Isotopic reservoirs of interstellar nitrogen

Recent results and new questions

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November 8-9th 2017

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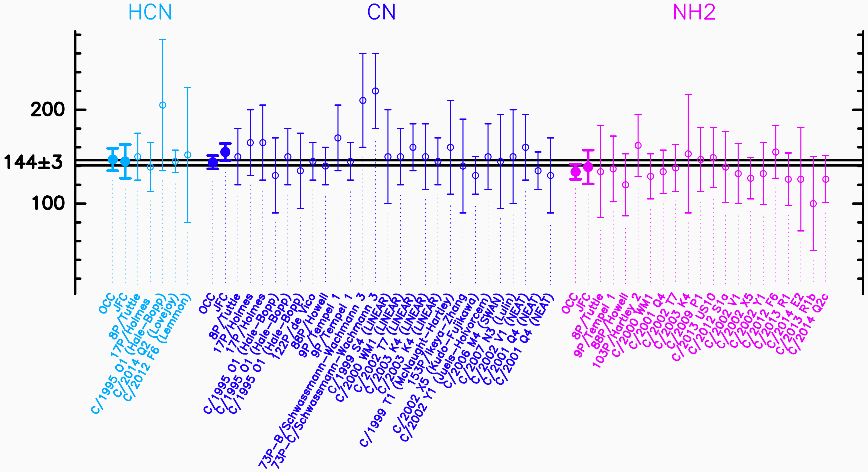
Introduction

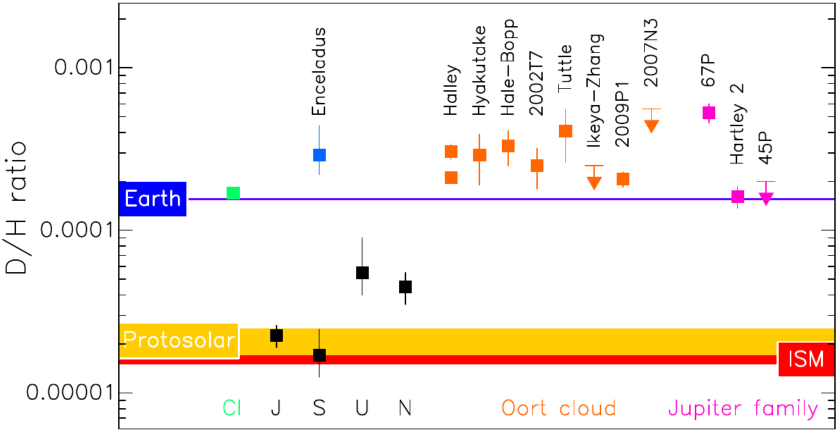
The message from comets



Bockelée-Morvan et al. (2015); Hily-Blant et al. (2017b)

- Cometary ratio: $\langle \mathcal{R} = {}^{14}\mathrm{N}/{}^{15}\mathrm{N} \rangle = 144 \pm 3$
- No dependence on comet type

The D/H in comets



D/H shows large variations in comets

The mysterious origin of N in the solar system

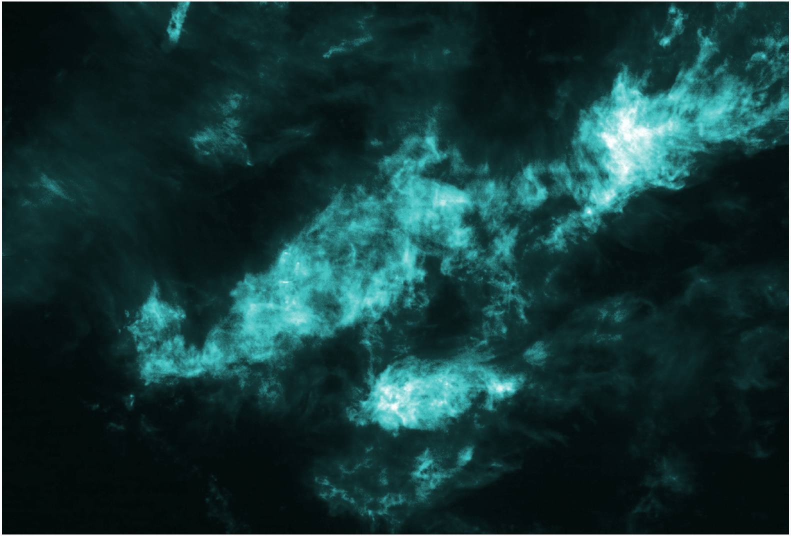
Evidences

- Bulk: protosun, Jupiter: $\mathcal{R} = 441 \pm 6$ (Marty et al. 2011)
- Comets: trace a secondary, widespread, reservoir
- Earth atmosphere: $\mathcal{R}$=272
- Large variations in the solar system: N is sensitive to ... something; could be a fantastic tool

