LUNAR MISSIONS: SCIENCE AND EXPLORATION

Bernard H. Foing (1) and ILEWG(2)

(1) Research Support Division, SCI-SR, ESTEC Postbus 299 2200 AG Noordwijk, NL, Europe
Email: Bernard.Foing@esa.int
Phone/Fax: (31) 71 565 5647/4699
sci.esa.int/smart-1/

(2) International Lunar Exploration Working Group www.estec.esa.nl/ilewg/

ABSTRACT

Results from the recent US missions “Clementine” and Lunar Prospector, will, in the near future, be used to prepare the ESA SMART-1 and Japanese Lunar-A and SELENE missions to the Moon. The scientific results of these missions will continue to answer open questions about the origin of the Earth–Moon system, the early evolution of life, the planetary environment and the existence of in-situ resources necessary to support human presence (e.g. water, oxygen). These science and technology missions can be considered as precursor missions for future human exploration of the solar system.

1. APOLLO AND LUNA MISSIONS

The rate of development and legacy of lunar missions, conducted by the US and the former Soviet Union is impressive (Figs 1-4):

1966-1965 Apollo Unmanned
1965-1970 Zond – Luna Soviet
1966-1967 Lunar Orbiter NASA mapping
1968-1972 Apollo Manned missions

Fig. 2: Schematic of Apollo Lunar Module

Fig. 1: Lunokhod automatic rover

Fig. 3: Apollo astronaut on the lunar surface
2. INTERNATIONAL LUNAR EXPLORATION

Spacefaring nations (including ESA and its Member States) have de facto engaged in a renewed International Lunar Exploration Programme:

1994: Clementine (US, BMDO): Multi-band Imaging, technology demonstration
       Neutron, gamma ray low resolution mapping
2003: SMART-1 (ESA Technology Mission):
       Instrument technology, high res., geochemistry
2004: Lunar A (J, ISAS Science): Two Penetrators with seismometers + equator cameras
2005: SELENE (J, ISAS/NASDA): Ambitious orbiter instruments for science

3. CLEMENTINE

This mission was developed by the American Dept of Defence as a technology demonstration mission. It was launched January 1994, on a Titan IIIG rocket. The objectives included the global 3D mapping of the composition of the lunar crust, and the study of illumination and ice at the South Pole (Figs 5-6).

Clementine included the following instruments:
- UV-vis camera
- Near - IR camera
- High Resolution Camera
- LIDAR system
- Long Wave Infrared Camera

Fig. 4: Earthrise as seen from Apollo. A picture that changed our view of planet Earth.

Fig. 5: Clementine Mosaic of the South pole region illumination, confirming areas of permanent shadow.

Fig. 6: FeO concentration derived from Clementine at 750 and 950 nm + Apollo 16 metric images. FeO concentration of 4-5% in the Cayley plains is consistent with returned samples.
4. LUNAR PROSPECTOR

The US NASA Discovery mission, Lunar Prospector, was launched on 6 January 1998 on an Athena II rocket, with the following objectives:
- Study of lunar formation and evolution
- Prospecting lunar resources

Lunar Prospector included the following instruments:
- Neutron Spectrometer (e.g. Polar ices, see Fig. 7)
- Gamma-Ray Spectrometer (see Fig. 8)
- Magnetometer / Electron reflectometer
- Doppler Gravity Experiment
- Alpha Particle Spectrometer

Fig. 8. (above) Lunar Prospector Gamma ray-spectra of the elements that LP is mapping.

(below) Map of the Thorium distribution inferred from Lunar Prospector.

Fig. 7: LP Neutron Spectrometer data from the North pole showing evidence of enhanced H or water ice
5. SMART-1

SMART (Small Missions for Advanced Research in Technology) are technology demonstration missions offering an early opportunity for science as well as a new management approach. SMART-1 is the first approved European mission to visit the Moon. Its main rationale is to demonstrate Deep Space Electric Propulsion and other technologies for the future.

