Scientific and Technical Challenges for Robotic and Human Deep Space Exploration Missions in Next 40 Years

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From the Key Questions of Planetary Sciences to the Representative Space Missions of the Next 40 Years

The Enabling Technologies of deep space missions
A

From the key questions of planetary sciences to the representative space missions of the next 40 years
Planetary Systems
A new class of astrophysical object

Extrasolar Planets
Systems

The Solar System

Giant planets
Systems

Circumstellar disks

IN SITU MEASUREMENTS

REMOTE SENSING (ASTRONOMICAL OBSERVATIONS)
Stellar formation region in the Large Magellanic Cloud
PROTOPLANETARY DISKS

HD 163296

HL TAU R

HD 169142

RX J1615

HD 135344B

TW HYDRAE

AS 209

ELIAS 2-27

Specimens exhibiting rings, gaps, & spirals

Seen by SPHERE on the VLT
Need to look inside the “Planet Factory”
Growth and formation scenario of a planet in a protoplanetary disk
(Baruteau et al., 2016)
Year 0:
Jupiter forms

Year 70,000:
Jupiter migrates inwards

Year 100,000:
Saturn migrates to 3:2 resonance
formation of terrestrial planets

Year 300,000:
outward migration

Year 500,000:
end of “Grand Tack”

Year 600,000 to present:
after “Nice scenario”
(b) FORMATION AND DIVERSITY OF PLANETARY SYSTEMS ARCHITECTURES: Comparing the Solar System with others

(c) DIVERSITY OF OBJECTS:
Terrestrial planets, Gas Giants, Ice giants...
What connection to exoplanets?
(D) HOW DO PLANETS AND THEIR SYSTEMS WORK?

**Gravitational coupling**
operates between planets or satellites, rings, small bodies and/or debris disks, gas and dust clouds and rings and one (or several) central object(s)

**Electrodynamic coupling**
maintains and populates a magnetosphere, drives aurorae, provides energy sources to the planetary environment and regulates the interaction with stellar output and activity

+ collisions, phase changes, chemical reactions, volcanism...
1. Why is Ganymede an habitable world?

FROM (e) EMERGENCE OF HABITABLE WORLDS TO (f) SEARCH FOR LIFE

THE «STANDARD» HABITABILITY CONDITIONS
- Liquid water
- Stable environment
- Essential elements (CHNOPS)
- Energy

Surface habitats
Deep habitats (Europa, Ganymede)
Deep habitats (Tian, Enceladus)

The Solar System: an ideal "habitability laboratory"
SIX MAJOR SCIENTIFIC QUESTIONS

(a) ORIGIN

(b) FORMATION AND DIVERSITY OF PLANETARY SYSTEMS ARCHITECTURES

(c) DIVERSITY OF OBJECTS

(d) HOW DO THEY WORK?

(e) EMERGENCE OF POTENTIAL HABITATS

(f) DETECTION OF LIFE

Studying Planetary Systems
A long-term perspective of Solar System Exploration, today and tomorrow

**Mission types:**
- Sample return (in situ analysis when possible) and giant planets entry probes.
- Orbiters and landers for architectures.
- In situ exploration of satellites of giant planets.
- Orbital observation of small bodies within each reservoir and of small irregular counterparts.

**Key measurements:**
- Cratering record throughout the Solar System (via H2O, NH3, CH4…)
- Giant planets' atmospheres elemental and isotopic composition
- Connect the small body and meteorite records
- Interstellar matters: molecular swarms
- Study habitability of surface habitats and deep habitats
- Detect the full spectrum of complexity (biomarkers and fresh molecules)
- Develop sensors to try and detect signs of life across the full spectrum of complexity

**Mission types and targets:**

<table>
<thead>
<tr>
<th>System</th>
<th>Sample Return</th>
<th>In Situ Exploration</th>
<th>Orbital Observation</th>
<th>Robotic Exploration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Giant Planets</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>Dwarf Stars</td>
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<td>KBO</td>
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<td>Heliopause</td>
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<td>Centaurs</td>
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<tr>
<td>Oort Cloud</td>
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<tr>
<td>Giant Stars</td>
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<tr>
<td>Proxima Centauri</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Alpha Centauri</td>
<td>Yes</td>
<td>Yes</td>
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</table>

**EMERGENCE OF POTENTIAL HABITATS**

**HORIZON 2061 APPROACH**

**OVERARCHING GOAL**

**INTEGRATED SPACE SCIENCE MISSIONS FLOWN OR DECIDED**

**HUMAN EXPLORATION**

**ROBOTIC EXPLORATION**

**DETAILED COVERAGE BY SPACE-BASED TELESCOPES**

**STEP**

**Jeremie.Lasue@irap.omp.eu**
Six « Provinces » to visit in the Solar System

1. Future Giant Space Observatories
2. The Earth-Moon System
3. Terrestrial planets
4. Giant planets and their systems
5. Small bodies
6. Heliosphere, Solar System, ISM and beyond
ELEVEN ways
For the scientific exploration of the Solar System

Instrument Platforms

• Earth-based telescopes
• Earth-vicinity telescopes
• Flybys
• Orbiters
• Landers
• Rovers
• Penetrators
• Sample extraction
• In situ sample analysis
• Sample return
• Earth laboratories
CHINA’S ROBOTIC EXPLORATION PROGRAM

Overview (2000 – 2030)

Past and current:
- Double Star, Chang’E 1, 2 and 3, DAMPE, QUESS, SHIJIAN, TanSat, HXMT, CSES

Future:
- SMILE, Chang’E 4 and 5, to Mars, land on Mars, sample return from Mars and asteroids, to Jupiter, remote sensing of Jupiter
## Future Earth-Moon System Science
addresses most of the Horizon 2061 questions
(source: SSERVI document « Transformative Lunar Science »)

### Science questions

- Early dynamical and collisional History of Solar System, volatile delivery to terrestrial planets
- Absolute chronology of collisions and bombardment in inner SS
- Moon’s water cycle
- Moon’s internal structure and relationship to formation scenario
- Long-term record of space weathering of Lunar surface
- Inventory of near-surface mineral resources and implications on crust formation History

### Missions and campaigns

#### SCIENCE OF THE MOON

- Multimessenger cartography of Moon terrains (remote + local)
- Network of geosciences stations
- Geochemical characterization of subsurface with drilling
- Sample return from a comprehensive set of representative sites
- First demonstrators of In Situ Utilization of Lunar Resources (ISRU)

#### SCIENCE FROM THE MOON

(ASTRONOMY AND EARTH MONITORING)

<table>
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<tr>
<th>SCIENCE FROM THE MOON</th>
<th>LF interferometric radioastronomy in Lunar orbit</th>
<th>LF interferometric radioastronomy from the surface</th>
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#### SCIENCE ON THE MOON

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<td>LUNAR BASES AND PERMANENT OBSERVATION NETWORKS</td>
</tr>
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</table>
China’s Lunar Exploration Program (CLEP)

1. Lunar Exploration
   - 2007.10 CE-1 Orbiter
   - 2010.10 CE-2 Lunar, L2 and Asteroids
   - 2013.12 CE-3 Softlanding
   - 2014.10 CE-5T Re-entry Experiment
   - 2018 CE-4 Far-side Landing
   - 2023 2nd Lunar South Pole Landing Exploration
   - 2024 2nd Sample Return Mission
   - 2027 2nd Lunar South Pole Landing Exploration
Venus

- Magellan mission ended in 1994
- Venus Express mission ended in 2014
- Akatsuki launched in 2010 still on going
- Envision topography mission in ESA’s Cosmic Vision M5 short list
- Option for a flagship Venus mission in the next US Decadal Survey?
- Atmospheric Sample Return in the mid-term?

Venus surface sample return would bring essential scientific results but will need previous demonstration of long lived landers and atmospheric balloons
Notional “Fast” MSR Timeline

Fast timeline could return samples to Earth ~3 yrs after SRL launch.
Science with depth

For Life, Water, Resources & Climate

• If we are looking for life and water, then there is no better place than the Martian subsurface.
  - Extinct life: longest living habitat. At greater depth (>1-5m) the likelihood of biosignature preservation is greater due to shielding from radiation.
  - Extant life: If life still exists on Mars, then it is most likely to be found where liquid water exists. Brines could be liquid at shallower depth. Spectral evidence suggests brines on or close to the surface. Pure water aquifers are more likely to be below 1-10 km.

• Follow & find the water
• Climate & planet evolution: volatiles & drill cores
DIVERSITY OF PLANETS

GIANT PLANETS SYSTEMS

Gas Giants

- **JUPITER**
  - Satellites: 67
  - Molecular hydrogen
  - Metallic hydrogen

- **SATURN**
  - Satellites: 62
  - Hydrogen, helium, methane gas

- **URANUS**
  - Satellites: 27
  - Mantle (water, ammonia, methane ices)

- **NEPTUNE**
  - Satellites: 14
  - Core (rock, ice)

Ice Giants

- **EARTH**
Diversity of satellites
Diversity of rings!

- Jupiter
- Saturn
- Uranus
- Neptune
Jupiter and the small regular satellites

Galilean satellites

Irregular satellites
The Jupiter System

ORIGINS & FORMATION

WHERE TO LOOK FOR?

CALLISTO

SMALL REGULAR SATELLITES

JUPITER’S INTERIOR

IRREGULAR SATELLITES

TROJANS

SMALL REGULAR SATELLITES
UNDERSTANDING HOW JUPITER FORMED

Main theme of NASA’s Juno mission
Probing the deep interior from orbit

Juno maps Jupiter from the deepest interior to the atmosphere using microwaves, magnetic and gravity fields.
CALLISTO and the search for the Origins

**Internal structure**

**Degree of differentiation**

**Surface geology**

**Impact record**

**Craterisation History**

**Detailed geochemistry at landing site**

**Callisto Lander?**

- Radius: 2410 km
- Density: 1.834
ORIGIN OF GIANT PLANETS
One atmospheric entry probe at each planet!

