The Role of Water in Understanding the Formation of the Solar System

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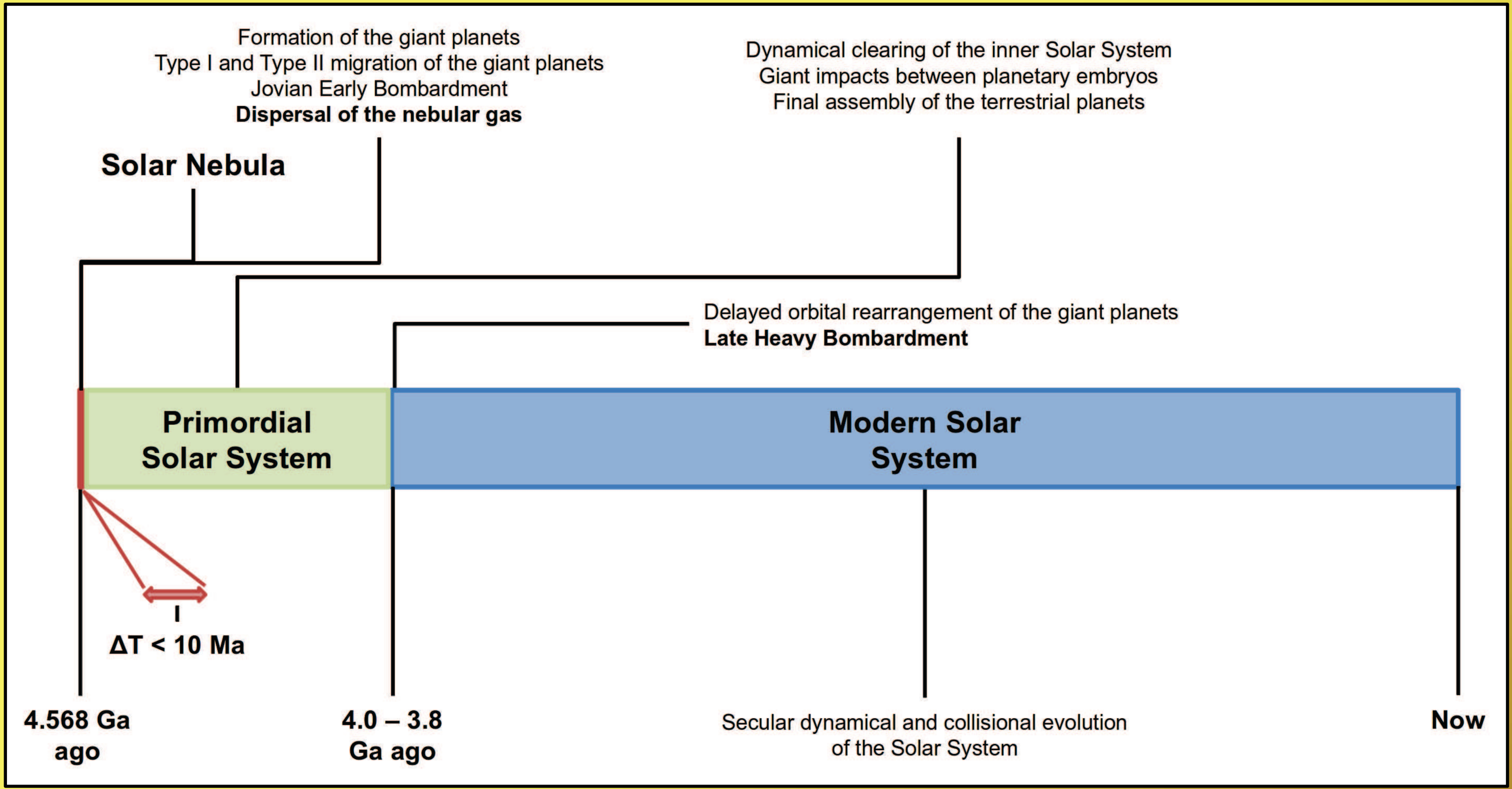
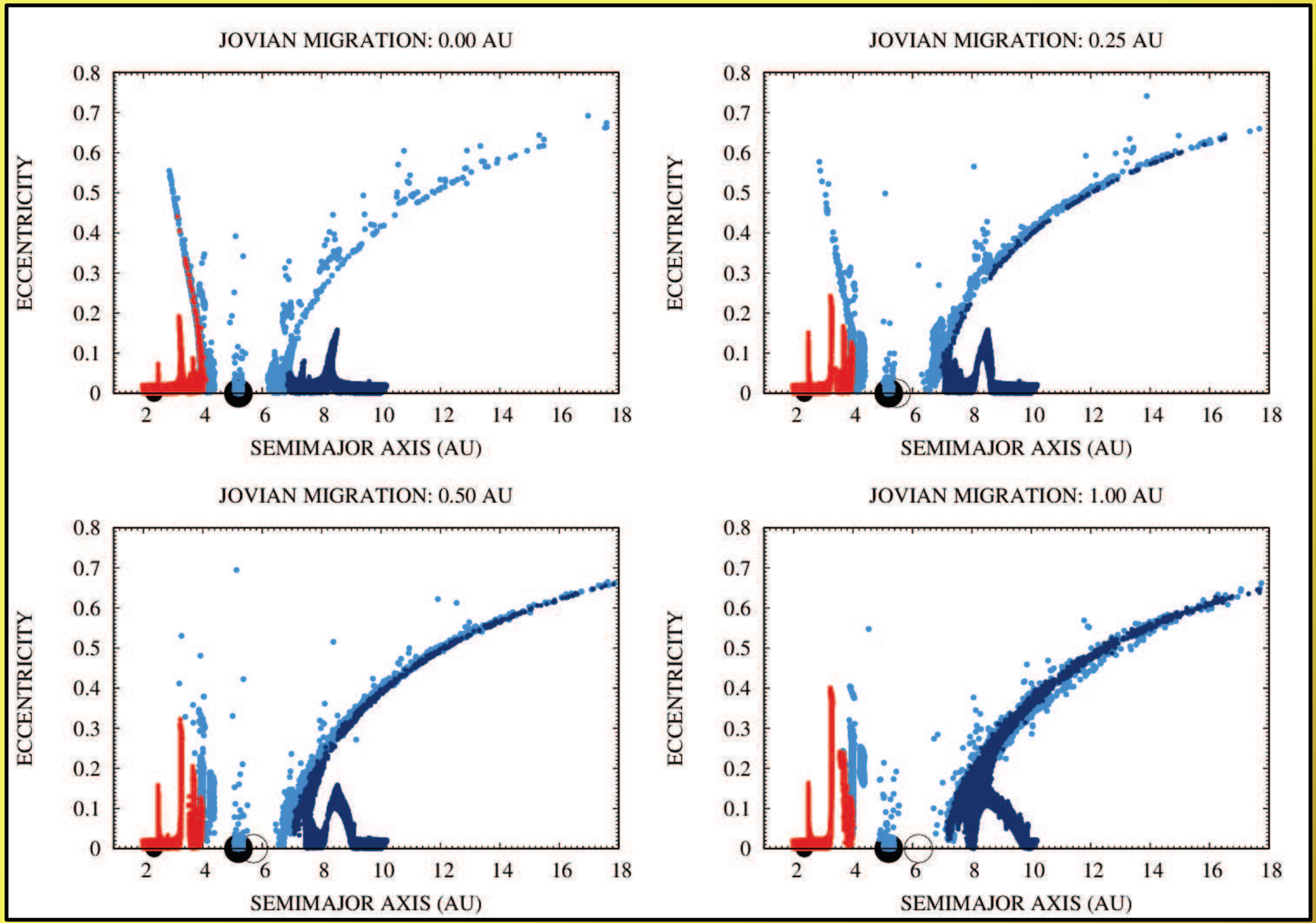
The Timeline of the Solar System



