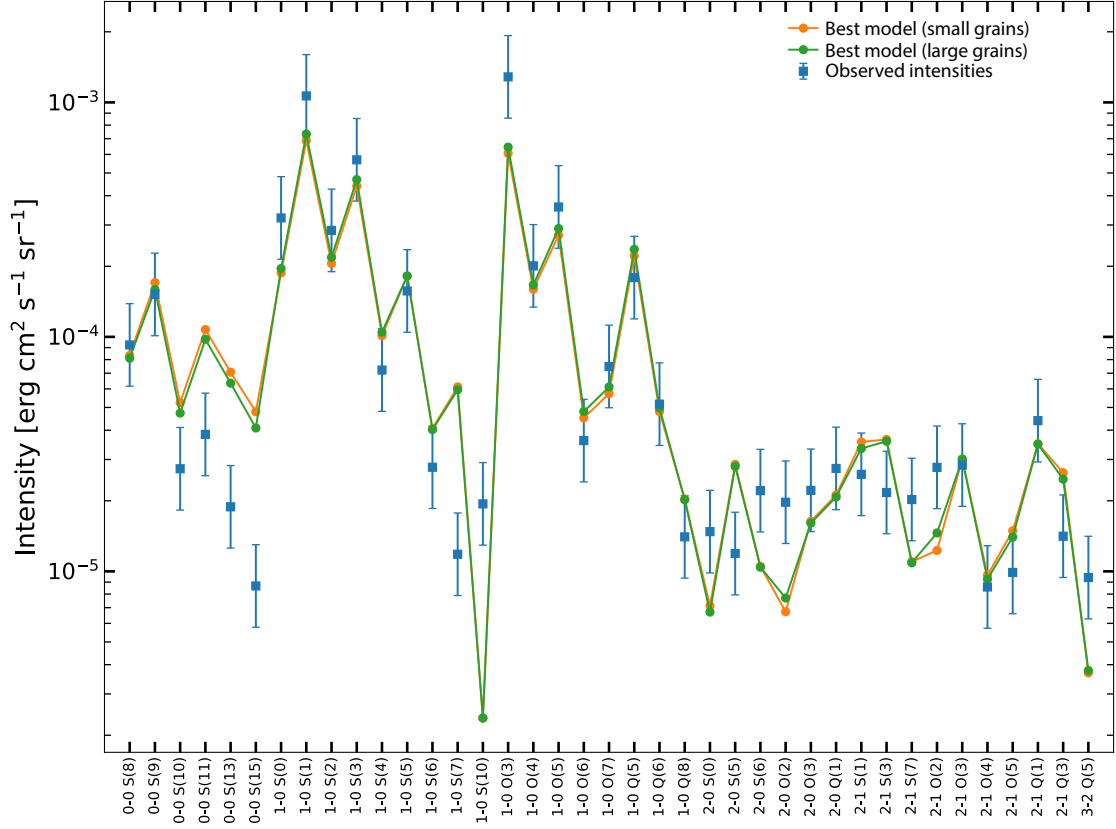


Figure 5: **Comparison of the observed and modeled H_2 line intensities for d203-506.** Observed intensities are the blue squares, the associated error bars represent a total uncertainty of 50%, as considered in the estimate of the χ^2 (35). The instrumental uncertainties are smaller than the markers, and given in table S2. Modelled intensities for the best models obtained using the MEUDON PDR code are shown with the orange (for the a model using small dust grains) and green circles, for models using small and large dust grains, respectively (35). The notations of the H_2 lines in the X axis are abbreviated, quantum levels corresponding to this notation are listed in table S2.

References

1. J. P. Williams, L. A. Cieza, *Annual Review of Astron. & Astrophys.* **49**, 67 (2011).
2. K. E. Haisch Jr, E. A. Lada, C. J. Lada, *Astrophys. J.* **553**, L153 (2001).
3. S. M. Andrews, *Annual Review of Astron. & Astrophys.* **58**, 483 (2020).
4. M. Keppler, *et al.*, *Astron. & Astrophys.* **617**, A44 (2018).
5. U. Gorti, R. Liseau, Z. Sándor, C. Clarke, *Space Science Reviews* **205**, 125 (2016).
6. U. Gorti, D. Hollenbach, *The Astrophysical Journal* **690**, 1539 (2008).
7. F. C. Adams, D. Hollenbach, G. Laughlin, U. Gorti, *Astrophys. J.* **611**, 360 (2004).
8. C. J. Lada, E. A. Lada, *Annual Reviews of Astron. & Astrophys.* **41**, 57 (2003).
9. M. Fatuzzo, F. C. Adams, *Astrophys. J.* **675**, 1361 (2008).
10. A. J. Winter, J. D. Kruijssen, M. Chevance, B. W. Keller, S. N. Longmore, *Mon. Notic. Roy. Soc.* **491**, 903 (2020).
11. A. J. Winter, T. J. Haworth, *The European Physical Journal Plus* **137**, 1132 (2022).
12. H. Störzer, D. Hollenbach, *Astrophys. J.* **515**, 669 (1999).
13. A. Scally, C. Clarke, *Mon. Notic. Roy. Soc.* **325**, 449 (2001).
14. C. J. Clarke, *Mon. Notic. Roy. Soc.* **376**, 1350 (2007).
15. F. Concha-Ramírez, M. J. C. Wilhelm, S. Portegies Zwart, T. J. Haworth, *Mon. Notic. Roy. Soc.* **490**, 5678 (2019).
16. A. J. Winter, *et al.*, *Mon. Notic. Roy. Soc.* **478**, 2700 (2018).

17. R. B. Nicholson, *et al.*, *Mon. Notic. Roy. Soc.* **485**, 4893 (2019).
18. G. A. L. Coleman, T. J. Haworth, *Mon. Notic. Roy. Soc.* **514**, 2315 (2022).
19. C. Walsh, T. J. Millar, H. Nomura, *Astrophys. J. Let.* **766**, L23 (2013).
20. T. J. Haworth, *Mon. Notic. Roy. Soc.* **503**, 4172 (2021).
21. R. D. Boyden, J. A. Eisner, *Astrophys. J.* **947**, 7 (2023).
22. A. J. Winter, T. J. Haworth, G. A. Coleman, S. Nayakshin, *Mon. Notic. Roy. Soc.* (2022).
23. C. R. O'Dell, Z. Wen, *Astrophys. J.* **436**, 194 (1994).
24. C. R. O'Dell, *Astron. J.* **115**, 263 (1998).
25. D. Johnstone, D. Hollenbach, J. Bally, *Astrophys. J.* **499**, 758 (1998).
26. W. Henney, S. Arthur, *Astron. J.* **116**, 322 (1998).
27. W. J. Henney, C. R. O'Dell, *Astron. J.* **118**, 2350 (1999).
28. A. Tielens, D. Hollenbach, *Astrophys. J.* **291**, 722 (1985).
29. H. Chen, *et al.*, *Astrophys. J.* **492**, L173 (1997).
30. J. Champion, *et al.*, *Astron. & Astrophys.* **604**, A69 (2017).
31. J. R. Goicoechea, *et al.*, *Nature* **537**, 207 (2016).
32. J. Bally, C. R. O'Dell, M. J. McCaughrean, *Astron. J.* **119**, 2919 (2000).
33. O. Berné, *et al.*, *Nature* **621**, 56 (2023).
34. E. Habart, *et al.*, *arXiv preprint arXiv:2206.08245* (2022).

35. Materials and methods are available as supplementary materials.
36. E. Peeters, *et al.*, *Astron. & Astrophys.* **390**, 1089 (2002).
37. S. Vicente, *et al.*, *Astrophys. J. Letters* **765**, L38 (2013).
38. F. Le Petit, C. Nehme, J. Le Bourlot, E. Roueff, *Astrophys. J. Suppl. Ser.* **164**, 506 (2006).
39. B. T. Draine, *Physics of the Interstellar and Intergalactic Medium* (2011).
40. D. Hollenbach, D. Johnstone, S. Lizano, F. Shu, *Astrophys. J.* **428**, 654 (1994).
41. H. J. Habing, *Bull. Astr. Inst. Netherlands* **19**, 421 (1968).
42. A. Stolte, *et al.*, *Astron. & Astrophys.* **578**, A4 (2015).
43. P. D. Sheehan, J. A. Eisner, *Astrophys. J.* **857**, 18 (2018).
44. J. A. Johnson, K. M. Aller, A. W. Howard, J. R. Crepp, *Publications of the Astronomical Society of the Pacific* **122**, 905 (2010).
45. S. Reffert, C. Bergmann, A. Quirrenbach, T. Trifonov, A. Künstler, *Astron. & Astrophys.* **574**, A116 (2015).
46. E. A. Bergin, C. Alexander, M. Drozdovskaya, M. Gounelle, S. Pflazner, *arXiv preprint arXiv:2301.05212* (2023).
47. <https://hubblesite.org/contents/media/images/2005/12/1674-Image.html>.
48. <https://doi.org/10.5281/zenodo.8196030>.
49. <https://zenodo.org/doi/10.5281/zenodo.10260214>.
50. <https://zenodo.org/records/10488834>.

51. [Http://casa.nrao.edu/](http://casa.nrao.edu/).
52. [Http://www.iram.fr/IRAMFR/GILDAS](http://www.iram.fr/IRAMFR/GILDAS).
53. M. J. Rieke, *et al.*, *Publications of the Astronomical Society of the Pacific* **135**, 028001 (2023).
54. J. P. Gardner, *et al.*, *Space Science Reviews* **123**, 485 (2006).
55. O. Berné, S. Foschino, F. Jalabert, C. Joblin, *Astron. & Astrophys.* **667**, A159 (2022).
56. [Https://zenodo.org/doi/10.5281/zenodo.6984365](https://zenodo.org/doi/10.5281/zenodo.6984365).
57. E. Habart, *et al.*, *arXiv e-prints* p. arXiv:2308.16732 (2023).
58. T. Böker, *et al.*, *Publications of the Astronomical Society of the Pacific* **135**, 038001 (2023).
59. T. Böker, *et al.*, *Astronomy & Astrophysics* **661**, A82 (2022).
60. E. Peeters, *et al.*, *arXiv e-prints* p. arXiv:2310.08720 (2023).
61. K. Menten, M. Reid, J. Forbrich, A. Brunthaler, *Astron. & Astrophys.* **474**, 515 (2007).
62. R. L. Kurucz, *Symposium-International Astronomical Union* (Cambridge University Press, 1992), vol. 149, pp. 225–232.
63. A. Marconi, L. Testi, A. Natta, C. Walmsley, *Astron. Astrophys* **330**, 696 (1998).
64. R. D. Boyden, J. A. Eisner, *Astrophys. J.* **894**, 74 (2020).
65. R. K. Mann, *et al.*, *Astrophys. J.* **784**, 82 (2014).
66. S. Beckwith, T. Henning, Y. Nakagawa, *Protostars and Planets IV* p. 533 (2000).
67. Woitke, P., *et al.*, *Astron. & Astrophys.* **586**, A103 (2016).

