Astrochemistry below 100 GHz in the SKA band 6, ALMA band 1, and ngVLA era

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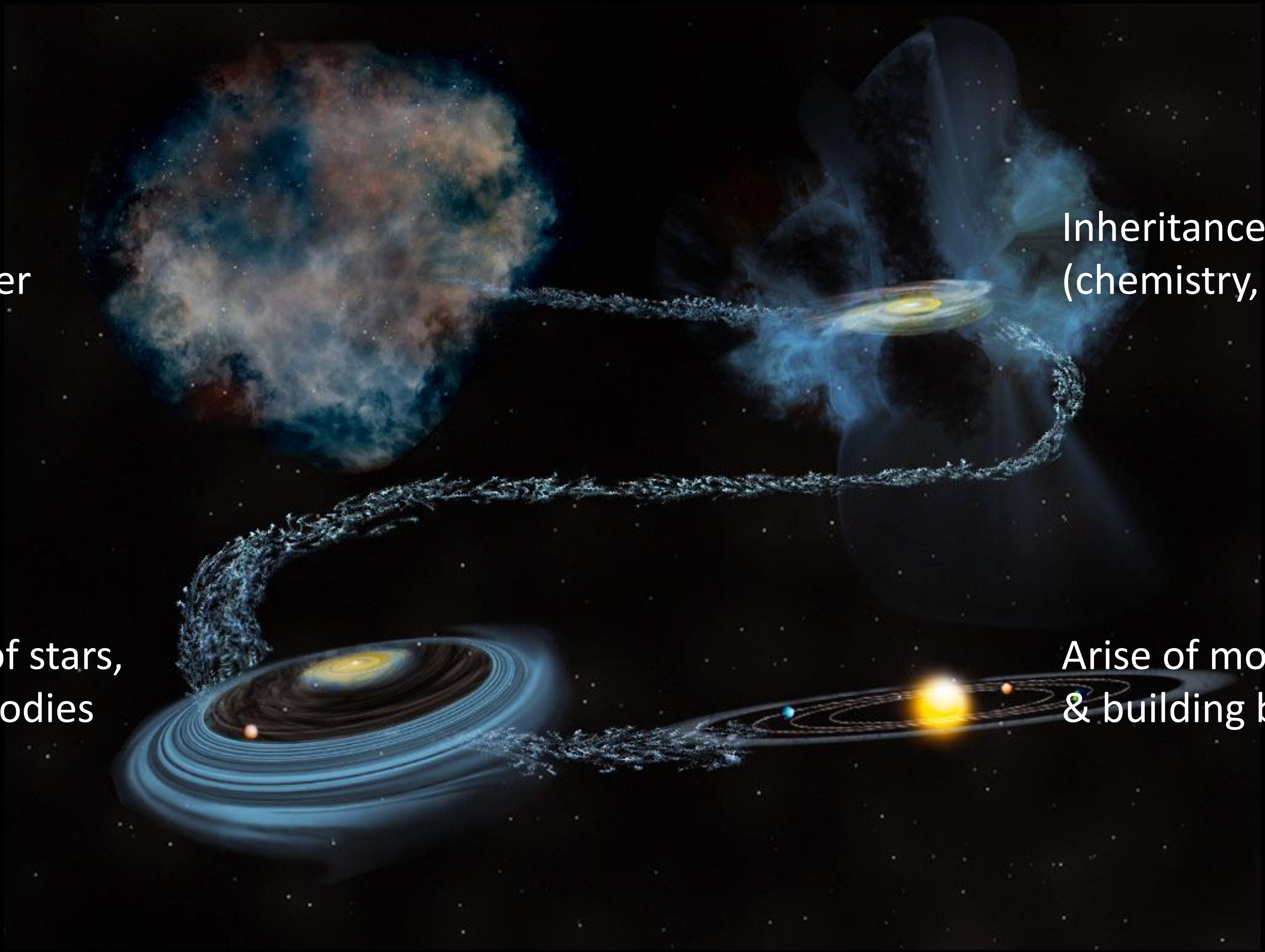
BErn Astrochemistry Research


Are we unique?