The history of the Solar System can be divided into three main phases: the **Solar Nebula**, the **Primordial Solar System** and the **Modern Solar System** (figure adapted from Coradini et al. 2011).

The Jovian Early Bombardment

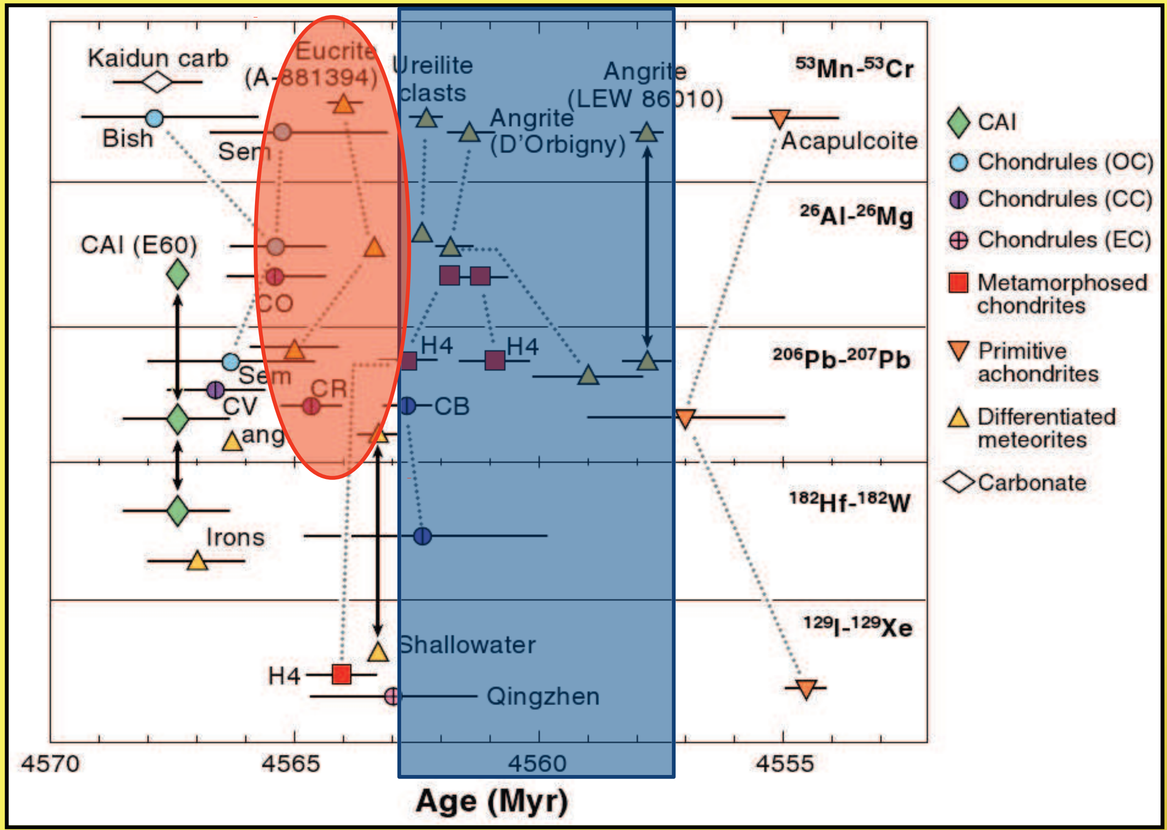
The **formation of Jupiter** destabilises the planetesimals and **causes a bombardment both in the inner and the outer Solar System** (Weidenschilling et al. 2001; Turrini et al. 2011, 2012; Coradini et al. 2011; Turrini 2013; Turrini & Svetsov 2014).