5.1 SMART-1 Solar Electric Propulsion to the Moon
SMART-1 will be launched in March 2003 on an Ariane 5. Its main characteristics are:
- Cyclade auxiliary passenger into Standard GTO
- test of Solar Electric Propulsion & cruise (15 month)
- lunar orbit 300-10000 km, 6 month +extension

5.2 SMART-1 Instruments
Six instruments will be operating in all mission phases (cruise/moon), performing 10 distinct science and technology investigations:
- SPEDE (Spacecraft Potential Electron and Dust Exp.)
- EPDP (Electric Propulsion Diagnostic Package)
- KATE (Ka-Band TT&C Experiment)
- RSIS (Radio-Science Investigations for SMART-1)
- AMIE (Advanced Moon micro-Imager Experiment)
- Laserlink (Experimental Deep-space Laser link)
- OBAN (On-Board Autonomous Navigation Exp.)
- SIR (SMART-1 Infrared Spectrometer)
- D-CIXS (Demo Compact Imaging Xray Spectrometer)
- XSM (X-ray Solar Monitoring)

5.3 Science Objectives for SMART-1
- CRUISE SCIENCE:
  - Earth and magnetospheric imaging
  - Longterm X-ray monitoring of Sun & cosmic sources
- LUNAR SCIENCE:
  - First X-ray mapping of Mg, Al, Si (50 km resolution)
  - First infrared spectral mineralogy mapping 0.9-2.5µm
  - Colour images 0.75,0.9, 0.95 µm + white
  - Local multiband mapping at res. 30 m from 300 km
  - Polar areas illumination and resource mapping

5.4 D-CIXS X-ray instrument objectives
PI: M. Grande (RAL), co-I's UK, FIN, F, E, S + ESA
- Demonstration of compact X-ray imaging spectrometer (12 x 32 deg FOV)
- Global mapping of lunar surface (elemental composition) via X-ray fluorescence
- X-ray celestial sources, Earth aurora and magnetotail
- New technologies: Micro-structure collimator
  - Swept Charge Devices (Detectors) 0.5 - 10 keV

XSM - PI: J. Huovelin (Obs. Helsinki – FIN)
Sun X-ray flares and coronal monitoring (calibration),
- Si-pin detectors 104° FOV; range: 0.8-20 keV

Fig.9 SMART-1 (http://sci.esa.int/smart-1/)

Fig.10: D-CIXS
D-CIXS science aims at providing 50 km res map of absolute abundances of Mg, Si, Al. Bulk crustal composition has bearing on theories of origin and evolution of the Moon. The mapping of Mg# = Mg/Mg+Fe is a key to study the evidence of a primitive source, the relations of Mg-suite rocks vs ferroan anorthosites or KREEP, the constraints on magma ocean model/ evolution. The South Pole-Aitken Basin (SPA) and impact effects in lunar basins will be studied.

Fig.11: Compared to Apollo Si/Al ratio maps on 10% of lunar surface, D-CIXS will have global X-ray cover.
5.5 SIR Infrared Mapping Spectrometer
PI: U. Keller (MPAe - D); Co-I:s D, UK, IRL, + ESA

Science and Technology Objectives:
- Near infrared point-spectrometer, NIR mapping of lunar southern hemisphere (300 m resolution), angular spectroscopy of the surface features
- Flight qualification of a miniature monolithic grating spectrometer derived from commercial device (Zeiss)
- 0.9±2.4 μm, 256 channels, resolution 6 nm/ pixel.
- Correlation to AMIE 950 nm filter

Fig. 12: SIR infrared spectrometer

- Lunar Spectral mapping:
  - Discrimination of pyroxenes and olivine
  - Olivine from mantle: crustal differentiation/evolution
  - SPA exposed materials from mantle
  - SIR highest spatial resolution 300 m of units on central peaks, walls, rims and ejecta blankets of large impact craters, giving stratigraphy of lunar crust

