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Ice Giants as Exoplanet Analogs

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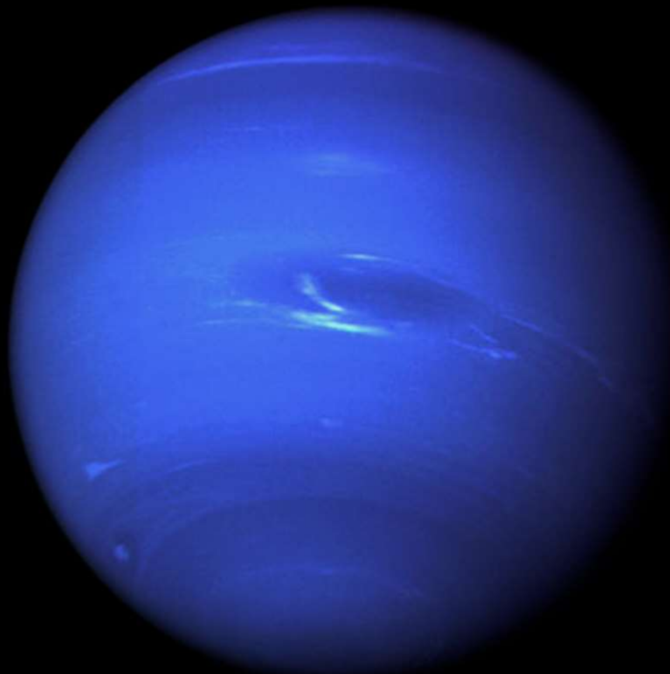
Ice Giants as Exoplanet Analogs

- Ice Giant mass/radius common among detected exoplanets
- Our Ice Giants only explored by single flybys
- Major questions remain about formation process, interior structure and composition, energy balance, and interaction with the Sun
- *Broad international support for a mission to Uranus and/or Neptune*

What observations of our Ice Giants would help advance Exoplanet characterization efforts?

Big questions about the Ice Giants

- Several studies have designed missions to Uranus and/or Neptune
- Common Science Goals
  - How did the Ice Giants form and evolve?
  - What is the interior structure of the Ice Giants?
  - How does the planetary dynamo work?
  - What is the heat balance of the Ice Giants?
  - What drives atmospheric dynamics?
  - How did the rings form and evolve?
  - How did the moons form and evolve?



Any mission to the Ice Giants must address system-level goals.
The greatest synergy with current exoplanet research is in the origin, evolution, and current state of the planet.

Giant Planet Formation and Evolution

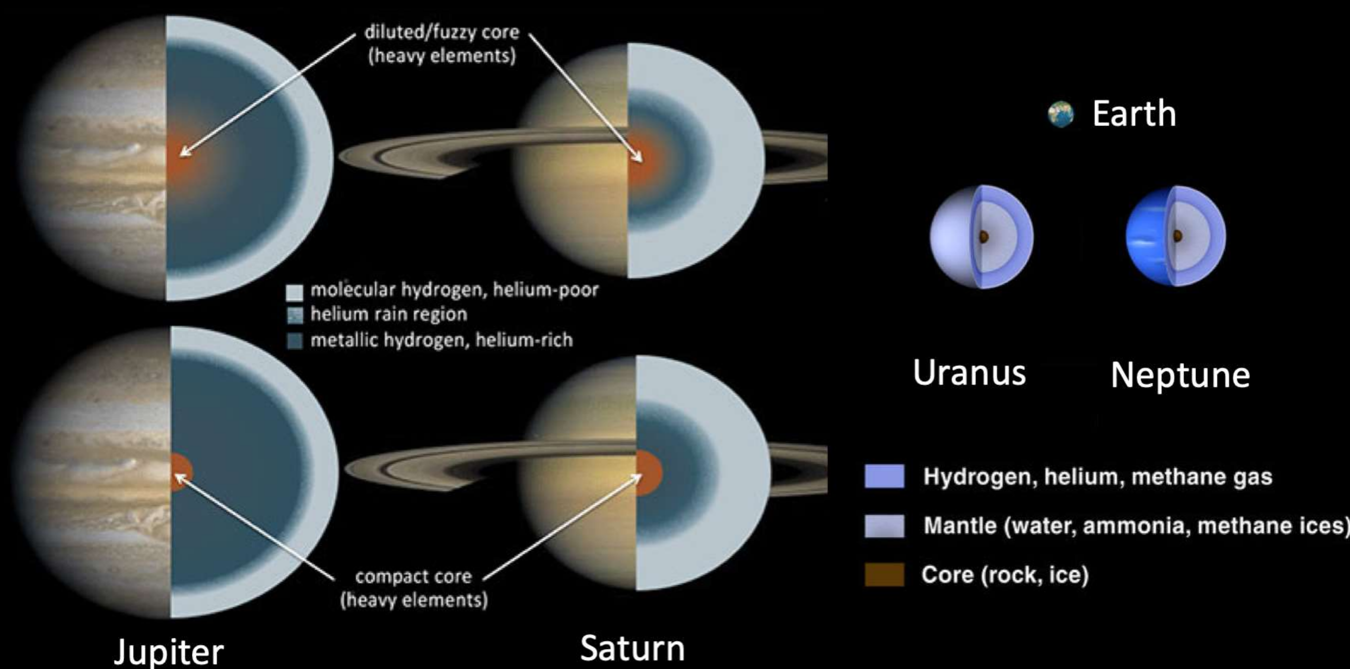
- What was the composition of the solid building blocks?
- Did the Protosolar Nebula (PSN) composition vary with distance from the Sun?
- What contributed to the noble gas isotope mixtures?