Black filled circles: Vesta and Jupiter (at its final position). Open black circles: initial position of Jupiter.

The uniqueness of Vesta

Vesta has been considered the **parent body of the HED meteorites** basing on spectral comparison (McCord et al. 1970), a link recently confirmed by the Dawn mission (De Sanctis et al. 2012; Prettyman et al. 2012).



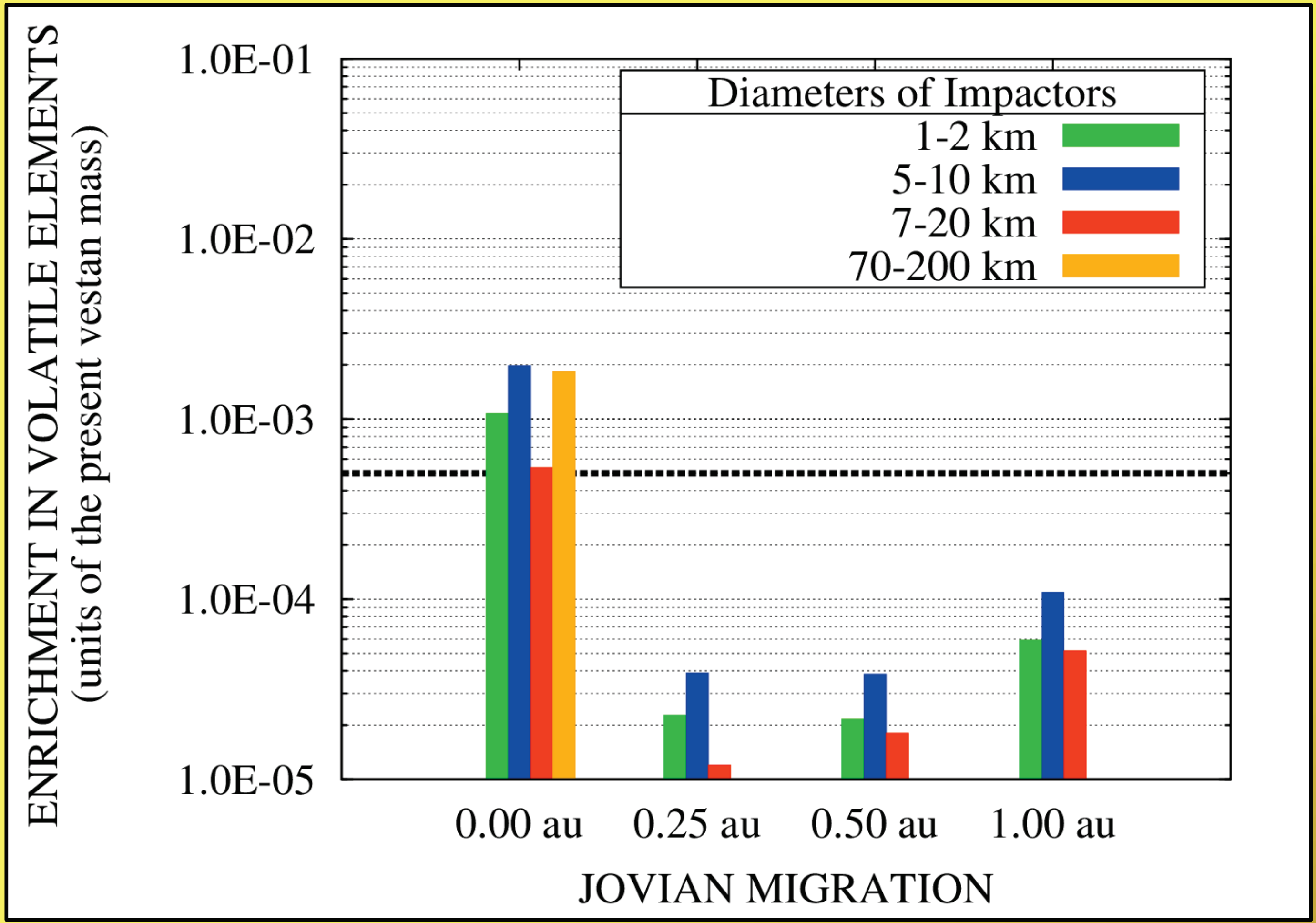
Chronology of the early Solar System from the radiometric ages of meteorites (Scott, 2007). The ***red area*** *shows the* ***crystallization of eucrites****. The* ***blue area*** *shows the* ***formation time of Jupiter****.*