- 68. S. M. Andrews, J. P. Williams, *Astrophys. J.* **631**, 1134 (2005).
- 69. E. Roueff, *et al.*, *Astron. & Astrophys.* **630**, A58 (2019).
- 70. Ismdb.obspm.fr.
- 71. E. L. Fitzpatrick, D. Massa, *Astrophys. J.* **72**, 163 (1990).
- 72. Y. Wan, *et al.*, *Astrophys. J.* **862**, 132 (2018).
- 73. D. Bossion, Y. Scribano, F. Lique, G. Parlant, *Mon. Notic. Roy. Soc.* **480**, 3718 (2018).
- 74. C. Joblin, *et al.*, *Astron. & Astrophys.* **615**, A129 (2018).
- 75. T. G. Bisbas, *et al.*, *Mon. Notic. Roy. Soc.* **454**, 2828 (2015).
- 76. T. J. Harries, T. J. Haworth, D. Acreman, A. Ali, T. Douglas, *Astronomy and Computing* **27**, 63 (2019).
- 77. D. McElroy, *et al.*, *Astron. & Astrophys.* **550**, A36 (2013).
- 78. S. Facchini, C. J. Clarke, T. G. Bisbas, *Monthly Notices of the Royal Astronomical Society* **457**, 3593 (2016).

Acknowledgments

The author thank the anonymous referees for providing helpful feedback and comments on this paper. The authors thank Chris O'Dell for providing comments on this manuscript. The JWST helpdesk is acknowledged for providing support with data reduction. Part of this work was performed using the DiRAC Data Intensive service at Leicester, operated by the University of Leicester IT Services, which forms part of the STFC DiRAC HPC Facility.

Funding:

AF thanks the Spanish MICIN for funding support from PID2019-106235GB-I00. OB, IS, AC are funded by the Centre National d'Etudes Spatiales (CNES) through the APR program. JRG and SC thank the Spanish MCINN for funding support under grant PID2019-106110GB-I00. PG thanks the University Pierre and Marie Curie, the Institut Universitaire de France, the CNES, the "Programme National de Cosmologie and Galaxies" (PNCG) and the "Physique Chimie du Milieu Interstellaire" (PCMI) programs of Centre National de la Recherche Scientifique/INSU for financial supports. EP and JC acknowledge support from the Institute for Earth and Space Exploration, the Canadian Space Agency, and the Natural Sciences and Engineering Research Council of Canada. CB is grateful for funding from the San José State University Research Foundation (80NSSC22M0107) and acknowledges support from the Internal Scientist Funding Model (ISFM) Laboratory Astrophysics Directed Work Package at NASA Ames. TO is supported by JSPS Bilateral Program, Grant Number 120219939. TJH is funded by a Royal Society Dorothy Hodgkin Fellowship. AF was supported by the Spanish program Unidad de Excelencia María de Maeztu CEX2020-001058-M, financed by MCIN/AEI/10.13039/501100011033. NN is funded through UAEU Program for Advanced Research (UPAR) grant G00003479. YZ is funded by the National Science Foundation of China (NSFC, Grant No. 11973099) and the science research grants from the China Manned

Space Project (NO. CMS-CSST-2021-A09 and A10). Work by M.R. and Y.O. are supported by the Collaborative Research Centre 956, sub-project C1, funded by the Deutsche Forschungsgemeinschaft (DFG)—project ID 184018867. P.M. acknowledges grants EUR2021-122006, TED2021-129416A-I00 and PID2021-125309OA-I00 funded by MCIN/AEI/10.13039/501100011033 and European Union NextGenerationEU/PRTR. A. Pathak acknowledges financial support from the Department of Science and Technology-Core Research Grant (DST-CRG) grant (SERB-CRG/2021/000907), Institutes of Eminence (IoE) incentive grant, BHU (incentive/2021- 22/32439). M. B. acknowledges DST INSPIRE Faculty fellowship. JL is sponsored by the Chinese Academy of Sciences (CAS), through a grant to the CAS South America Center for Astronomy (CAS-SACA) in Santiago, Chile. HZ acknowledges support from the Swedish Research Council (contract No 2020-03437).

Author contributions: O. B., E. H., and E. P., led the JWST observing program. O. B. led the study and drafted the manuscript, and made Figs. 1, 3, 4, S1, S3, S4. E. B. and F. L. P. produced the PDR models and Figs 5, S4, S5, S6, and 4. T. J. H. produced the 1d dynamical models and Fig. S7. F. A. produced the the disk 3D radiative transfer models and Fig. S2. A. Canin produced Fig. 2. Jason C. led PI the ALMA observing program. Jason C. and Edwige C. conducted the ALMA data reduction. P. K. analyzed the ALMA data. I.S., A.S., R.C., D.V.P. and F.A. reduced the NIRSpec data. A. C. and B. Tr. reduced the NIRCам data. I. S. produced the extraction of the NIRSpec spectrum. I. S. and M. Z. extracted the line intensities. M. Z. provided conducted the LTE radiative transfer models for CH^+ and OH. J. C. provided the radiative transfer models for CO. All other authors contributed to the research presented in this paper or provided detailed feedback on the manuscript. All authors meet the journal’s authorship requirement.

Competing interests: The authors declare no competing interests.

Data and material availability: The JWST data are available on the MAST portal (<http://mast.stsci.edu>) using the program ID 1288. The Hubble Space Telescope data are available through the same portal, using program ID 6603. The ALMA raw data is available on the ALMA archive (<https://almascience.eso.org/aq/>) using program ID 2017.1.01478.S. Our reduced ALMA data are available on Zenodo (48), as well as the reduced NIRSPec spectrum of d203-506 (49). The TORUS-3DPDR code is available at <https://bitbucket.org/tjharries/torus/src/master/>. The MEUDON PDR code used in this paper (50) is available at <https://zenodo.org/records/10488834>.

Supplementary materials:

PDRs4All Team authors and affiliations

Materials and Methods

Figures S1 to S7

Tables S1 to S2

References

Supplementary Materials for

A far-ultraviolet-driven photoevaporation flow observed in a protoplanetary disk

O. Berné, *et al.*

Corresponding author Email: olivier.berne@irap.omp.eu

This PDF file includes:

PDRs4All Team authors and affiliations

Materials and Methods

Figures S1 to S7

Tables S1 to S2

References 50 - 78

PDRs4All Team authors and affiliations

Olivier Berné ^{1,*}, Emilie Habart ², Els Peeters ^{3,4,5}, Ilane Schroetter ¹, Amélie Canin ¹, Ameek Sidhu ^{3,4}, Ryan Chown ^{3,4}, Emeric Bron ⁶, Thomas J. Haworth ⁷, Pamela Klaassen ⁸, Boris Trahin ², Dries Van De Putte ⁹, Felipe Alarcón ¹⁰, Marion Zannese ², Alain Abergel ², Edwin A. Bergin ¹⁰, Jeronimo Bernard-Salas ^{11,12}, Christiaan Boersma ¹³, Jan Cami ^{3,4,5}, Sara Cuadrado ¹⁴, Emmanuel Dartois ¹⁵, Daniel Dicken ², Meriem Elyajouri ², Asunción Fuente ¹⁶, Javier R. Goicoechea ¹⁴, Karl D. Gordon ^{9,17}, Lina Issa ¹, Christine Joblin ¹, Olga Kannavou ², Baria Khan ³, Ozan Lacinbala ², David Languignon ⁶, Romane Le Gal ^{1,18,19}, Alexandros Maragkoudakis ¹³, Raphael Meshaka ², Yoko Okada ²⁰, Takashi Onaka ^{21,22}, Sofia Pasquini ³, Marc W. Pound ²³, Massimo Robberto ^{9,17}, Markus Röllig ²⁰, Bethany Schefter ³, Thiébaud Schirmer ^{2,24}, Thomas Simmer ², Benoit Tabone ², Alexander G. G. M. Tielens ^{23,25}, Sílvia Vicente ²⁶, Mark G. Wolfire ²³, Isabel Aleman ²⁷, Louis Allamandola ^{23,28}, Rebecca Auchettl ²⁹, Giuseppe Antonio Baratta ³⁰, Clément Baruteau ¹, Salma Bejaoui ²³, Partha P. Bera ^{23,28}, John H. Black ³², Francois Boulanger ³³, Jordy Bouwman ^{34,35,36}, Bernhard Brandl ^{20,37}, Philippe Brechignac ¹¹, Sandra Brünken ³⁸, Mridusmita Buragohain ³⁹, Andrew Burkhardt ⁴⁰, Alessandra Candian ^{20,41}, Stéphanie Cazaux ¹⁰, Jose Cernicharo ¹⁴, Marin Chabot ⁴², Shubhadip Chakraborty ^{43,44}, Jason Champion ¹, Sean W.J. Colgan ²⁴, Ilsa R. Cooke ⁴⁵, Audrey Coutens ¹, Nick L.J. Cox ^{11,12}, Karine Demyk ¹, Jennifer Donovan Meyer ⁴⁶, Cécile Engrand ⁴², Sacha Foschino ⁴, Pedro García-Lario ⁴⁷, Lisseth Gavilan ²⁴, Maryvonne Gerin ⁴⁸, Marie Godard ¹⁵, Carl A. Gottlieb ⁴⁹, Pierre Guillard ^{50,51}, Antoine Gusdorf ^{33,48}, Patrick Hartigan ⁵², Jinhua He ^{53,54,55}, Eric Herbst ⁵⁶, Liv Hornekaer ⁵⁷, Cornelia Jäger ⁵⁸, Eduardo Janot-Pacheco ⁵⁹, Michael Kaufman ⁶⁰, Francisca Kemper ^{61,62,63}, Sarah Kendrew ⁶⁴, Maria S. Kirsanova ⁶⁵, Collin Knight ³, Sun Kwok ⁶⁶, Álvaro Labiano ⁶⁷, Thomas S.-Y. Lai ⁶⁸, Timothy J. Lee ²⁴, Bertrand Lefloch ²⁵, Franck Le Petit ⁹, Aigen Li ⁶⁹, Hendrik Linz ⁷⁰, Cameron J. Mackie ^{71,72}, Suzanne C. Madden ⁷³, Joëlle Mascetti ⁷⁴, Brett A. McGuire ^{75,76}, Pablo Merino ⁷⁷, Elisabetta R. Micelotta ⁷⁸, Jon A. Morse ⁷⁹, Giacomo Mulas ^{80,1}, Naslim Neelamkodan ⁸¹, Ryou Ohsawa ⁸², Roberta Paladini ⁶⁸, Maria Elisabetta Palumbo ³⁰, Amit Pathak ⁸³, Yvonne J. Pendleton ⁸⁴, Annemieke Petrignani ⁸⁵, Thomas Pino ¹², Elena Puga ⁴⁷, Naseem Rangwala ¹³, Mathias Rapacioli ⁸⁶, Alessandra Ricca ^{24,3}, Julia Roman-Duval ¹⁵, Evelyne Roueff ¹⁰, Gaël Rouillé ⁵⁸, Farid Salama ¹³, Dinalva A. Sales ⁸⁷, Karin Sandstrom ⁸⁸, Peter Sarre ⁸⁹, Ella Sciamma-O'Brien ¹³, Kris Sellgren ⁹⁰, Matthew J. Shannon ¹³, Adrien Simonnin ¹, Sachindev S. Shenoy ⁹¹, David Teyssier ⁴⁷, Richard D. Thomas ⁹², Aditya Togi ⁹³, Laurent Verstraete ², Adolf N. Witt ⁹⁴, Alwyn Wootten ⁴⁶, Nathalie Ysard ^{2,1}, Henning Zettergren ⁹², Yong Zhang ⁹⁵, Ziwei E. Zhang ⁹⁶, Junfeng Zhen ⁹⁷