Astrochemistry: studying the molecular building blocks

Composition of interstellar matter

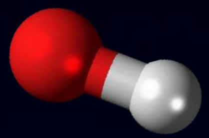
Inheritance vs. reprocessing (chemistry, radiation, heating)



Building blocks of stars, planets, minor bodies

Arise of molecular complexity & building blocks of life

Credit: Bill Saxton, NSF / AUI / NRAO

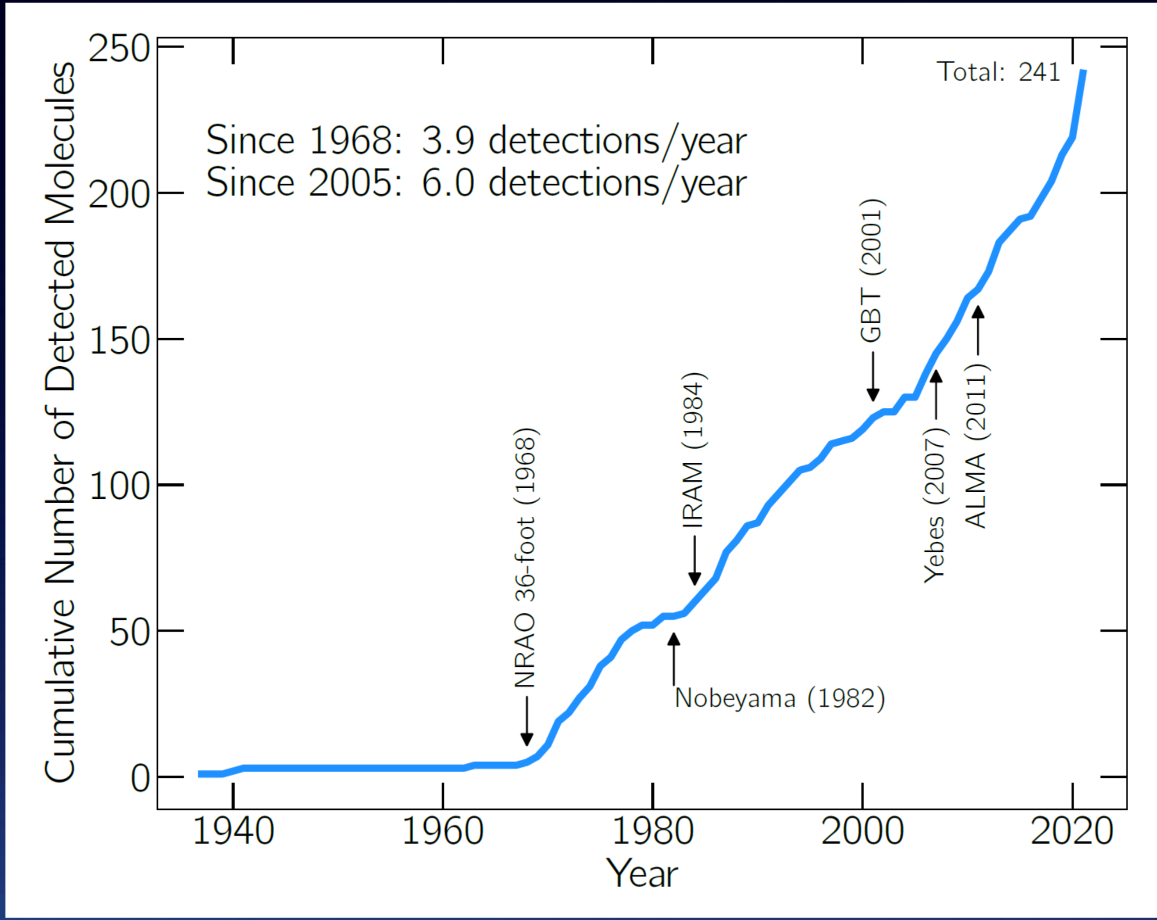


Inventory molecules in space

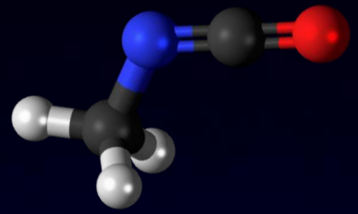
More than 320 interstellar molecules identified to date (thereof 74 also in other galaxies)

