Onsala Proposal

Trapman — 0108.F-9314

Testing the robustness of N2H+ as CO iceline tracer in protoplanetary disks using N2H+ J=7-6

Semester: may2021 **Science Cat.: ISM and star formation**

Abstract

The molecule N2H+, a chemical tracer of CO-poor gas, is frequently used to locate the CO iceline in planet-forming disks, thought to play a crucial role in planet formation.
However, astrochemical models predict the existence of second N2H+-rich surface layer, whose origins are unrelated to CO freeze-out. We used APEX to detect N2H+ 7-6 in the nearby planet-forming disk TW Hya, confirming the existence of this N2H+-rich surface layer. If this layer proves common, we may need to re-evaluate N2H+ as a CO iceline tracer.

We propose to observe N2H+ 7-6 with APEX-SEPIA660 in two planet-forming disks, LkCa 15 and V4046 Sgr. We will show if their distinctive differences in N2H+ 3-2 emission morphology observed with ALMA are indicative of the presence/absence of a N2H+-rich surface layer and we will establish how well N2H+ really traces the CO iceline.

Applicants

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Is this a long term proposal: No

No overall scheduling requirements

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	SEPIA660 (581-727 GHz)	10h (10h)	652	< 0.5mm		The target for this proposal is the N2H+ J=7-6 line at 652.0956 GHz

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
LkCa 15	04:39:17.79	+22:21:03.3	J2000	6.2	71	A	integration time is without overheads
V4046 Sgr	18:14:10.47	-32:47:34.4	J2000	2.9	71	A	integration time is without overheads

Testing the robustness of N_2H^+ as CO iceline tracer in protoplanetary disks using N_2H^+ J = 7 - 6

1 Scientific justification: is N_2H^+ a good CO iceline tracer?

Ice lines are defining locations inside planet-forming disks, where dominant volatiles (e.g., H_2O, CO, N_2) freeze out onto dust grains. These ice lines are thought to play crucial roles in planet formation by enhancing the sticking probability of grains, significantly increasing the solid surface density, and influencing the planetary bulk volatile compositions (e.g., Blum & Wurm 2008; Öberg et al. 2011; Ros & Johansen 2013). **Direct detection of ice lines is difficult:** the mid-plane location of the CO ice line is 'hidden' by gas-phase CO present at higher layers in the disk where temperatures are higher.

Using ALMA, the N_2H^+ molecule has been successfully used to locate the CO ice line (Qi et al., 2013, 2015, 2019; Huang & Öberg, 2015). N_2H^+ is formed through proton transfer from H_3^+ to N_2. If CO is present in the gas it competes N_2 for the available H_3^+, thus impeding the formation of N_2H^+. In addition, N_2H^+ is rapidly destroyed by gas-phase CO. As a result, **N_2H^+ is therefore expected to be abundant between the CO iceline and the N_2 iceline** (see Figure 1). The ring-shaped N_2H^+ emission that is detected should signal CO freeze-out at the inner radius of the ring.

However, there is increasing evidence for **a second N_2H^+-rich layer, situated higher up in the disk, that is unrelated to CO freeze-out**. This layer is the result of N_2 having a slightly lower photo-dissociation rate compared with CO. N_2 is thus able to self-shield higher up in the disk than CO, creating a layer of N_2-rich, CO-poor gas where N_2H^+ can easily form, similar to the layer found between the two icelines (see Figure 1). This layer is seen clearly in physical-chemical models and can contribute significantly to the emission of low$-J$ N_2H^+ lines (van 't Hoff et al., 2017). However, existence of this second layer of N_2H^+ higher up in the disk has not yet been conclusively proven with observations of low$-J$ N_2H^+ lines (see Schwarz et al. 2019; Nomura et al. 2016).

Recently, **we detected N_2H^+ $J = 7 - 6$ with the APEX telescope in the nearby TW Hya disk (see Figure 2)**. Due to its upper level energy of 125 K, N_2H^+ (7-6) only significantly emits at the high temperatures found higher up in the disk. This makes it an excellent probe of the N_2H^+-rich surface layer: **detecting N_2H^+ (7-6) is equivalent to detecting the N_2H^+-rich surface layer.** Moreover, the first detection of N_2H^+ (7-6) in TW Hya shows that line is 3× brighter than current models predict, suggesting that the N_2H^+-rich surface layer is an integral part of the N_2H^+ abundance structure in disks. If the N_2H^+-rich surface layer is a common occurrence in protoplanetary disks, we might need to re-evaluate the use of N_2H^+ as a CO iceline tracer.