¹Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, Centre National de la Recherche Scientifique, Centre National d'Etudes Spatiales, 31028, Toulouse, France

²Institut d'Astrophysique Spatiale, Université Paris-Saclay, Centre National de la Recherche Scientifique, 91405 Orsay, France

³Department of Physics & Astronomy, The University of Western Ontario, London ON N6A 3K7, Canada

- ⁴Institute for Earth and Space Exploration, The University of Western Ontario, London ON N6A 3K7, Canada
- ⁵Carl Sagan Center, Search for ExtraTerrestrial Intelligence Institute, Mountain View, CA 94043, USA
- ⁶Laboratoire d'Etudes du Rayonnement et de la Matière, Observatoire de Paris, Université Paris Science et Lettres, Centre National de la Recherche Scientifique, Sorbonne Universités, F-92190 Meudon, France
- ⁷Astronomy Unit, School of Physics and Astronomy, Queen Mary University of London, London E1 4NS, UK
- ⁸UK Astronomy Technology Centre, Royal Observatory Edinburgh, Blackford Hill EH9 3HJ, UK
- ⁹Space Telescope Science Institute, Baltimore, MD 21218, USA
- ¹⁰Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA
- ¹¹*ACRI-ST*, Centre d'Etudes et de Recherche de Grasse, F-06130 Grasse, France
- ¹²Innovative Common Laboratory for Space Spectroscopy, 06130 Grasse, France
- ¹³NASA Ames Research Center, Moffett Field, CA 94035-1000, USA
- ¹⁴Instituto de Física Fundamental, Consejo Superior de Investigación Científica, 28006, Madrid, Spain
- ¹⁵Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, Centre National de la Recherche Scientifique, 91405 Orsay, France
- ¹⁶Centro de Astrobiología, Consejo Superior de Investigación Científica, Instituto Nacional de Técnica Aeroespacial, 28850, Torrejón de Ardoz, Spain
- ¹⁷Johns Hopkins University, Baltimore, MD, 21218, USA
- ¹⁸Institut de Planétologie et d'Astrophysique de Grenoble, Université Grenoble Alpes, Centre National de la Recherche Scientifique, F-38000 Grenoble, France
- ¹⁹Institut de Radioastronomie Millimétrique, F-38406 Saint-Martin d'Hères, France
- ²⁰I. Physikalisches Institut Universität zu Köln, 50937 Köln, Germany
- ²¹Department of Astronomy, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
- ²²Department of Physics, Faculty of Science and Engineering, Meisei University, Hino, Tokyo 191-8506, Japan
- ²³Astronomy Department, University of Maryland, College Park, MD 20742, USA
- ²⁴Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, SE-439 92 Onsala, Sweden
- ²⁵Leiden Observatory, Leiden University, 2300 RA Leiden, The Netherlands
- ²⁶Instituto de Astrofísica e Ciências do Espaço, P-1349-018 Lisboa, Portugal
- ²⁷Instituto de Física e Química, Universidade Federal de Itajubá, Itajubá, Brazil
- ²⁸Bay Area Environmental Research Institute, Moffett Field, CA 94035, USA
- ²⁹Australian Synchrotron, Australian Nuclear Science and Technology Organisation, Victoria, Australia
- ³⁰INAF - Osservatorio Astrofisico di Catania, 95123 Catania, Italy

- ³¹Department of Physics, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia
- ³²Department of Space, Earth, and Environment, Chalmers University of Technology, Onsala Space Observatory, 43992, Onsala, Sweden
- ³³Laboratoire de Physique de l'École Normale Supérieure, Université Paris Science et Lettres, Centre National de la Recherche Scientifique, Sorbonne Université, Université de Paris, 75005, Paris, France
- ³⁴Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA
- ³⁵Department of Chemistry, University of Colorado, Boulder, CO 80309, USA
- ³⁶Institute for Modeling Plasma, Atmospheres, and Cosmic Dust, University of Colorado, Boulder, CO 80303, USA
- ³⁷Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS Delft, The Netherlands
- ³⁸Radboud University, Institute for Molecules and Materials, Free-Electron Lasers for Infrared eXperiments Laboratory, 6525 ED Nijmegen, the Netherlands
- ³⁹School of Physics, University of Hyderabad, Hyderabad 500 046, India
- ⁴⁰Department of Physics, Wellesley College, 106 Central Street, Wellesley, MA 02481, USA
- ⁴¹Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
- ⁴²Laboratoire de Physique des deux infinis Irène Joliot-Curie, Université Paris-Saclay, Centre National de la Recherche Scientifique, 91405 Orsay Cedex, France
- ⁴³Institut de Physique de Rennes, Centre National de la Recherche Scientifique 6251, Université de Rennes 1, 35042 Rennes Cedex, France
- ⁴⁴Department of Chemistry, Gandhi Institute of Technology and Management, Bangalore, India
- ⁴⁵Department of Chemistry, The University of British Columbia, Vancouver, British Columbia, Canada
- ⁴⁶National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
- ⁴⁷European Space Agency, Villanueva de la Cañada, E-28692 Madrid, Spain
- ⁴⁸Observatoire de Paris, Paris Science et Lettres University, Sorbonne Université, Laboratoire d'Etudes du Rayonnement et de la Matière, 75014, Paris, France
- ⁴⁹Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge MA 02138, USA
- ⁵⁰Sorbonne Université, Centre National de la Recherche Scientifique, Institut d'Astrophysique de Paris, 75014 Paris, France
- ⁵¹Institut Universitaire de France, Ministère de l'Enseignement Supérieur et de la Recherche, 1 rue Descartes, 75231 Paris, France
- ⁵²Department of Physics and Astronomy, Rice University, Houston TX, 77005-1892, USA
- ⁵³Yunnan Observatories, Chinese Academy of Sciences, 396 Yangfangwang, Guandu District, Kunming, 650216, China
- ⁵⁴Chinese Academy of Sciences South America Center for Astronomy, National Astronomical Observatories, Chinese Academy of Science, Beijing 100101, China

- ⁵⁵Departamento de Astronomía, Universidad de Chile, Santiago, Chile
- ⁵⁶Departments of Chemistry and Astronomy, University of Virginia, Charlottesville, Virginia 22904, USA
- ⁵⁷Center for Interstellar Catalysis, Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark
- ⁵⁸Laboratory Astrophysics Group of the Max Planck Institute for Astronomy at the Friedrich Schiller University Jena, Institute of Solid State Physics, 07743 Jena, Germany
- ⁵⁹Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, 05509-090 São Paulo, Brazil
- ⁶⁰Department of Physics and Astronomy, San José State University, San Jose, CA 95192, USA
- ⁶¹Institut de Ciències de l'Espai, Consejo Superior de Investigación Científica, E-08193, Barcelona, Spain
- ⁶²Institución Catalana de Investigación y Estudios Avanzados, Pg. Lluís Companys 23, E-08010 Barcelona, Spain
- ⁶³Institut d'Estudis Espacials de Catalunya, E-08034 Barcelona, Spain
- ⁶⁴European Space Agency, Space Telescope Science Institute, Baltimore MD 21218, USA
- ⁶⁵Institute of Astronomy, Russian Academy of Sciences, 119017, Moscow, Russia
- ⁶⁶Department of Earth, Ocean, & Atmospheric Sciences, University of British Columbia, Canada V6T 1Z4
- ⁶⁷*Telespazio UK*, European Space Agency, E-28692 Villanueva de la Cañada, Madrid, Spain
- ⁶⁸Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125, USA
- ⁶⁹Department of Physics and Astronomy, University of Missouri, Columbia, MO 65211, USA
- ⁷⁰Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
- ⁷¹Chemical Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
- ⁷²Kenneth S. Pitzer Center for Theoretical Chemistry, Department of Chemistry, University of California – Berkeley, Berkeley, California, USA
- ⁷³AIM, Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Centre National de la Recherche Scientifique, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, 91191 Gif-sur-Yvette, France
- ⁷⁴Institut des Sciences Moléculaires, Centre National de la Recherche Scientifique, Université de Bordeaux, 33405 Talence, France
- ⁷⁵Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
- ⁷⁶National Radio Astronomy Observatory, Charlottesville, VA 22903, USA
- ⁷⁷Instituto de Ciencia de Materiales de Madrid, Consejo Superior de Investigación Científica, E28049, Madrid, Spain
- ⁷⁸Department of Physics, PO Box 64, 00014 University of Helsinki, Finland
- ⁷⁹Steward Observatory, University of Arizona, Tucson, AZ 85721-0065, USA
- ⁸⁰Osservatorio Astronomico di Cagliari, Istituto Nazionale di Astrofisica, 09047 Selargius,