Questions

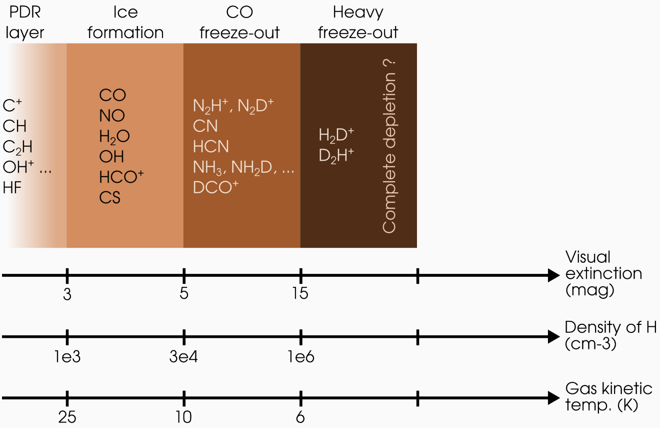
- Where did comets form ?
- Is there any trace of the bulk reservoir in comets ?
- Origin of nitrogen on Earth ?
- Several reservoirs: when, where, and how ?

Molecular clouds



All stars and planets form in molecular clouds

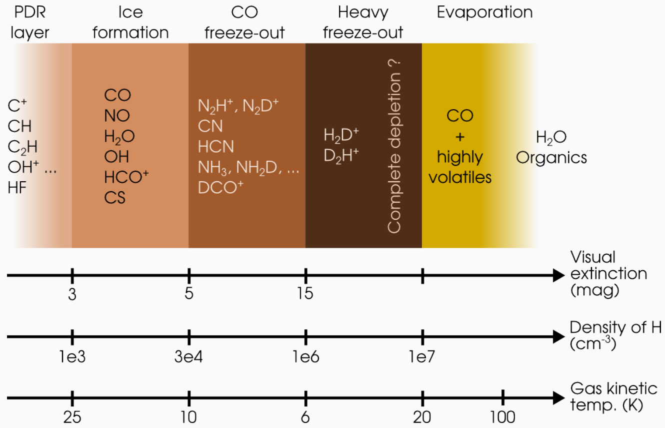
From cores to protostars to disks



adapted from Bergin & Tafalla 2007

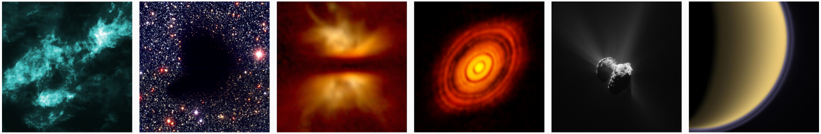
- prestellar cores: chemical factory

From cores to protostars to disks



- prestellar cores: chemical factory
- Protostars: fraction of ices evaporating during protostellar phase is unclear; at most 10-20% ? (van Dishoeck et al. 2014)

The interstellar heritage of planetary systems



Interstellar phase Primitive solar system

- PSN stage: major reset of chemistry ?
- Are cometary ices inherited from the prestellar phase ? (Rosetta results on O_2 and S_2)
- To which extent are interstellar-chemistry products preserved into planetary systems ?

Origin of the isotopic reservoirs in the PSN

- Interstellar: molecular clouds, prestellar cores, protostars
    - chemical fractionation: ZPE defects; questionable (Roueff et al. 2015)
    - selective photodissociation: inoperant at $A_{\mathrm{V}} \sim 10$mag
    - exchange in ices (known for H/D in methanol, e.g. Faure et al 2015) ?
- In situ, within the PSN
    - selective photodissociation (Heays et al. 2014); potentially efficient
    - chemical fractionation: heavy freeze-out where T are low; inefficient
    - exchange in ices: unknown
- Posterior to formation of bodies
    - exchange in ices: unknown

