CHEMICAL DIVERSITY IN PROTOPLANETARY DISCS AND ITS IMPACT ON THE FORMATION HISTORY OF GIANT PLANETS

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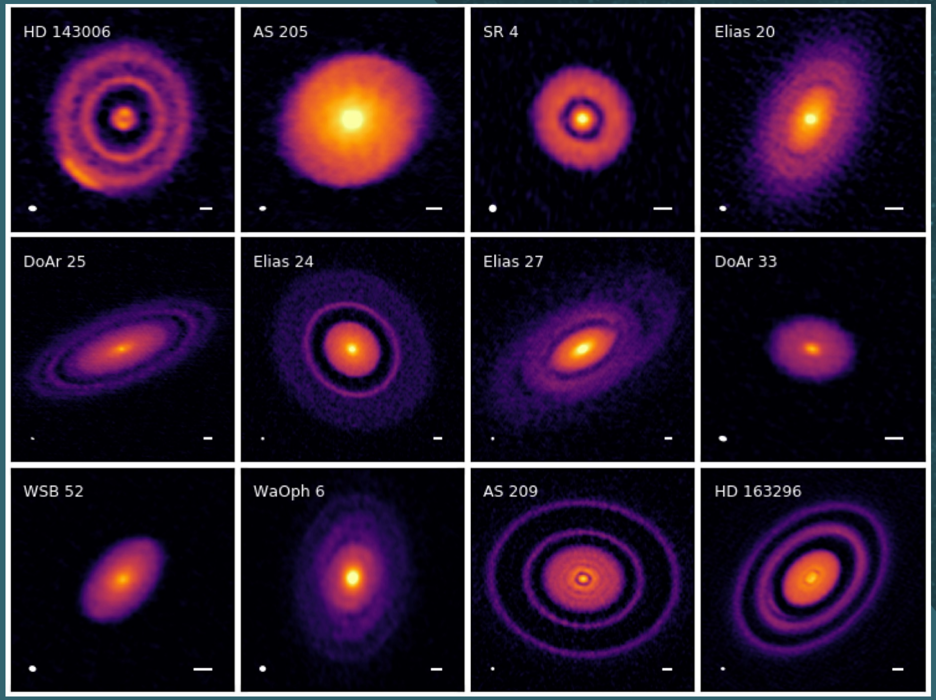
WHERE AND HOW DO GIANT PLANETS FORM?



Dust morphology in the circumstellar discs observed by the ALMA Large Program DSHARP (Andrews et al., 2018).

Observations of exoplanetary systems and protoplanetary discs:

- **large extension** of the planet-forming region.
- Giant planets over a **wide range of orbital radii** (0.01-100s au).

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INWARD MIGRATION

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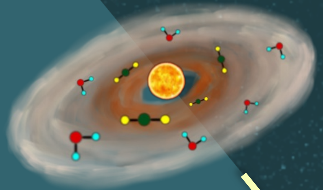
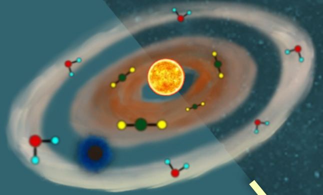
The composition of the planet's **atmosphere** keeps records of the planet **formation and migration history** (Öberg et al., 2011).

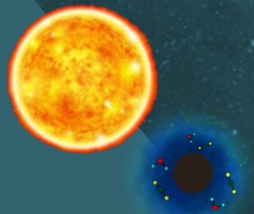
THE CHALLENGE OF CONNECTING PLANETARY AND DISC COMPOSITION



Giant planets can interact with multiple and chemically **diverse environments** in protoplanetary discs while they form and migrate to their final orbits.



The way this interaction affects the **accretion of gas and solids** shapes the chemical composition of the planets and of their atmospheres.



Chemical tracers in planetary atmospheres can be identified and used as observables in upcoming missions (e.g., JWST and Ariel).

Turrini et al. 2021 — Giant planet formation in the inheritance scenario of the protoplanetary disc.

the **composition of the disc** midplane is **not unique** but it is shaped by the pre-stellar core composition, the physical structure of the disc itself, and its level of chemical activity.