From « ICE GIANTS », pre-decadal survey mission study report, NASA
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Deep habitats (Tian, Enceladus)

The Solar System: an ideal “habitability laboratory”
- Ganymede’s habitability
- Jupiter system: how does it work?
  - Jupiter orbiter
  - Multiple flybys of Europa+ Callisto
  - Ganymede orbiter

- Europa’s habitability
  - Spacecraft remains in orbit around Jupiter
  - Multiple flybys of Europa
  - Altitudes: 25 – 2700 km
Europa Lander?

SEARCH FOR LIFE
THE SATURN SYSTEM:
TITAN AND ENCELADUS

Titan’s North Polar Lakes and Seas
as revealed by the Cassini Titan RADAR Mapper

The Cassini RADAR images in this map were obtained in multiple operating modes with resolutions of 0.3-1.5 km, 2-10 km, and 40-200 km. False coloring is used to distinguish bodies of liquid hydrocarbon (blue-black) from dry land (brown) and does not represent the visual appearance of Titan’s surface.
Just a few of the CONCEPTS for future missions to Titan and the Saturn System

Titan Explorer
NASA Flagship study (2007)

Titan and Enceladus Mission (TandEM)
ESA L1-CV candidate (2007)

Titan Aerial Explorer (TAE)
ESA M3-CV candidate (2010)

Titan and Saturn System Mission (TSSM)
ESA-NASA joint mission study (2008)

Titan Aerial Vehicle for In Situ and Airborne Reconnaissance (AVIATR)
NASA Discovery candidate (2010)

Titan Mare Explorer (TiME)
NASA Discovery candidate (2008-2012)

Journey to Enceladus and Titan (JET)
NASA Discovery candidate (2010)
The near future for Titan?: Dragonfly
NF4 finalist for NASA's decision in mid-2019

http://dragonfly.jhuapl.edu/
Enceladus’ interior at the end of Cassini: structure

- buried global ocean
- 30-40 km thick
  (Thomas et al., 2016)
- very uneven ice shell
- 25-30 km thick in average
  up to 35 km at equator
  less than 5 km at south pole
  (Čadek et al., 2016 ;
  Beuthe et al., 2016)
- porous rock core
- filled with 20-30 % water
  (e.g. Roberts, 2015 ;
  Waite et al., 2017)
Returning samples from the active jets of Enceladus?

SEARCH FOR LIFE
EMERGENCE OF HABITABLE WORLDS

Exploring the active moons of the Ice Giants?

« Natives »?

A unique opportunity for a close-in investigation of a captured TNO

TRITON
LUCY
1\textsuperscript{st} mission to the Trojans in 2021

SMALL BODIES
CAST’s concept mission design

Mission profile:

- **Phase 1**: NEA  Sample return  In-situ analysis  Remote sensing
- **Phase 2**: MBC  Investigation
Caesar, Comet Sample Return

Finalist of New Frontiers 4, in view of launch in 2025
Target = Churyumov - Gerasimenko, explored by Rosetta
Osiris Rex heritage, Next ion propulsion, Hayabusa’s Sample Return Capsule
Samples must be kept at T < 0°C
Voyager I left our solar system in 2012

Voyager I
- Launched in 1977 (40 years ago!)
- Current Speed: 17 km/s
- 140 AU from the Sun
- Downlink telemetry: 16 bits/sec
- Uplink telemetry: 160 bits/sec
- Onboard Computer Memory: 70 kBytes
- Power available: 249 W
- Flight Software: FORTRAN/C

What will the Voyager of 2061 be like?

voyager.jpl.nasa.gov

INTERSTELLAR PROBE!
(NASA STUDY)
Future Science Targets

**Target 1:** Interstellar Medium and Heliosphere

**Target 2:** Circum-Solar Dust Disk

**Target 3:** Kuiper Belt Objects

**Target 4:** Trans-Neptunian Planet?

**NASA’s Interstellar Probe study**

**CHINA’s Interstellar Express project**
Horizon 2061 Synthesis Workshop

How to meet the major science goals of Deep Space Exploration by breaking technology challenge walls!

TOULOUSE, September 11th to 13th, 2019

https://h2061-tlse.sciencesconf.org
OBJECTIVE:
Design and deliver with the community a mutually consistent, non binding projection of the four pillars of Solar System exploration in the broader context of the science of Planetary Systems.

METHOD:
1. Build each pillar (from the results of steps 1 and 2) on the basis of reports submitted to the critical analysis of the participants;
2. Produce a report of Solar System H2061 foresight as a « topical series » of peer-reviewed articles (the ISSI model);
3. Lay the foundations for an exoplanet science H2061 exercise.