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	$MgCN$	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	$HCOOH$	$CNCHO$	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	$SiCN$	$HNCO$	C_3N^-	CH_2NH	$HNCNH$	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	$AlNC$	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	$SiNC$	C_2H_2	$HCNO$	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	$HOCN$	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	$HNCS$	$HSCN$	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	$AlOH$	$HOCO^+$	$HOOH$	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	$HMgNC$	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	$HCCO$	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	$FeCN$	H_3O^+	$CNCN$	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	$HONO$	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	$MgCCH$	$HCCNC$	C_4S	HC_4N	HC_3HNH
$NaCl$	SH	C_2S	CCN	HC_2N	$HCCS$	$HNCCC$	$CHOSH$	c-H_2C_3O	c-C_3HCCH
$AlCl$	TiO	C_3	$SiCSi$	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					$HNCHCN$	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	$MgNC$	NCO					MgC_4H	
CP		NH_2	$CaNC$					CH_3CO^+	
		$NaCN$	NCS					H_2CCCS	
		N_2O						CH_2CCH	

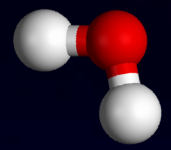
8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	PAHs	Fullerenes
$HCOOCH_3$	CH_3OCH_3	CH_3COCH_3	HC_9N	C_6H_6	C_6H_5CN	1-$C_{10}H_7CN$	C_{60}
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
HC_6H	CH_3CONH_2						
CH_2CHCHO	C_8H^-						
CH_2CCHCN	CH_2CHCH_3						
NH_2CH_2CN	CH_3CH_2SH						
CH_3CHNH	HC_7O						
CH_3SiH_3	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	$HCCCHCHCN$						
CH_2CHCCH	H_2CCHC_3N						



McGuire 2022, ApJ SS 259, 30



Astrochemistry below 100 GHz

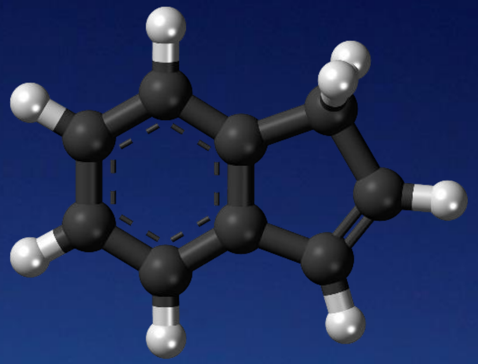


- Rotational transitions of larger, heavier molecules (e.g., including prebiotic species) often occur at frequencies ≤ 70 GHz
- Less line confusion (number of lines per frequency unit) and line blending (overlapping lines) at those frequencies compared to millimeter regime
- About 60 new detections since last edition of the "2021 Census of interstellar molecules" (McGuire 2022, ApJ SS 259, 30), majority of them either with the Yebes 40m or the Greenbank telescope, i.e. at "long wavelengths" (> 4mm)

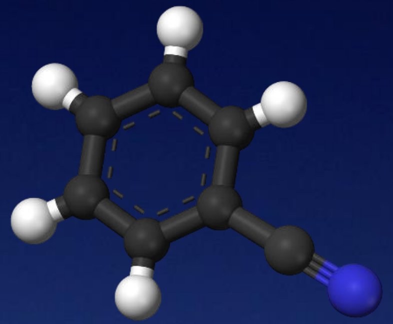
→ radio domain has proven to be a treasure trove for new species!

Limitations of current single-dish observations

- QUIJOTE (PI: Cernicharo) molecular survey of TMC-1 carried out with the Yebes 40m, GOTHAM (PI: McGuire) survey with the Green Bank telescope
- Line stacking required for some detections → need higher sensitivity
- Single point observations → require high angular resolution and sensitivity for spatial information (crucial for understanding chemical links!)