Pacetti et al. (submitted to ApJ) — effects of different disc chemical scenarios on the final elemental ratios in the atmospheres of giant planets

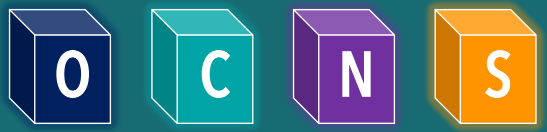
DISC COMPOSITIONAL MODEL

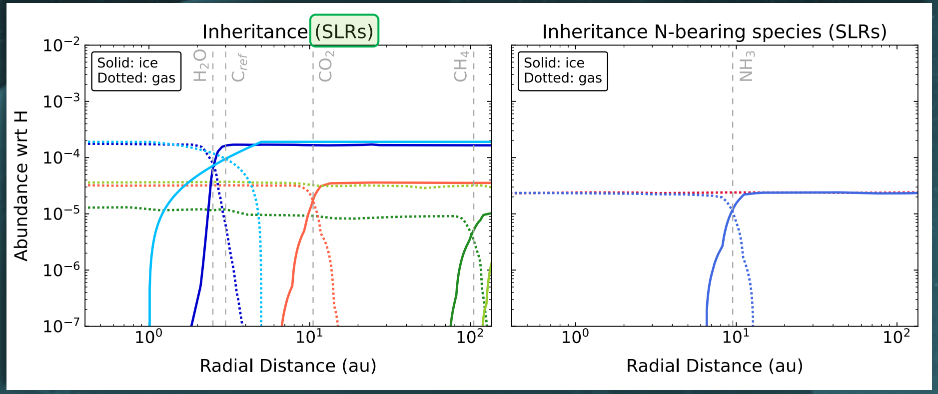
Two scenarios based on the astrochemical models by Eistrup et al. 2016 at 1Myr:

- **Inheritance** of the volatile species from the pre-stellar core.
- **Reset** of the chemistry to elemental species and their recombination

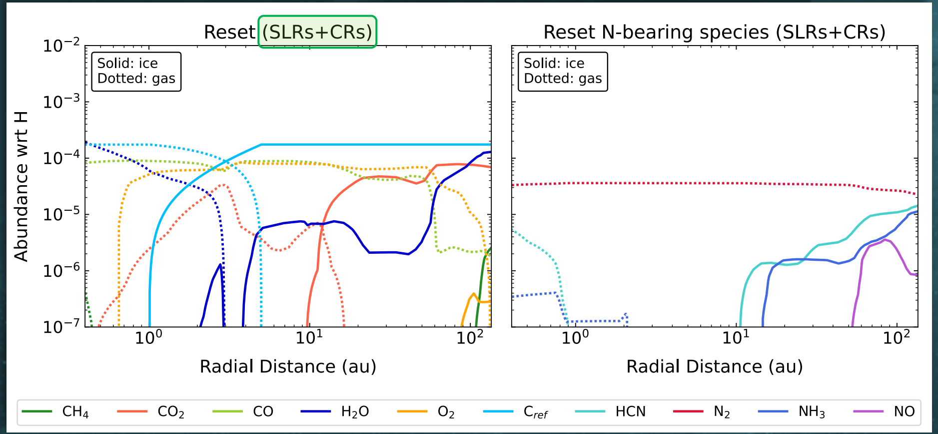
+ **rocks** calibrated against extrasolar and Solar System data (Lodders et al., 2010)

Our focus: set of four **elemental tracers**:





Increasing chemical complexity

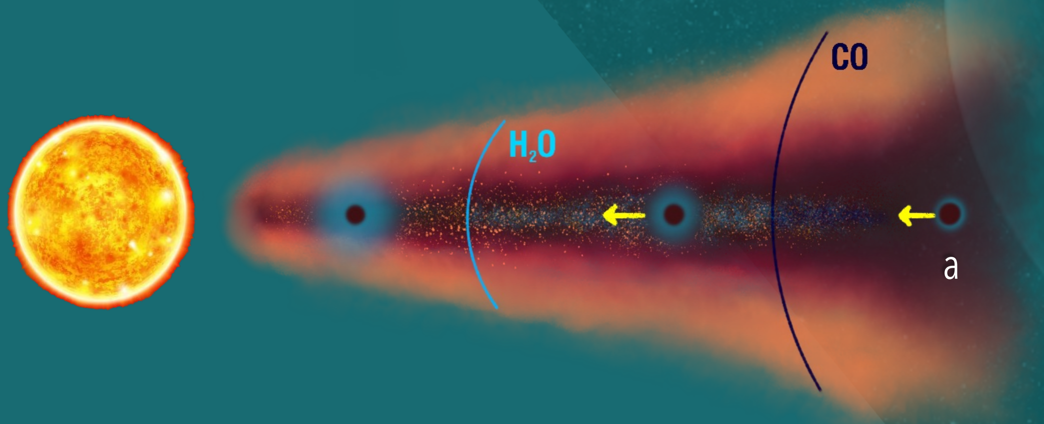


Radial profiles of molecular abundances of the key volatile C-, O-, and N-bearing species with respect to total H atoms.