Italy

⁸¹Department of Physics, College of Science, United Arab Emirates University, Al-Ain, 15551, UAE

⁸²National Astronomical Observatory of Japan, Tokyo 181-8588, Japan

⁸³Department of Physics, Institute of Science, Banaras Hindu University, Varanasi 221005, India

⁸⁴Department of Physics, University of Central Florida, Orlando, FL 32816-2385, USA

⁸⁵Van't Hoff Institute for Molecular Sciences, University of Amsterdam, PO Box 94157, 1090 GD, Amsterdam, The Netherlands

⁸⁶Laboratoire de Chimie et Physique Quantiques, Université de Toulouse, Centre National de la Recherche Scientifique, Toulouse, France

⁸⁷Instituto de Matemática, Estatística e Física, Universidade Federal do Rio Grande, 96201-900, Rio Grande, Brazil

⁸⁸Center for Astrophysics and Space Sciences, Department of Physics, University of California, San Diego, CA 92093, USA

⁸⁹School of Chemistry, The University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom

⁹⁰Astronomy Department, Ohio State University, Columbus, OH 43210 USA

⁹¹Space Science Institute, 4765 Walnut St., R203, Boulder, CO 80301, USA

⁹²Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden

⁹³Department of Physics, Texas State University, San Marcos, TX 78666 USA

⁹⁴Ritter Astrophysical Research Center, University of Toledo, Toledo, OH 43606, USA

⁹⁵School of Physics and Astronomy, Sun Yat-sen University, Zhuhai 519000, China

⁹⁶Star and Planet Formation Laboratory, Rikagaku Kenkyusho (RIKEN) Cluster for Pioneering Research, Saitama 351-0198, Japan

⁹⁷University of Science and Technology of China, Chinese Academy of Science Key Laboratory of Crust-Mantle Materials and Environment, Anhui 230026, China

Materials and methods

Observations and data reduction

ALMA

ALMA observations were taken in December 2017 as part of project 2017.1.01478.S (Principal Investigator J. Champion). The configuration for the observations was C43-6 with 46 antennas, corresponding to 1035 baselines ranging from 15.1 m to 3.3 km. We observed the HCO^+ ($v = 0, J = 4 \rightarrow 3$) line at 356.734242 GHz and the HCN ($v = 0, J = 4 \rightarrow 3$) line at 354.505473 GHz, at a velocity resolution of 0.21 km s^{-1} . In addition, we obtained dust continuum emission at 344.0 GHz. The weather conditions were average. Low altitude antennas did experience humidity while observing. The data were reduced and calibrated using the CASA (version 5.5.5-5) software (51). For each spectral window (corresponding to observation of the continuum, HCO^+ and HCN), the measurement of system noise temperature was performed in a spectral window in time division mode (TDM) with low-spectral resolution: 128 channels in a bandwidth of 2 GHz. The continuum was calibrated in its own spectral window but the windows for the lines were calibrated with others dedicated windows. We performed automatic flagging to remove outliers, incomplete data, or artificial lines due to systematic noise. During this procedure, we found that antenna DV07 measured only noise so we discarded its data. The phase calibration was done by measuring the amount of water towards quasars QSO B0539-057 and QSO B0507+179 using a sensor of the H_2O 183GHz line in each antenna. The calibrator for absolute flux was the quasar QSO B0507+179. Our observation was on December 10 2017 and the quasar was observed the day before (9 December 2017) with a flux value of $1.25 \pm 0.08 \text{ Jy}$ at 343.5 GHz. Following the calibration, the images were reconstructed. We used the GILDAS (Oct. 2019 version) software (52) to produce the Fourier space visibility tables, derive clean maps and subtract the local continuum around lines. The final beam size in these maps is $0.13'' \times 0.08''$ with a position angle of 123° with respect to the East-West axis.

JWST NIRCam

Observations with NIRCam (53) on the JWST (54) were obtained as part of the PDRs4All early release science (ERS) program (55) Sep. 10, 2022. The filters used in this paper are F140M, F164N, F187N, F121N, and F335M. We used the RAPID readout with 2 groups per integration, 2 integrations, and 4 dithers, providing a total on-source exposure time of 214.73s in each filter. These observations were reduced using the JWST pipeline version 1.7.1 (56) with calibration reference data system (CRDS) context file `jwst_0969.pmap`. No sky background emission was subtracted. The NIRCam images are diffraction limited and provide an angular resolution of $0.07''$ (28 au) at $2 \mu\text{m}$. More details on NIRCam data reduction are presented in (57).

JWST NIRSpec

Observations with the NIRSpec (58) integral field unit (IFU, (59)) were obtained as part of the PDRs4All Early Release Science program 1288 (55) on Sep. 10, 2022. The observations were processed with version 1.8.2 of the JWST pipeline (56). We used the F100LP, F170LP, and F290LP filters and the NRSRAPID readout pattern, with 5 groups, one integration and 4 dithers, yielding a total integration time of 257.68s for each filter. More details on the observations and data reduction are presented elsewhere (60). We then extracted a spectrum over the full wavelength range (1 to 5.2 μm) in two apertures; one corresponding to the d203-506 disk, the other to a position near the disk, providing an off-target reference. The disk spectrum was obtained with an elliptical aperture centered on coordinates: right ascension $\text{RA} = 5^{\text{h}}35^{\text{m}}20^{\text{s}}.357$, declination $\text{Dec} = -05^{\circ}25'05''.81$ (J2000 equinox), with dimension length $l = 0.52''$, height $h = 0.38''$ and a position angle $\text{PA}=33$ degrees East of North. This aperture is shown in Fig. 2. The off-target spectrum was obtained in a circular aperture of radius $r=0.365''$ centered on coordinates: $\text{RA} = 5^{\text{h}}35^{\text{m}}20^{\text{s}}.370$, $\text{Dec} = -5^{\circ}25'04''.97$.

Radiation field

d203-506 is situated in the Orion Bar, at an angular distance of $120''$ from the Trapezium cluster, corresponding to a projected distance of 0.25 pc, for a distance to the Orion Nebula of 414 pc (61). Θ^1 Ori C, the most massive star of the Trapezium cluster, is of spectral type O6 and is the dominant source of UV photons in the nebula. Using a synthetic O6 star spectrum from (62) and applying spherical dilution for a radius equal to the projected distance of 0.25 pc, we calculate an expected FUV radiation field $G_0 = 4 \times 10^4$ after normalization (41). This calculation adopts a definition (38) of FUV photons as those with energies between 5.17 and 13.60 eV. d203-506 is also situated $40''$ west of the B0-2 star Θ^2 Ori A, a projected distance of 0.08 pc. With the same approach, this yields $G_0=8 \times 10^4$ at the position of d203-506. These calculations assume that d203-506 and the massive stars are located at the same distance from us, any offset along the line of sight would reduce the FUV radiation field. We therefore set an upper limit for the radiation field received by d203-506 at $G_0 \leq 1.2 \times 10^5$.

The intensity of the atomic oxygen line at $1.3168 \mu\text{m}$ can also be used to estimate the radiation field (63). This method has been applied to the same NIRSpec observations as we use (60), which indicated the median radiation field at the position of the ionization front of the Orion Bar has an intensity $G_0=5.9 \times 10^4$. The observed average [O I] intensity at the position d203-506 is 40% of the value at the ionization front, indicating a radiation field $G_0=2.4 \times 10^4$. In the rest of the study we adopt $G_0=2 \times 10^4$.

Disk dimensions and mass

We derived the disk dimensions from the ALMA continuum emission (Fig. 2G), using the `imfit` task in CASA (51) with a single Gaussian component. This yields a major axis size

of 237.6 ± 3.4 milliarcseconds (mas), a minor axis size 129.8 ± 3.4 mas, and a disk position angle of 20.3 ± 1.3 degrees East of North. At a distance of 414 pc (61), this implies a physical radius $r_d^{\text{ALMA}} = 98 \pm 1$ au and a disk thickness $E_d^{\text{ALMA}} = 54 \pm 1$ au for the dust disk. We applied the same method to the NIRCам 1.4 μm (Fig. 2B) image, finding radius 234 ± 80 mas, so $r_d^{\text{NIRCам}} = 97 \pm 13$ au, and thickness 141 ± 80 mas, that is $E_d^{\text{NIRCам}} = 58 \pm 13$ au. We also use the HCN ($v = 0, J = 4 \rightarrow 3$) maps to derive the gas disk size, finding $r_g^{\text{ALMA}} = 124$ au. This value is ~ 1.26 times larger than for the dust derived radius, consistent with previous measurements that gas derived radii are ~ 1.4 times larger than those derived from dust (64). The central star is not visible, so we derive a lower limit for the disk inclination: $i \gtrsim 90 - \arctan(\frac{E_d}{2r_d})$, finding $i \gtrsim 75^\circ$. Dimensions of d203-506 extracted in this section are summarized in Table S1.