Fig. 13: Reflectance spectra of the main lunar minerals

5.6 SMART-1 AMIE Multicolour Camera
PI: J.L. Josset, Co-I:s: F, I, FI, N, ESA

Science and Technology Objectives:
Miniature camera for medium/high-res. multi-spectral imaging (27 m Moon South pole)
- Extension of data-set Apollo/Clementine
- Support to laser-link, OBAN, RSIS; aligned to SIR
Main Experiment features:
- 5.3° FOV, 1024 x 1024 Si-CCD, 3 fixed wide-band filters (0.75±0.96 μm) + panchromatic + laser-link
- High-density CCD electronics. & Micro-DPU
- Packaged 3-D interconnect technology
- Shielded Off The Shelf components.
- 1.8 kg (Opt.Head 400 gr), 9W

Fig. 14 AMIE camera
- Average pixel resolution of 80 m (30 m near perilune)
- Geological context for SIR & D-CIXS data
- Stereo and multi-phase angle observations
- Lunar south pole repeated and deep high res. image
- Identification of (double) shadowed areas
- Search for potential ‘water ice traps’ or ‘cold traps’
- Preparation for future lunar exploration: mapping of sites of “eternal” light or shadow or landing sites
- Potential sites for lunar bases: power, resources

Fig. 14: AMIE Laserlink experiment
6. LUNAR–A

Lunar–A will be launched in mid-2004, on an M-V rocket, from Kagoshima Space Center. It is expected to arrive at the Moon in mid-2005. Its objectives include:
- Study of lunar interior
- Seismometers and Heat flow probes
- Two penetrators (near and far side)
- Study of deep moonquakes (see Fig. 17)
- Mapping topographic data with B&W camera with emphasis on the near terminator

7. SELENE

SELENE, to be launched in 2005, covers 3 broad science objectives with a suite of instruments:
Elemental and mineralogical composition:
- X-ray spectrometer
- Gamma Ray spectrometer
- Multiband imager and Spectral Profiler
Surface and subsurface structure/ tectonics:
- Terrain Camera &Laser Altimeter
- Lunar Radar Sounder
- Gravity Field (VLBI and data relay)
Lunar environment studies:
- Lunar Magnetometer- Plasma Imager
- Charged Particle Spectrometer and Plasma analyser
- Radio Science S and X

Fig. 18: View of SELENE

Fig. 19: Schematics of SELENE subsystems

Fig. 20: SELENE mission profile
8. KEY LUNAR SCIENCE ISSUES

Fundamental science topics can be addressed by lunar exploration:

8.1 Formation and Evolution of Planets
- Understanding how rocky planets form and evolve
- Chemical constraints on Earth-Moon origin
- Signatures of accretional processes in inner planets
- South Pole Aitken Basin and large impact basins
- Evolution of Earth/Moon system
- Impacts: giant bombardment in the inner solar system

8.2 Comparative Geophysical Processes
- Volcanism, tectonics, cratering, erosion,
- Deposition of ices and volatiles
- Geophysics and Geochemistry

8.3 The Moon as collector of extraterrestrial samples
- Regolith Sample of the solar wind history
- Samples of ice cometary deposits in the last 10⁶ years
- Samples from the Early and Evolving Earth
- Samples from Venus, Mars and asteroids

8.4 Preparing for Future Lunar Exploration
- Survey of lunar resources
  (minerals, volatiles, lighting)
- High resolution studies for landing sites/outposts
- Coordination between lunar missions.
- Environment studies in support of human exploration

Fig. 21: Phased International Lunar Exploration (ILEWG)

9. INTERNATIONAL LUNAR EXPLORATION

9.1 ILEWG

ILEWG, the International Lunar Exploration Working Group organized the ICEUM International Conferences on Exploration & Utilisation of the Moon (Beatenberg 94, Kyoto 96, Moscow 98, ESTEC 00) to consult the community on the definition of recommendations for the future.