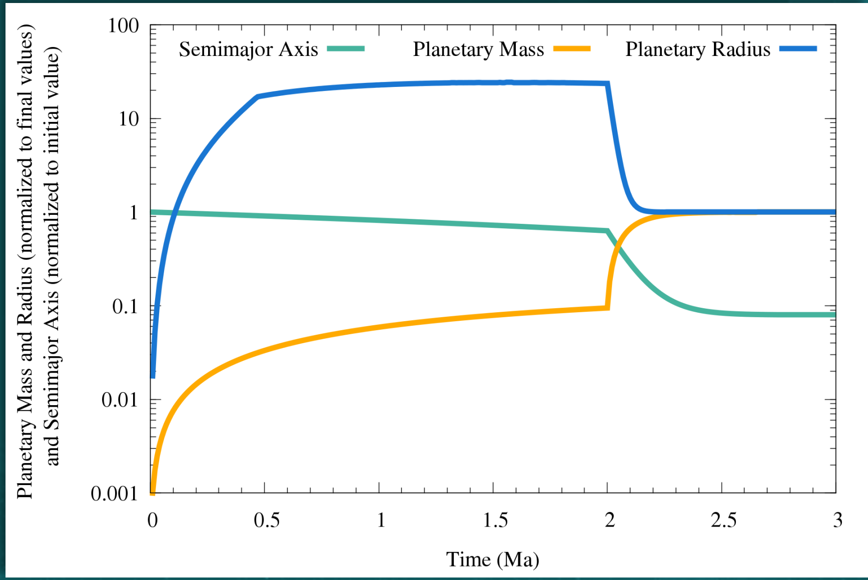
PLANET FORMATION MODEL

N-body simulations of a forming and migrating giant planet that account for:

- The **mass growth** and planetary **radius evolution** of the forming planet (core-accretion scenario),
- The orbital **migration** during the different phases of the formation,
- The effects of the **disc self-gravity** and of the **gas drag** on the dynamical evolution of bodies.