To derive the total mass of the disk, we adopt a previous method (65) so use ALMA 344 GHz continuum observations to derive the masses of disks in Orion. The mass of the disk is:

$$M_d = \frac{F_{\text{dust}} d^2}{k_\nu B_\nu(T_d)}, \quad (1)$$

where F_{dust} is the flux of dust emission at 344 GHz, d is the distance to Orion, k_ν is the dust grain opacity at 344 GHz for a gas-to-dust-mass-ratio of 100, B_ν is the Planck function, and T_d is the characteristic dust temperature. We measure $F_{\text{dust}} = 22.1$ mJy from our ALMA observations of the dust continuum emission (Fig. 2G) using the `imfit` task in CASA. Adopting $k_\nu = 0.034 \text{ cm}^2 \text{g}^{-1}$ (66), $T_d = 20 \text{ K}$ (65), and $d = 414$ pc yields $M_d = 11.8 M_{\text{Jup}}$, where $1 M_{\text{Jup}} = 1.87 \times 10^{27} \text{ kg}$ is the mass of Jupiter. This value is consistent with disk masses derived for other disks in Orion by (65). The derivation of disk masses using this approach is highly uncertain. First, the adopted value of k_ν is intrinsically uncertain; using an alternative opacity of $k_\nu = 0.058 \text{ cm}^2 \text{g}^{-1}$ from (67) yields $M_d = 6.9 M_{\text{Jup}}$. Second, Eq. 1 is applicable only in the case of optically thin emission at 344 GHz, and self absorption becomes an issue for fluxes above 100 mJy (68). The flux for d203-506 is 22 mJy so this effect might be negligible. The uncertainty on the mass derivation by this method has been estimated as ~ 0.2 dex (68). The value of T_d is also a source of uncertainty, however the choice of $T_d = 20 \text{ K}$ has been shown to minimize this (68). Incorporating the uncertainty associated with optical depth of 0.2 dex and on the value of k_ν (using the two values above), we find a range of masses $M_d = 4.4$ to $18.7 M_{\text{Jup}}$.

Stellar mass

To constrain the stellar mass, we use the gas kinematics as traced by the HCN ($v = 0, J = 4 \rightarrow 3$) emission observed with ALMA. Given the spatial resolution, and velocity dispersion (expected for a low mass star) we expect this method to provide only an upper limit on the stellar mass. Fig. S1 shows a position velocity diagram of the HCN ($v = 0, J = 4 \rightarrow 3$) emission and predicted velocities for stellar masses $M_\star = 0.1, 0.2, 0.3 M_\odot$. There is no high velocity emission that would imply $M_\star > 0.3 M_\odot$. We used the radiative transfer code RADMC-3D version 2.0 to simulate the d203-506 disk assuming the same values of the stellar mass (i.e. 0.1

$M_\odot$, $0.2 M_\odot$ and $0.3 M_\odot$). We assumed a viscous accretion disk following Keplerian rotation using the parameters listed in Table S1 (except mass) and a constant HCN abundance fraction of 10^{-8} with respect to H. The synthetic spectral cubes of the HCN ($v = 0, J = 4 \rightarrow 3$) line cubes were calculated with a 0.05 km/s channel-spacing, then resampled to a 0.1 km/s velocity resolution. The spatial axes were convolved with the synthesized beam from the ALMA observations. Fig. S2 compares the first moment map (velocity centroid) of the three synthetic spectral cubes and the observations. We find that for a stellar mass $> 0.3 M_\odot$, the Keplerian rotation velocities are faster than observed, consistent with the upper limit provided by the P-V diagram. We therefore set an upper limit of $M_\star < 0.3 M_\odot$.

H₂ emitting layer dimensions and surface area

Fig. S3 shows the NIRCам F212N image of d203-506, which traces emission in the H₂ ($v = 1 \rightarrow 2, J = 3 \rightarrow 1$) line.

The thickness of the H₂ emitting surface layer is spatially unresolved. We see limb brightening on the contour of the envelope with a thickness close to the beam size. With a spatial resolution of $0.07''$, this implies a maximum thickness $t_{\text{H}_2}^{\text{max}} = 2 \times 0.07 \times 414 \approx 60$ au for the H₂ emitting layer.

We modelled the observed emission H₂ emission ring in Fig. S3 by fitting an ellipse with $r_{\text{H}_2} = 132$ au and $h_{\text{H}_2} = 59$ au. For both dimensions, we estimate the uncertainty as one NIRCам pixel, 13 au in physical scale. To derive the surface area S of the H₂ emitting layer, we consider a spheroid :

$$S = 2\pi r_{\text{H}_2}^2 + \frac{\pi h_{\text{H}_2}^2}{e} \ln \frac{1+e}{1-e}, \quad (2)$$

where the ellipticity $e = \sqrt{1 - h_{\text{H}_2}^2 / r_{\text{H}_2}^2}$. The result is listed in Table S1.

Gas density and temperature in the PDR

We detect over 30 ro-vibrational lines of molecular hydrogen in the spectrum of d203-506. We extracted the intensities of these lines by subtracting a linear continuum and fitting Gaussian functions at wavelengths taken from a H₂ line list (69). We exclude lines for which there is an H I line closer than $10^{-3} \mu\text{m}$ in wavelength, to avoid contamination. We also exclude lines with an upper energy level above 2.15 eV to limit contamination from shock-excited gas. We only consider a line to be detected if it has an intensity $> 8 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The measured line intensities are listed in Table S2. To determine the physical conditions of the H₂ emitting gas, we fit them using the MEUDON PDR code (38) in a two step process.

First, we use the interstellar medium database (ISMDB) of pre-computed MEUDON PDR models (version 1.5.4 (70)), to determine the PDR parameters that best reproduce the H₂ emission lines. We assume standard Galactic extinction properties from (71), that is a reddening $R_V = 3.1$, and a ratio of the hydrogen column density (N_{H}) to extinction parameter $E(B - V)$,

$N_{\text{H}}/E(B - V) = 5.8 \times 10^{21} \text{ cm}^{-2}$. We consider constant density models with a maximum visual extinction $A_V = 10$. The choice of this parameter has little influence on the results, because most of the H_2 emission occurs at low A_V . The free parameters are the FUV radiation field intensity and the gas density n_{H} . Fig. S4 shows the discrepancy measure between these models and the observations computed for a range of values for these two parameters. The best fitting models have high radiation fields ($G_0 > 10^4$), consistent with values derived above via a different method. Fig. S4 shows that models with densities $n_{\text{H}} = 1 \times 10^5 \text{ cm}^{-3}$ to $\times 10^7 \text{ cm}^{-3}$ provide the best fit.

In a second step, we run specific PDR models. We use an updated version of the Meudon PDR code, with the addition of collisional deexcitation data for H_2 in excited vibrational states (72, 73). The source code used in this paper is available online (50). We fix the total $A_V = 10$ and intensity of the UV radiation field $G_0 = 2 \times 10^4$ as derived from the [O I] line intensity. We run models for 9 logarithmically-spaced gas density values spanning a smaller range of densities ($n_{\text{H}} \in [10^4, 10^8] \text{ cm}^{-3}$), corresponding to the range favored in the first step above with a one order of magnitude margin.

We run these models for two sets of extinction properties and grain size distributions. The first set, which we refer to as small grains, uses extinction properties typical of dense molecular gas in the Orion Bar (74) ($R_V = 5.5$, $N_{\text{H}}/E(B - V) = 1.05 \times 10^{22} \text{ cm}^{-2}$, the HD 38087 extinction curve (71), and a grain size distribution extending from 3 nm to 0.3 μm). The second set, which we refer to as large grains, uses larger grain sizes (grain size distribution extending from 20 nm to 1 μm , $R_V = 5.9$, $N_{\text{H}}/E(B - V) = 1.5 \times 10^{22} \text{ cm}^{-2}$).

We assume all H_2 emission lines are emitted in the same layer of the PDR and are all optically thin and account for possible geometrical effects (beam dilution of the emitting structure, or inclination of the PDR surface with respect to the line-of-sight) with a scaling parameter α (multiplying all observed line intensities) that is adjusted simultaneously with density during model fitting. To account for both calibration uncertainties and model uncertainties, we consider a multiplicative lognormal error of 50% on all line intensities and minimize the corresponding negative log-likelihood, then convert them to the corresponding reduced χ^2 .

Fig. S5 shows the χ^2 values of the models fitted to the observations, for both extinction settings. We find a bimodal distribution in both cases: one minimum of the χ^2 is found at densities $n_{\text{H}} = 1.5 \times 10^5 \text{ cm}^{-3}$, with $\chi^2 = 3.0$, for the molecular extinction models, and $n_{\text{H}} = 4.4 \times 10^5 \text{ cm}^{-3}$, with $\chi^2 = 2.1$, for the large grains models), and a second minimum at $n_{\text{H}} = 5.5 \times 10^6 \text{ cm}^{-3}$, with $\chi^2 = 3.4$, for the molecular extinction models, and $n_{\text{H}} = 7.2 \times 10^6 \text{ cm}^{-3}$, with $\chi^2 = 3.0$, for the large grains models. Both minima are consistent with the range of values determined from the grids discussed above. Fig. S5 also shows similar χ^2 values are found for density values between these two minima (although for lower scaling factor values), and for densities up to $\sim 10^7 \text{ cm}^{-3}$.

In these models, we define the emitting layer of the H_2 ($v = 1 \rightarrow 2, J = 3 \rightarrow 1$) line as the region in which the line integrated emissivity is 80% of the total intensity of the line and that has the same emissivity value at its left and right bounds. We measure the width of this emitting layer in each model; Fig. S6 shows an example. We find that the size constraint

from the observations (that the maximum thickness of the H_2 emitting layer is $t_{\text{H}_2}^{\text{max}} = 60$, see above) eliminates the lowest density solution for both model sets: it constrains the density to $n_{\text{H}} > 5.5 \times 10^5 \text{ cm}^{-3}$ for the molecular extinction models, and to $n_{\text{H}} > 9.8 \times 10^5 \text{ cm}^{-3}$ for the large grains models.