Recent ALMA observations of N_2H^+ (3-2) show that protoplanetary disks can be divided into two categories based on their N_2H^+ (3-2) emission morphology (see Qi et al. 2019). Half of the disks show a bright ring of N_2H^+ (3-2), surrounded by more tenuous emission. The other half instead show a more extended N_2H^+ (3-2) emission ring. Qi et al. (2019) attribute this difference to the vertical thickness of the N_2H^+ layer between the CO and N_2 icelines (see Figure 4): A thick layer results in a bright, narrow ring of N_2H^+ (3-2), whereas a thin layer results in a broad N_2H^+ (3-2) emission ring.

However, **another explanation is that the thick vertical layer between the two icelines is the result of a N_2H^+-rich surface layer**. The high N_2H^+ column density inferred from the bright, narrow ring would be the sum of the N_2H^+-rich surface layer and the N_2H^+ layer between the two icelines. If this is the case, then the inner edge of the N_2H^+ emission will be confused by the surface layer and would no longer trace the CO iceline (see Figure 4). The N_2H^+ (4-3) emission morphology and N_2H^+ (7-6) detection in TW Hya support this explanation.

Conversely, **the thin N_2H^+ vertical layer inferred from the broad emission ring could indicate that there is no N_2H^+-rich vertical layer**, or at least that it contributes only minimally to the total N_2H^+ column density. In that case, the broad emission ring would instead just trace the N_2H^+ between the CO and N_2 icelines, and can be used to determine the location of the CO iceline.

After our first successful detection of N_2H^+ (7-6) with APEX, we propose to observe N_2H^+ (7-6) in two protoplanetary disks, LkCa 15 and V4046 Sgr, to prove the existence, or absence of the N_2H^+-rich layer higher up the disk between the CO and N_2 photo-dissociation fronts (see Figure 4).

2 Description of Observations

The goal of this proposal is to detect the N_2H^+ $J = 7 - 6$ in two protoplanetary disks, LkCa 15 and V4046 Sgr. To detect this line we will use the new APEX-SEPIA660 heterodyne receiver (analogue to ALMA Band 9). This instrument has already been successfully used to detect N_2H^+ $J = 7 - 6$ in the nearby TW Hya protoplanetary disk (see Figure 2).

Detection experiment: Due to the high temperature required to excite the N_2H^+ $J = 7$ level (T_{ex} = 125.2 K) only the upper regions of the disk are expected to be warm enough to produce significant N_2H^+ (7-6) emission (see Fig. 1). With our observations we aim to carry out a direct experiment: **detecting the N_2H^+ (7-6) line is equivalent to detecting the N_2H^+-rich layer higher up in the disk**. A non-detection of N_2H^+ (7-6) indicates that the N_2H^+-rich layer is absent.

Selected sources: We select two sources, LkCa 15 and V4046 Sgr, that have similarly bright N_2H^+ (3-2) emission, but very different morphology. As shown at the top of Figure 4, LkCa 15 is a clear example of the bright, narrow ring of N_2H^+ emission, and V4046 Sgr is an example of the broad ring N_2H^+ emission morphology. These two disks are similar in both disk mass and size, as inferred from existing ALMA continuum and line observations (e.g., Loomis et al. 2020; Kastner et al. 2018).

Required sensitivity: Using the thermochemical code DALI (Bruderer et al., 2012) combined with the N_2H^+ chemical network presented in van 't Hoff et al. (2017), we compute N_2H^+ abundances and N_2H^+ (3-2) and (7-6) integrated intensities for a suite of disk models with different vertical structures and CO and N_2 abundances (see Figure 3). Comparing these models to the observed N_2H^+ (3-2) fluxes of our two sources **we find a minimal N_2H^+ (7-6) total intensity of 47 mK km/s if the N_2H^+-rich surface layer is present** (See Figure 3)

In agreement with the official APEX time estimator and similar to our previous observations of TW Hya, for ON/OFF observations, using SEPIA660, and assuming PWV = 0.5 mm, a source elevation of 45 degrees, and a spectral resolution for the XFFTS backends of 1.5 km/s, a total observing time of 4.98 hours per source (including overheads) yields a final rms of 7 mK, which is sufficient to detect the N_2H^+ (7-6) line at a S/N > 3 in our two disks. APEX observations with similar sensitivity were able to detect N_2H^+ (7-6) at 10σ in the TW Hya disk (see Figure 2). **We therefore request a total of 10 hours of APEX observing time (including tunings and overheads) with SEPIA660 in order to detect the N_2H^+ J=7-6 line in LkCa 15 and V4046 Sgr**.

Immediate objective: Calibrating N_2H^+ as CO iceline tracer: The usage of N_2H^+ as a tracer of the CO iceline is linked to the assumption that N_2H^+ is only abundant between the CO and N_2 icelines. We will analyze our N_2H^+ (7-6) observations together with existing N_2H^+ (3-2) observations using DALI models to constrain the full N_2H^+ abundance structure in LkCa 15 and V4046 Sgr. Based on our N_2H^+ (7-6) observations we will determine if the existence of a N_2H^+-rich surface layer can explain the difference in N_2H^+ (3-2) emission morphology. Furthermore we will constrain whether the N_2H^+ (3-2) emission originates from the N_2H^+-layer between the CO and N_2 ice surfaces or from the N_2H^+ surface layer and therefore calibrate the usage of N_2H^+ emission as a CO iceline tracer.

Secondary goal: CO underabundance in disk surface layer: van 't Hoff et al. (2017) showed that presence and thickness of the N_2H^+-rich surface layer is directly linked to the CO/N_2 abundance ratio higher up in the disk. Using the characteristics of the N_2H^+ surface layer obtained from our N_2H^+ (7-6) observations we will constrain the CO/N_2 ratio in the surface layer of the disk. Coupled with the underabundance of CO inferred low$-J$ CO isotopologue lines deeper in the disk, this will provide valuable information about the processes responsible for this underabundance (e.g., the importance of vertical mixing; Kama et al. 2016; Krijt et al. 2020).

References Blum & Wurm 2008, ARA&A, 46, 21 • Bruderer et al. 2012, A&A, 541, A91 • Huang & Öberg 2015, ApJL , 809, L26 • Kama et al. 2016, A&A, 592, A83 • Kastner et al. 2018, ApJ, 863, 106 • Krijt et al. 2020, ApJ, 899, 134 • Loomis et al. 2020, ApJ, 893, 101 • Nomura et al. 2016, ApJL , 819, L7 • Öberg et al. 2011, ApJL , 743, L16 • Qi et al. 2015, ApJ, 813, 128 • Qi et al. 2013, Science, 341, 630 • Qi et al. 2019, ApJ, 882, 160 • Ros & Johansen 2013, A&A, 552, A137 • Schwarz et al. 2019, ApJ, 877, 131 • van 't Hoff et al. 2017, A&A, 599, A101

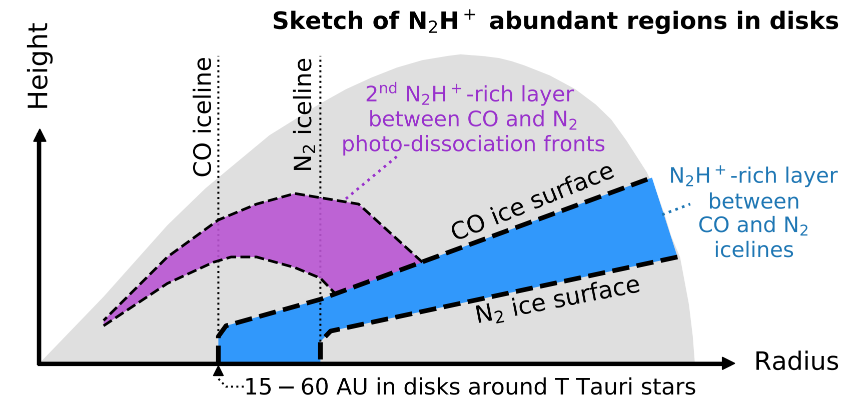

Figure 1: *Sketch of the two N_2H^+-rich layers expected in protoplanetary disk (e.g. van 't Hoff et al. 2017). The N_2H^+-rich layer between the CO and N_2 ice surface is shown in blue. Shown in purple is the second N_2H^+-rich layer close to the disk surface, between the N_2 and CO photo-dissociation fronts.*

