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

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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 Millimetre 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  $\text{H}_2$ , O and  $\text{C}^+$ ) 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,  $1 \text{ pc} = 3,086 \times 10^{16}$  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  $T \sim 500$ -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  $\sim 40$  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<sup>+</sup> at a velocity resolution of 0.2 km s<sup>-1</sup> (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  $\mu\text{m}$ ) 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  $\lambda = 845.664 \mu\text{m}$ , Fig. 2H), which traces cold molecular gas. ALMA HCO<sup>+</sup> ( $v = 0, J = 4 \rightarrow 3$ ) at 356.734 GHz ( $\lambda = 840.381 \mu\text{m}$ ) and NIRCam H<sub>2</sub> ( $v = 1 \rightarrow 0, J = 3 \rightarrow 1$ ) at 2.12  $\mu\text{m}$  emission maps (Figs. 2I and 2E, respectively) trace emission from the PDR surrounding the disk and absorption in the center. Both H<sub>2</sub> ro-vibrational and HCO<sup>+</sup> rotational emission lines trace warm (gas kinetic temperatures  $T_{\text{gas}} = 500\text{-}1000$  K) molecular gas in PDRs (31). The PDR is also bright in the 3.35  $\mu\text{m}$  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  $\mu\text{m}$  (Fig. 2C). A bright emission spot is present in the H<sub>2</sub> and HCO<sup>+</sup> images in the northwestern part of the PDR. This spot is also visible in the broad-band filter at 1.4  $\mu\text{m}$  (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  $\mu\text{m}$  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<sup>+</sup> ( $v = 1 \rightarrow 0$ ) and H<sub>2</sub> (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 H<sub>2</sub> lines using the MEUDON PDR code (38), which calculates the H<sub>2</sub> excitation in PDRs (Fig. 5). We derive the Hydrogen number density  $n_H$  and temperature of the gas in the H<sub>2</sub> 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  $M_* < 0.3 M_\odot$  (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  $\mu$  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)  $r_g \equiv \frac{G M_*}{c_S^2}$ . For  $M_* < 0.3 M_\odot$ , and  $T_{\text{gas}} = 1250$  K,  $r_g < 26$  au. This is much smaller than the observed radial extent of the H<sub>2</sub> 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 H<sub>2</sub> emitting layer (35). Including the uncertainties on  $r_{\text{H}_2}$ ,  $h_{\text{H}_2}$ ,  $n_H$ , and  $T_{\text{gas}}$  (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.