Combining these constraints for the molecular extinction case, our best fitting model has a gas density of $n_{\text{H}} = 5.5 \times 10^6 \text{ cm}^{-3}$ and a scaling factor of 0.8. Its H_2 emitting layer is 2.5 au wide, with an average temperature of $1.24 \times 10^3 \text{ K}$. For the “large grains” case, the best fitting model has a gas density of $n_{\text{H}} = 7.2 \times 10^6 \text{ cm}^{-3}$ and a scaling factor of 1.4. The H_2 emitting layer is 2.8 au wide, with an average temperature of $1.26 \times 10^3 \text{ K}$. Fig. 5 shows the H_2 line intensities predicted by these two best-fitting models compared to the observed intensities. As discussed above, models with similarly good χ^2 can be found over a range of density values: density values between the spatial scale constraint ($5.5 \times 10^5 \text{ cm}^{-3}$ for molecular extinction, $9.8 \times 10^5 \text{ cm}^{-3}$ for large grains) and $\sim 10^7 \text{ cm}^{-3}$ are found to be compatible with the observations. This implies that the overall acceptable range of densities is $n_{\text{H}} = 5.5 \times 10^5$ to $1.0 \times 10^7 \text{ cm}^{-3}$.

1D models of external photoevaporation

To assess the photoevaporation of the d203-506 disk, we compare our derived mass-loss rate to PDR-dynamics calculations of external photoevaporative winds using the TORUS-3DPDR code (75, 76). The code uses an operator splitting approach in which hydrodynamics and PDR/radiative transfer steps are performed iteratively. The reduced University of Manchester Institute of Science and Technology (UMIST) PDR network is used with 33 species and 330 reactions (77). The 1D models the flow structure is solved along a path from the mid-plane to the disk outer edge, then converted into a total mass-loss rate estimate (7). We set up models with the parameters expected for the d203-506 disk and external UV field as summarized in Table S1. We consider three values of the stellar mass, $M_{\star} = 0.1, 0.2, 0.3 M_{\odot}$ and a disk radius of 100 au. Since we do not have constraints on the dust size distribution for d203-506, we vary the effective UV absorption cross section of dust at a wavelength $\lambda = 0.1 \mu\text{m}$ σ_{UV} in from 10^{-23} cm^{-2} to 10^{-21} cm^{-2} . $\sigma_{\text{UV}} = 10^{-23} \text{ cm}^{-2}$ corresponds to dust which has evolved due to grain growth inside the disk (78), while $\sigma_{\text{UV}} = 10^{-21} \text{ cm}^{-2}$ corresponds to small dust grains which have not yet grown as found in the interstellar medium in the Orion Nebula (12). The mass-loss rate from these 1D models as a function σ_{UV} in the wind is shown in Fig. S7. The derived values range between $\dot{M} = 3.3 \times 10^{-8}$ and $\dot{M} = 1.1 \times 10^{-6} M_{\odot}\text{yr}^{-1}$, a range that overlaps the mass-loss rates we derived from the observations.

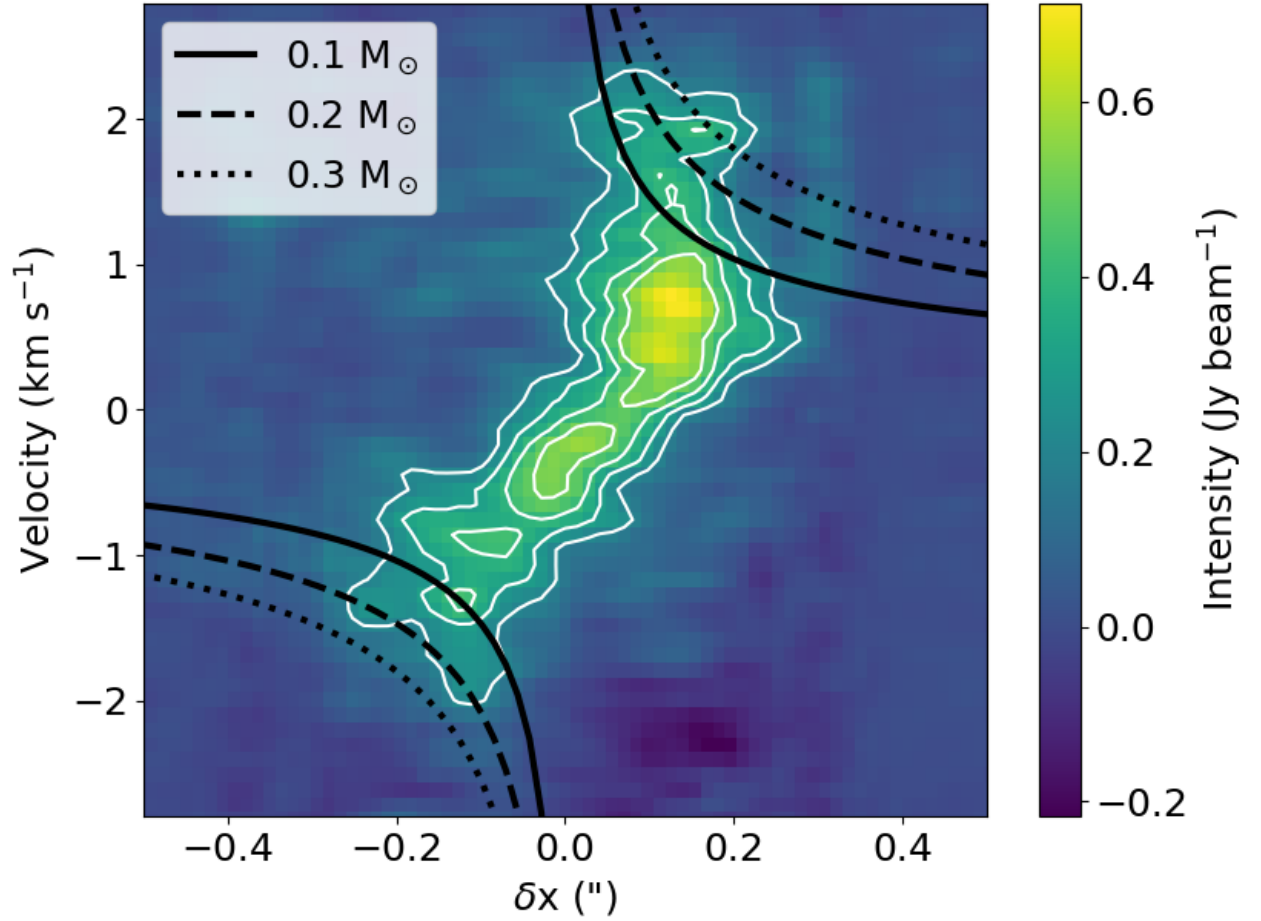


Figure S1: Position velocity (PV) diagram of d203-506 along the direction of the disk plane. δx is the angular scale along this axis, with $\delta x = 0$ corresponding to the position of the central star. The black thick curves indicate Keplerian orbital velocities for $M_{\star} = 0.1, 0.2, 0.3 M_{\odot}$. The white contours correspond to intensities from 0.2 to 0.5 Jy beam⁻¹ in steps of 0.1 Jy beam⁻¹. Most of the observed emission ends close to the $0.2 M_{\odot}$ curve.

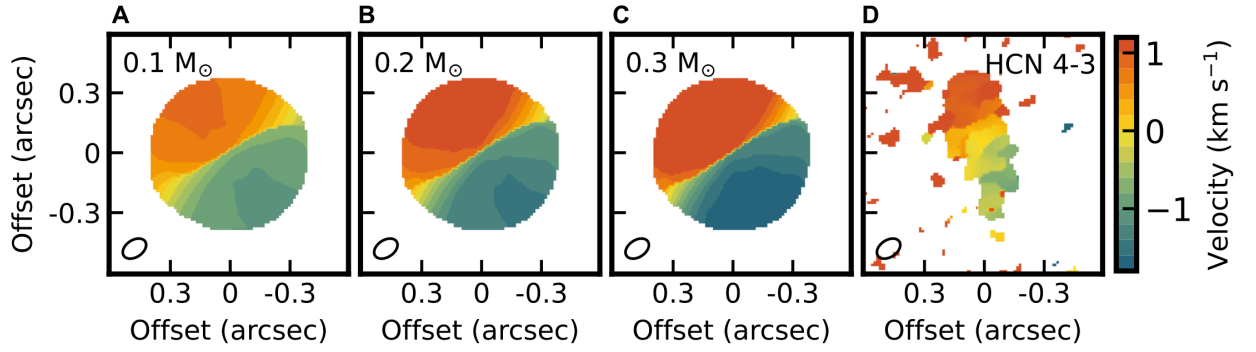


Figure S2: Comparison between modelled and observed velocity fields in d203-506. The panels show the first moment maps from radiative transfer models of the HCN ($v = 0, J = 4 \rightarrow 3$) emission of d203-506 assuming $M_{\star} = 0.1 M_{\odot}$ (**A**), $M_{\star} = 0.2 M_{\odot}$ (**B**), $M_{\star} = 0.3 M_{\odot}$ (**C**), compared to ALMA observations (**D**). The offset in the X and Y axis is given in arcseconds with respect to the position of the central star. The ellipse shows the reconstructed beam of the telescope.

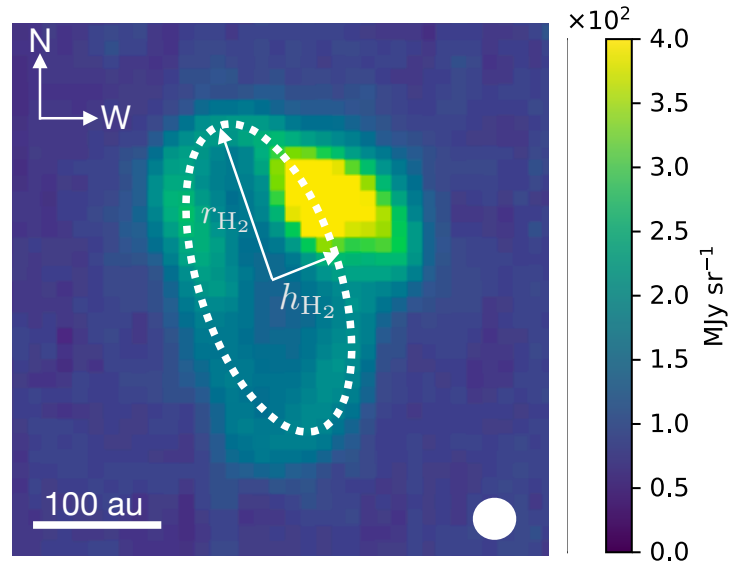


Figure S3: **Image of d203-506 in the NIRCам F212N filter tracing the emission of the H_2 ($v = 1 \rightarrow 2, J = 3 \rightarrow 1$) line at $2.12 \mu\text{m}$.** The horizontal scale bar is 100 au. The white circle indicates the size of the JWST PSF. The dashed white line shows the elliptical model fitted to the data. The white arrows indicate its major and minor axes. North and West directions are indicated in the upper left corner. The image is centered at coordinates $\text{RA} = 5^{\text{h}}35^{\text{m}}20^{\text{s}}.357$ and $\text{Dec} = -5^{\circ}25'05''.81$.