Heavy elements trace building block formation, PSN composition, planet formation, and planet evolution

Image credit: NASA/STScI

The Interior Structure of Jupiter and Saturn is better understood than the Ice Giants

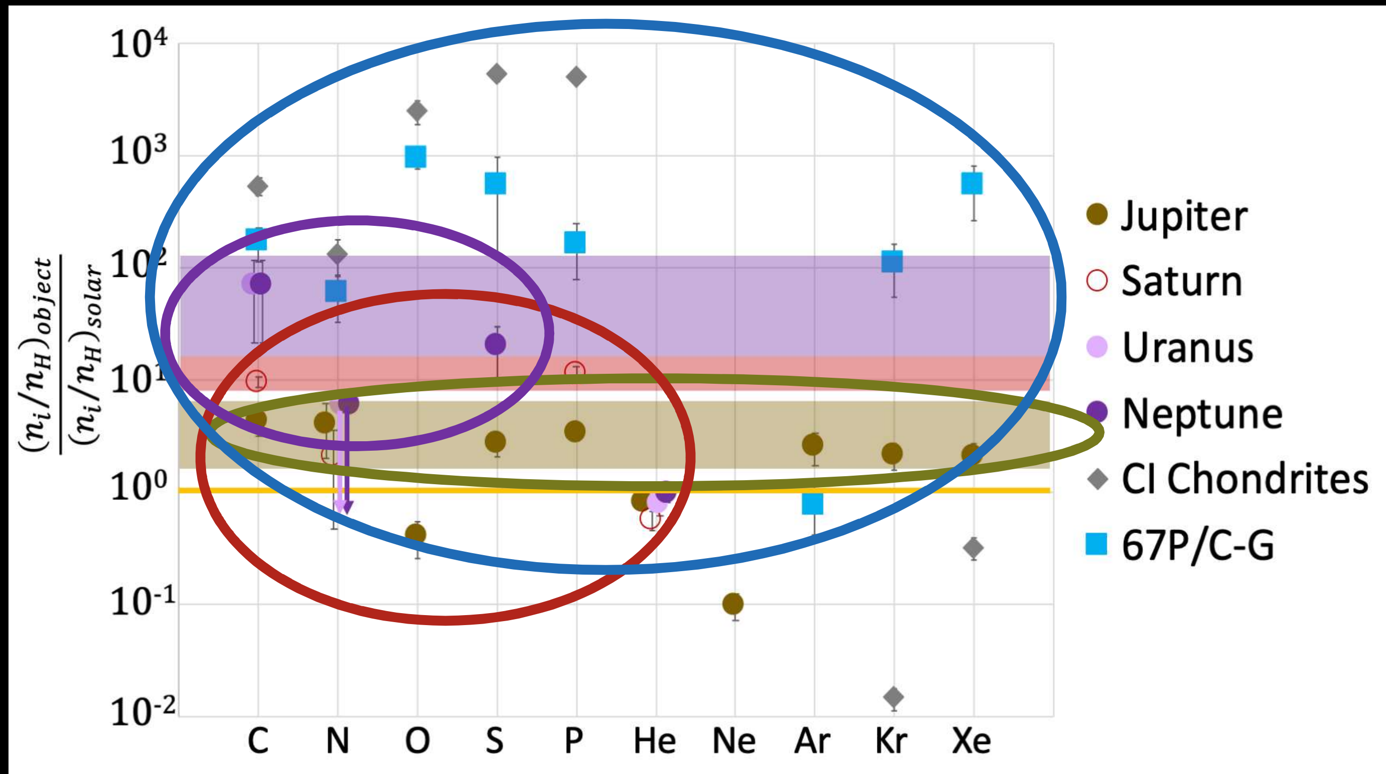
- Core
  - Jupiter's core (possibly Saturn's too) is "fuzzy"
  - Do the Ice Giants have "fuzzy" or solid cores?
  - What are the layers in the Ice Giant interiors?
- Do interior processes change the composition of the envelope?
  - Helium & Neon
  - Core erosion



Measuring heavy elements in the atmospheres can help to constrain the interior structure and interior processes

Current State of Knowledge

- Jupiter
  - Solar composition enhanced x 2-4
  - Either formed in enriched nebula or had solar composition building blocks
- Saturn, Uranus, & Neptune
  - Non-solar enhancements
  - Building blocks?
  - Protosolar Nebula?