HED meteorites (Howardites, Eucrites, Diogenites) are a family of meteorites originated from a **parent body** that **differentiated before 3 Ma after the condensation of CAIs** (see e.g. Keil 2002; Bizzarro et al. 2005; Schiller et al. 2011).

HED meteorites tell us that Vesta is **globally** a **volatile-depleted** body but **small quantities of water** were **present at** the time of its **differentiation** (Sarafian et al. 2013).

JEB and Primordial Water on Vesta

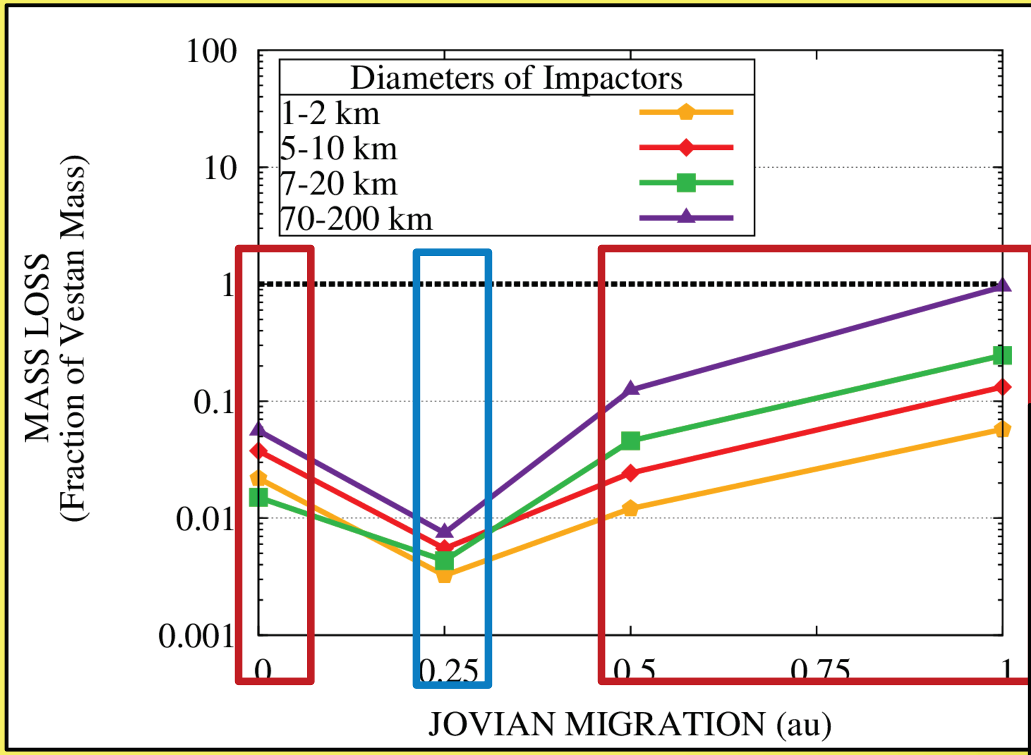
The **primordial Vesta was globally a volatile-depleted asteroid** (see e.g. Sarafian et al. 2013 and references therein). However, **few eucrites** show evidences for the **presence of water** and/or volatile elements **when they crystallized** (Sarafian et al. 2013).