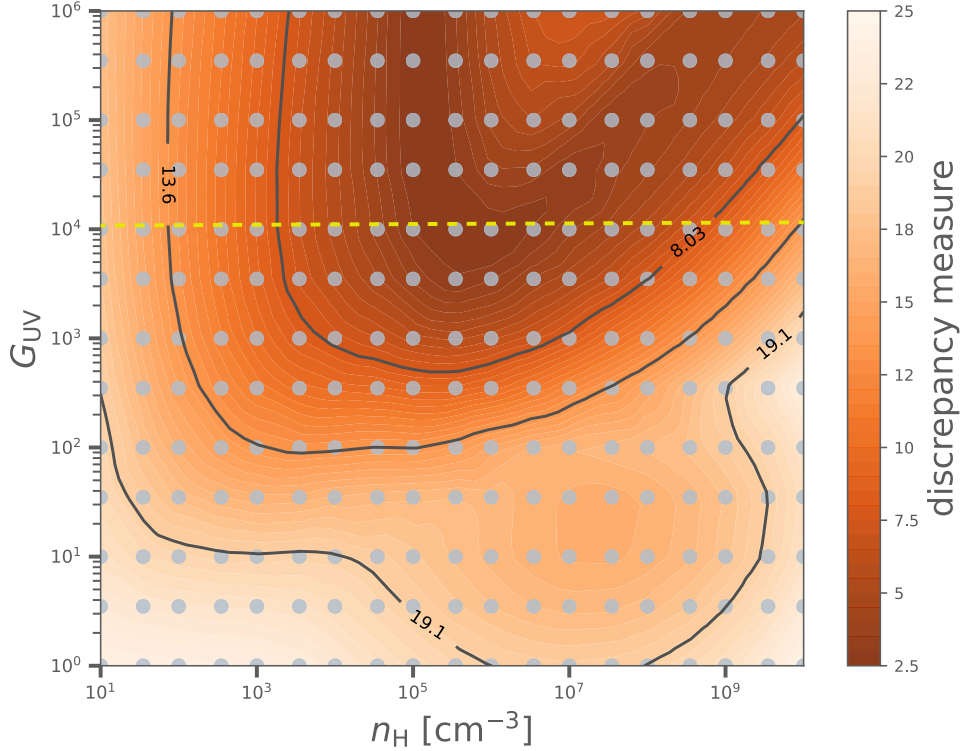


Figure S4: Results from the PDR model fitting to the H_2 ro-vibrational lines. The map shows a measure of discrepancy (sum of squared distances to the closest bound of the uncertainty intervals for each observed line, in logarithm) for a grid of different UV radiation field strength (G_{UV} in units of the Mathis ISRF field, that is 1.56 times the Habing field, $G_{\text{UV}} = 1.56 G_0$), and gas density (n_{H}). Grey circles indicate the models in the grid, while the contours and color map are computed by interpolation. The adopted value for the intensity of the radiation field for d203-506 (35), $G_0 = 2 \times 10^4$ corresponding to $G_{\text{UV}} = 1.28 \times 10^4$ is shown by the yellow horizontal dashed line. For this value of the intensity of FUV radiation, models with densities in the range $n_{\text{H}} = 10^5 - 10^7 \text{ cm}^{-3}$ provide the lowest values of the discrepancy measure.

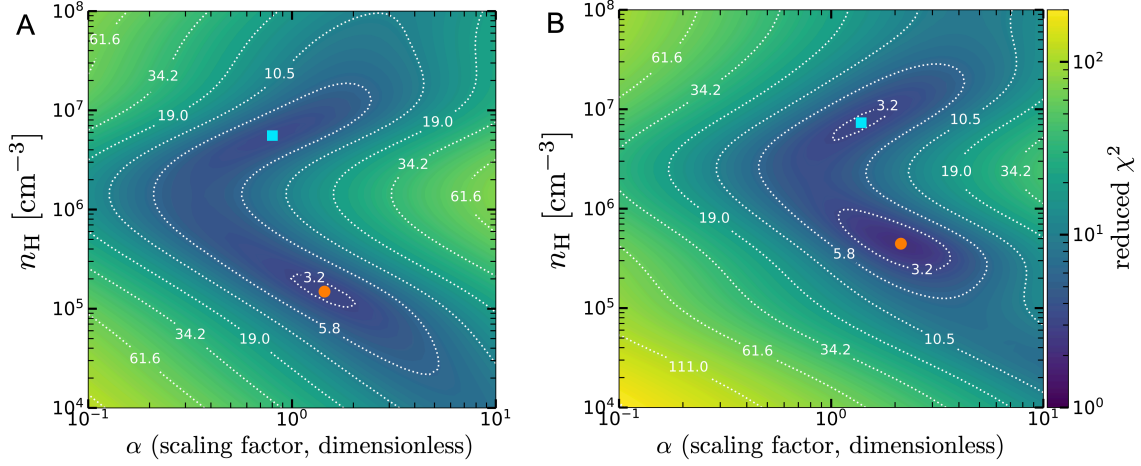


Figure S5: Deviation between observed and modelled H_2 emission intensities. Reduced χ^2 map, for a grid of values of the gas density n_H and scaling factor α used in the Meudon PDR models, using small grains (A) and large grains (B) in the model. Both panels show a clear bimodal distribution, the orange circle indicates the position of minimum in the low density mode and the blue square the position of the minimum of the high density mode.

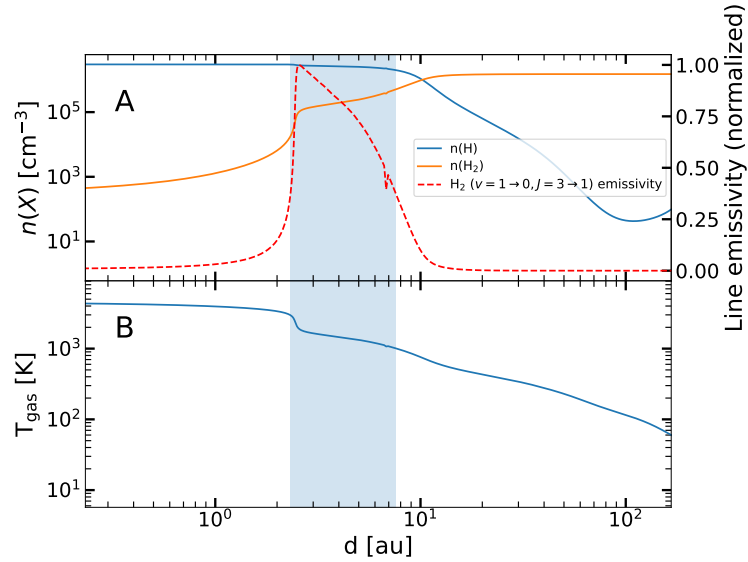


Figure S6: Spatial structure of a Meudon PDR model (using the small grains setup) for $n_H = 3 \times 10^6 \text{ cm}^{-3}$. The UV illumination ($G_0 = 2 \times 10^4$) is from the left side of this plot. Panel (A) shows the densities of H (blue) and H_2 (orange), both on the left axis. The emissivity of the $(v=1 \leftarrow 0, J=3 \leftarrow 1)$ line is shown with the red dashed line (right axis). Panel (B) shows the gas temperature profile. The blue shaded area shows the H_2 emitting layer as defined in the text.

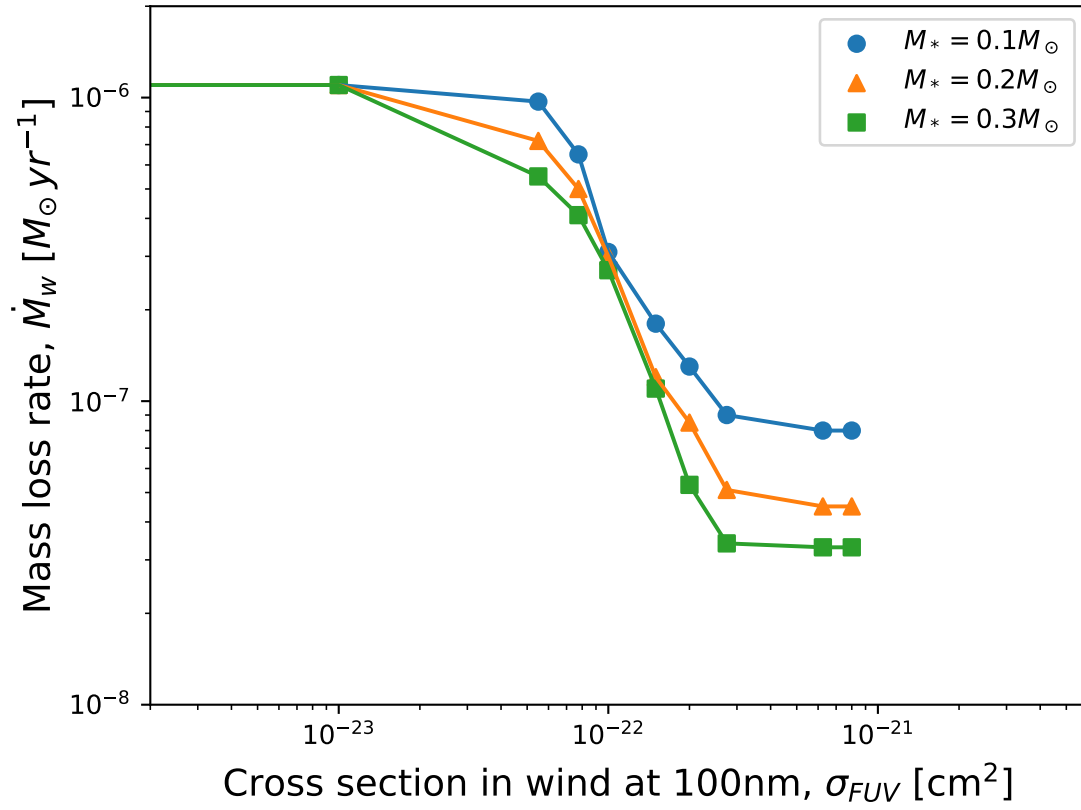


Figure S7: Mass-loss rates from 1D TORUS-3DPDR external photoevaporation calculations as a function of the effective grain cross section in the wind. The different sets of lines/points correspond to different masses of the central star that the disk orbits.