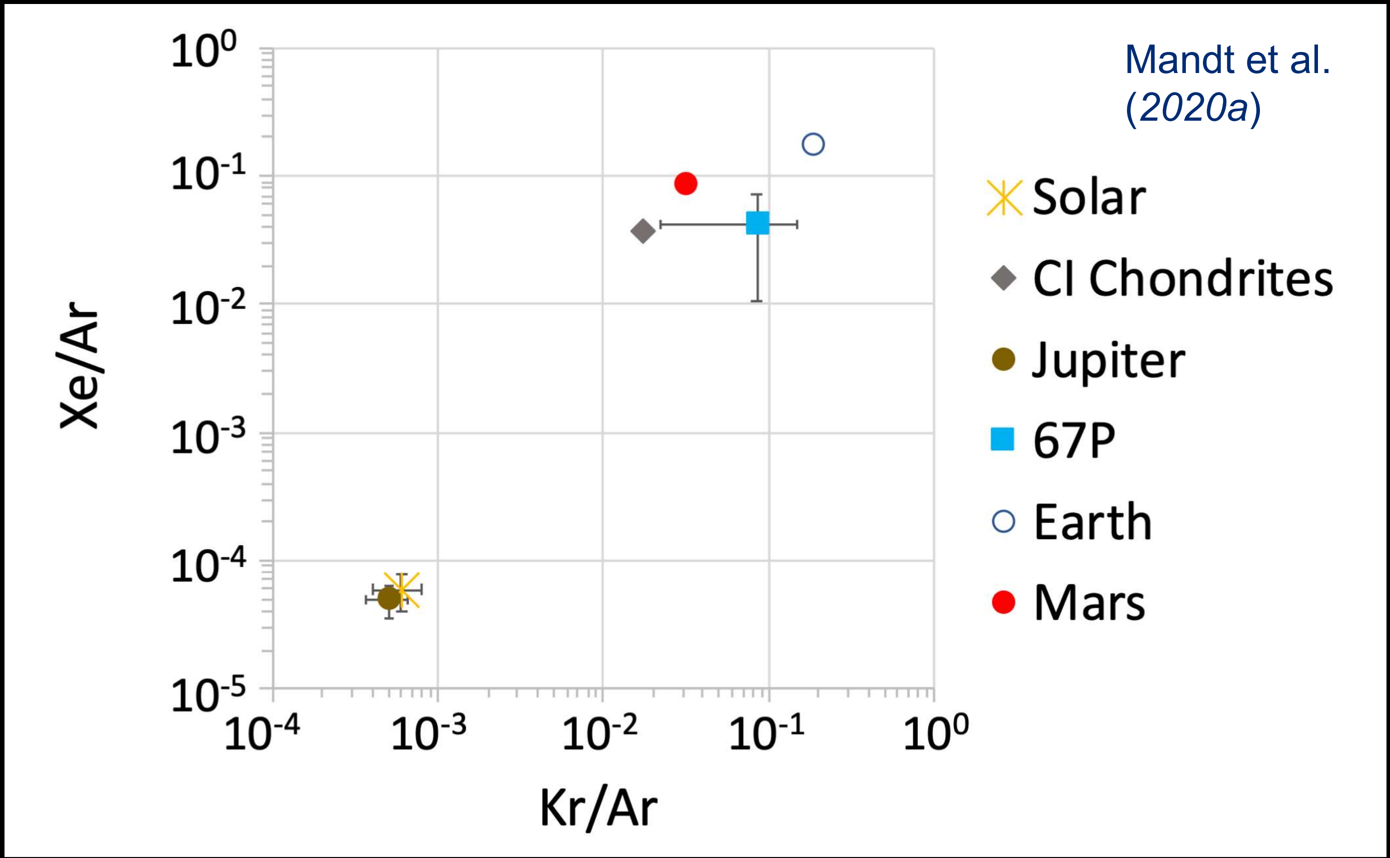


In situ measurements of the noble gases in the giant planets will help to constrain their origin and evolution and improve interpretation of CNOSP

Heavy noble gas abundances are a valuable tracer for solid building blocks

- Jupiter composition is solar
- Xe/Ar and Kr/Ar in solid building block analogs are supersolar

Is Kr/Ar and Xe/Ar in the Ice Giant atmospheres like Jupiter or like Chondrites and Comet 67P

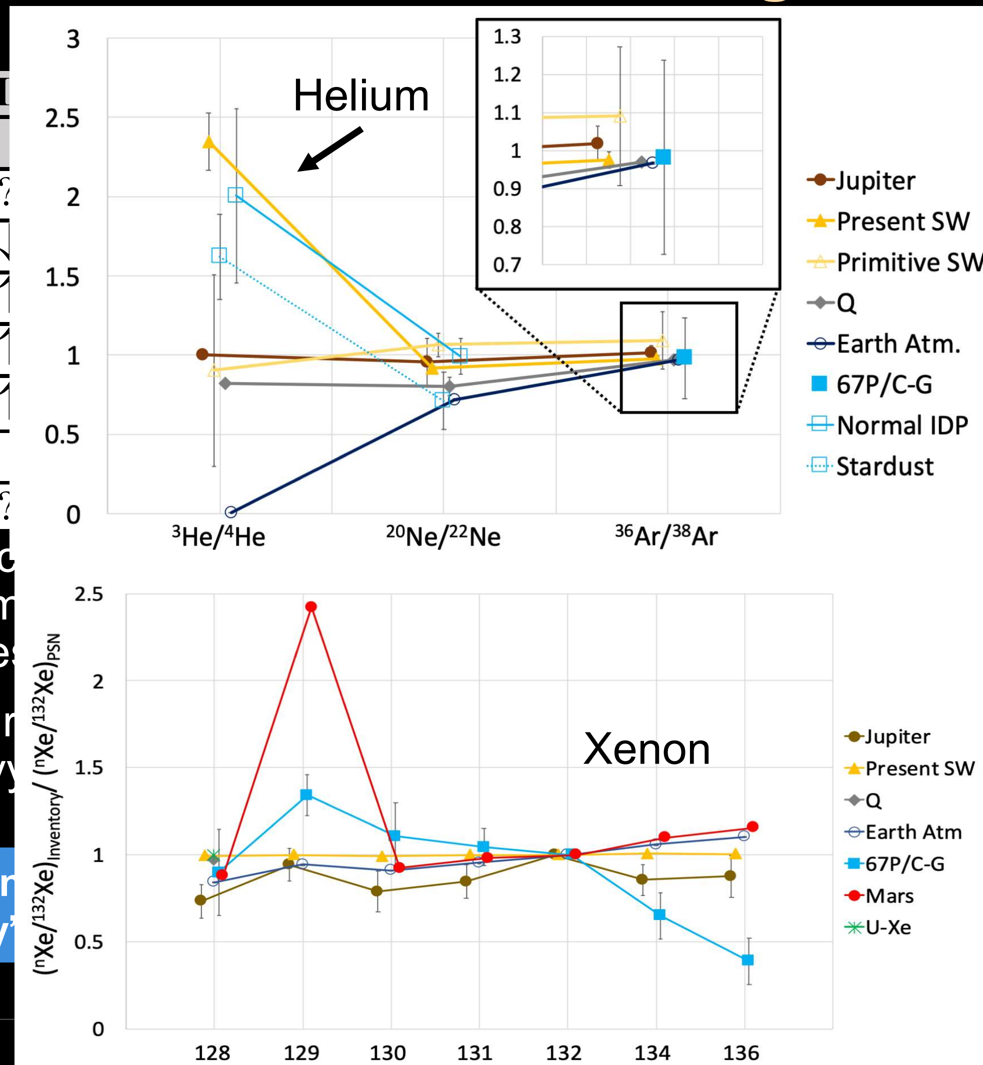


How will formation and evolution influence the noble gas abundances? *(Mandt et al., 2020a)*

1. Planet formation
2. Core formation
3. Photoevaporation
4. Impacts
5. Core erosion
6. Phase separation (likely relevant only to Jupiter and Saturn)
7. Net effect on current atmosphere

	Disk I		
	He	Ne	
1	?	?	?
2	□	↓	↓
3	↑	↑	↑
4	□	↑	↑
5	↑	↑	↑
6	↓/□	↓/□	
7	↓/□	↓/□	?