Following the trail of volatiles

Challenges

- Major elemental reservoirs not visible (N, O, S): rely on trace species and chemical models
- Heavy/complete depletion (Walmsley et al. 2004; Friesen et al. 2014): how to follow unvisible volatile reservoirs ?
- Strategy: use isotopic ratios to identify the reservoirs

Problems

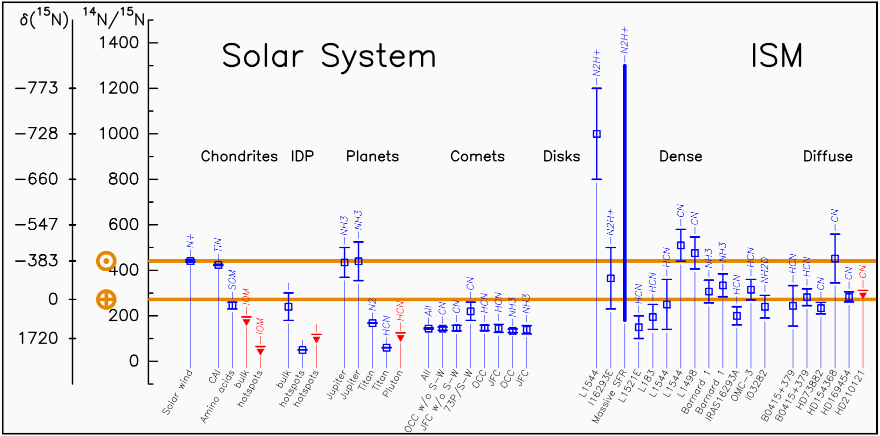
- Elemental volatile reservoirs of the main elements (C, N, O, S) are poorly known: uncertainties in model predictions
- Chemical fractionation in dark clouds: open issue
- Impacting issues: oxygen and sulfur chemistry

This talk

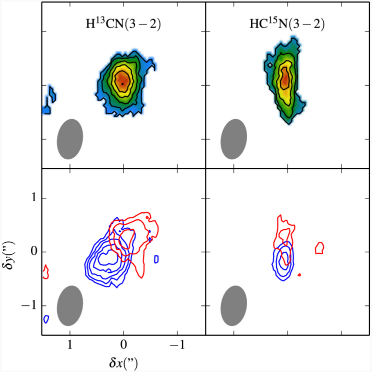
- What is the present-day $^{14}N/^{15}N$ isotopic ratio in the local ISM ?
- Evince two isotopic reservoirs in protoplanetary disks
- Isotopic reservoirs in prestellar cores

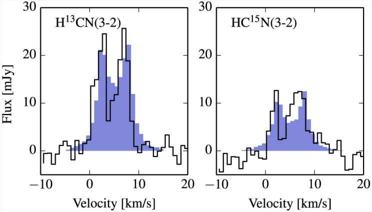
$^{14}N/^{15}N$ in protoplanetary disks

The $^{14}N/^{15}N$: overview



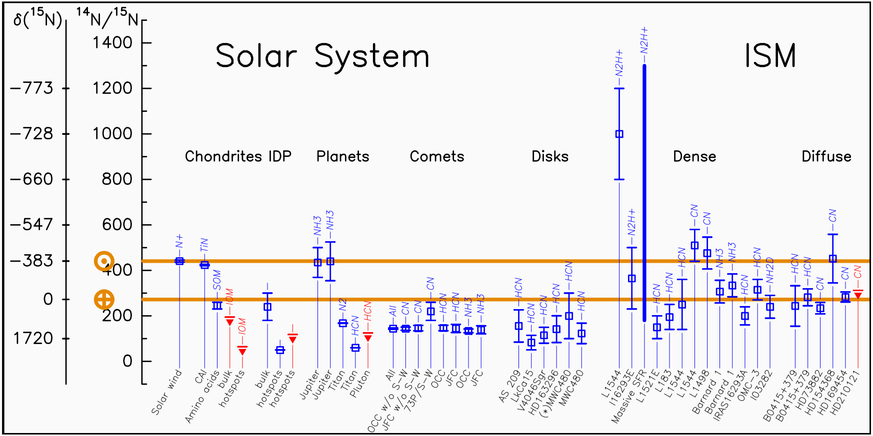
$^{14}N/^{15}N$ in HCN in disks: MWC 480