Table S1: **Derived physical properties of d203-506**

Parameter	Notation	Value	Method or reference
Distance	d	414 ± 7 pc	(61)
Disk radius (dust emission)	r_d^{ALMA}	98 ± 1 au	Dust emission (ALMA)
Disk radius (dust absorption)	r_d^{NIRCam}	97 ± 13 au	Dust absorption (NIRCam)
Disk radius (HCN emission)	r_g^{ALMA}	124 ± 3 au	HCN emission (ALMA)
Disk thickness (dust emission)	E_d^{ALMA}	54 ± 1 au	Dust emission (ALMA)
Disk thickness (dust absorption)	E_d^{NIRCam}	58 ± 13 au	Dust absorption (NIRCam)
Radius of H ₂ emitting layer	r_{H_2}	127 ± 13 au	H ₂ ($v = 2 \rightarrow 1, J = 3 \rightarrow 1$) (NIRCam)
Height of H ₂ emitting layer	h_{H_2}	56 ± 13 au	H ₂ ($v = 2 \rightarrow 1, J = 3 \rightarrow 1$) (NIRCam)
Max. thickness of the H ₂ emitting layer	$t_{\text{H}_2}^{\text{max}}$	60 ± 13 au	H ₂ ($v = 2 \rightarrow 1, J = 3 \rightarrow 1$)
Disk inclination	i	$\gtrsim 75^\circ$	Dust absorption (NIRCam)
Disk mass	M_d	4.4 to 18.7 Jupiter mass (M_{Jup})	Dust emission (ALMA)
Stellar mass	$M_\star$	$< 0.3 M_\odot$	HCN ($J = 4 \rightarrow 3$) emission (ALMA)
Ambient radiation field	G_0	2.4×10^4	[O I] line emission (NIRSpec)
Gas temperature (PDR)	T_{gas}	1240 to 1260 K	H ₂ rovib. lines (NIRSpec)
Gas density (PDR)	n_{H}	5.5×10^5 to $1.0 \times 10^7 \text{ cm}^{-3}$	H ₂ rovib. lines (NIRSpec)
Surface of H ₂ emitting layer	S	$1.3 \pm 0.4 \times 10^5 \text{ au}^2$	H ₂ ($v = 2 \rightarrow 1, J = 3 \rightarrow 1$)(NIRCam)
Mass-loss rate	$\dot{M}$	1.4×10^{-7} to $4.6 \times 10^{-6} M_\odot/\text{yr}$	(35)

Table S2: **Detected H₂ lines towards the PDR in d203-506.** Rest wavelengths are from (69).

Line (quantum levels)	Transition (abbreviation)	Rest wavelength (μm)	Intensity ($\text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$)	Uncertainty (1σ) ($\text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$)
$(v = 0, J = 10 \rightarrow 8)$	0-0 S(8)	5.0531	9.24×10^{-5}	1.19×10^{-7}
$(v = 0, J = 11 \rightarrow 9)$	0-0 S(9)	4.6946	1.51×10^{-4}	4.59×10^{-8}
$(v = 0, J = 12 \rightarrow 10)$	0-0 S(10)	4.4097	2.73×10^{-5}	1.63×10^{-7}
$(v = 0, J = 13 \rightarrow 11)$	0-0 S(11)	4.1810	3.83×10^{-5}	3.49×10^{-8}
$(v = 0, J = 15 \rightarrow 13)$	0-0 S(13)	3.8461	1.88×10^{-5}	2.05×10^{-8}
$(v = 0, J = 17 \rightarrow 15)$	0-0 S(15)	3.6261	8.66×10^{-6}	2.69×10^{-8}
$(v = 1 \rightarrow 0, J = 1 \rightarrow 3)$	1-0 O(3)	2.8025	1.28×10^{-3}	1.16×10^{-6}
$(v = 1 \rightarrow 0, J = 2 \rightarrow 4)$	1-0 O(4)	3.0038	2.00×10^{-4}	3.63×10^{-8}
$(v = 1 \rightarrow 0, J = 2 \rightarrow 0)$	1-0 S(0)	2.2232	3.21×10^{-4}	1.32×10^{-6}
$(v = 1 \rightarrow 0, J = 3 \rightarrow 5)$	1-0 O(5)	3.2349	3.58×10^{-4}	1.57×10^{-7}
$(v = 1 \rightarrow 0, J = 3 \rightarrow 1)$	1-0 S(1)	2.1218	1.06×10^{-3}	1.87×10^{-6}
$(v = 1 \rightarrow 0, J = 4 \rightarrow 6)$	1-0 O(6)	3.5008	3.61×10^{-5}	7.48×10^{-9}
$(v = 1 \rightarrow 0, J = 4 \rightarrow 2)$	1-0 S(2)	2.0337	2.84×10^{-4}	1.75×10^{-6}
$(v = 1 \rightarrow 0, J = 5 \rightarrow 7)$	1-0 O(7)	3.8074	7.47×10^{-5}	3.89×10^{-9}
$(v = 1 \rightarrow 0, J = 5)$	1-0 Q(5)	2.4547	1.78×10^{-4}	1.47×10^{-6}
$(v = 1 \rightarrow 0, J = 5 \rightarrow 3)$	1-0 S(3)	1.9575	5.69×10^{-4}	2.79×10^{-6}
$(v = 1 \rightarrow 0, J = 6)$	1-0 Q(6)	2.4755	5.16×10^{-5}	6.69×10^{-7}
$(v = 1 \rightarrow 0, J = 6 \rightarrow 4)$	1-0 S(4)	1.8919	7.21×10^{-5}	1.16×10^{-6}
$(v = 1 \rightarrow 0, J = 7 \rightarrow 5)$	1-0 S(5)	1.8357	1.56×10^{-4}	3.15×10^{-6}
$(v = 1 \rightarrow 0, J = 8)$	1-0 Q(8)	2.5280	1.40×10^{-5}	1.02×10^{-6}
$(v = 1 \rightarrow 0, J = 8 \rightarrow 6)$	1-0 S(6)	1.7880	2.78×10^{-5}	3.29×10^{-6}
$(v = 1 \rightarrow 0, J = 9 \rightarrow 7)$	1-0 S(7)	1.7479	1.18×10^{-5}	5.68×10^{-7}
$(v = 1 \rightarrow 0, J = 12 \rightarrow 10)$	1-0 S(10)	1.6664	1.93×10^{-5}	2.17×10^{-6}
$(v = 2 \rightarrow 0, J = 0 \rightarrow 2)$	2-0 O(2)	1.2932	1.97×10^{-5}	3.05×10^{-6}
$(v = 2 \rightarrow 1, J = 0 \rightarrow 2)$	2-1 O(2)	2.7861	2.77×10^{-5}	5.09×10^{-7}
$(v = 2 \rightarrow 0, J = 1 \rightarrow 3)$	2-0 O(3)	1.3354	2.21×10^{-5}	3.17×10^{-6}
$(v = 2 \rightarrow 0, J = 1)$	2-0 Q(1)	1.2383	2.74×10^{-5}	1.50×10^{-6}
$(v = 2 \rightarrow 1, J = 1 \rightarrow 3)$	2-1 O(3)	2.9740	2.84×10^{-5}	1.98×10^{-7}
$(v = 2 \rightarrow 1, J = 1)$	2-1 Q(1)	2.5509	4.39×10^{-5}	6.45×10^{-7}
$(v = 2 \rightarrow 0, J = 2 \rightarrow 0)$	2-0 S(0)	1.1895	1.47×10^{-5}	3.12×10^{-6}
$(v = 2 \rightarrow 1, J = 2 \rightarrow 4)$	2-1 O(4)	3.1898	8.57×10^{-6}	1.45×10^{-7}
$(v = 2 \rightarrow 1, J = 3 \rightarrow 5)$	2-1 O(5)	3.4378	9.89×10^{-6}	2.31×10^{-8}
$(v = 2 \rightarrow 1, J = 3)$	2-1 Q(3)	2.5698	1.41×10^{-5}	5.04×10^{-7}
$(v = 2 \rightarrow 1, J = 3 \rightarrow 1)$	2-1 S(1)	2.2477	2.59×10^{-5}	7.90×10^{-7}
$(v = 2 \rightarrow 1, J = 5 \rightarrow 3)$	2-1 S(3)	2.0734	2.16×10^{-5}	1.97×10^{-6}
$(v = 2 \rightarrow 0, J = 7 \rightarrow 5)$	2-0 S(5)	1.0851	1.19×10^{-5}	1.87×10^{-6}
$(v = 2 \rightarrow 0, J = 8 \rightarrow 6)$	2-0 S(6)	1.0732	2.20×10^{-5}	2.59×10^{-6}
$(v = 2 \rightarrow 1, J = 9 \rightarrow 7)$	2-1 S(7)	1.8528	2.02×10^{-5}	2.89×10^{-6}
$(v = 3 \rightarrow 2, J = 3 \rightarrow 5)$	3-2 Q(5)	2.7692	9.40×10^{-6}	3.25×10^{-7}