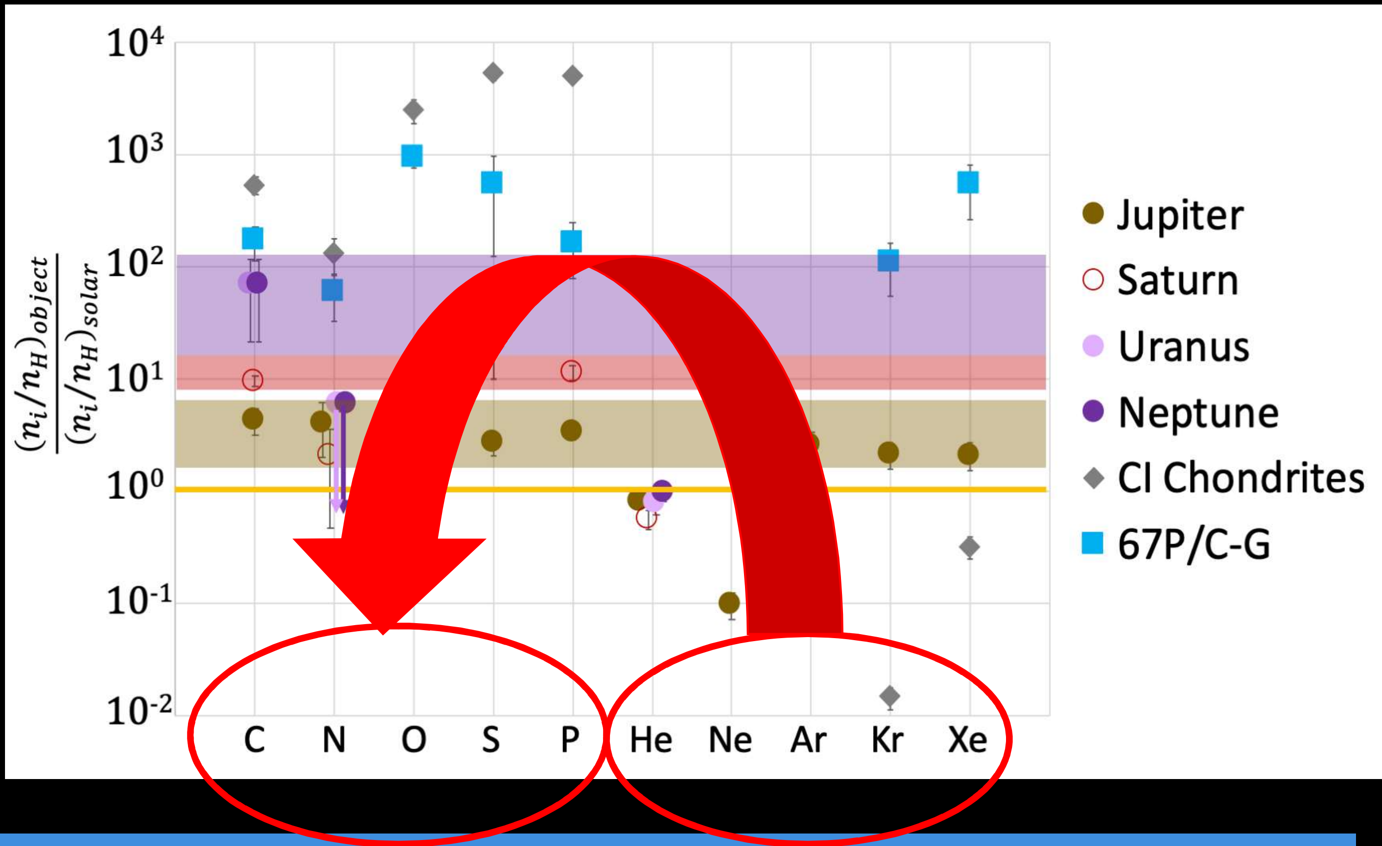
- Disk instability c determined prim formation proce
- Core accretion r enhanced heavy



Heavy noble gases are an important tool for understandin enrichment in giant planets – "metallicity"

Connecting to Exoplanets

- Noble gases and their isotopes constrain formation and interior evolution
- Provide better understanding to interpret measurements accessible to exoplanets (e.g. C/O)



We need in situ measurements of the noble gases in the giant planets to understand their origin and evolution and apply this knowledge to exoplanet observations