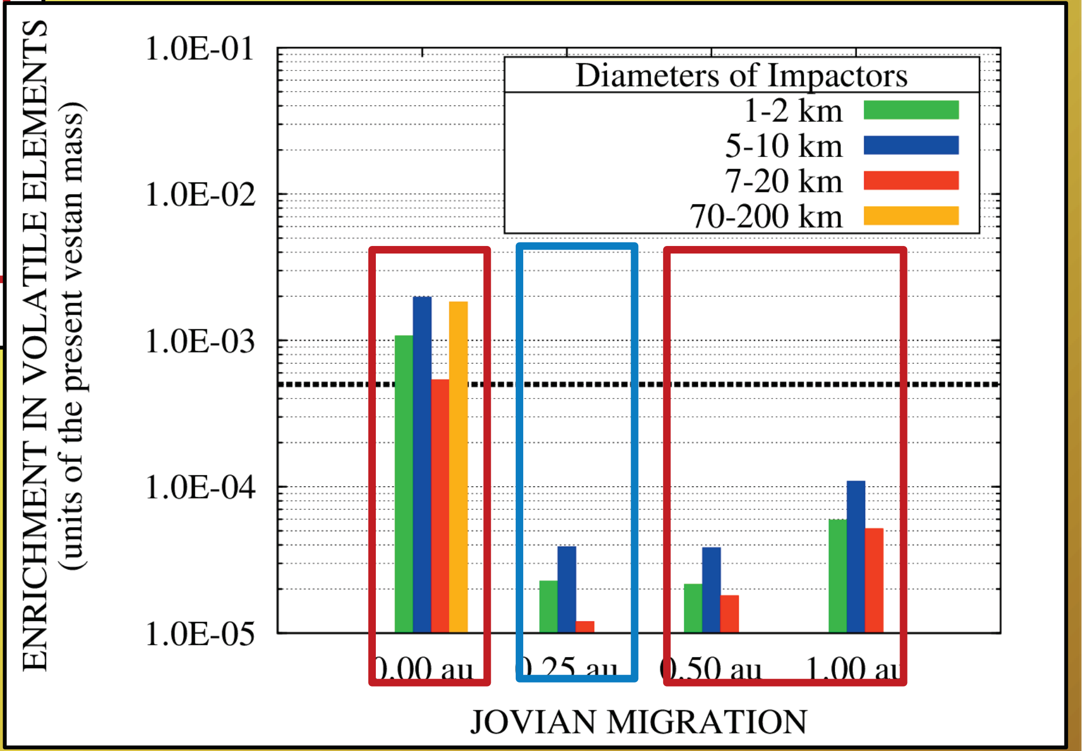


The JEB can bring to Vesta **as much water as** is present **on the Earth today** (Turrini & Svetsov 2014).

However, to match the eucritic samples, **water** should be **delivered to the molten interior** of Vesta (Sarafian et al. 2013).

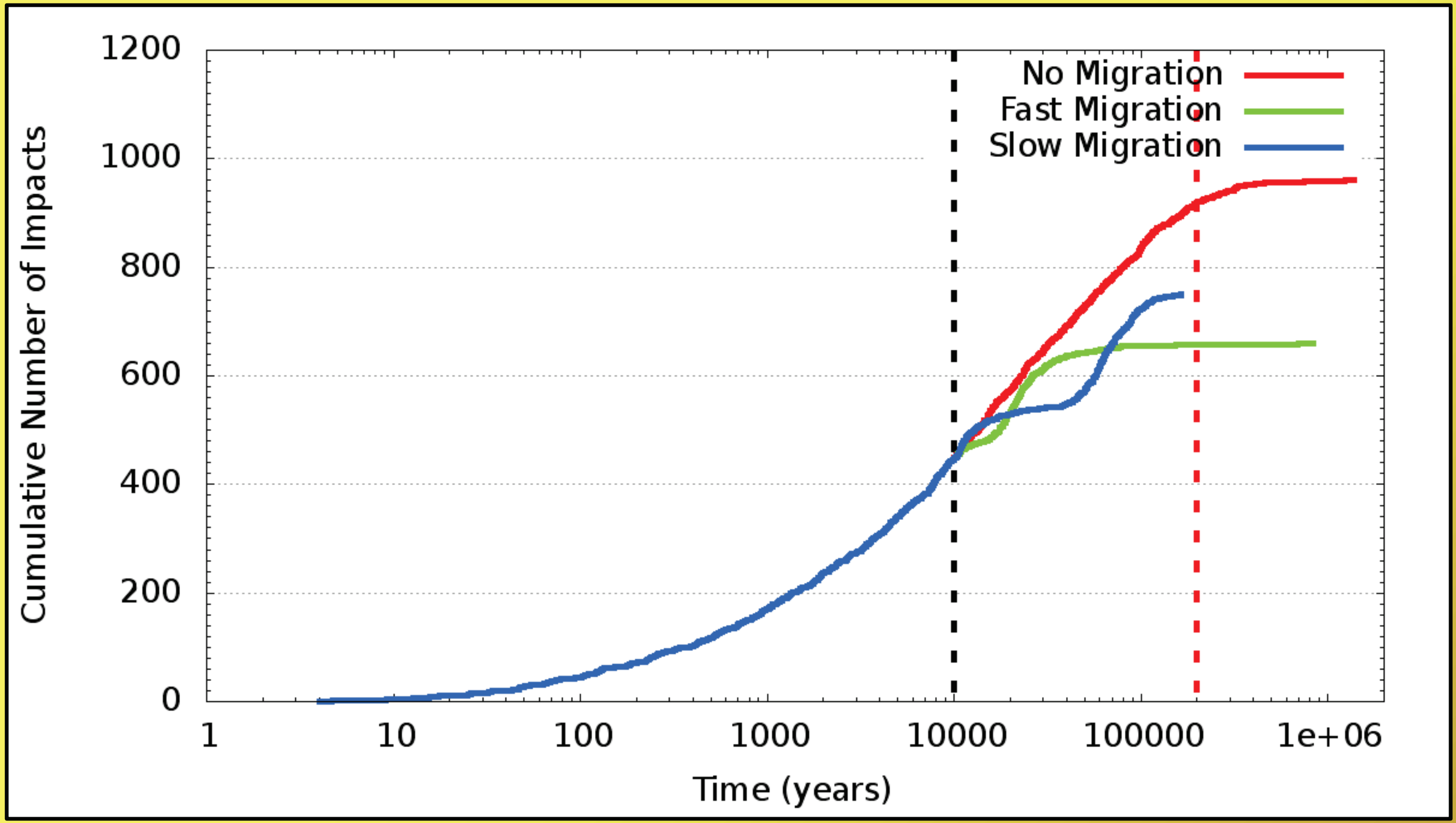
The JEB on Vesta: Erosion + Water + HSE





JEB & Late Accretion of Jupiter

The **bulk of the late accretion** of Jupiter is **completed in about 3x10^5 years** since the beginning of the simulations, consistently with the duration of the bulk of the JEB (0.3-0.5 Ma, Turrini et al. 2011, 2012).