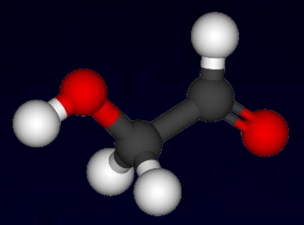


Indene

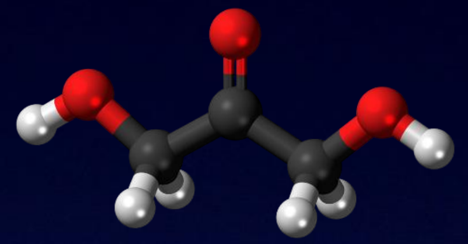


Benzonitrile

Detection of new species: sugars

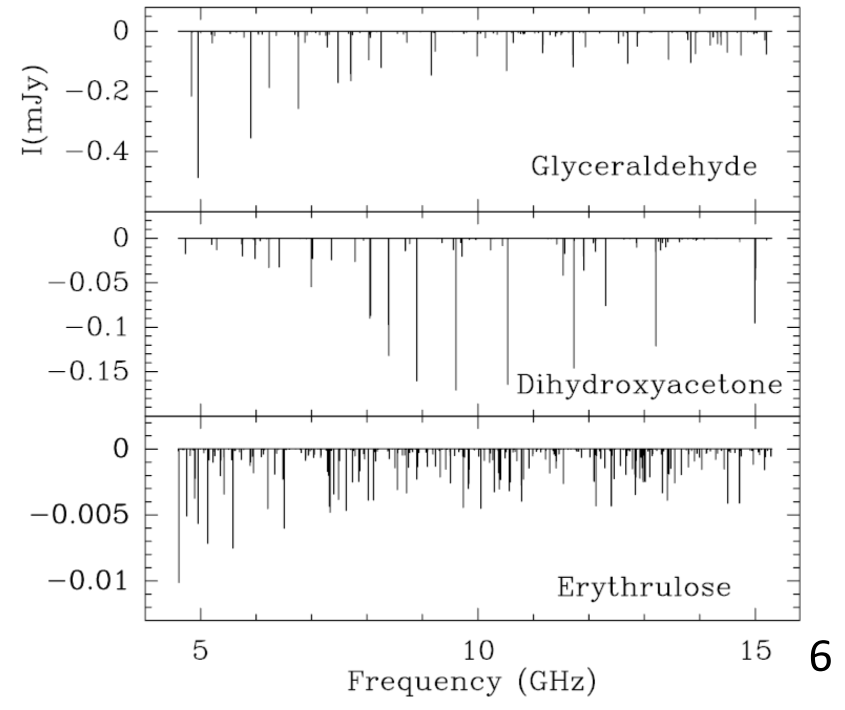


- C2-"sugar" glycolaldehyde CH_2OHCHO detected (e.g., Hollis et al. 2000, Halfen et al. 2006, Jørgensen et al. 2012)



- Unsuccessful searches for C3 sugars like glyceraldehyde ($CHOCHOHCH_2OH$) or dihydroxyacetone ($CH_2OHCOCH_2OH$) Present in meteorites!

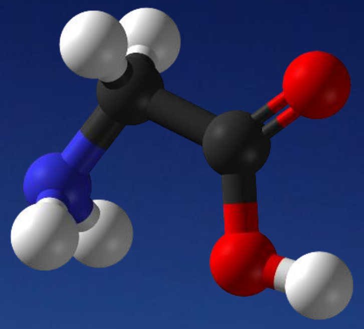
- SKA band 5 and 6 well suited for observing prebiotic species (strength of rotational transitions for high dipole moment molecules drops dramatically at lower freq.)

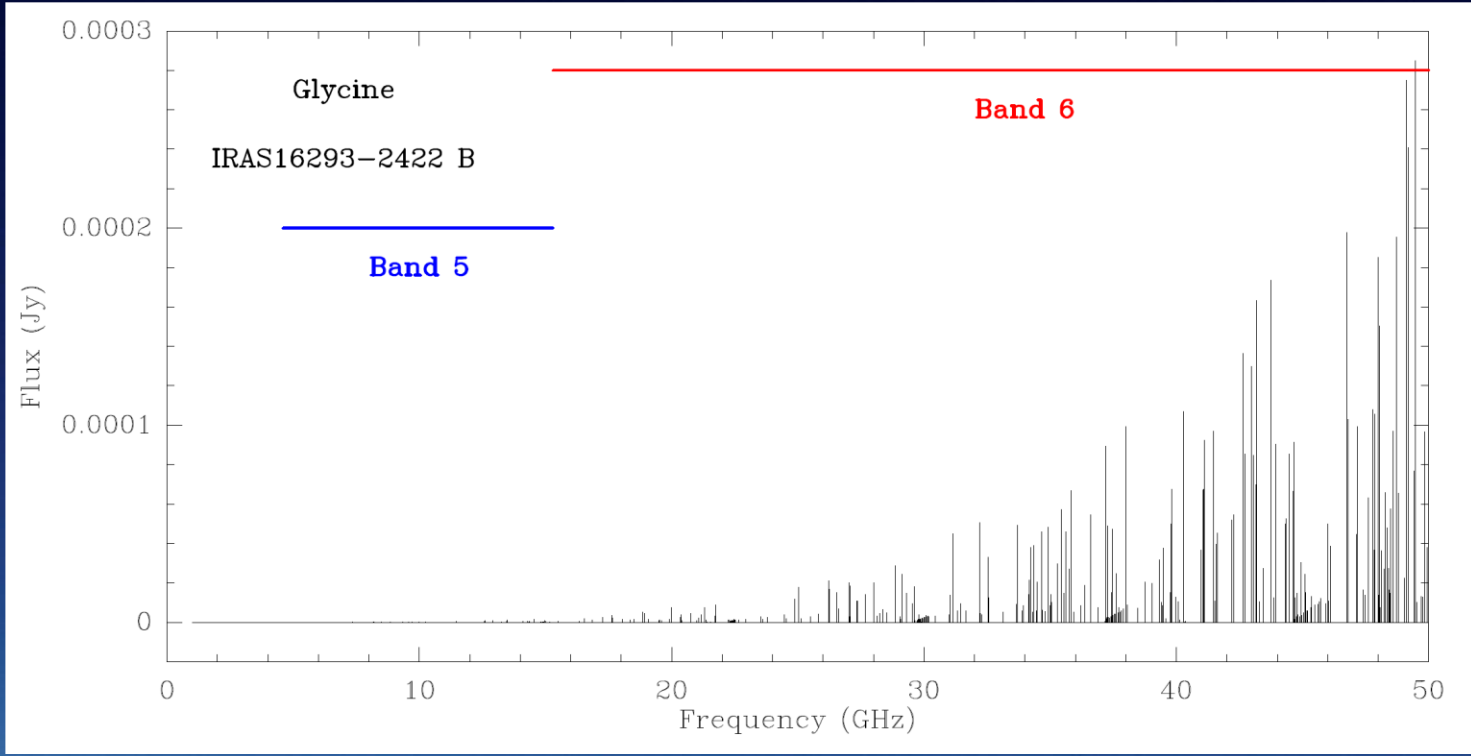


Predicted absorption spectra for prebiotic species
Jiménez-Serra et al. 2022, FSPAS 9, 843766

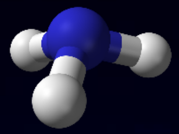
Glycine – the simplest amino acid

- The holy grail in astrochemistry
- Detected in meteorites and comet 67P/Churyumov–Gerasimenko
- Sub-/Millimeter detections not confirmed – best observed in SKA band 6 (too faint in band 5!) or ALMA band 1

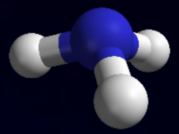




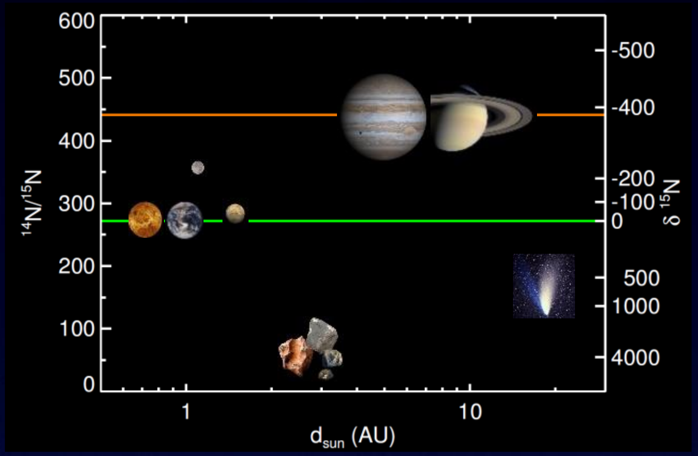
SKA Memo 20-01
Conway et al. (2020)



Volatiles like Ammonia

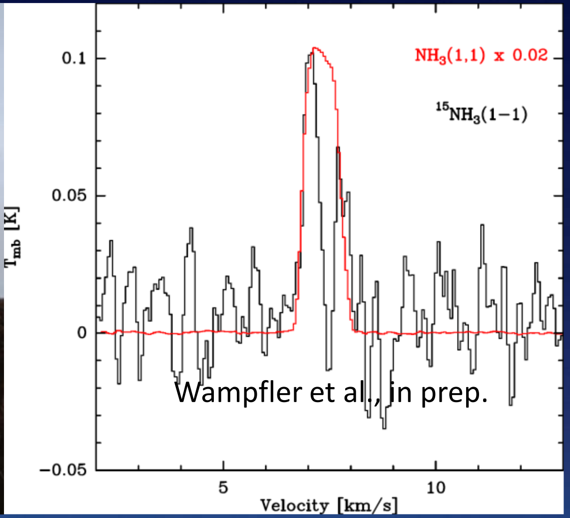


- Ammonia is an important reservoir of nitrogen
- Nitrogen inversion transitions in band 6
  NH_3 at 23.7 GHz
  $^{15}NH_3$ at 22.6 GHz (potential issue: frequency protection!)



- Band 6 opportunities:
  - mapping
  - higher sensitivity & angular resolution for faint sources
  - increasing chances of detection for comets
    (ammonia photo-dissociated on short scale)

Effelsberg 100m



Wampfler et al., in prep.

ALMA band 1 now available

- Band 1 (35-50 GHz, 6-8.6mm) are the longest wavelengths offered at ALMA
- First light achieved in August 2021
- Shared risk observations offered to PIs for the first time in cycle 10 (Oct. 23-Sept. 24)
- Regular observing available for cycle 11, starting October 1st, 2024

Credit: ASIAA/Yuh-Jing Hwang and ASRD

ALMA band 1 challenges & opportunities

- High spectral resolution line surveys of galactic sources will remain challenging until ALMA correlator upgrade (increased instantaneous bandwidth) with the ALMA 2030 roadmap

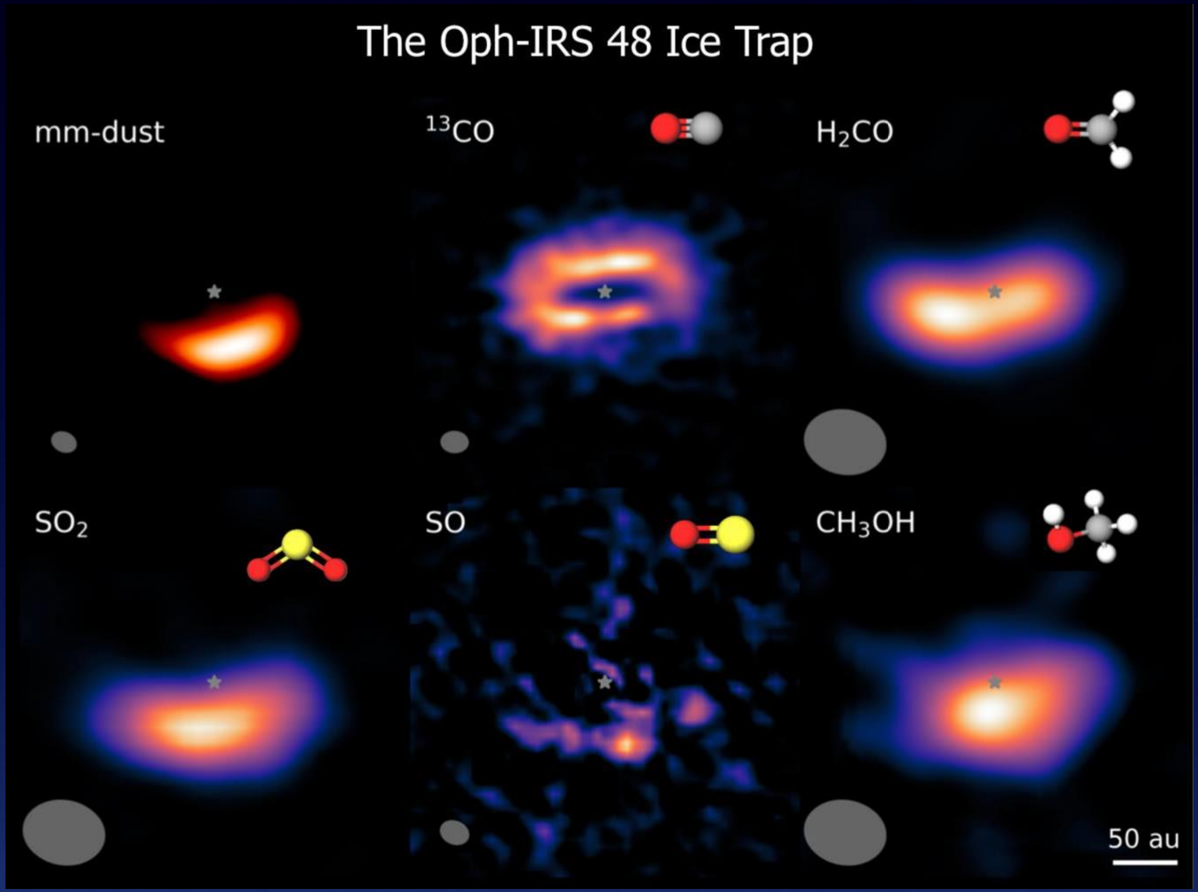
- Science verification data for high-mass star-forming region W51 available, as well as observatory projects (public data, continuum and CS) for protoplanetary disks HL Tau and HD 163296

Credit: ASIAA/Yuh-Jing Hwang and ASRD

- A number of us are looking into potential projects for cycle 12 (deadline in April 2025) as a pathfinder for Swiss activities related to SKA band 6

Synergies with ALMA – multiscale probing

- Complex physical and chemical structures of star-forming regions and disks
- Ability to probe different scales crucial for understanding evolution of disks (e.g. dust traps vs. rings for µm, mm, (and cm?) dust, different temperature regimes for molecular transitions at different wavelengths)
- Band 6 – especially if frequencies extend beyond 24 GHz – would close the gap between ALMA band 1 and SKA band 5.



Credit: Nienke van der Marel

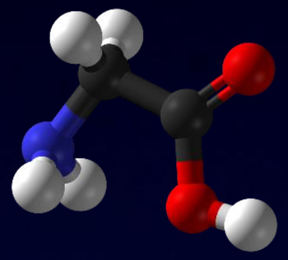
Solar system/star and planet formation

- Protoplanetary disk structure from **continuum emission at cm wavelengths** as constraints for planet formation models and pebble accretion scenarios, and peering into the terrestrial planet forming zone that may be opaque at higher frequencies

- Study youngest embedded exoplanets and star-planet interactions (aurorae from magnetic interactions, e.g. Pineda & Villadsen 2023)

- Solar system bodies (comets, moons (in particular Enceladus and Titan, planets) – higher angular resolution at shorter wavelengths – in support of space missions and centered around origin of life questions

Astrochemistry with SKA band 6, ALMA band 1, and ngVLA



- Detection of large prebiotic species including building blocks of life such as sugars and amino acids heavily **relies on availability of frequencies < 70 GHz**

- **Closing frequency gap with ALMA** indispensable for comprehensive picture of chemistry (inventory of species/spectral surveys, constraining excitation conditions, spatial distribution) and understanding link between chemical composition and dust structure in planet-forming regions of disks

- A new promising ground in the radio regime for **detections of complex molecules** opens with SKA bands 5/6, ALMA band 1, and the ngVLA will be highly complementary!