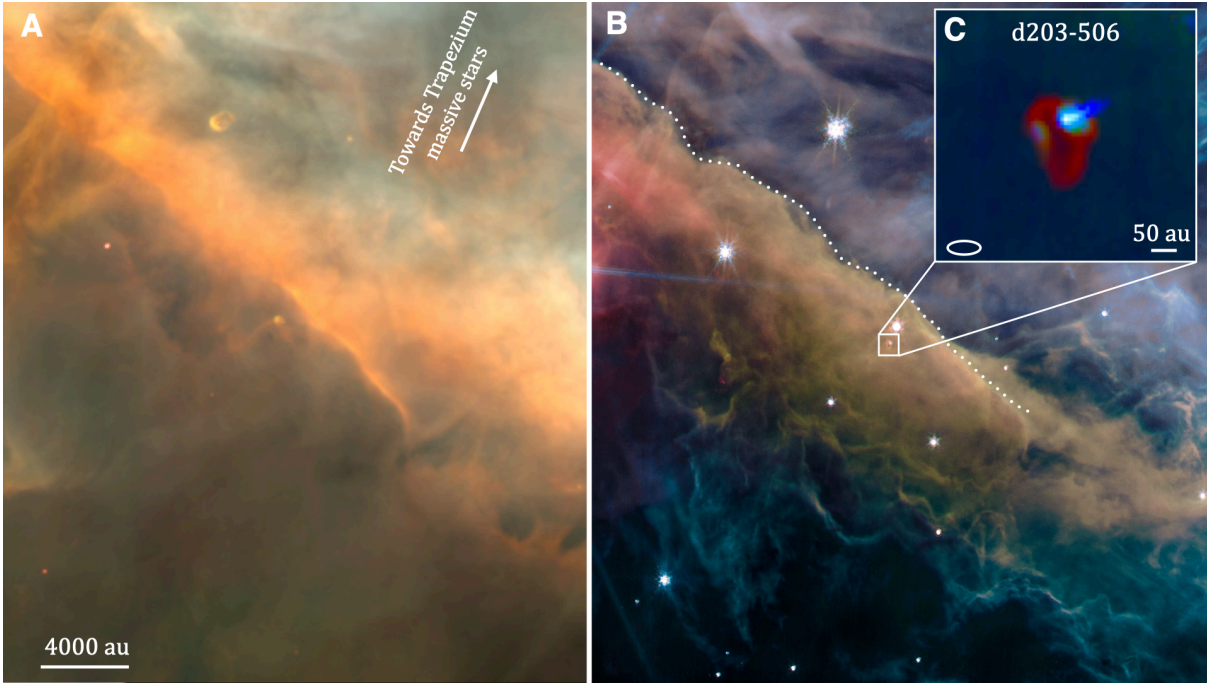


Figure 1: **Optical and near-infrared images of the Orion Bar region** (A) Hubble space telescope optical image. In blue is [OIII] at 502 nm, green  $H\alpha$  at 656 nm and red [NII] at 658 nm. (B) JWST near-infrared image of the same region at the same scale. Filters centered at 1.4 and 2.0  $\mu\text{m}$  are in blue; at 2.77, 3.00, 3.23, 3.35 and 3.32  $\mu\text{m}$  in green; 4.05  $\mu\text{m}$  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  $\mu\text{m}$  filter, tracing molecular hydrogen, blue is the 1.64  $\mu\text{m}$  filter tracing the emission of [FeII], and green is the emission in the 1.40  $\mu\text{m}$  broad-band filter that traces scattered light. Panel (A) credits : NASA/STScI/Rice Univ./C.O'Dell et al (47).

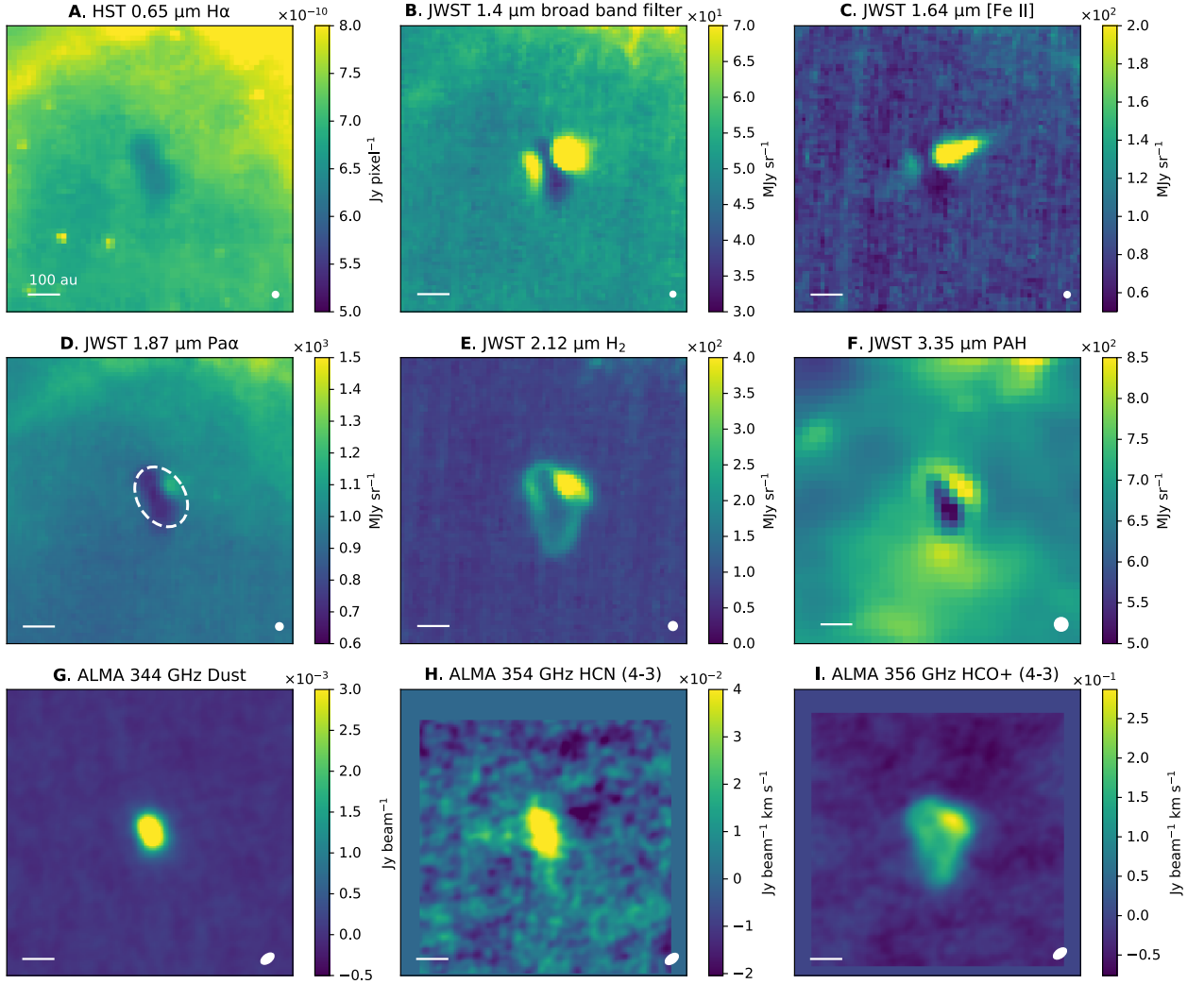


Figure 2: **Multi-wavelength images of the d203-506 disk.** (A) Optical image from HST (23), in a  $H\alpha$  filter. (B-F) Near-infrared images from JWST (35). Panel E is reproduced from (33) with permission. (G-I) Sub-millimetre images from ALMA (35). In all panels the white filled ellipse indicates 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.  $1 \text{ Jy} = 1 \times 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ .

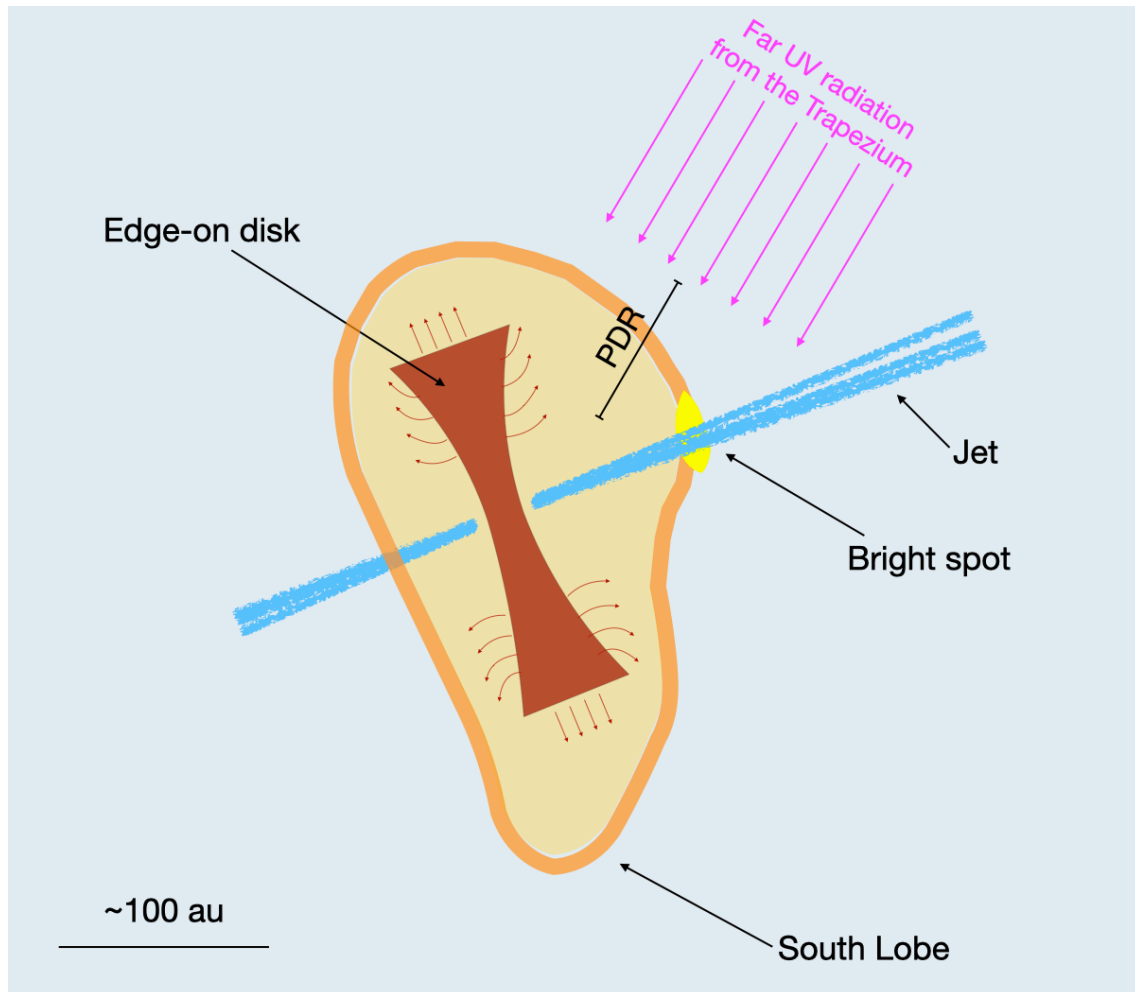


Figure 3: **Schematic diagram of our interpretation of d203-506.** The edge-on disk consisting of cold molecular gas, corresponding to absorption in the NIRcam images and HCN and dust emission in ALMA images (Fig. 2), is shown in dark brown. Molecular gas escapes from this disk (brown arrows), feeding 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.

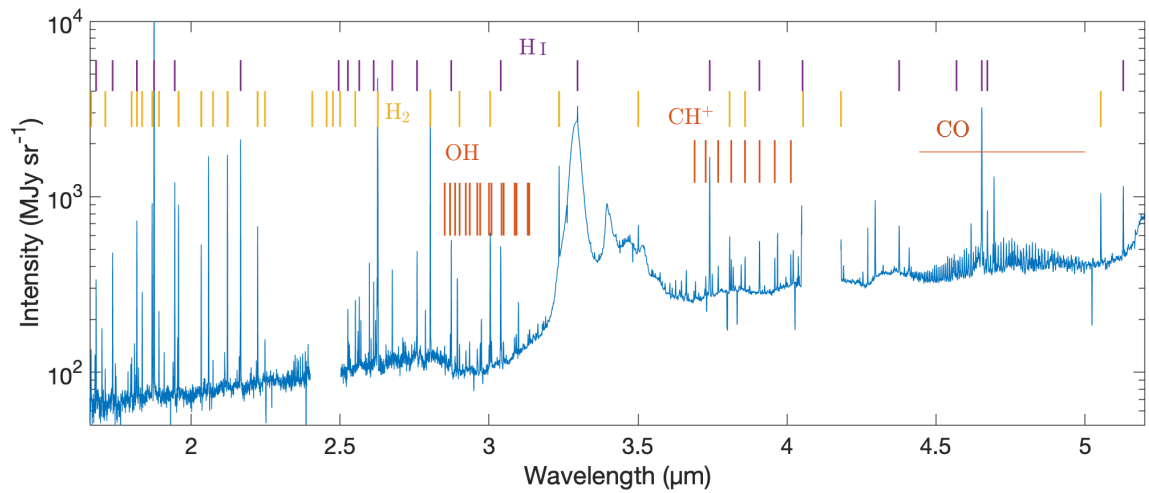


Figure 4: **JWST NIRSpec spectrum of d203-506.** Wavelength positions of the detected species are indicated. The broad emission bands at 3.3 and 3.4  $\mu\text{m}$  are from the C-H vibrational emission of polycyclic aromatic hydrocarbon (PAH) molecules. Unlabeled lines are, in most cases, atomic lines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

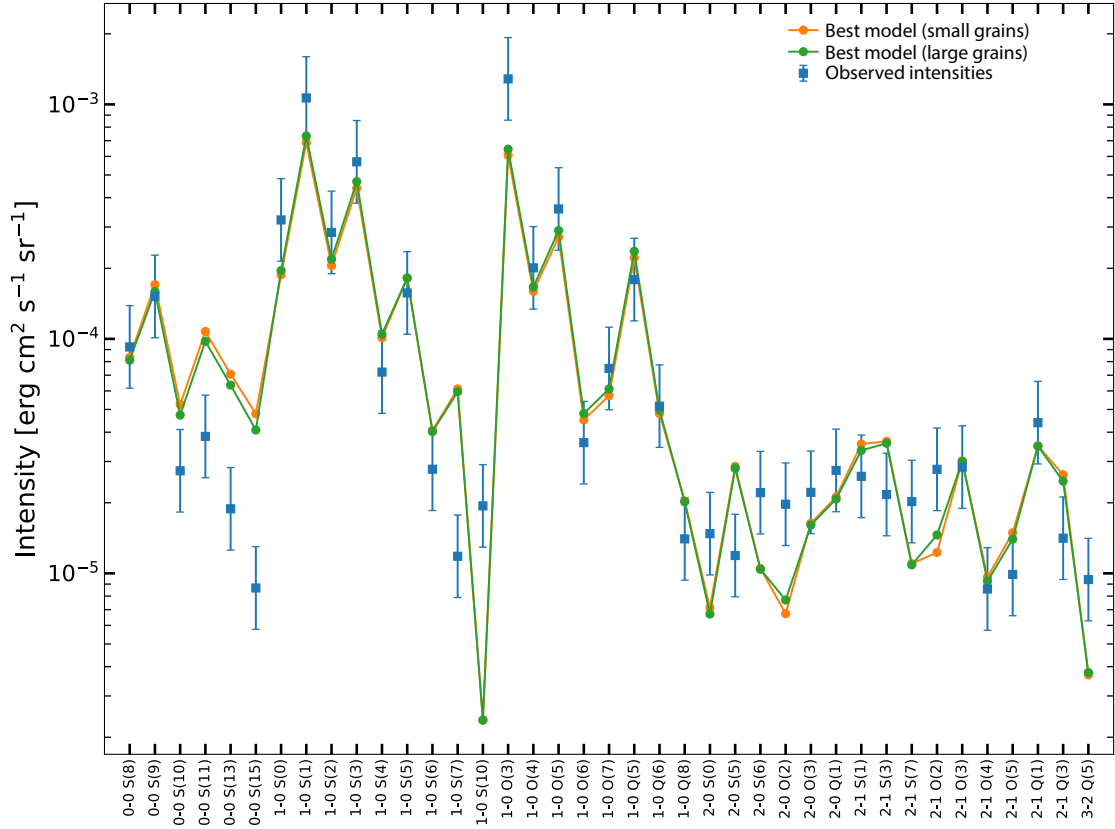


Figure 5: **Comparison of the observed and modeled  $H_2$  line intensities for d203-506.** Observed intensities are the blue squares, the associated error bars represent a total uncertainty of 50%, as considered in the estimate of the  $\chi^2$  (35). The instrumental uncertainties are smaller than 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.

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**Supplementary materials:**

PDRs4All Team authors and affiliations

Materials and Methods

Figures S1 to S7

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References

## Supplementary Materials for

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

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# 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<sup>+</sup> ( $v = 0, J = 4 \rightarrow 3$ ) 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<sup>-1</sup>. 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<sup>+</sup> 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<sub>2</sub>O 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  $1.25 \pm 0.08$  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  $123^\circ$  with respect to the East-West axis.

### JWST NIRCcam

Observations with NIRCcam (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 `rwst_0969.pmap`. No sky background emission was subtracted. The NIRCcam images are diffraction limited and provide an angular resolution of  $0.07''$  (28 au) at 2  $\mu$ m. More details on NIRCcam 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  $\mu\text{m}$ ) 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).  $\Theta^1$  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  $\Theta^2$  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  $237.6 \pm 3.4$  milliarcseconds (mas), a minor axis size  $129.8 \pm 3.4$  mas, and a disk position angle of  $20.3 \pm 1.3$  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  $\mu\text{m}$  (Fig. 2B) image, finding radius  $234 \pm 80$  mas, so  $r_d^{\text{NIRCам}} = 97 \pm 13$  au, and thickness  $141 \pm 80$  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  $\sim 1.26$  times larger than for the dust derived radius, consistent with previous measurements that gas derived radii are  $\sim 1.4$  times larger than those derived from dust (64). The central star is not visible, so we derive a lower limit for the disk inclination:  $i \gtrsim 90 - \arctan\left(\frac{E_d}{2r_d}\right)$ , 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  $F_{\text{dust}}$  is the flux of dust emission at 344 GHz,  $d$  is the distance to Orion,  $k_\nu$  is the dust grain opacity at 344 GHz for a gas-to-dust-mass-ratio of 100,  $B_\nu$  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  $1 M_{\text{Jup}} = 1.87 \times 10^{27}$  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  $k_\nu$  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  $\sim 0.2$  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  $k_\nu$  (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  $M_{\star} < 0.3 M_{\odot}$ .

## H<sub>2</sub> emitting layer dimensions and surface area

Fig. S3 shows the NIRCcam F212N image of d203-506, which traces emission in the H<sub>2</sub> ( $v = 1 \rightarrow 2, J = 3 \rightarrow 1$ ) line.

The thickness of the H<sub>2</sub> 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 H<sub>2</sub> emitting layer.

We modelled the observed emission H<sub>2</sub> 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 NIRCcam pixel, 13 au in physical scale. To derive the surface area  $S$  of the H<sub>2</sub> 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 H<sub>2</sub> 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 H<sub>2</sub> 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 H<sub>2</sub> 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 ( $N_{\text{H}}$ ) 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  $\text{H}_2$  emission occurs at low  $A_V$ . The free parameters are the FUV radiation field intensity and the gas density  $n_{\text{H}}$ . 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  $\text{H}_2$  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  $\mu\text{m}$ ). The second set, which we refer to as large grains, uses larger grain sizes (grain size distribution extending from 20 nm to 1  $\mu\text{m}$ ,  $R_V = 5.9$ ,  $N_{\text{H}}/E(B - V) = 1.5 \times 10^{22} \text{ cm}^{-2}$ ).

We assume all  $\text{H}_2$  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  $\alpha$  (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  $\chi^2$ .

Fig. **S5** shows the  $\chi^2$  values of the models fitted to the observations, for both extinction settings. We find a bimodal distribution in both cases: one minimum of the  $\chi^2$  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  $\chi^2$  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  $\text{H}_2$  ( $v = 1 \rightarrow 2, J = 3 \rightarrow 1$ ) 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emitting layer is 2.8 au wide, with an average temperature of  $1.26 \times 10^3 \text{ K}$ . Fig. 5 shows the H<sub>2</sub> line intensities predicted by these two best-fitting models compared to the observed intensities. As discussed above, models with similarly good  $\chi^2$  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  $\lambda = 0.1 \mu\text{m}$   $\sigma_{\text{UV}}$  in from  $10^{-23} \text{ cm}^{-2}$  to  $10^{-21} \text{ cm}^{-2}$ .  $\sigma_{\text{UV}} = 10^{-23} \text{ cm}^{-2}$  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  $\sigma_{\text{UV}}$  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.

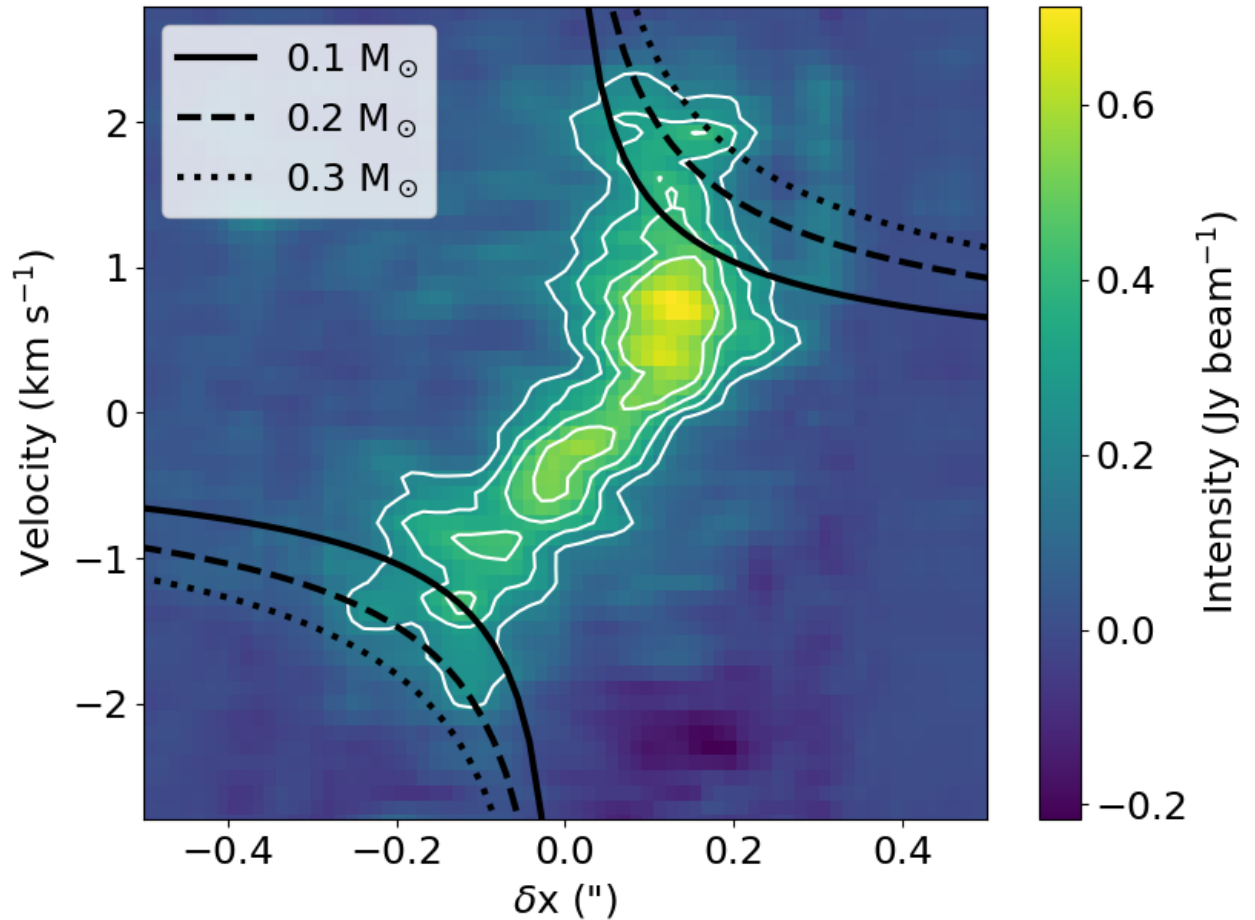


Figure S1: **Position velocity (PV) diagram of d203-506 along the direction of the disk plane.**  $\delta x$  is the angular scale along this axis, with  $\delta x = 0$  corresponding to the position of the central star. The black thick curves indicate Keplerian orbital velocities for  $M_{\star} = 0.1,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

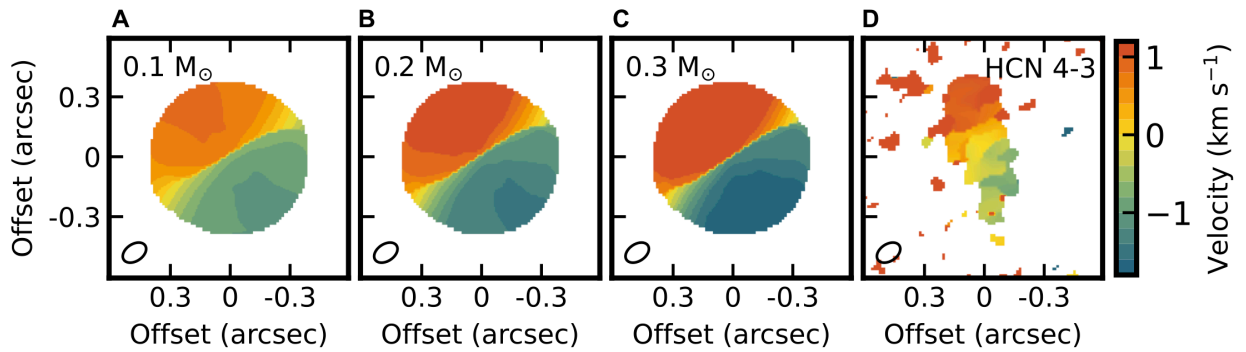


Figure S2: **Comparison between modelled and observed velocity fields in d203-506.** The panels show the first moment maps from radiative transfer models of the HCN ( $v = 0, J = 4 \rightarrow 3$ ) emission of d203-506 assuming  $M_{\star} = 0.1 M_{\odot}$  (**A**),  $M_{\star} = 0.2 M_{\odot}$  (**B**),  $M_{\star} = 0.3 M_{\odot}$  (**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.

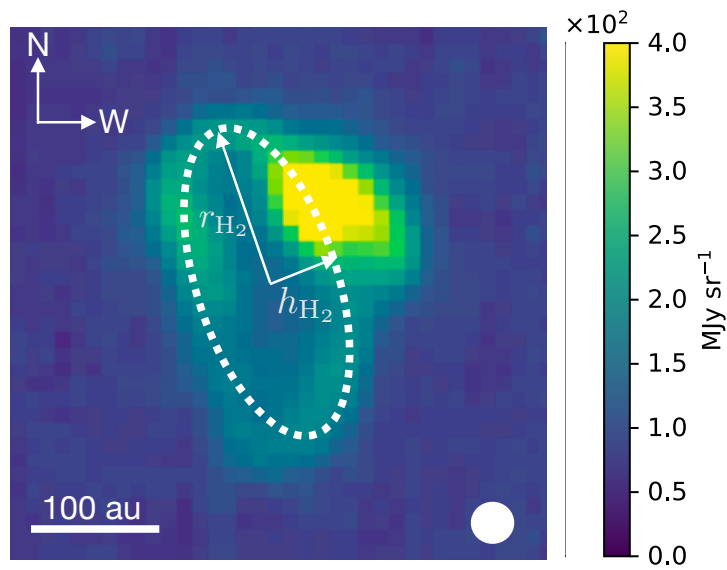
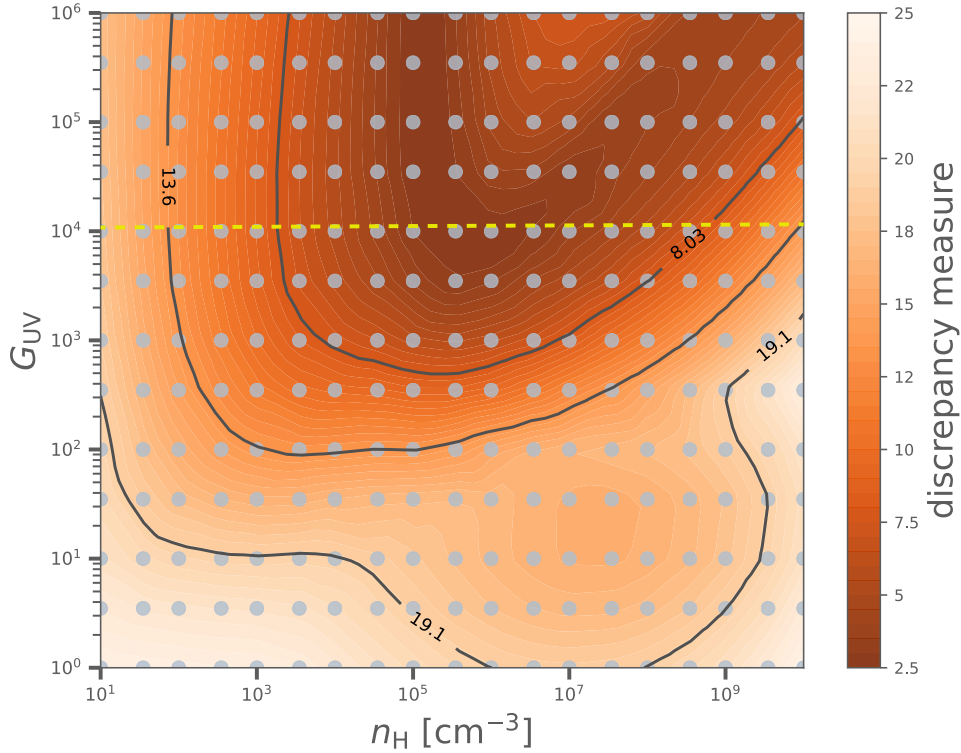


Figure S3: **Image of d203-506 in the NIRCcam F212N filter tracing the emission of the  $\text{H}_2$  ( $v = 1 \rightarrow 2, J = 3 \rightarrow 1$ ) line at  $2.12 \mu\text{m}$ .** The horizontal scale bar is 100 au. The white circle indicates the size of the JWST PSF. The dashed white line shows the 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  $\text{H}_2$  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 ( $G_{\text{UV}}$  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 ( $n_{\text{H}}$ ). 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.

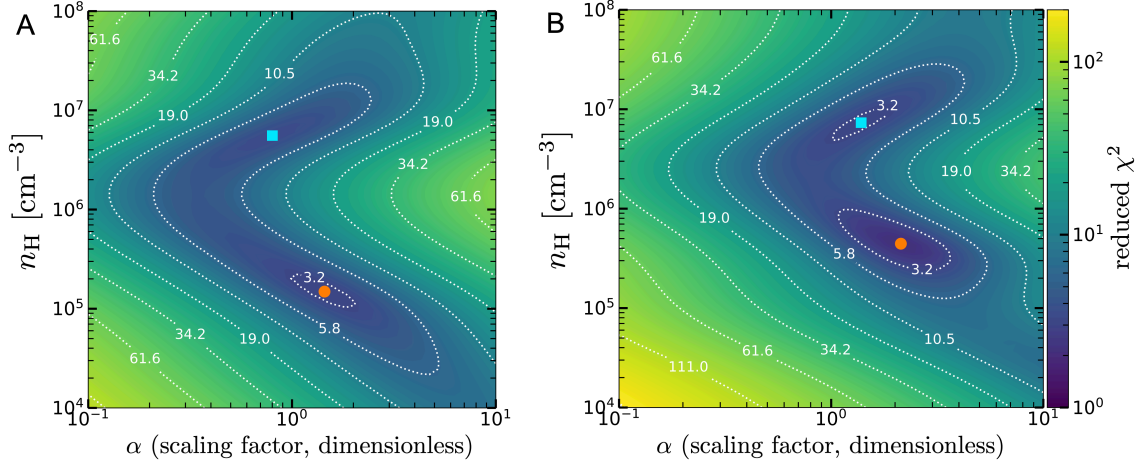


Figure S5: **Deviation between observed and modelled  $\text{H}_2$  emission intensities.** Reduced  $\chi^2$  map, for a grid of values of the gas density  $n_{\text{H}}$  and scaling factor  $\alpha$  used in the Meudon PDR models, using small grains (A) and large grains (B) in the model. Both panels 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.