The total accretion efficiencies are:

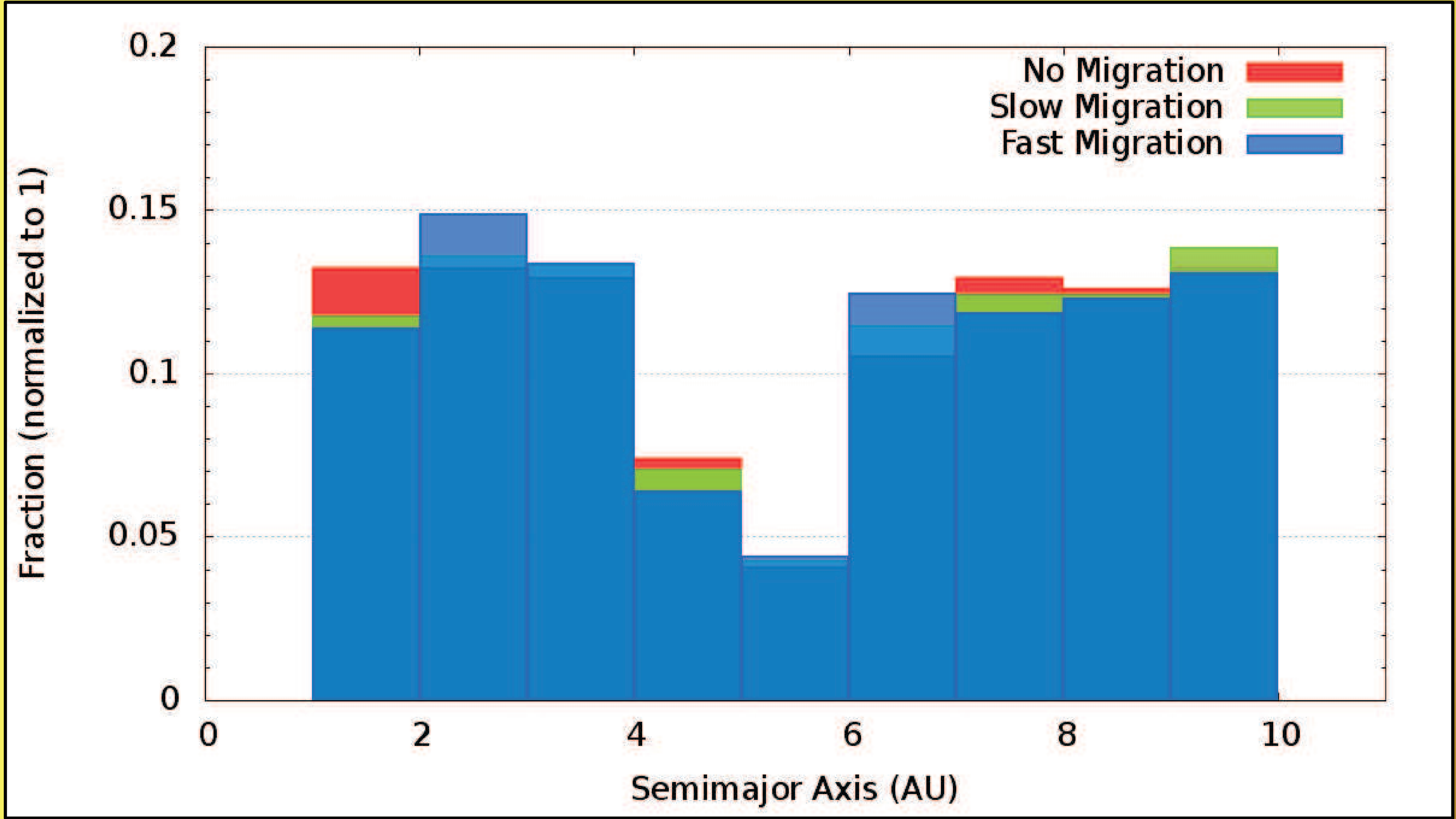
- No Migration: 4.8%;
- Fast Migration: 3.3%
- Slow Migration: 3.8%

Translated into units of $M_\oplus$, these become:

- No Migration: 1.1 $M_\oplus$;
- Fast Migration: 0.86 $M_\oplus$;
- Slow Migration: 0.75 $M_\oplus$;

JEB & Late Accretion: Source Regions

Unexpectedly, **~40% of the accreted masses** come **from the inner region** (i.e. volatile-depleted, **silicate- and metal-rich**) of the planetary system **independently on migration**.