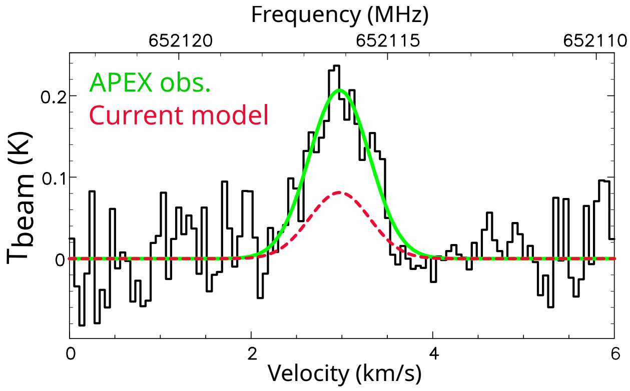

Figure 2: *First APEX detection of N_2H^+ (7-6) in the nearby disk TW Hya (project 0106.C-0669(A), PI: Trapman). Green line shows a Gaussian fit to the observations, which is 3× brighter than the expected N_2H^+ (7-6) flux from existing models (van 't Hoff et al., 2017)*

Table 1: Source information

Source	Dist (pc)	M_* ($M_\odot$)	T_{eff} (K)	L_* ($L_\odot$)	N_2H^+ (3-2) flux (Jy km/s)	N_2H^+ (3-2) morphology
LkCa 15	158	1.2	4365	1.0	1.82	narrow ring
V4046 Sgr	72	1.75	4370	0.49	3.76	broad ring

Notes: Stellar properties are adopted from Gaia DR2. N_2H^+ (3-2) emission properties from Qi et al. (2019)

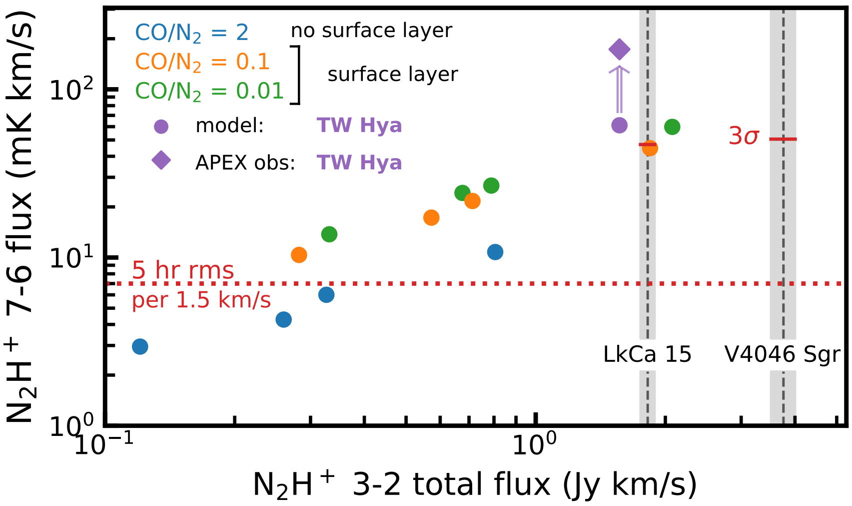

Figure 3: *N_2H^+ (7-6) and N_2H^+ (3-2) integrated intensities for a suite of disk models of similar size and with similar mass to LkCa 15 and V4046 Sgr, but with different vertical structures (scale height, flaring angle and gas-to-dust mass ratio in the surface layer). Note that N_2H^+ 76 integrated intensity was calculated using the APEX beam at 652 GHz. Colors show different CO/N_2 ratios, where $CO/N_2 \leq 1$ results in a N_2H^+-rich surface layer. Integrated N_2H^+ (3-2) line fluxes for LkCa 15 and V4046 Sgr are shown in gray (Qi et al., 2019). The purple markers show N_2H^+ fluxes for TW Hya, where the APEX detection of N_2H^+ 7-6 (diamond; see Figure 2) is 3× brighter than what current models predict (circle; van 't Hoff et al. 2017). The red dotted lines shows the requested rms. The red lines show the 3σ level for our two sources, based on the requested rms and the expected N_2H^+ (7-6) line width ($\sim 4-5$ km/s).*

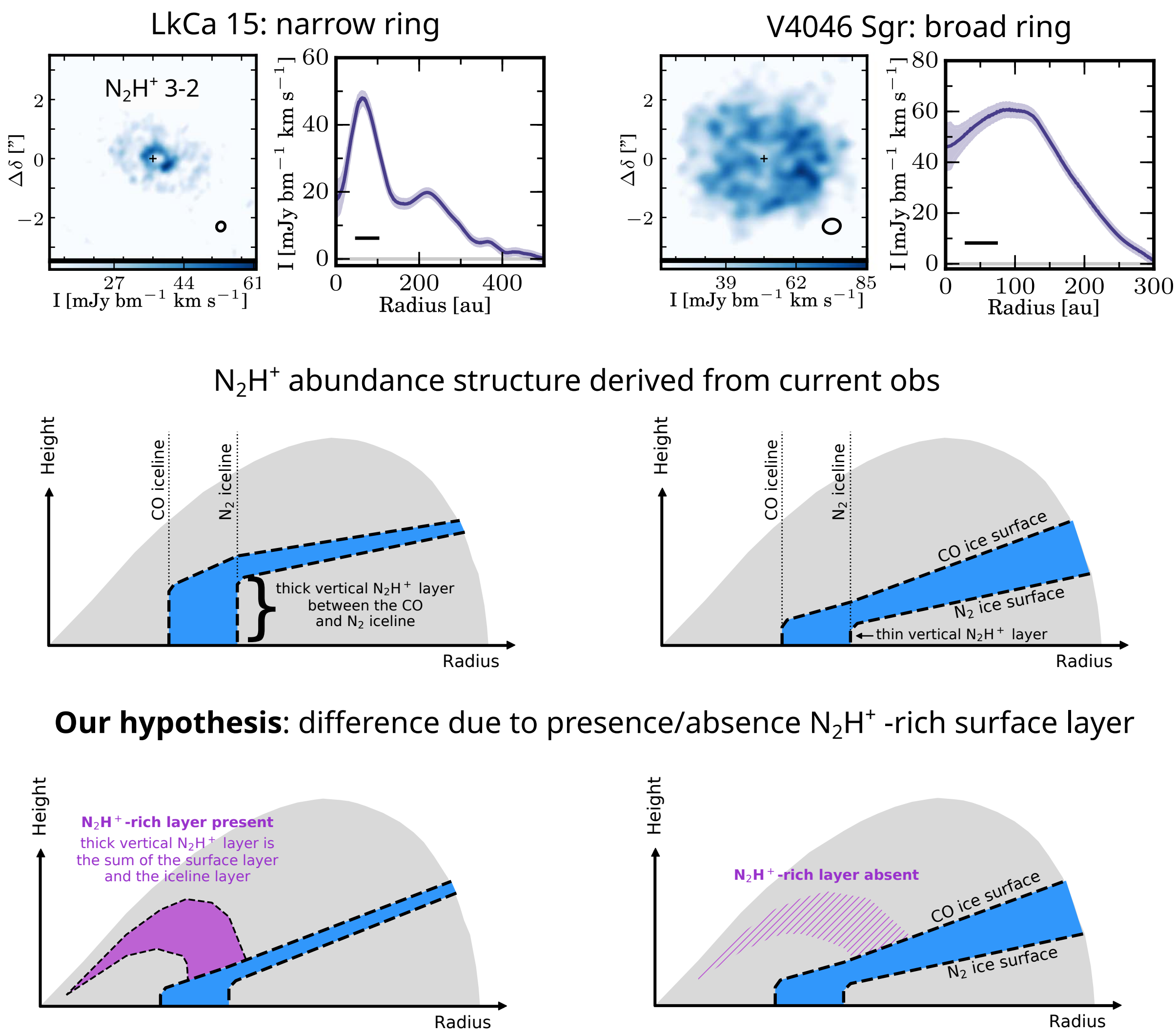

Figure 4: ***Top panels:*** *N_2H^+ (3-2) moment zero maps and radial intensity profiles of LkCa 15 (left), showing a narrow ring, and V4046 Sgr (right), showing a broad ring (Qi et al., 2019).* ***Middle panels:*** *sketches of the two types of N_2H^+ abundance structures inferred from these observations, assuming N_2H^+ is only abundant between the CO and N_2 icelines (adapted from Qi et al. 2019).* ***Bottom panels:*** *Our hypothesis for the inferred N_2H^+ abundance structure, where the thick vertical N_2H^+ layer on the left is the sum of a N_2H^+-rich surface layer and the N_2H^+-rich layer between the two iceline.*

No PhD Students involved

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

We used APEX SEPIA660 to detect N2H+ 7-6 (S/N=10) in the nearby protoplanetary disk TW Hya (project 0106.C-0669(A)). This detection was obtained with 5 hours of observing time, including overheads.

Additional remarks

ESO=ltrapman

Observing run info :