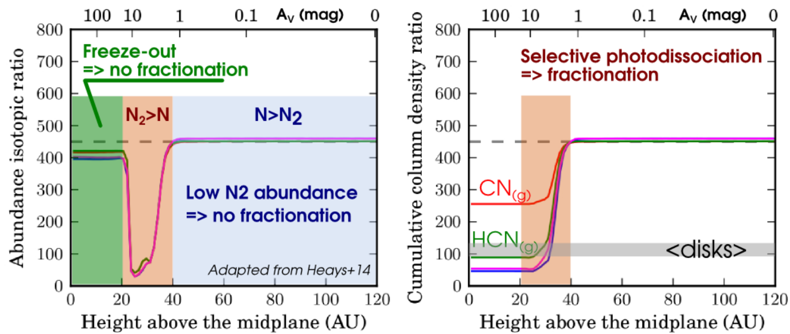
- MWC 480: Herbig Ae star, $d = 140$ pc
- Guzmán et al. (2015): $H^{13}CN/HC^{15}N$=2.8±1.4, $\mathcal{R}$=200±110
- using our method: $H^{13}CN/HC^{15}N$ 1.9±0.4, $\mathcal{R}=132 \pm 24$
- Guzmán et al. (2017): 1.8±0.3, $\mathcal{R}$=142±59

The nitrogen ratio in disks



- ALMA: $\langle \mathrm{H}^{13}\mathrm{CN}/\mathrm{HC}^{15}\mathrm{N}\rangle = 1.6 \pm 0.1$ (Guzmán et al. 2017)
- Assuming HCN/H^{13}CN=70 $\Rightarrow \langle \mathrm{HCN}/\mathrm{HC}^{15}\mathrm{N}\rangle = 111 \pm 19$

Fractionated reservoir: in situ origin



- Fractionated reservoir in disks
- Ratio in HCN close to that of solar system comets
- Proposed explanation (Guzman): selective photodissociation of N_2 in the PSN (Heays et al. 2014) $\Rightarrow$ No interstellar origin

Fractionated reservoir: in situ origin

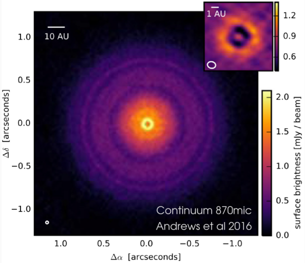
Caveats

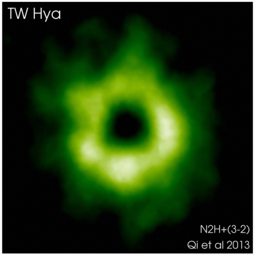
- Double-isotopic ratio: indirect determination
- Disk sample: different masses (X-UV flux) and ages (dust size) but uniform ratio: compatible with selective photodissociation ?
- $HCN/H^{13}CN$ or as low as 30-45 (Daniel et al. 2013, Magalhaes et al to be submitted): $\mathcal{R}$=55±10
- $HCN/H^{13}CN$ as high as 140 (Roueff et al. 2015): $HCN/HC^{15}N$=222±40

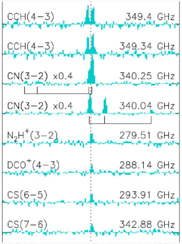
⇒ is this a fractionated reservoir ? or the bulk ?