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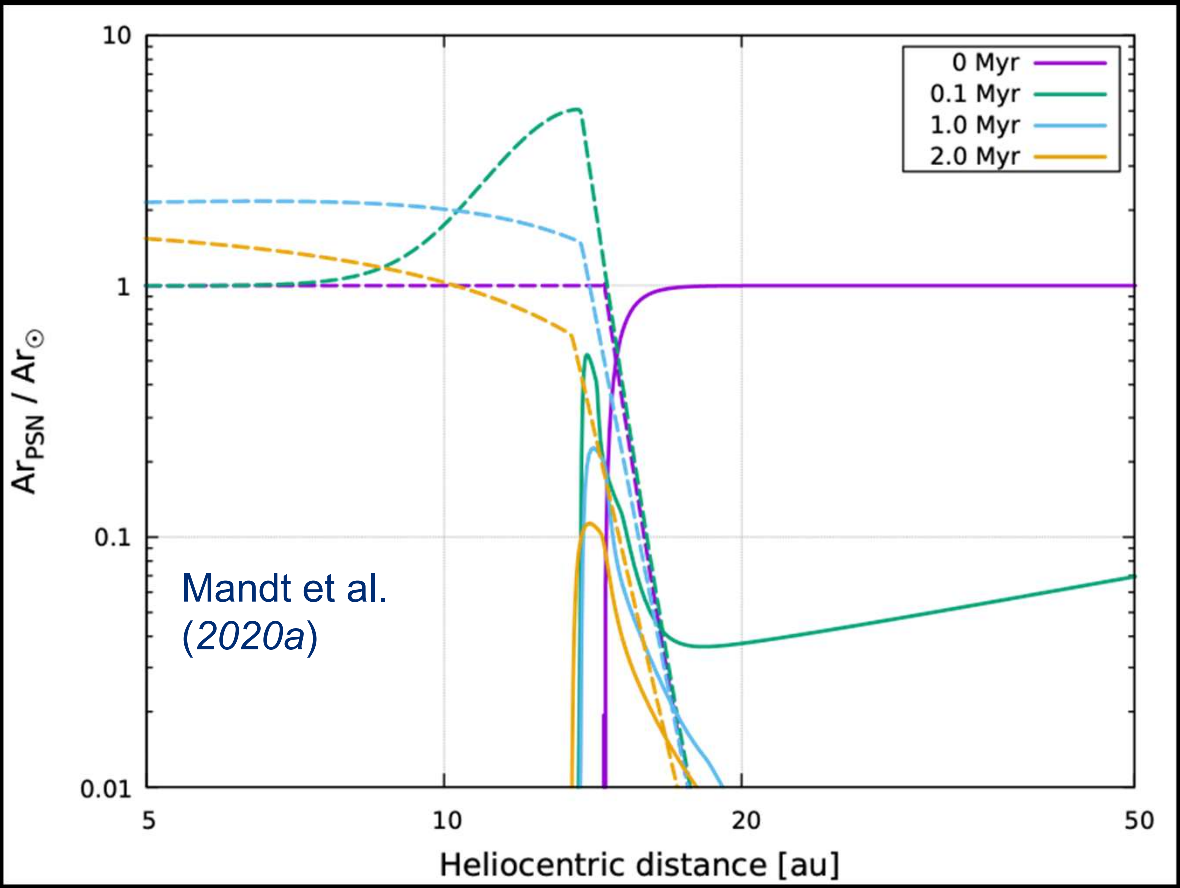
Backup

Enhancement by the Protosolar Nebula (PSN)



- PSN temperature varied with distance from the Sun
- Condensed volatiles can be released into the PSN when they cross their snowline
- Example here shows Argon enhancement in PSN gas

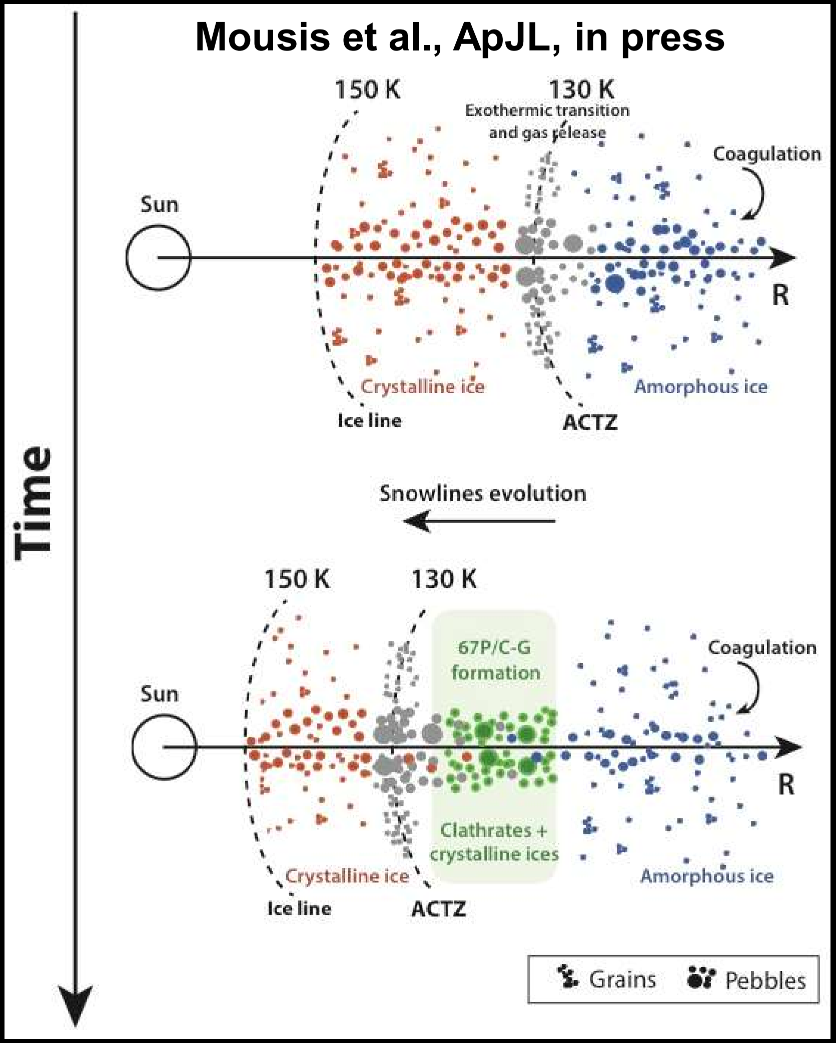
The giant planets could have become enriched in heavy elements from enriched PSN gas

Formation location of 67P/C-G's building blocks

- The temperature in the disc was not static
- Propose 3 boundaries based on the temperature effects on ice
  - Amorphous to crystalline transition starts at 130 K
  - Ice sublimates above 150 K
- 67P/C-G formed in exothermic transition region
  - Water ice transitioned from amorphous to crystalline but did not sublimate
  - Volatiles trapped in clathrates as temperature dropped
  - When the water ice ran out, pure condensates formed as the temperature dropped to ~24 K

If the ices were heated to transition but did not sublimate, O_2 remains trapped

(see Mousis et al., 2016)



We need noble gas measurements to understand formation and evolution of the Ice Giants

Outer Solar System Exploration

- ESS Goals
  - Formation and Evolution of Planetary Systems
  - Properties of Exoplanets and Potential for Habitability

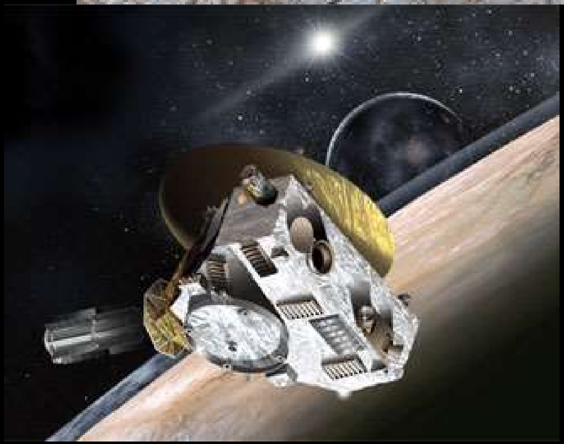
- Future exploration?
  - Comets ESA Comet Intercepter
  - Ice Giants Uranus and Neptune
  - Ocean Worlds
    - Triton – does Neptune host an ocean world?
    - Enceladus – plumes from an internal ocean!
    - Europa – ongoing development of a landed mission
  - Io – extreme case of tidal heating
  - Pluto – KBO and past ocean world?