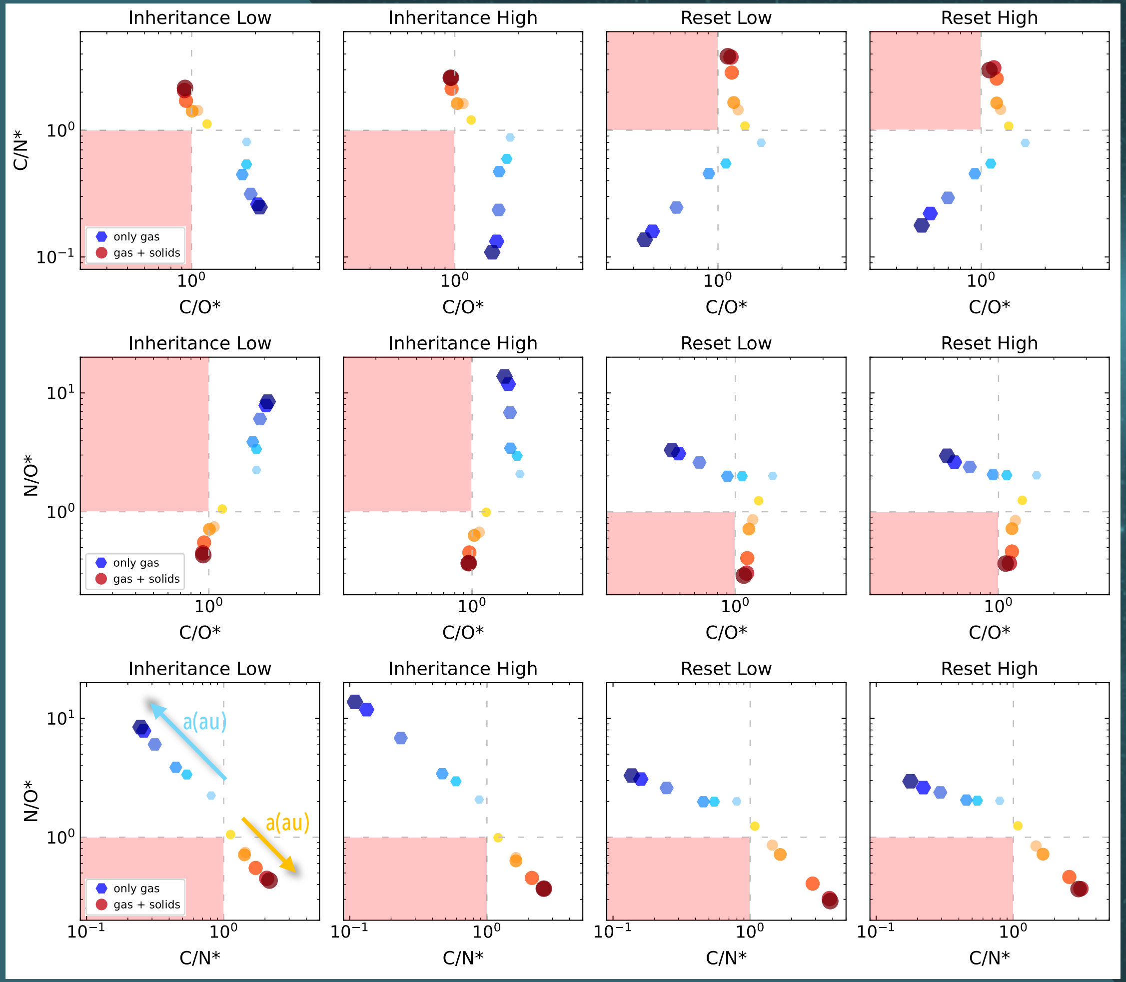


a(au) = initial semimajor axis



Normalised growth and migration tracks (Turrini et al., 2021).

PAIRWISE COMPARISON OF MULTIPLE NORMALISED ELEMENTAL RATIOS

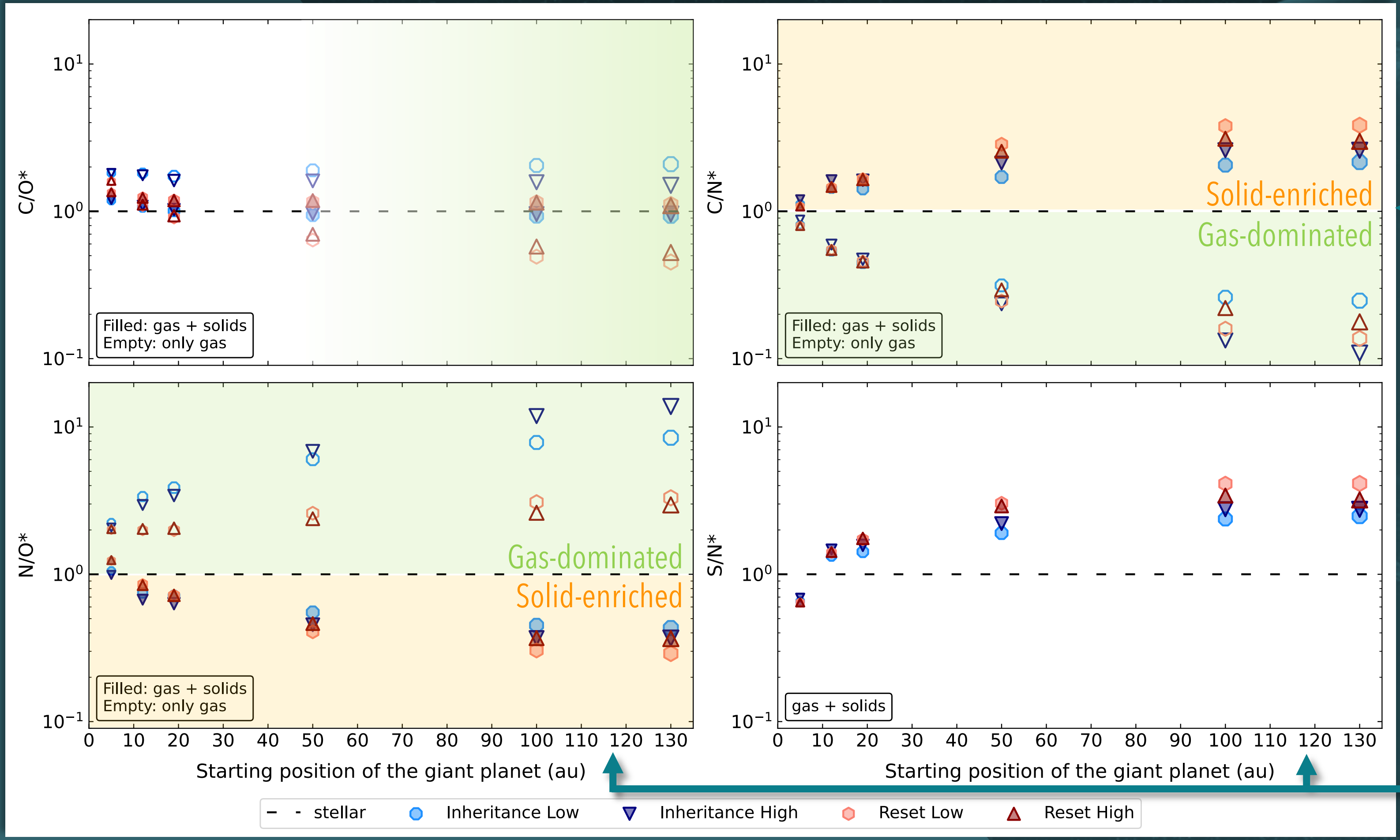


Comparison between pairs of normalised elemental ratios in the planet's atmosphere. Results are shown for the Inheritance and reset scenarios with low (SLRs) and high (SLRs+CRs) ionisation levels. Each point on the plots represents one of the six analysed simulations.

Allows to immediately identify the conditions that favour one scenario over the others, hence providing an effective tool for the **interpretation of observational data**

		super-stellar	sub-stellar
		C/O*	C/O*
super-stellar	C/N*	• solid-enriched • reset	• solid-enriched • inheritance
sub-stellar	C/N*	• gas-dominated • inheritance	• gas-dominated • reset

NORMALISED ELEMENTAL RATIOS IN DIFFERENT CHEMICAL SCENARIOS



Solid-enriched giant planets:
stellar C/O* ratio

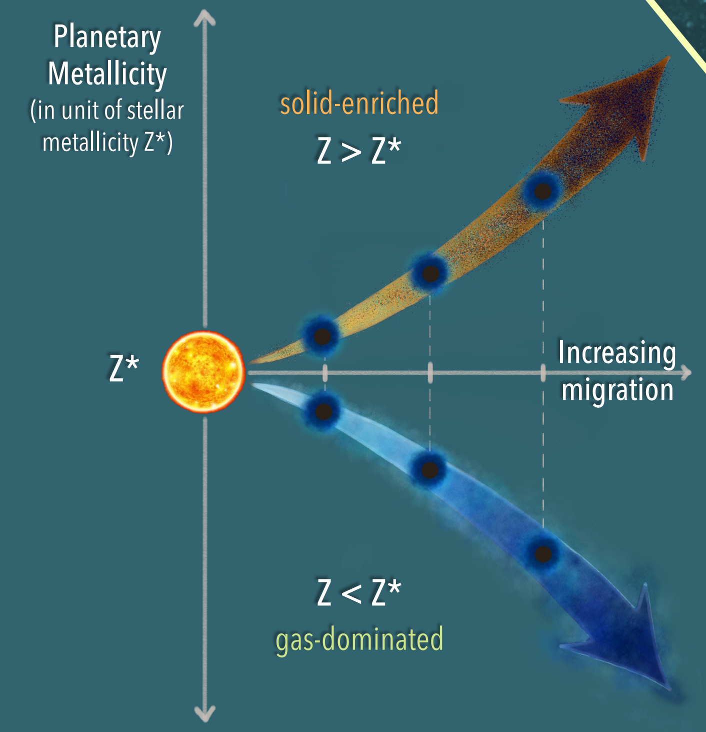
Gas-dominated giant planets:
constraints on the disc chemical structure only for large-scale migration scenarios

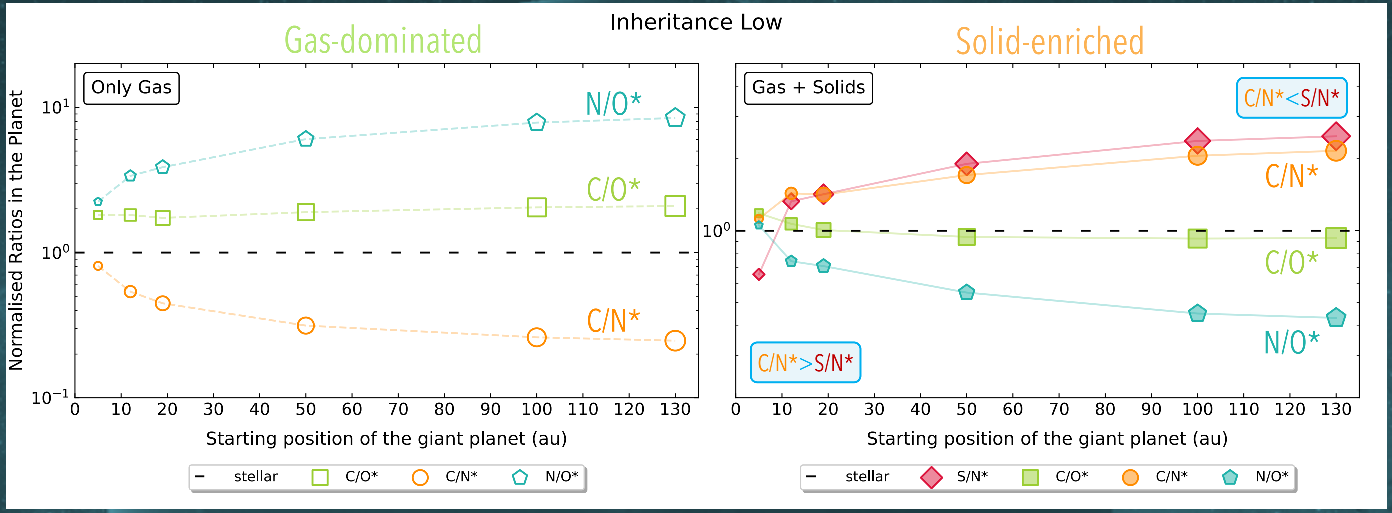
The global trends of the **C/N***, **N/O***, and **S/N*** ratios are **preserved** in both the inheritance and reset scenarios

Gas-dominated and solid-enriched giant planets show opposite trends for **C/N*** and **N/O***.

Elemental ratios C/O*, C/N*, N/O*, and S/N* normalised to their respective stellar values in the Inheritance and reset scenarios with low (SLRs) and high (SLRs+CRs) ionisation levels. The results are plotted for six migration scenarios, with increasing size of the markers corresponding to initial semimajor axes of 5, 12, 19, 50, 100, and 130 au.

NORMALISED ELEMENTAL RATIOS FOR A FIXED CHEMICAL SCENARIO





Normalised elemental ratios in the final atmosphere of the planet in the inheritance scenario with low (SLRs) ionisation. The results are shown for six migration scenarios, with increasing size of the markers corresponding to initial semimajor axes of 5, 12, 19, 50, 100, and 130 au.

Solid-enriched giant planets: stellar to super-stellar metallicity

C/N* > C/O* > N/O*

Gas-dominated giant planets: stellar to sub-stellar metallicity

N/O* > C/O* > C/N*

KEY RESULTS

- The **atmospheric composition** of giant planets is markedly **non-stellar**, being shaped by the interplay between migration and concurrent accretion of gas and solids.
- **Normalised elemental ratios**, expressed as function of stellar abundances, allow to directly compare the formation histories of giant planets orbiting different stars.
- **Gas-dominated** giant planets are characterised by **N/O*>C/O*>C/N***, while solid-enriched giant planets are characterised by **C/N*>C/O*>N/O***, independently on the disc chemical scenario.
- The **C/O*** ratio provides information on the migration history and on the disc chemical scenario **only** for **gas-dominated** giant planets experiencing large-scale migration. **Solid-enriched** giant planets show **stellar C/O*** ratios independently on how much the planet migrates.
- The comparison between **S/N*** and **C/N*** constraints the relative contribution of gas and solids to the total metallicity.
- **Pairwise comparison** of multiple normalised elemental ratios provides effective tools for the interpretation of observational data.