CN/C^{15}N towards TW Hya

A protostellar analog: TW Hya



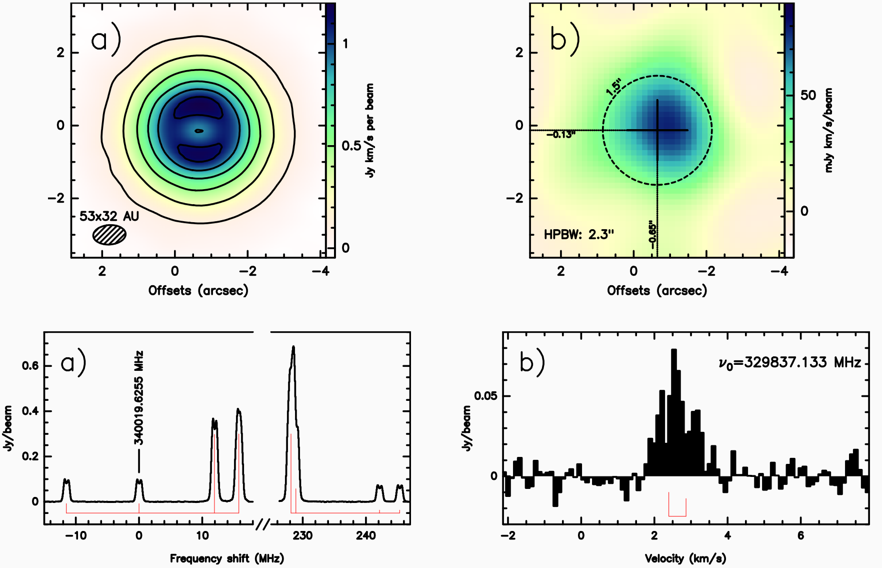




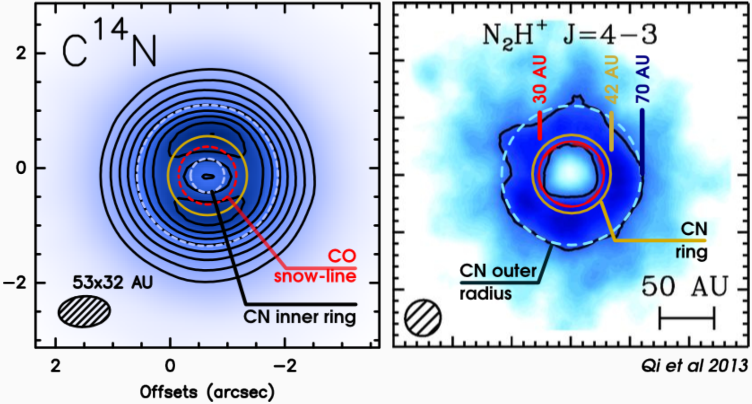
APEX line survey / Kastner et al 2014

- close by: 59.5±1 pc (ESA/GAIA)
- strong CN(3-2) line
- face-on: hf structure is resolved
- 8 Myr, ∼ giant planet formation stage
- ALMA: the only facility to measure N-isotopic ratios in disks

CN and $C^{15}N$ towards TW Hya



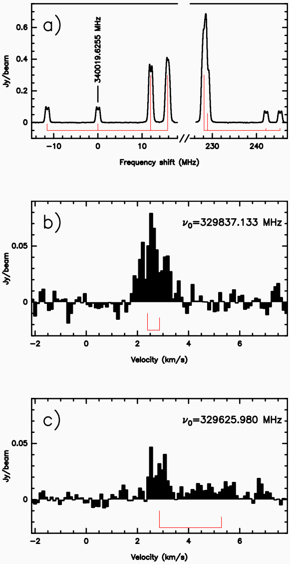
Ring-like CN emission



Qi et al 2013

- Ring: $R = 42$ AU, FWHM=54 AU ($d = 59.5 \pm 1.0$)
- Simple analysis in the direct plane: no sharp inner edge
- Radiative transfer modelling in the *uv*-plane is required
- Related to chemistry of CN in disks (Cazzoletti et al. 2017)

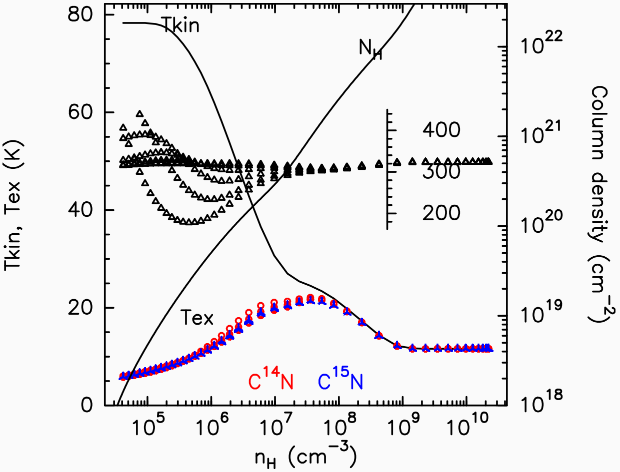
CN and C^{15}N towards TW Hya



- high SNR of CN: optically thin hf lines
- three C^{15}N hf lines: optically thin
- Direct determination of the column density ratio
- analysis in the *uv* plane: co-spatial distributions (Gaussian disks), single excitation temperature

$$\mathrm{CN/C^{15}N} = 323 \pm 30$$

Origin of the CN emission



- Excitation: thermalized (2-1) and (3-2) transitions
- Equal excitation temperature for both isotopologues
- CN emission from the cold molecular layer (narrow lines)