Possible future missions could provide direct connections to Exoplanet Science Strategy (ESS) goals

Outer Solar System Exploration

Active and past missions explored

- The Giant Planets
  - Jupiter & Saturn
  - Uranus & Neptune
- Moons of the Giant Planets
  - Europa
  - Ganymede & Callisto
  - Titan
- Comets and the Kuiper Belt
  - Pluto and Arrokoth
  - Comets



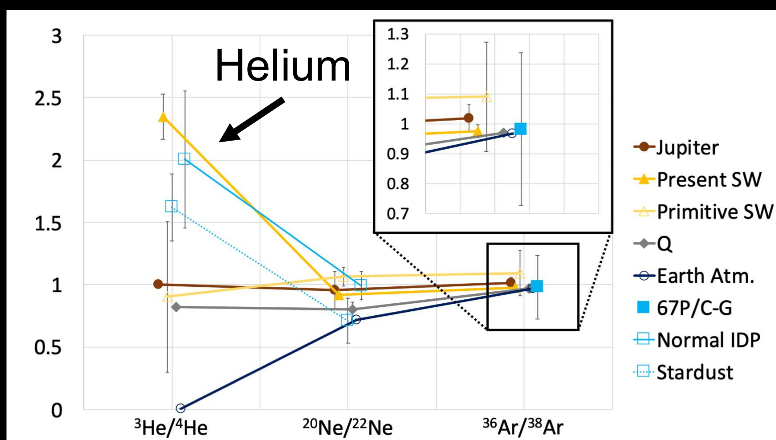
- Future exploration?
  - Ice Giants Uranus and Neptune
  - Triton
  - Enceladus
  - Europa
  - Io

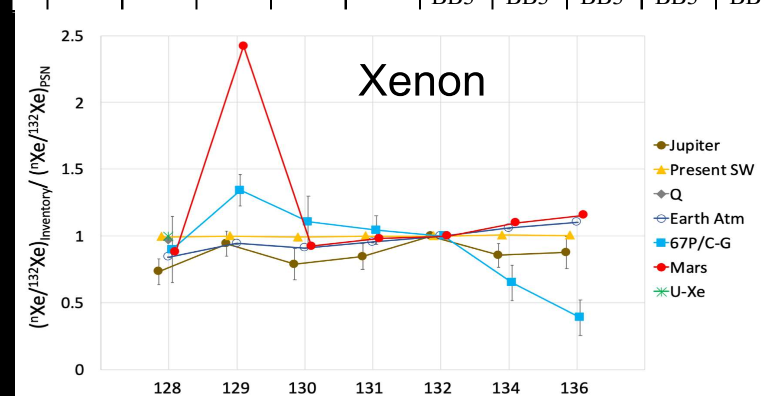
Many targets in the outer solar system provide science results relevant to characterizing exoplanets

Noble Gas Isotopes trace solid and gas that formed the planet

- Four potential sources of noble gas isotopes *(Mandt et al., 2020)*
  - The Protosolar Nebula (PSN)
  - Solid planetesimals in region where planet formed (BB1)
  - Planetesimals accreted in stage 2 of core accretion (BB2)
  - Post-formation impactors (BB3)

	Disk Instability					Core Accretion				
	He	Ne	Ar	Kr	Xe	He	Ne	Ar	Kr	Xe
1	PSN	PSN	PSN	PSN	PSN	PSN BB2	PSN BB2	PSN BB2	PSN BB2	PSN BB2
2	PSN	PSN	PSN	PSN	PSN	n/a				
3	PSN	PSN	PSN	PSN	PSN	PSN BB2	PSN BB2	PSN BB2	PSN BB2	PSN BB2
4	PSN	BB3	BB3	BB3	BB3	PSN BB2 BB3	PSN BB2 BB3	PSN BB2 BB3	PSN BB2 BB3	PSN BB2 BB3
5	PSN BB1 BB3	PSN BB1 BB3	PSN BB1 BB3	PSN BB1 BB3	PSN BB1 BB3	PSN BB2	PSN BB2	PSN BB2	PSN BB2	PSN BB2
6	PSN BB3	PSN BB3	n/a			PSN BB1 BB2 BB3	PSN BB1 BB2 BB3	n/a		
7	PSN BB1 BB3	PSN BB1 BB3	PSN BB1 BB3	PSN BB1 BB3	PSN BB1 BB3	PSN BB1 BB2 BB3	PSN BB1 BB2 BB3	PSN BB1 BB2 BB3	PSN BB1 BB2 BB3	PSN BB1 BB2 BB3