NEXT: IMPLEMENTATION OF A FULL CHEMICAL NETWORK

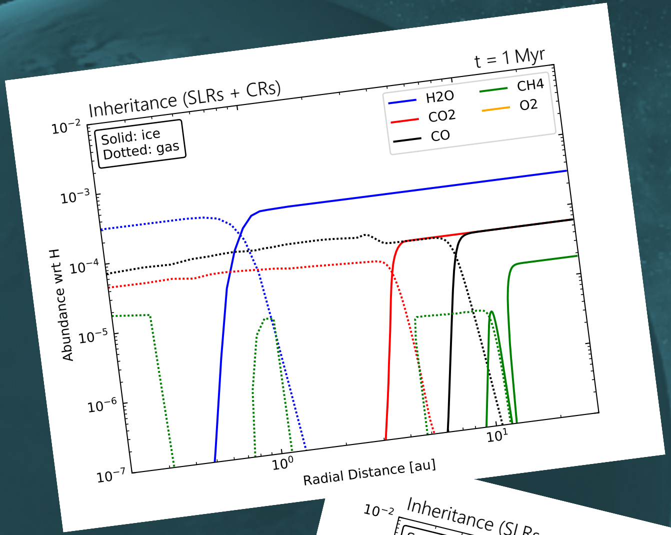
We are currently working on implementing a **full chemical network** to compute radial profiles of molecular abundances in discs, in order to being able to explore a larger parameter space.

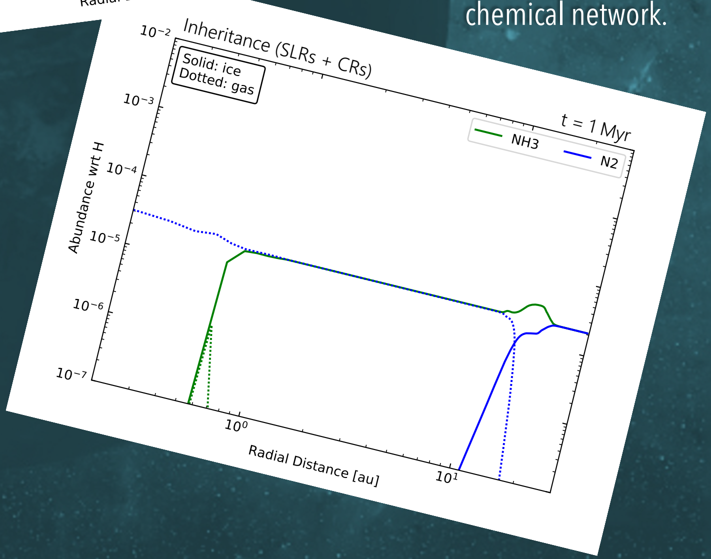
Chemical Network
total reactions: 3585
• Gas phase • Adsorption • Surface reactions • Desorption (Thermal + CRs-induced)

(In collaboration with C. Ceccarelli)

Evolution of the chemical network by the **KROME** solver for astrochemistry, in collaboration with its developers (T. Grassi, S. Bovino).

KROME
better science through chemistry





Preliminary tests with KROME and the new chemical network.

NEXT: IMPLEMENTATION OF VISCOUSLY EVOLVING DISCS

Ongoing collaboration with C. Dullemond for a fully consistent implementation of the **viscous evolution** of protoplanetary discs, coupled with the chemical evolution.