Multiple isotopic reservoirs in PSN

- HCN in MWC 480: $H^{13}CN/HC^{15}N$ $1.9 \pm 0.4 \times 70 = 132 \pm 24$
- HCN in 5-disks sample: $\langle \mathcal{R} \rangle = 111 \pm 19$
- CN in TW Hya: $CN/^{15}N = 323 \pm 30$
- all located in the solar neighbourhood
- Solar neighbourhood: chemically homogeneous within $\sim$1.5 kpc (Sofia & Meyer 2001)

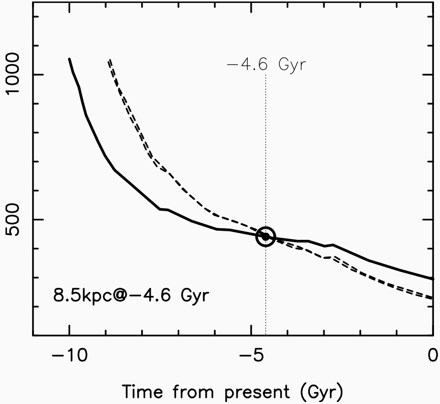
$\Rightarrow$ All those disks carry the same elemental $^{14}N/^{15}N$

Results

1. Two isotopic reservoirs of nitrogen at the PSN stage: elemental and fractionated
2. Present in comet forming regions; comets retained only one reservoir

The present-day elemental $^{14}N/^{15}N$ ratio in the local ISM

Galactic chemical evolution models

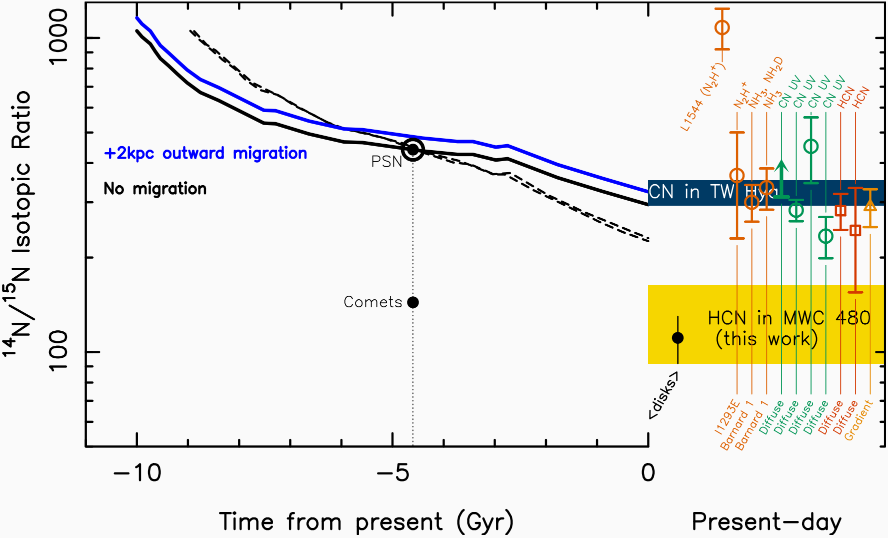


- Stellar nucleosynthesis: $^{14}N/^{15}N$ decreases with time (Romano & Matteucci 2003; Romano et al. 2017)
- 441 is the elemental ratio 4.6 Gyr ago, where the PSN formed
- Where did the Sun formed ?

Where was the sun formed ?

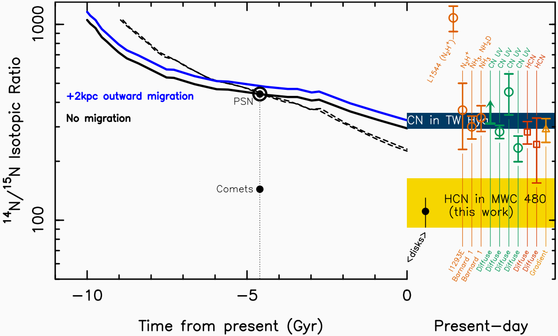
- $\mathcal{R}$=441: protosun, 4.6 Gyr ago, but where ?
- evidences from metallicty for a formation at smaller galactic radius (Nieva & Przybilla 2012; Minchev et al. 2013)
- pure dynamical evolution: inward migration (Martínez-Barbosa et al. 2015)

The present-day $^{14}N/^{15}N$



Hily-Blant et al. (2017b)