Also scientists, engineers and exploration experts have discussed their priorities e.g. at COSPAR (Washington 92, Hamburg 94, Nagoya 98, Warsaw 00, Houston 02) and at EGS lunar sessions (Vienna 97, Nice 98, The Hague 99, Nice 00 – 04) [2,3,4,5]

10.2 ESA Lunar Exploration Studies

ESA has conducted several studies for lunar missions in the past, including a study for a Lunar Polar Orbiter (POLO) in the 80’s. The beginning of the 90’s, a large consultation of the community led to the survey of possible science and social benefits for a renewed lunar exploration (cf ESA Report: Missions to the Moon [1]). A strategy for progressive exploration in 4 phases (precursor missions, landers, resource utilisation and deployment of large infrastructures, human permanent presence) was proposed by ESA, and agreed with other space agencies coordinated by ILEWG, the International Lunar Exploration Working Group, after the Beatenberg International Lunar Workshop [2].
Between 1994 and 1996 ESA studied a scientific lunar mission (MORO) as a contender for a medium cost mission. Technical studies (1994-1996) were also conducted on a lunar lander LEDA, and in 1996-1998 on the Euromoon study to land near the lunar south pole peak of quasi-eternal light. In parallel a series of key technologies for future lunar and planetary exploration were developed. ESA’s Long Term Space Policy Committee made recommendations for the future of European Space, including the emplacement of a permanent lunar base, and robotic precursors.

Other synergies for lunar exploration include:
- Preparation for Bepi Colombo
- Synergies with other science planetary missions (Rosetta, Mars express)
- ESA Advanced Technologies (Propulsion, Landing, Robotics, Telepresence…)

9.3 ICEUM4 ESTEC 2000, 10-14 July

http://solarsystem.estec.esa.nl/Moon2000/ilewg4_frame.htm
The highlights from this symposium included [6]:
- Young Lunar Explorers Special Session
- Science of the Moon: Clementine, Prospector
- Key science issues
- Technology activities /Future Missions to the Moon:
  SMART-1, Lunar-A, SELENE
- Moon testbed for robotic outposts & telepresence
- Infrastructure, resources, expansion in solar system
- Recommendations and Space Agencies plans:
  - synergies with Mars and solar system exploration
  - new approaches and long term perspectives
- Foundation of Lunar Explorers Society
http://lunarexplorer.org/

Fig. 22: Brainstorming of Young Lunar Explorers

9.4 International Lunar Missions under study
Several missions are under study, with very tentative launch dates:

2005? Ice Breaker Moon Rover
  US commercially sponsored lander/rover
2006? LUNARSAT
  educational mission by young lunar explorers
2006 Indian Lunar Mission
2008 Chinese Lunar Mission
  US Discovery Lunar Proposals
2007 SELENE B
  Soft Landing Technology Mission
2009 SELENE II
  Lunar Global Net/ Rover

10. TOOLS FOR LUNAR EXPLORATION

10.1 Tools for Science of and on the Moon
Technologies have to be further developed e.g.:
  - Remote sensing miniaturised instruments
  - Surface geophysical and geochemistry package
  - Instrument deployment and robotic arm
  - Close mobility, nano-rover, sampling , drilling
  - Sample finder and collector
  - Regional mobility: rover, navigation
  - Resource utilisation, outpost installation
  - Life sciences laboratories

10.2 Tools for Science from the Moon
Tools needed for autonomous robotic telescopes, and for the deployment of large telescopes:
  - Deep Surveys Lunar transit telescope
  - Dark Matter Lensing Telescope
  - Near Earth Object telescopes
  - Submm- IR telescopes in dark cold sites
  - Hypertelescope interferometers for exoplanet studies
  - Very Low Frequency astronomy on limb/far side sites
  - SETI telescopes

10.3 The Moon Testbed for Exploration Technologies
The Moon can be used to demonstrate new technologies, and system level engineering e.g. for:
  - Robotic laboratory
    Mecha-electronics-sensors
    Tele control, Telepresence, Virtual reality
    Autonomy and Navigation
    Artificially intelligent robots
  - In-Situ Utilisation of lunar resources
    Regolith, Oxygen, glasses, metals utilisation
  - Long term: He3 extraction
  - Establishment of permanent lunar infrastructure
  - Environmental protection aspects
  - Support to human expansion to the Moon and beyond
11. THE MOON AS A STEP TO THE SOLAR SYSTEM

The following is a list of aspects where science and technology demonstration on the Moon, will prepare for the expansion of human activities in the solar system:

11.1 Moon as a test bed for solar system exploration:
- Moon-Mars science synergies
- Instrument technologies
- Robotic outposts
- Tele-presence, