No nitrogen fractionation on 600 au scale in the Sun progenitor analogue OMC–2 FIR4

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ABSTRACT
We show the first interferometric maps of the 14N/15N ratio obtained with the Atacama Large Millimeter Array (ALMA) towards the Solar-like forming protocluster OMC–2 FIR4. We observed N2H+, 15NNH+, N15NH+ (1–0), and N2D+ (2–1) from which we derive the isotopic ratios 14N/15N and D/H. The target, OMC–2 FIR4, is one of the closest analogues of the environment in which our Sun may have formed. The ALMA images, having synthesized beam of ∼1.5 arcsec × 1.8 arcsec, i.e. ∼600 au, show that the emission of the less abundant isotopologues is distributed in several cores of ∼10 arcsec (i.e. ∼0.02 pc or 4000 au) embedded in a more extended N2H+ emission. We have derived that the 14N/15N ratio does not vary from core to core, and our interferometric measurements are also consistent with single-dish observations. We also do not find significant differences between the 14N/15N ratios computed from the two 15N-bearing isotopologues, 15NNH+ and N15NH+. The D/H ratio derived by comparing the column densities of N2D+ and N2H+ changes by an order of magnitude from core to core, decreasing from the colder to the warmer cores. Overall, our results indicate that: (1) 14N/15N does not change across the region at core scales, and (2) 14N/15N does not depend on temperature variations. Our findings also suggest that the 14N/15N variations found in pristine Solar system objects are likely not inherited from the protocluster stage, and hence the reason has to be found elsewhere.

Key words: Stars: formation – ISM: clouds – ISM: molecules.

1 INTRODUCTION
One of the unsolved mysteries about the Solar system is why the nitrogen isotopic ratio, \( R = \frac{14N}{15N} \), was ∼440 in the Proto Solar Nebula (PSN, Owen et al. 2001; Fouchet et al. 2004; Marty et al. 2010), while now it is ∼270 in the Earth atmosphere (Marty, Zimmermann & Burnard 2009), ∼140 in comets (Manford et al. 2009; Shinnaka et al. 2016), and 50–300 in the insoluble organic matter (e.g. Bonal et al. 2009; Matrajt et al. 2012; Nittler et al. 2018) and soluble organic compounds (e.g. Pizzarello & Holmes 2009; Chan et al. 2014; Pizzarello 2014) of meteorites. What causes such variations was (and still is) puzzling astronomers and cosmochemists for decades. It is now clear that there are up to three different reservoirs of nitrogen in the Solar system, which have distinct N isotopic ratios (see, for example, the discussion in Furi & Marty 2015): the PSN, where \( R \sim 440 \); the inner Solar system, in which planets and bulk meteorites appear enriched in \( 15N \) by a factor \( \sim 1.6 \) with respect to the PSN; and the cometary ices, enriched up to a factor of \( \sim 3 \) relative to the PSN, although the inner Solar system reservoir could be a mixture of the two ‘extreme’ values: the Sun and the cometary material. Nonetheless, it remains the question of what causes the relatively large range of \( R \) in cometary and meteoritic material, and whether this has an ISM origin.

One popular explanation for the nitrogen isotopic fractionation has been that, as for the hydrogen isotopic one, it has to be attributed to (low) temperature effects (Terzieva & Herbst 2000; Rodgers & Charney 2008; Furuya & Aikawa 2018). However, several theoretical studies have excluded low-temperature isotopic exchange reactions as the main way to enhance \( 15N \) in molecular species (e.g. Wirstöm et al. 2012; Roueff, Loison & Hickson 2015; Wirstöm & Charney 2018; Loison et al. 2019). At odd with theory,
in an environment similar to the one in which our Sun may have been born.

3 OBSERVATIONS

Observations towards OMC–2 FIR4 using 40 antennas of the Atacama Large Millimeter Array (ALMA) in Cycle 4 were carried out as part of the project 2016.1.00681.S (PI: F. Fontani), in band 3 (3 mm) in 2016 December 23–25, and in band 4 (2 mm) in 2017 March 11. The correlator was configured in four different spectral windows to cover lines of N$_2$H$^+$, $^{15}$NNH$^+$, $^{15}$NH$^+$ (1–0) at 3 mm, and N$_2$D$^+$ (2–1) at 2 mm. Relevant spectral parameters are given in Table 1. Flux and bandpass calibration were obtained through observations of J0423-0120. Visibility phases and amplitudes were calibrated on quasar J0541-0541. Some important observational parameters (baseline range, precipitable water vapour, system temperature, on-source total observing time, synthesized beam, and spectral resolution) are reported in Table 1. The coordinates of the phase centre were RA = 05h35m27.0, Dec = −05°09'56.8".

The data were calibrated using standard ALMA calibration scripts of the Common Astronomy Software Applications (CASA, 1 version 4.7.0) package. The calibrated data cubes were converted in fits format and analysed in GILDAS$^2$ format and then imaged and deconvolved with software MAPPING of the GILDAS package using standard procedures. Continuum subtraction was performed by taking the line-free channels around the lines in each individual spectral window and subtracted from the data directly in the ($\nu$, $\nu$) domain. The nominal maximum recoverable scale (MRS) was ∼25 arcsec in band 3 and ∼19 arcsec in band 4.

4 RESULTS

The N$_2$H$^+$, $^{15}$NNH$^+$, and $^{15}$NH$^+$ (1–0) lines, and the N$_2$D$^+$ (2–1) line, were all clearly detected towards OMC–2 FIR4. The maps of their intensity averaged over the full-line profiles are shown in Fig. 1. As reference, in the same plot, we show the 82-GHz continuum map published by Fontani et al. (2017). We do not show the ALMA continuum maps obtained from the data set presented in Section 3 because a high-angular resolution map of the continuum is not crucial for the analysis we make in this work, and a study totally devoted to the continuum emission will be presented in a forthcoming paper (Neri et al. in preparation).

We detect significant emission over an angular region as extended as ∼30 arcsec in N$_2$H$^+$ and up to ∼20 arcsec in N$_2$D$^+$. In particular, N$_2$H$^+$ shows two main intensity peaks separate by ∼15 arcsec in the east–west direction, embedded in an irregular diffuse envelope, while N$_2$D$^+$ is concentrated in two cores partly overlapping along a north–south direction, whose peaks are separated by ∼10 arcsec. The extension of the N$_2$H$^+$ and N$_2$D$^+$ maps overall overlaps well with that of the mm continuum. The rough angular size of each core is smaller than the nominal MRS (see Section 3) of its observing band. The most intense N$_2$D$^+$ core coincides with the strongest N$_2$H$^+$ emission peak, while the second one is offset by ∼10
The complexity of the emission morphology in all lines makes it difficult to divide OMC–2 FIR4 in well-separated structures. Therefore, we have manually identified five ‘coarse’ regions defined in a very schematic way: their borders contain one dominant intensity peak of one isotopologue and follow as much as possible the contours of one of the average maps of the rare isotopologues shown in Figs 1 and 2. More specifically:

(i) ‘FIR4-east’ and ‘FIR4-west’ contain the two intensity peaks resolved in N$_2$H$^+$, and the borders follow roughly the 3σ rms contour of the average $^{15}$NNH$^+$ and N$^{15}$NH$^+$ (1–0) emission maps.

(ii) ‘FIR4-peak’ includes the most intensity peak seen in N$_2$D$^+$ and roughly follows its 15σ rms contour to well separate this peak to the secondary one.

(iii) ‘FIR4-north’ includes the less intense N$_2$D$^+$ emission peak located $\sim$10 arcsec north of the main one and roughly follows its 15σ rms contour.

(iv) ‘FIR4-tot’ coincides with the union of regions ‘FIR4-east’, ‘FIR4-west’, and ‘FIR4-peak’ and encompasses roughly the bulk of both $^{15}$NNH$^+$ and N$^{15}$NH$^+$ emission.

The spectra of N$_2$H$^+$, $^{15}$NNH$^+$, and N$^{15}$NH$^+$ (1–0) in flux density unit, and the N$_2$D$^+$(2–1) spectrum in brightness temperature unit, extracted from these regions are shown in Fig. 3. The conversion between flux density units and brightness temperature units for N$_2$D$^+$ has been performed according to the equation: $T_{SB} = 1.222 \times 10^3 F_s (v/v_s^2)$, where $v$ is the observing frequency in GHz units and $\theta_s$ is the angular source size, in arcsecond units, defined as the diameter of the circular region having the same area of the core considered. We display different y-axis units for the different isotopologues because of the different methods used to derive $R$ and D/H, which will be discussed in the following sections.

### 4.1 $^{14}$N/$^{15}$N

From the N$_2$H$^+$, $^{15}$NNH$^+$, and N$^{15}$NH$^+$ (1–0) spectra shown in Fig. 3, we have first derived the $^{14}$N/$^{15}$N ratios, $R$, following this approach: we have divided the flux density peak of the $F_1 = 0–1$ hyperfine component of N$_2$H$^+$ (1–0), with rest frequency 93.17613 GHz, by that of the $F = 0–1$ one of both $^{15}$NNH$^+$ and N$^{15}$NH$^+$ (1–0), at rest frequencies 90.2645 and 91.2086 GHz, respectively. These components are indicated in Fig. 3. Full spectroscopic parameters of the hyperfine structure of the three lines are given, e.g. in Kahane et al. (2018) and Colzi et al. (2019). If the compared hyperfine

| Band–molecule | Baseline range (m) | $T_{sys}$ (K) | pwv (mm) | Int. time (min) | $\theta_{SB}$ (″) | $\Delta V_c$ (mJy) |
|---------------|--------------------|-------------|----------|-----------------|-----------------|----------------|
| 3 – N$_2$H$^+$ | 15–491             | 50–130      | 3.2      | 136             | 1.5 × 1.8       | ~1.5           |
| 3 – $^{15}$NNH$^+$ | 15–491         | 50–100      | 3.2      | 136             | 1.5 × 1.8       | ~1.2           |
| 3 – N$^{15}$NH$^+$ | 15–491         | 50–100      | 3.2      | 136             | 1.5 × 1.8       | ~1.2           |
| 4 – N$_2$D$^+$ | 15–321             | 60–100      | 3.1      | 32              | 1.4 × 1.8       | ~3             |

$^a$Root mean square (rms) noise per channel in each spectral window.

$^b$Taken from the Cologne Molecular Database for Spectroscopy (CDMS; Endres et al. 2016).

* Spectral resolution.

The 15N isotopologues show emission much more compact than that of N$_2$H$^+$. This could just be the consequence of the (almost) uniform sensitivity we achieved in both the main and rare isotopologues, which likely prevents the detection of the fainter rare isotopologues in the more diffuse envelope. Overall, the two 15N-isotopologues show a very similar morphology. They both mostly arise from the western portion of FIR4. Significant emission (≥3σ rms) is also detected towards FIR5. Because the nature of FIR5 is still unclear, and it is not the target of the current work, this source will be discussed in a forthcoming paper presenting more extensively the ALMA data set. To better compare the emission morphology of all N$_2$H$^+$ isotopologues, in Fig. 2 we superimpose the average map of the emission integrated over the profile of the $F = 0–1$ hyperfine component of N$_2$H$^+$: even though the overall morphology is similar, clearly the rare isotopologues are not detected towards the diffuse N$_2$H$^+$ emission.

We have checked if we miss some extended flux by extracting spectra from a circular region corresponding to the single-dish beam of the observations presented by Kahane et al. (2018): we recover the whole flux in the 15N isotopologues, and we miss at most 10 per cent of extended flux in N$_2$H$^+$(1–0), which is comparable to the uncertainty on the flux calibration. Hence, we can conclude that our analysis is not affected by any significant extended emission resolved out. The fact that there is not extended emission in N$_2$H$^+$ in OMC–2 FIR4 makes it peculiar with respect to similar clustered star-forming regions (e.g. Henshaw et al. 2014), in which very often interferometric N$_2$H$^+$ emission maps suffer from extended flux resolved out. We speculate that this could be due to a very efficient destruction of N$_2$H$^+$ in the external layers, perhaps due to the high irradiation by cosmic rays, known to affect the chemistry of the envelope of the OMC–2 FIR4 from different observational evidence (Ceccarelli et al. 2014; Fontani et al. 2017; Favre et al. 2018).
Figure 1. Averaged emission of the $N_2H^+$ isotopologues studied in this work obtained over the whole line profile, unless when differently specified. The maps show, pixel per pixel, the arithmetic mean of the flux density calculated over the line profiles and are equivalent to the integrated intensity maps, used more often in the literature, when multiplied by the velocity interval (given below) over which the intensity is averaged. 

**Top panels** (from left to right): $^{15}NNH^+$ (1–0) emission averaged over the velocity range of 8.18–13.72 km s$^{-1}$ (contours start from the 3σ rms level of the averaged map, 1.5 mJy/beam, and are in steps of 1 mJy/beam), and the $N^{15}NH^+$ (1–0) emission averaged over the velocity range of 0.29–19.30 km s$^{-1}$ (first contour and step are the same as in the $^{15}NNH^+$ map). Both velocity ranges include all hyperfine components. Please note that the noise of the average map is equivalent to that of a spectrum smoothed to a spectral resolution equal to the velocity interval covered by the considered channels (hence, much smaller than that of the spectral cube with resolution \(\sim 0.4\) km s$^{-1}$, listed in Table 1).

**Middle panels** (from left to right): emission on the hyperfine component $N_2H^+$ (1–0) $F_1=0$–1, averaged over the velocity interval 0.38–3.72 km s$^{-1}$ (contours start from 12 mJy/beam, corresponding to the 3σ rms level of the average map, and are in steps of 36 mJy/beam), and total $N_2H^+$ (1–0) emission averaged over all hyperfine components in the velocity interval 0.38–18.48 km s$^{-1}$. This plot also shows the four contours in which we have extracted the spectra that have been used to derive and discuss the $^{14}N/^{15}N$ and D/H ratios: ‘FIR4-west’ (in red), ‘FIR4-east’ (in white), ‘FIR4-peak’ (in yellow), and ‘FIR4-north’ (in green). Spectra were also extracted from a region called ‘FIR4-tot’, which is not shown because it is the union of polygons ‘FIR4-west’, ‘FIR4-east’, and ‘FIR4-peak’. 

**Bottom panels** (from left to right): 82-GHz continuum observed with NOEMA (Fontani et al. 2017), and $N_2D^+$ (2–1) averaged over the velocity range of 2.87–16.79 km s$^{-1}$, which includes all the hyperfine components (contours start from 2.1 mJy/beam, corresponding to the 3σ rms level of the average map, and are in steps of 6.3 mJy/beam). The map shown in the bottom right-hand panel is an enlargement of the region identified by the dashed square in the bottom left-hand panel. In each frame: the ellipse in the bottom left corner shows the synthesized beam (see Table 1 for the ALMA maps and Fontani et al. 2017, for the NOEMA continuum map), while the dashed circle depicts the ALMA primary beam (\(\sim 68\) arcsec and \(\sim 41\) arcsec in bands 3 and 4, respectively). The wedge on the right indicates the range of flux density (Jy/beam). The white triangles indicate the position of the far-infrared sources FIR3, FIR4, and FIR5 (see Section 1).
have the same line width, and are optically thin, the methods are considered hyperfine components of the different isotopologues by us and also assuming optically thin conditions. Hence, if the intensity of the same isolated hyperfine component considered which is, however, derived by them from the velocity-integrated et al. (2018) compute the 14N/15N ratio from the total line intensity, ∼ have the same relative intensity [which indeed is \( \sim 0.1111 \)] for all isotopologues for the considered hyperfine components, see e.g. Dore et al. (2009) for \( ^{15}N\text{NH}^+ \) and \( ^{13}N\text{NH}^+ \) (1–0), and the Jet Propulsion Laboratory catalogue\(^3\) for \( ^{2}H\text{H}^+ \) (1–0)], then the ratio between the peak flux densities of these components is equivalent to the ratios between the total flux densities of the lines. Kahane et al. (2018) compute the \( ^{14}N/^{15}N \) ratio from the total line intensity, which is, however, derived by them from the velocity-integrated density of the same isolated hyperfine component considered by us and also assuming optically thin conditions. Hence, if the considered hyperfine components of the different isotopologues have the same line width, and are optically thin, the methods are equivalent, and the ratios between the peak intensities of the considered hyperfine components and the total line intensities are the same.

The best-fitting peak fluxes, \( F_\nu \), of the analysed hyperfine components have been obtained with the software MADCUBA,\(^4\) which performs a fit to the lines hyperfine structure creating a synthetic profile assuming for all components a single excitation temperature, \( T_{ex} \), full width at half-maximum, FWHM, and separation in velocity given by the laboratory value. The software also computes the best-fitting line velocity at the intensity peak, \( V_p \), the opacity of the various components, and the total column density of the molecule. The best-fitting \( F_\nu \) are listed in Table 2, where we also give \( R \) computed in the four regions identified in Fig. 1. By comparing the 1σ rms noise level in the spectra (Table 1) with the peak intensities of the analysed hyperfine components (Table 2), we can see that the faintest hyperfine components are all detected with a signal-to-noise ratio \( \gtrsim 5 \), except for \( ^{15}N\text{NH}^+ \) in FIR4-east for which the signal-to-noise ratio is \( \sim 4.2 \).

The fits shown in Fig. 3 provide generally good results, except in some \( ^{15}N\text{NH}^+ \) spectra in which an extra feature at \( \sim 9 \) km s\(^{-1}\) above 3σ in the residuals is revealed. Given that at the feature frequency (\( \sim 91206.5 \) GHz) there are no lines of other species that can reasonably be attributed to this feature, it could be a second velocity component. However, this feature is significantly detected only in the main hyperfine component of \( ^{13}N\text{NH}^+ \), which is not the one we use in our analysis. Close to the component used in our analysis, we never detect a significant secondary peak. Therefore, this extra feature has probably no influence on the isotopic ratios that we derive.

Fig. 4 shows the comparison between \( R \) derived in the different regions shown in Fig. 1 and that obtained by Kahane et al. (2018) with the IRAM-30m telescope: it is apparent that in OMC-2 FIR4 \( R \) does not change either from region to region or going from the single-dish scale to the interferometric scale, within the error bars. The isotopic ratios derived in each core from the two isotopologues do not show significant differences between them as well. The core in which the two values show the largest discrepancy is ‘FIR4–east’ (360 ± 140 and 200 ± 70 from \( ^{15}N\text{NH}^+ \) and \( ^{13}N\text{NH}^+ \), respectively), but even here the two estimates are consistent within the (large) error bars.

As pointed out above, our method is based on the fact that the relative intensity of the aforementioned components with respect to the others of their hyperfine pattern is the same in all isotopologues (see e.g. Dore et al. 2009). Thus, their ratio depends only on the isotopic ratio \( ^{14}N/^{15}N \) provided that the compared hyperfine components: (1) have the same excitation temperature, (2) have the same line widths, and (3) are all optically thin.

Condition (1) is very likely because the three transitions have very similar critical densities. However, let us discuss better this approximation: from a non-Local Thermodynamic Equilibrium (non-LTE) analysis, Hily-Blant et al. (2013) found differences in \( T_{ex} \) for lines with the same quantum numbers of the different isotopologues of HCN. But these differences are in all (but one) cases below \( \sim 10 \) per cent, indicating that a significantly different \( T_{ex} \) for lines with the same quantum numbers is unlikely for isotopologues of the same species. Regarding the possibility that different hyperfine components of the same isotopologue line can

\(^3\)https://spec.jpl.nasa.gov/ftp/pub/catalog/catform.html

\(^4\)Madrid Data Cube Analysis on ImageJ is a software developed in the Center of Astrobiology (Madrid, INTA-CSIC) to visualize and analyse single spectra and data cubes (Martín et al. 2019; Rivilla et al. 2016).
Figure 3. Spectra of, from left to right, $^{15}\text{NNH}^+$ (1–0), $\text{N}^{15}\text{NH}^+$ (1–0), $\text{N}_2\text{H}^+$ (1–0), and $\text{N}_2\text{D}^+$ (2–1) extracted from the five regions defined in Fig. 1, namely (from top to bottom): ‘FIR4-tot’, ‘FIR4-east’, ‘FIR4-west’, ‘FIR4-peak’, and ‘FIR4-north’ (see Section 4 for details). In each spectrum, the vertical dashes line indicates the systemic velocity of 11.4 km s$^{-1}$, and the horizontal dotted line corresponds to $y = 0$. The $^{15}\text{NNH}^+$, $\text{N}^{15}\text{NH}^+$, and $\text{N}_2\text{H}^+$ spectra are in flux density units, because $R$ is derived from the peak fluxes of the hyperfine components labelled in the top spectra of each column. For the $^{15}\text{NNH}^+$, $\text{N}^{15}\text{NH}^+$, and $\text{N}_2\text{H}^+$ spectra, the red curve is the best fit to the line hyperfine structure obtained with MADCUBA, whose components are indicated by vertical, solid lines under each spectrum, the length of which is proportional to the expected relative intensity in LTE; The $\text{N}_2\text{D}^+$ spectra are in brightness temperature ($T_{SB}$) units and the red curve shows the best fit obtained with MADCUBA because the parameters reported in Section 4 and Table 4 were derived from the $\text{N}_2\text{D}^+$ spectra converted in these units (see Section 4). The hyperfine structure of $\text{N}_2\text{D}^+$ (2–1) is shown only in the spectrum of FIR4-tot for clarity of the figure.

Table 2. Peak flux densities, $F_{\nu}$, of the faintest hyperfine component in the spectra shown in Fig. 3 [$F_1 = 0$–1 of $\text{N}_2\text{H}^+$, and $F = 0$–1 of $^{15}\text{NNH}^+$ and $\text{N}^{15}\text{NH}^+$ (1–0)] and their ratios, $R$, calculated from both $^{15}\text{NNH}^+$ and $\text{N}^{15}\text{NH}^+$. $F_{\nu}$ has been estimated by fitting the lines with MADCUBA (Section 4.1). Their error bars include the calibration uncertainty on the absolute flux density scale of 10%, and the 1$\sigma$ rms in the spectrum. This latter was computed, to be conservative, in each region from the line-free channels around each detected transition. In the uncertainties on $R$, calculated from the propagation of the errors, the calibration errors on $F_{\nu}$ cancel out because the compared spectra were calibrated in the same data cube.

| Region     | $F_1 = 0$–1 ($\text{N}_2\text{H}^+$) (mJy) | $F = 0$–1 ($^{15}\text{NNH}^+$) (mJy) | $F = 0$–1 ($\text{N}^{15}\text{NH}^+$) (mJy) | $R$ | $\text{N}^{15}\text{NH}^+$ (mJy) | $R$ |
|------------|-------------------------------------------|----------------------------------------|------------------------------------------|-----|-----------------------------------|-----|
| FIR4-tot   | 11 ± 1                                    | 40 ± 10                                | 40 ± 10                                  | 280 ± 60 | 280 ± 50                           |
| FIR4-east  | 1.8 ± 0.2                                 | 5 ± 2                                  | 9 ± 3                                    | 360 ± 140 | 200 ± 70                           |
| FIR4-west  | 10 ± 1                                    | 30 ± 10                                | 30 ± 10                                  | 330 ± 80  | 330 ± 80                           |
| FIR4-peak  | 4.4 ± 0.5                                 | 12 ± 6                                 | 12 ± 6                                   | 370 ± 150 | 370 ± 150                          |
| FIR4-north | 2.7 ± 0.3                                 | 8 ± 4                                  | 10 ± 5                                   | 330 ± 120 | 270 ± 100                          |

Table 2. Peak flux densities, $F_{\nu}$, of the faintest hyperfine component in the spectra shown in Fig. 3 [$F_1 = 0$–1 of $\text{N}_2\text{H}^+$, and $F = 0$–1 of $^{15}\text{NNH}^+$ and $\text{N}^{15}\text{NH}^+$ (1–0)] and their ratios, $R$, calculated from both $^{15}\text{NNH}^+$ and $\text{N}^{15}\text{NH}^+$. $F_{\nu}$ has been estimated by fitting the lines with MADCUBA (Section 4.1). Their error bars include the calibration uncertainty on the absolute flux density scale of 10%, and the 1$\sigma$ rms in the spectrum. This latter was computed, to be conservative, in each region from the line-free channels around each detected transition. In the uncertainties on $R$, calculated from the propagation of the errors, the calibration errors on $F_{\nu}$ cancel out because the compared spectra were calibrated in the same data cube.

have a different $T_{ex}$, Daniel, Cernicharo & Dubernet (2006) showed that high optical depths in $\text{N}_2\text{H}^+$ (1–0) could indeed cause deviations from the line profile expected when each component has the same excitation temperature. According to Table 2, the optical depth of the $F_1 = 0$–1 component of $\text{N}_2\text{H}^+$ (1–0) is in between ~0.3 and ~0.4, which translates into high total opacities of the lines and hence possible hyperfine ‘anomalies’ in their profiles. However, both theoretical (Daniel et al. 2006) and observational (Caselli,
Figure 4. Isotopic ratio $R = \frac{^{14}\text{N}}{^{15}\text{N}}$ computed from either $^{15}$NH$^+$ (black symbols) or $^{15}$NH$^+$ (red symbols). The ratios have been derived for the five regions discussed in Section 4 and Fig. 1 following the method described in Section 4.1. The horizontal dashed lines correspond to the average of $R$ in the five regions from $^{15}$NH$^+$ (black) and $^{15}$NH$^+$ (red). For comparison, we also show the single-dish measurements obtained by Kahane et al. (2018), squares. It is apparent that the $^{14}$N/$^{15}$N ratios do not change from region to region and are all comparable to the corresponding single-dish values, within the error bars. No statistically significant differences are found between the two $^{15}$N isotopologues either.

Myers & Thaddeus (1995) works show that $T_\text{ex}$ of the component analysed in our work would deviate from the local thermodynamic equilibrium value by 10−15 per cent at most and only at $H_2$ volume densities below $10^5 \text{cm}^{-3}$ [see fig. 6 in Daniel et al. 2006]. Because in OMC–2 FIR4 the average $H_2$ volume density is $1.2 \times 10^6 \text{cm}^{-3}$ (Ceccarelli et al. 2014a), where the predicted deviation from the equilibrium $T_\text{ex}$ is negligible (fig. 6 in Daniel et al. 2006), we are confident that hyperfine anomalies are not affecting significantly the $T_\text{ex}$ of the analysed component. This is also confirmed by the qualitative agreement between data and fits (which indeed assume a single $T_\text{ex}$ for all hyperfine components) for $N_2H^+ (1−0)$ in Fig. 3 around the $F_1 = 0−1$ components.

About assumptions (2) and (3), let us first discuss the $^{15}$NNH$^+$ and $^{15}$NH$^+$ (1−0) lines. As stated above, the fit performed with MADCUBA provides several parameters, among which are $V_p$, FWHM, and the opacity of each hyperfine component. The tool MADCUBA-AUTOFIT provides the best-fitting parameters via a non-linear least-squared fit algorithm (see also Colzi et al. 2019). The results of these fits are shown in Table 3 and indicate that the FWHM of the two isotopologues are the same within the uncertainties, and that the optical depth of the compared components is well below 0.1. The fact that the $^{15}$NNH$^+$ and $^{15}$NH$^+$ opacities are so low in the less-intense component is consistent with our expectations, given the low abundance of these two isotopologues. However, we stress that in some cases the uncertainties on the opacities are underestimated. In fact, as discussed in Martin et al. (2019), when one of the fit parameters in MADCUBA is fixed, then the error associated is zero, and hence the uncertainties of all quantities calculated from this parameter do not include its error. As we will illustrate in the following, sometimes we fixed $T_\text{ex}$, and hence in these cases the errors on the optical depth will be underestimated. However, the main point of this analysis is simply to confirm that the lines are optically thin, which indeed is confirmed.

For $N_2H^+(1−0)$, for which some hyperfine components are overlapping and the line optical depth could be higher, we have performed a more accurate analysis of the line profile assuming three different $T_\text{ex}$: the best-fitting $T_\text{ex}$ when leaving this parameter free, and the two extreme values of kinetic temperature measured in the envelope of OMC–2 FIR4, namely 35 and 45 K, in previous works (Ceccarelli et al. 2014a; Friesen et al. 2017). The results are shown in Tables 4–6. By comparing the parameters shown in these tables and those reported in Table 3, for each single core, we find that the $N_2H^+$, $^{15}$NNH$^+$, and $^{15}$NH$^+$ lines have the same FWHM, within the uncertainties, and that the optical depth of the $F_1 = 0−1$ component is at most 0.4. Thus, conditions (2) and (3) are also satisfied.

For completeness, we have quantified the error that we make in the most unfavourable case in our simplified approach: because at most, $\tau$ of the $F_1 = 0−1$ component is $0.4 \pm 0.1$ for FIR4-tot, and $0.40 \pm 0.08$ for FIR4-west, in both cases the peak brightness temperature should be corrected by the factor $\tau/(1 − \exp(−\tau)) \sim 1.21$. For FIR4-tot, the $^{14}$N/$^{15}$N ratio would change from 280 ± 60 and 280 ± 50 for $^{15}$NNH$^+$ and $^{15}$NH$^+$, respectively, to about 340 ± 100 for both, and for FIR4-west it would change from 330 ± 80 from both $^{15}$NNH$^+$ and $^{15}$NH$^+$ to 400 ± 120. These values are still consistent, within the uncertainties, to those derived in the other regions. Therefore, even considering the correction for the optical depth, the $^{14}$N/$^{15}$N ratio does not change from region to region within the uncertainties.

4.2 D/H

We have derived the D/H ratio from the $N_2H^+(1−0)$ and $N_2D^+ (2−1)$ lines. Due to the different quantum numbers of these transitions, we could not use the approach adopted to evaluate $R$. Therefore, the D/H ratio has been estimated by dividing the total column densities of $N_2D^+$ and $N_2H^+$ computed by fitting the lines with MADCUBA. We have fitted the lines with three temperatures, as explained in Section 4.1. The fits to the hyperfine structure have been performed to both $N_2H^+$ and $N_2D^+$ spectra converted to the optical depth of the $F = 0−1$ hyperfine component (see Fig. 3).
Table 4. Best-fitting line parameters of N$_2$H$^+$ (1–0) and N$_2$D$^+$ (2–1); in columns 2–5, we list excitation temperatures ($T_{ex}$), peak velocities ($V_p$), full widths at half-maximum (FWHM), and opacity of the $F_1 = 0–1$ hyperfine component of N$_2$H$^+$ (1–0) obtained by fitting the line hyperfine structure. The fit procedure is explained in Section 4.1. In columns 6–8, we show the best-fitting $V_p$, FWHM, and opacity of the main hyperfine component, $\tau_{\text{main}}$, of N$_2$D$^+$ (2–1), obtained fixing $T_{ex}$ to the value given in column 2. This was necessary, because for N$_2$D$^+$ the fit leaving $T_{ex}$ as free parameter could not converge. The best-fitting column densities are reported in Table 7.

| Core       | $T_{ex}$ K | $V_p$ km s$^{-1}$ | FWHM km s$^{-1}$ | $\tau_{F_1=0–1}$ | $V_p$ km s$^{-1}$ | FWHM km s$^{-1}$ | $\tau_{\text{main}}$ |
|------------|------------|-------------------|------------------|------------------|-------------------|------------------|-------------------|
| FIR4-tot   | 12.5 ± 0.6 | 11.3 ± 0.2        | 1.0 ± 0.2        | 0.4 ± 0.1        | 10.6 ± 0.1       | 1.0 ± 0.1        | 0.012 ± 0.001     |
| FIR4-east  | 14.6 ± 0.5 | 11.4 ± 0.2        | 0.8 ± 0.2        | 0.35 ± 0.07      | 11.0 ± 0.1       | 0.4 ± 0.1        | 0.014 ± 0.001     |
| FIR4-west  | 12.3 ± 0.6 | 11.3 ± 0.2        | 1.0 ± 0.2        | 0.40 ± 0.08      | 10.8 ± 0.1       | 1.0 ± 0.1        | 0.014 ± 0.001     |
| FIR4-peak  | 12.9 ± 0.9 | 11.2 ± 0.2        | 1.3 ± 0.2        | 0.30 ± 0.1       | 10.6 ± 0.1       | 0.7 ± 0.1        | 0.032 ± 0.004     |
| FIR4-north | 11.3 ± 0.4 | 11.2 ± 0.2        | 0.5 ± 0.2        | 0.35 ± 0.08      | 11.2 ± 0.2       | 0.4 ± 0.2        | 0.068 ± 0.005     |

The best-fitting $V_p$, FWHM, and opacity of the main hyperfine component with quantum numbers $F_1 = 3–2$, $F = 4–3$ (Gerin et al. 2001), derived with MACDUCABA (Section 4.2).

Table 5. Same as Table 4, fixing $T_{ex}$ to 35 K. The best-fitting column densities are reported in Table 7.

| Core       | $T_{ex}$ K | $V_p$ km s$^{-1}$ | FWHM km s$^{-1}$ | $\tau_{F_1=0–1}$ | $V_p$ km s$^{-1}$ | FWHM km s$^{-1}$ | $\tau_{\text{main}}$ |
|------------|------------|-------------------|------------------|------------------|-------------------|------------------|-------------------|
| FIR4-tot   | 35         | 11.3 ± 0.2        | 1.2 ± 0.2        | 0.12 ± 0.01      | 10.6 ± 0.1       | 1.1 ± 0.1        | 0.003 ± 0.001     |
| FIR4-east  | 35         | 11.4 ± 0.2        | 0.9 ± 0.2        | 0.15 ± 0.01      | 11.0 ± 0.1       | 0.4 ± 0.1        | 0.005 ± 0.001     |
| FIR4-west  | 35         | 11.3 ± 0.2        | 1.3 ± 0.2        | 0.11 ± 0.01      | 10.8 ± 0.1       | 1.0 ± 0.1        | 0.004 ± 0.001     |
| FIR4-peak  | 35         | 11.2 ± 0.2        | 1.4 ± 0.2        | 0.10 ± 0.01      | 10.6 ± 0.1       | 0.7 ± 0.1        | 0.009 ± 0.004     |
| FIR4-north | 35         | 11.2 ± 0.2        | 0.6 ± 0.2        | 0.15 ± 0.01      | 11.2 ± 0.2       | 0.4 ± 0.2        | 0.015 ± 0.005     |

The best-fitting $V_p$, FWHM, and opacity of the main hyperfine component with quantum numbers $F_1 = 3–2$, $F = 4–3$ (Gerin et al. 2001), derived with MACDUCABA (Section 4.2).

Table 6. Same as Table 4, fixing $T_{ex}$ to 45 K. The best-fitting column densities are reported in Table 7.

| Core       | $T_{ex}$ K | $V_p$ km s$^{-1}$ | FWHM km s$^{-1}$ | $\tau_{F_1=0–1}$ | $V_p$ km s$^{-1}$ | FWHM km s$^{-1}$ | $\tau_{\text{main}}$ |
|------------|------------|-------------------|------------------|------------------|-------------------|------------------|-------------------|
| FIR4-tot   | 45         | 11.3 ± 0.2        | 1.2 ± 0.2        | 0.10 ± 0.01      | 10.6 ± 0.1       | 1.1 ± 0.1        | 0.002 ± 0.0005    |
| FIR4-east  | 45         | 11.4 ± 0.2        | 0.9 ± 0.2        | 0.11 ± 0.01      | 11.0 ± 0.1       | 0.4 ± 0.1        | 0.004 ± 0.001     |
| FIR4-west  | 45         | 11.3 ± 0.2        | 1.3 ± 0.2        | 0.08 ± 0.01      | 10.8 ± 0.1       | 1.0 ± 0.1        | 0.003 ± 0.001     |
| FIR4-peak  | 45         | 11.2 ± 0.2        | 1.4 ± 0.2        | 0.08 ± 0.01      | 10.6 ± 0.1       | 0.7 ± 0.1        | 0.007 ± 0.002     |
| FIR4-north | 45         | 11.2 ± 0.2        | 0.6 ± 0.2        | 0.11 ± 0.02      | 11.2 ± 0.2       | 0.4 ± 0.2        | 0.012 ± 0.005     |

Table 7. Best-fitting column densities in ‘synthesised temperature’ units. Generally, the lines are well fitted, although in all N$_2$D$^+$ (2–1) spectra a residual emission partly overlapping the hyperfine pattern is apparent at $\sim$154.2165 GHz (right-hand panels in Fig. 3). This could be due to a contamination from the transition (8_4,4 – 7_3,3) of CH$_3$CHO at 154216.68 GHz ($E_u \sim$ 69 K, S$_{21}$$\mu^2$ = 75.9 D$^2$). However, the large number of hyperfine components not contaminated by this excess emission (which, however, is always smaller than 5 per cent of the total line integrated intensity, i.e. smaller than the calibration error) allows us to well fit the hyperfine pattern in all N$_2$D$^+$ spectra.

The best-fitting $V_p$, FWHM, and opacity of the main hyperfine component of N$_2$D$^+$ (2–1) are shown in Table 7, and are in the range of $\sim$0.7 – 1.7 $\times$ 10^{14} cm$^{-2}$ for N$_2$H$^+$, and $\sim$2.5 – 13.8 $\times$ 10^{13} cm$^{-2}$ for N$_2$D$^+$, which translate into D/H values in between 2.6 $\times$ 10$^{-5}$ towards ‘FIR4-east’ and 1.4 $\times$ 10$^{-4}$ towards ‘FIR4-north’. We stress that, even though the total column densities in each region change by a factor of $\sim$1.5 assuming different excitation temperatures, the D/H ratios do not change within the uncertainties.

5 DISCUSSION AND CONCLUSIONS

Fig. 5 shows the H/D ratio against $R$; while H/D varies from $\sim$70 in ‘FIR4-north’ to $\sim$380 in ‘FIR4-east’, $R$ does not. This demonstrates that there is no correlation between N and H fractionation, as also deduced by previous studies both in the same molecule (Fontani et al. 2015a) and in nitriles (Colzi et al. 2018b). Finally, it is worth noticing that the highest H/D ratio measured in ‘FIR4-east’ agrees with previous observations, which indicate that the eastern part of the protocluster is warmer than the western one (Fontani et al. 2017; Favre et al. 2018). On the opposite, ‘FIR4-north’, having the lowest H/D and located to the north-western part of the protocluster, is likely the coldest (and maybe less evolved) condensation. The D/H ratio of N$_2$H$^+$ is a clear evolutionary indicator in low- and high-mass...
the envelope surrounding FIR4, in which N$_2$H$^+$ increases from envelope to protocluster scale in OMC–2 FIR4 as reported in Table 4, $T_{\text{ex}}$, and two fixed values, 35 and 45 K, corresponding to the extrema of the kinetic temperature range estimated for the envelope of OMC–2 FIR4 by Ceccarelli et al. (2014a).

We note that although the total column densities change with $T_{\text{ex}}$ by a factor of $\sim 1.5$, the D/H ratios are equal within the uncertainties.

### Table 7. Total column densities of N$_2$H$^+$ and N$_2$D$^+$ and their ratio, D/H, derived fitting the spectra in Fig. 3 with MADCUBA (see Section 4.2) assuming three different $T_{\text{ex}}$: the best-fitting value for N$_2$H$^+$ reported in Table 4, $T_{\text{ex}}^\text{fit}$, and two fixed values, 35 and 45 K, corresponding to the extrema of the kinetic temperature range estimated for the envelope of OMC–2 FIR4 by Ceccarelli et al. (2014a).

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