The present-day $^{14}N/^{15}N$

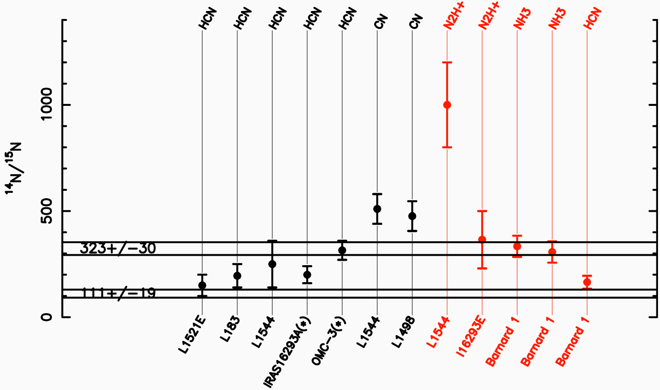


Hily-Blant et al. (2017b)

- CN/C^{15}N ratio in TW Hya reflects the present-day ratio
- Consistent w/ direct dense and (S-P–corrected) diffuse measurements
- Consitent w/ outward migration from 5–6 kpc (Minchev et al. 2013)

Identify isotopic reservoirs in prestellar cores

The $^{14}N/^{15}N$ ratio in prestellar cores in the LISM

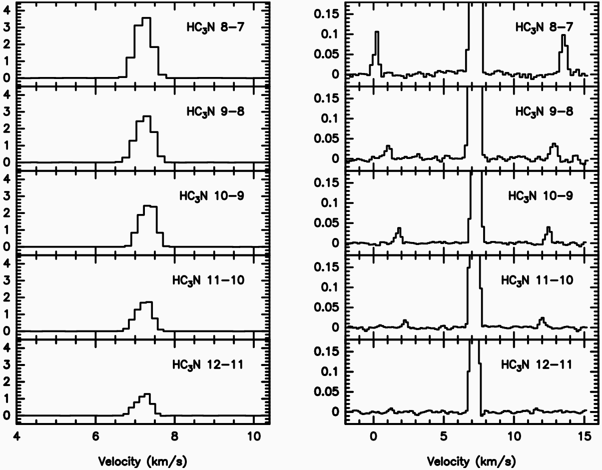


- Direct measurements: consistent with the two reservoirs seen in disks (Hily-Blant et al. 2013)
- N_2H^+: a problem...

Observations of HC_3N and $HC_3^{15}N$ towards L1544

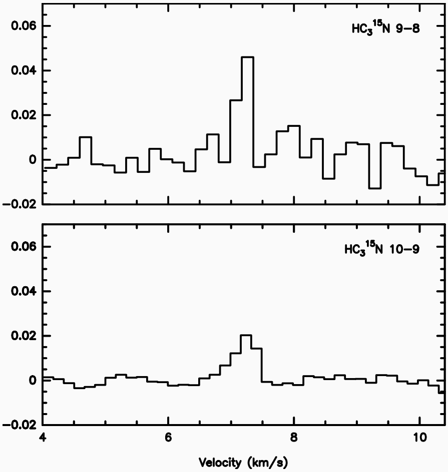
- L1544: prestellar core; signatures of collapse; before first Larson core
- Observations in the ASAI large program (Lefloch & Bachiller; Vastel subgroup leader)
- Motivation: direct measurement; HCN challenging because of hyperfine anomalies (Magalhaes talk)

HC_3N and $HC_3^{15}N$ spectra towards L1544



- exquisite sensitivity
- hf structure
- one position; multiple lines; no single excitation temperature

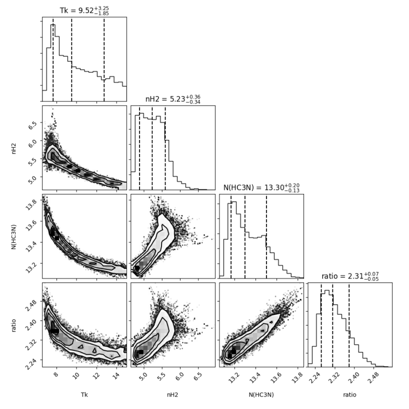
HC_3N and $HC_3^{15}N$ spectra towards L1544



- exquisite sensitivity
- hf structure
- one position; multiple lines; no single excitation temperature