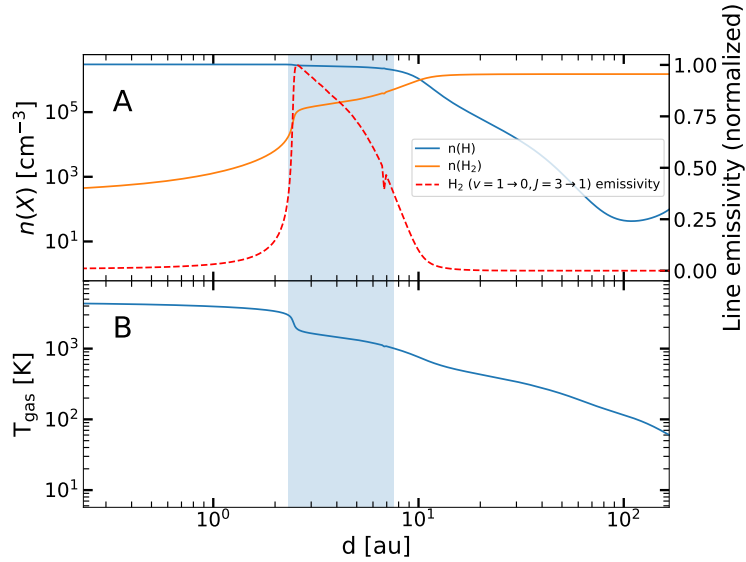


Figure S6: **Spatial structure of a Meudon PDR model (using the small grains setup) for  $n_{\text{H}} = 3 \times 10^6 \text{ cm}^{-3}$ .** The UV illumination ( $G_0 = 2 \times 10^4$ ) is from the left side of this plot. Panel (A) shows the densities of H (blue) and  $\text{H}_2$  (orange), both on 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  $\text{H}_2$  emitting layer as defined in the text.

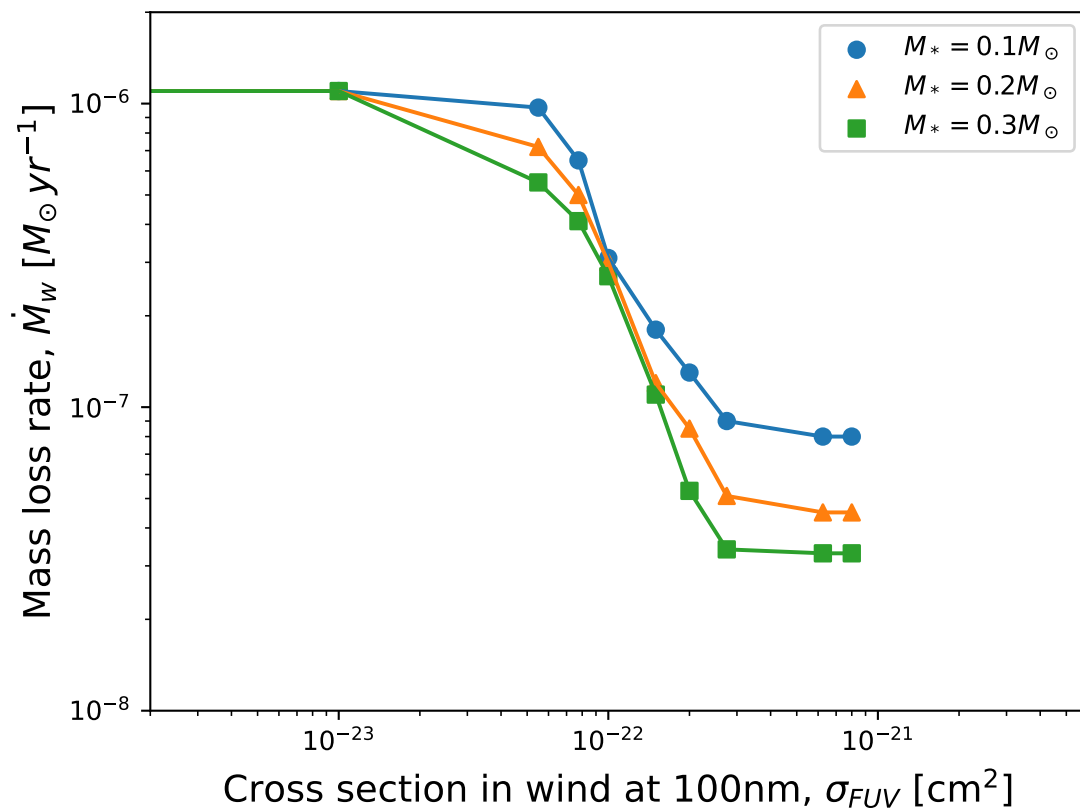


Figure S7: Mass-loss rates from 1D TORUS-3DPDR external photoevaporation calculations as a function of the effective grain cross section in the wind. The different sets of lines/points correspond to different masses of the central star that the disk orbits.

Table S1: Derived physical properties of d203-506

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

Table S2: Detected H<sub>2</sub> lines towards the PDR in d203-506. Rest wavelengths are from (69).

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