The Composition of the Planetesimals

To estimate the mass delivered to Jupiter by the captured planetesimals we assumed that:

- Our simulated disk was a **Minimum Mass Solar Nebula** (Weidenschilling 1977) with a surface density of **2700 g cm^{-2} at 1 AU** and a **R$^{-3/2}$ density profile** (Coradini et al. 1981);
- In the **outer Solar System** the total **mass of the disk** was **reduced by 5 Earth masses** to account for the gap due to the formation of Jupiter's core.

Our disk was divided into 3 regions with different planetesimal composition:

- **Region A (1-3 AU)**: planetesimals are assumed similar to **ordinary chondrites** (~25 wt% Fe, ~19 wt% Si, ~05 wt% C, ~1.8 wt% S);
- **Region B (3-4 AU)**: planetesimals are assumed similar to **carbonaceous chondrites** (~25% Fe, ~14% Si, ~2 wt% C, 1.8 wt% S, ~10 wt% H_2O);
- **Region C (4-10 AU)**: planetesimals are assumed similar to **comets** (half carbonaceous chondrites, half as ~74 wt% H_2O, ~24 wt% C, ~0.7 wt% N, ~1.2 wt% S);

Planetary and Atmospheric Enrichment

If the **accreted mass** is distributed:

- over the **whole planet**, the **enrichment** is still low (**16%**) and the Jovian high-Z fraction is only 2.4% instead of the lower limit of 3% (Lunine et al. 2004).
- over the **molecular shell with thickness of 5000 km**, the produced **enrichment** is **of** about **a factor 2**;

Element/Molecule	Enrichment (no migration)	Enrichment (fast migration)	Enrichment (slow migration)
Fe	5.9	4.4	4.8
Si	6.44	4.7	5.2
C	1.5	1.4	1.4
N	1.2	1.1	1.1
S	2.5	2.0	2.2
H_2O	2.5	2.0	2.2

Exploring the Outer Solar System: The ODINUS Mission Concept

The ODINUS white paper proposed a ESA mission to the two ice giants Uranus and Neptune using a fleet of twin spacecraft for the L3 mission slot of the Cosmic Vision 2015-2025 program.