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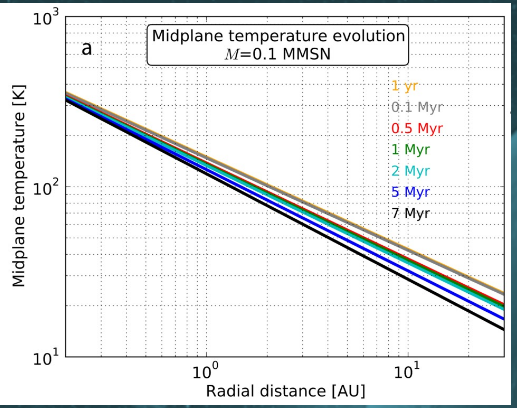
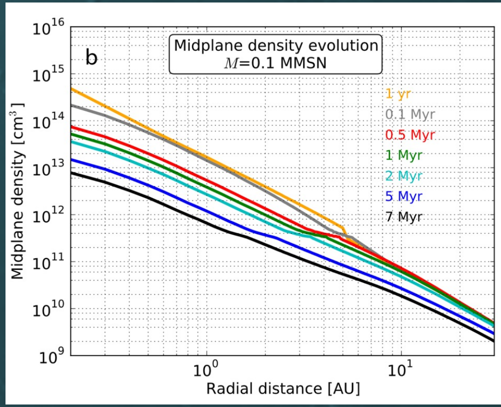
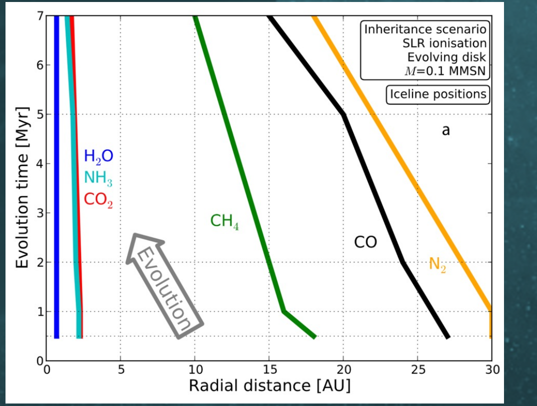
Goal: building a self-consistent model for the evolution of the physical and chemical properties of the protoplanetary disc.



Viscous evolution of the midplane temperature profile (left) and of the midplane surface density (bottom) in a alpha-steady disc 0.1 MMSN, by Eistrup et al., 2017





Evolution of the position of the snowlines in a 0.1 MMSN disc, by Eistrup et al., 2017

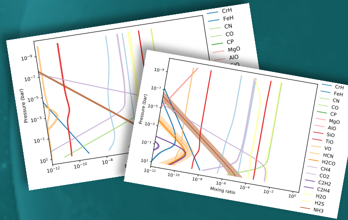
NEXT: TESTING THE PREDICTIONS OF OUR MODEL

A number of **ongoing works** are testing our methodology on real data in preparation of its use for interpreting the observations of **JWST** and **Ariel**:

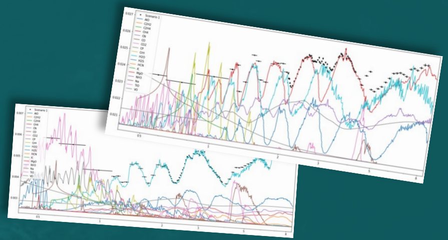
- **Normalised elemental ratios** have been recently employed by Kolecki & Wang, 2021 and Biazzo et al., 2022
- The trends of the **C/O*** ratio coupled with **metallicity** have been used by G. Guilluy et al. (sub.) and I. Carleo et al. (sub.) for interpreting the data of the GAPS 2 program.

NEXT →

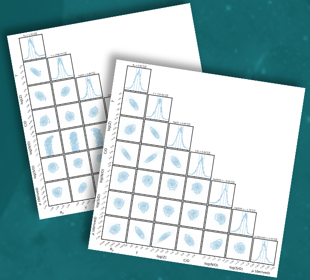
New collaboration between the Planetary formation, Spectral retrieval, and Stellar Characterisation working groups in the Ariel consortium to **test the real potential of Ariel** in retrieving the elemental ratios in planetary atmospheres.



Equilibrium chemistry



Ariel simulated spectra



Spectral retrieval

CONCLUSIONS

- We investigated the effects of **different disc chemical scenarios** on the final elemental ratios in the atmospheres of giant planets.
- Our results allow to properly interpret the compositional signatures left by the planet formation process and to provide **constraints on how and where** giant planets form.

NEXT:

- Finalising the implementation of the new **chemical network** and of the **viscous evolution** of the disc.
- Building a **self-consistent model** for the physical and chemical evolution of the disc.
- Linking our predictions to **observable** planetary atmospheres (ground-based, JWST, Ariel).

- Turrini et al. 2021 - "Tracing the Formation History of Giant Planets in Protoplanetary Disks with Carbon, Oxygen, Nitrogen, and Sulfur" – DOI: 10.3847/1538-4357/abd6e5
- Pacetti et al. - "Chemical diversity in protoplanetary discs and its impact on the formation history of giant planets" – (submitted to ApJ)

Thank you