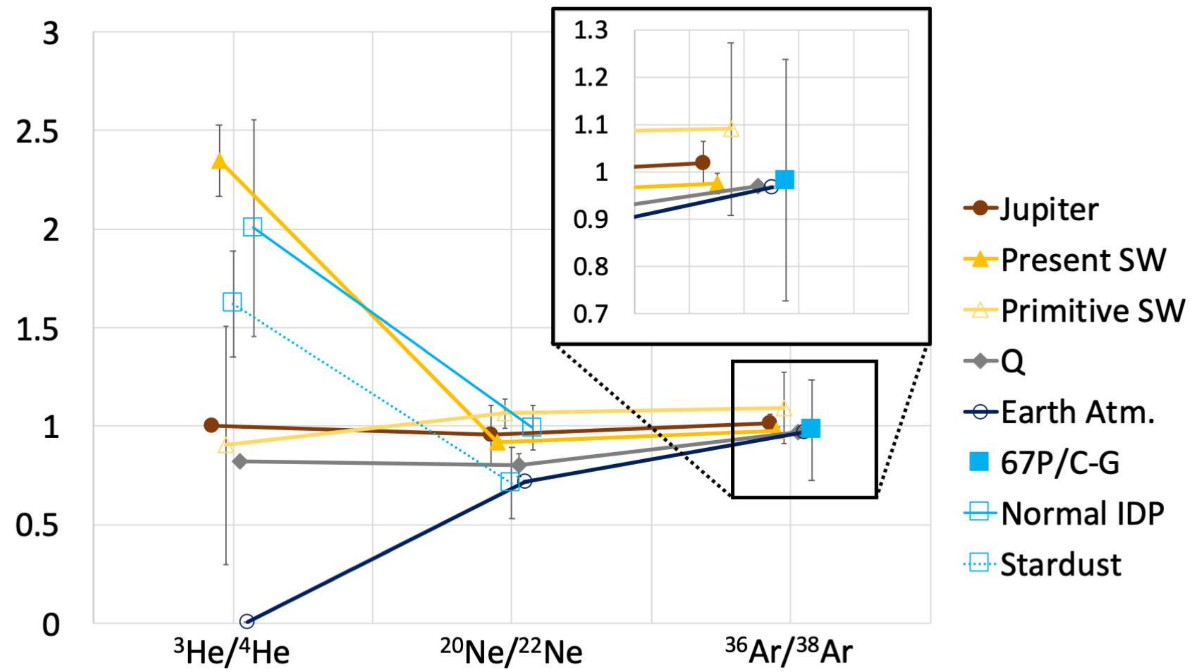


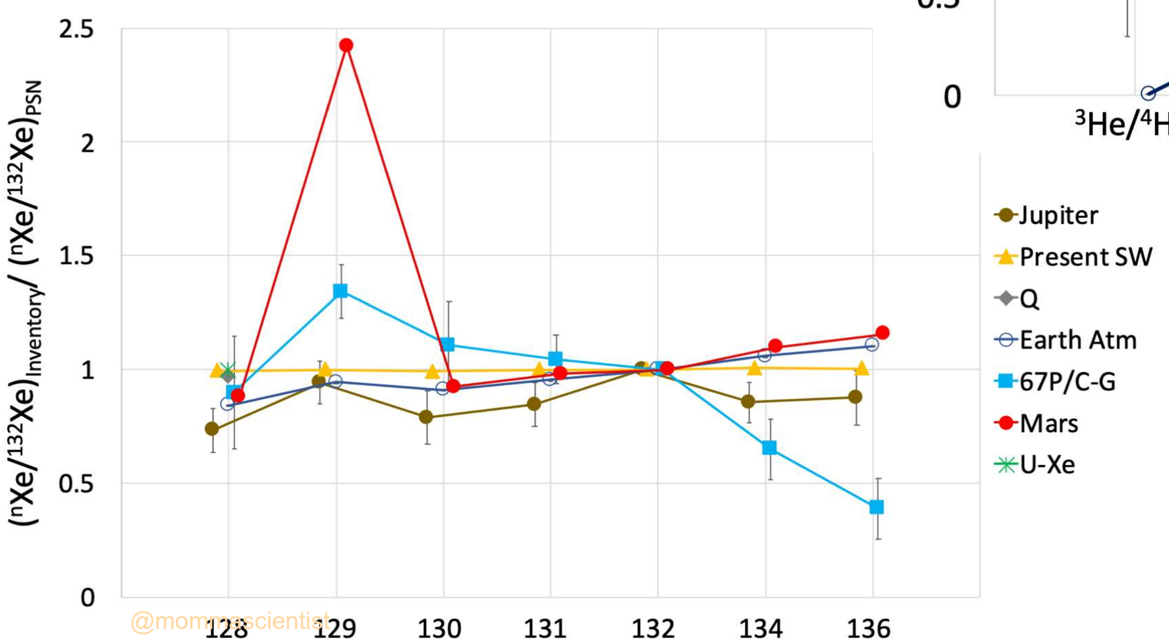


Noble Gas Isotopes, particularly helium and xenon, provide important clues to the formation of the ice giants

Noble gas isotopes

- Jupiter is solar
- Building blocks differ from solar in many cases

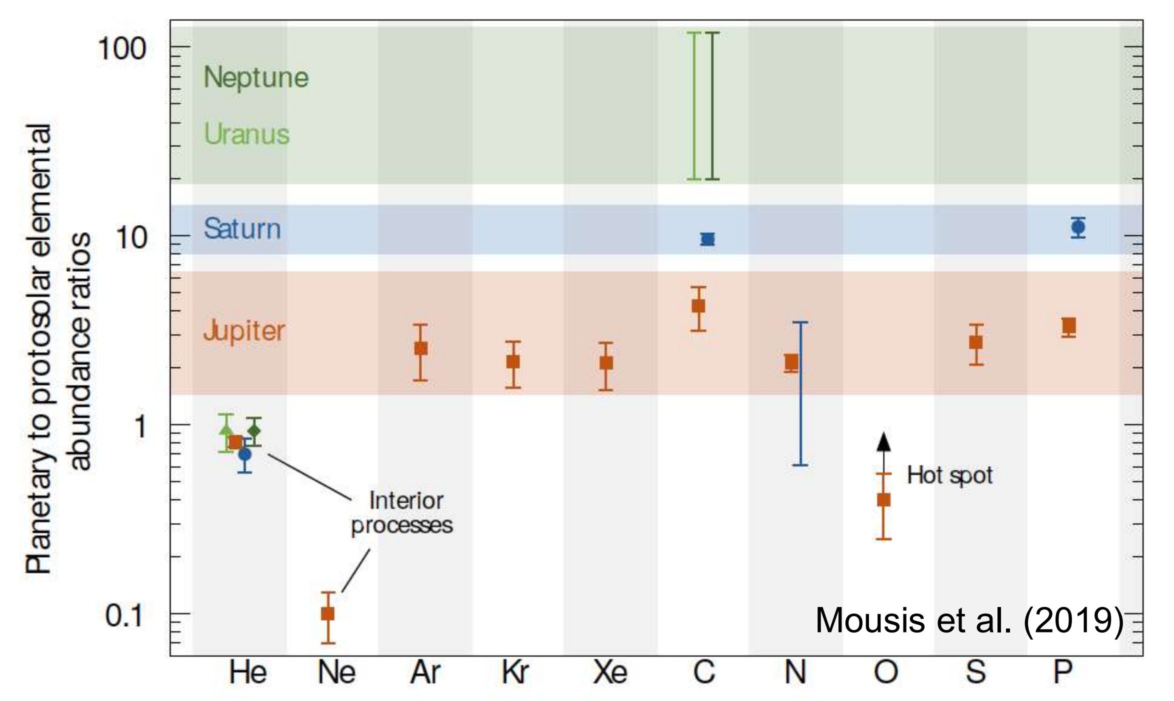




The noble gas isotope ratios, particularly helium and xenon, provide important clues to the formation of the ice giants

What was the composition of the solid building blocks?

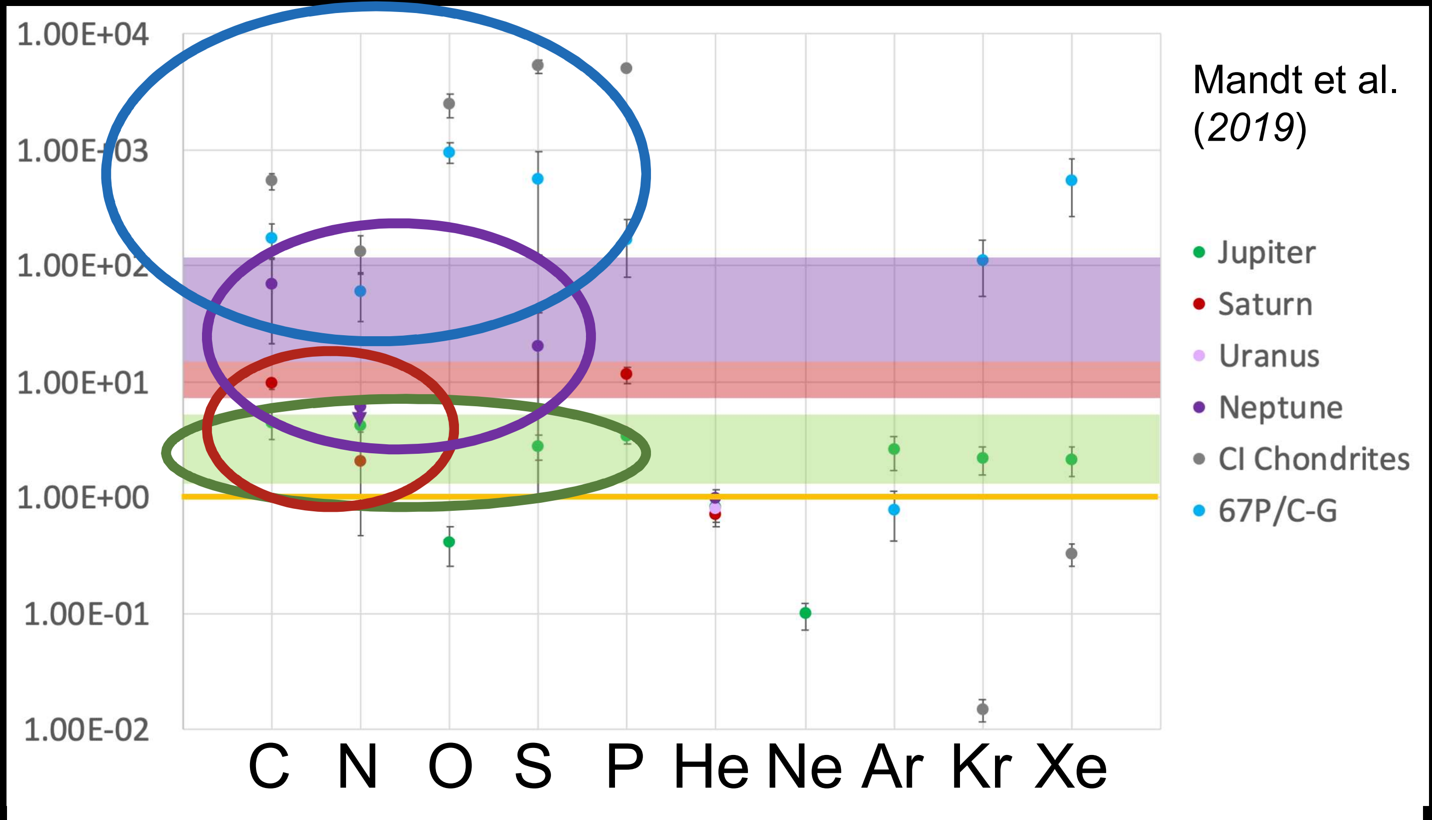
- Approach: compare heavy element abundances in atmosphere relative to Protosolar Nebula (PSN) abundances
  - Compare heavy elements to hydrogen (most abundant element of PSN)
- Bars show prediction for relative protosolar composition building blocks (e.g.protosolar Kr/Ar, Xe/Ar)



Is it appropriate to assume that the building blocks have protosolar composition?

Adding analogs for building block composition

- Note
  - Cometary H comes from water, Chondritic comes from organics
  - Need to compare heavy elements to heavy elements
- Carbon, Nitrogen, and Sulfur (C/N, S/N)
  - Jupiter ratios are solar
  - Saturn C/N is supersolar
  - Ice Giant C/N and S/N is supersolar



Only Jupiter measurements support protosolar C/N, S/N or C/S. Saturn, Uranus and Neptune are non-solar.