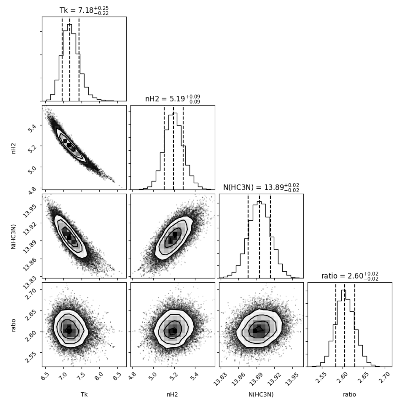
Two analysis: two results

Rotational analysis



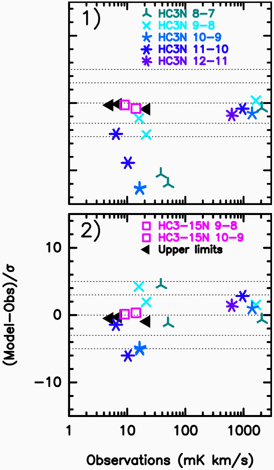
$\mathcal{R}$=216±30

Hyperfine analysis



$\mathcal{R}$=400±20

Two analysis: two results



- hyperfine analysis: better overall agreement
- $\mathcal{R}$=400±20

The isotopic ratio in HC_3N

Source	Species	$\mathcal{R}$	Method§	Reference
TMC1(CP)	HC_3N	270±57	Direct	(1–3)
	HC_3N	257±54	Indirect	(1–2)
	HC_5N	323±80	Direct	(1)
	HC_5N	344±80	Indirect	(1)
L1527	HC_3N	338±12	Indirect	(4)
L1544	HC_3N	400±20	Direct	This work
	HCN	140–350	Indirect	(5)
	CN	500±75	Indirect	(6)
TW Hya	CN	323±30	Direct	

§ Direct methods measure the $X^{15}N/X^{14}N$ abundance ratio; indirect methods use double isotopic ratios.

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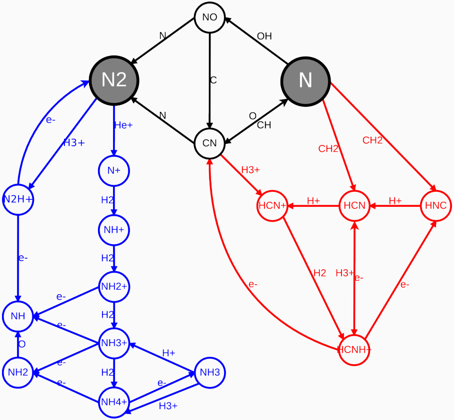
- $\mathcal{R}$=400±20
- Chemistry: which formation route dominates ?
- $C_2H_2 + CN \longrightarrow HC_3N + H$
- $HNC + C_2H \longrightarrow HC_3N + H$
- Recent work: source dependent (**?**)
- This work: marginally supports CN route;

Conclusions and perspectives

Conclusions

1. Direct measurement of CN/C^{15}N in TW Hya: 323±30
2. HCN/HC^{15}N in sample of disks: 111±19
3. Direct evidence for multiple reservoirs in PSN analogs
4. Two reservoirs have 3:1 ratio, just like PSN:comets
5. CN not a photoproduct of HCN
6. CN traces the molecular layer
7. Present-day elemental ^{14}N/^{15}N ratio in LISM: 323±30
8. Consistent with all (but N_2H^+) direct measurements in dense & diffuse ISM
9. Consistent with Galactic Chemical Evolution models

New scenario



Hily-Blant et al. (2013)

- Two isotopic, interstellar, reservoirs of nitrogen: N (≈ 140) and N_2 (≈ 441) in parent molecular cloud
- Cometary measurements: atomic N reservoir
- N_2 was the dominant reservoir in the PSN
- N_2 too volatile: not trapped in cometary ices
- cometary NH_3 from hydrogenation of N
- Earth: mixture of the two reservoirs ?

Observations

- Measure radial gradient of $^{14}N/^{15}N$ in disks
- Measure $HCN/HC^{15}N$ in TW Hya for direct comparison to $CN/C^{15}N$
- Measure $CN/C^{15}N$ in other disks (V4046Sgr)
- Measure directly $HCN/HC^{15}N$ in cores

Theory and chemical modelling

- Chemical fractionation of nitrogen in prestellar cores (N_2H^+)
- Direct measurement of $HCN/HC^{15}N$ in disks
- Collision cross sections for isotopologues of HC_3N

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