ODINUS

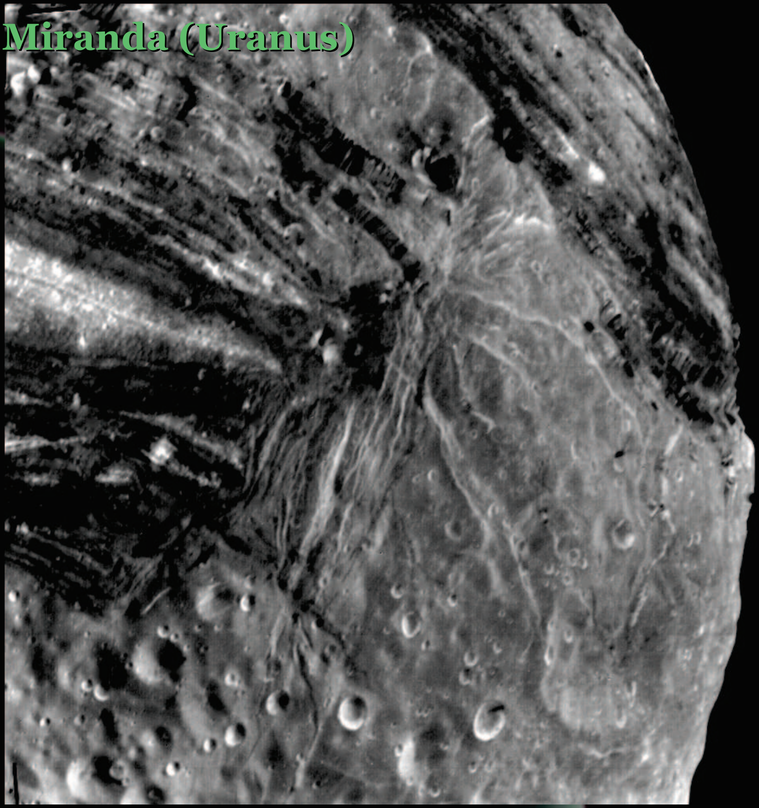
↓

Origins, Dynamics and Interiors of the Neptunian and Uranian Systems

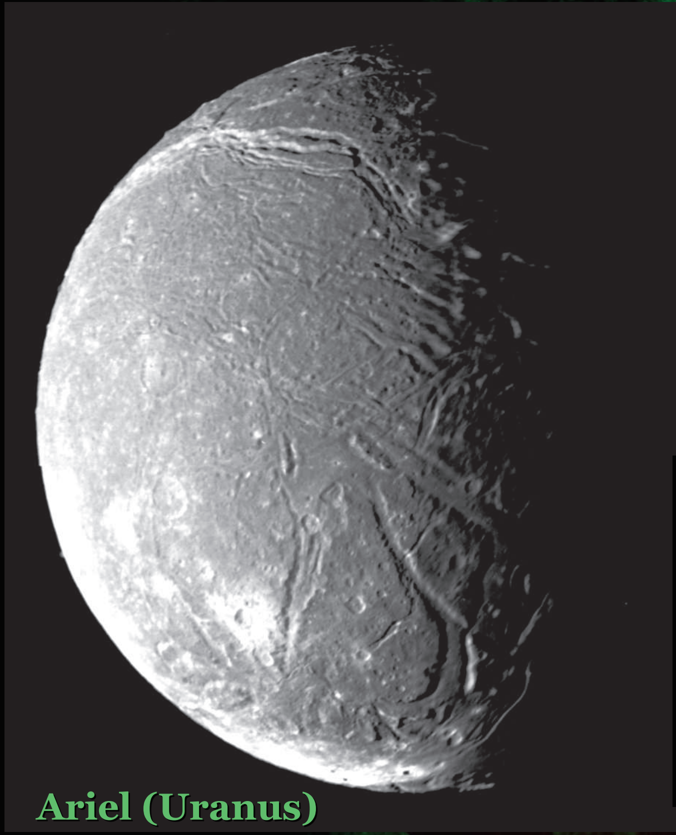
↓

Exploration and Comparative Planetology of Uranus, Neptune and their Satellite Systems

Exploring the Outer Solar System: The Satellites of Uranus

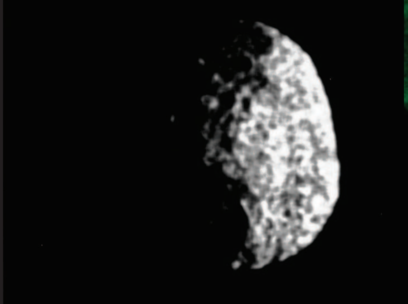


Miranda (Uranus)

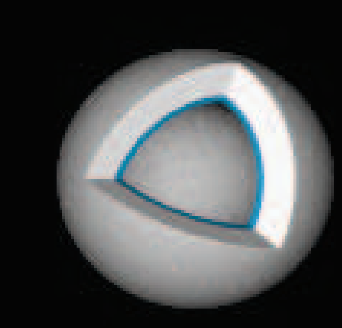


Ariel (Uranus)

NASA/JPL/Voyager Program



Proteus (Neptune)



Titania (Uranus)

- What is the bulk and surface composition of the icy moons?
- What is the interior structure of the main five Uranian satellites?
- How have impacts and space weathering modified their surfaces?
- What influence do tidal interactions have in these systems?

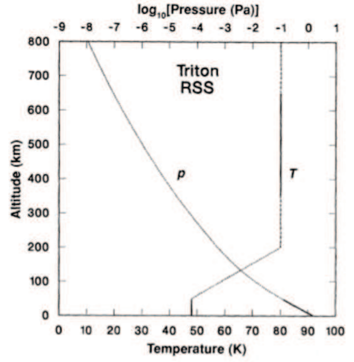
Exploring the Outer Solar System: Triton

Captured Kuiper belt object

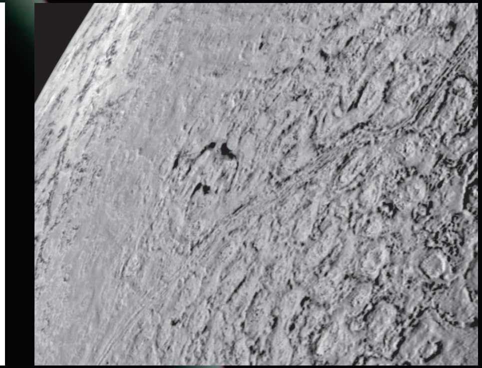
Appears to be geologically active with plumes.

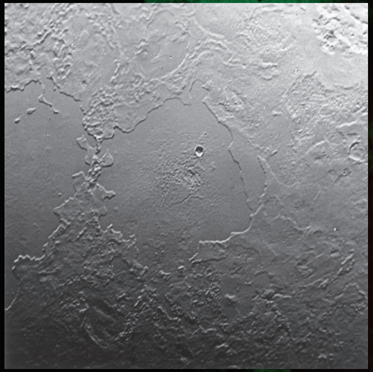
Thin atmosphere with plumes.

Mass source for the magnetosphere.



Tyler et al. (1989)





NASA/JPL/Voyager Program

- What physical memory does Triton retain from its dwarf planet origin?
- How did Triton’s capture affect the Neptune system?
- What is the composition of Triton’s surface?
- How geologically active is Triton and what powers Triton’s plumes?

Exploring the Outer Solar System: On the Path to Uranus

During the L2-L3 themes selection, the ODINUS white paper was grouped together a Uranus (P.I.: C. Arridge) and a Neptune & Triton (P.I.: A. Masters) proposals in the "Ice Giants" theme.

After evaluating the three white papers, **ESA ranked the "Ice Giants" theme third** and defined it "**a timely milestone, fully appropriate for an L class mission**" (http://sci.esa.int/jump.cfm?oid=53261).

In view of the incoming ESA M4 call, we are preparing a **proposal for a joint ESA-NASA mission to Uranus** (P.I.: C. Arridge), building upon the previous M3 proposal "Uranus Pathfinder" and the L2-L3 experience.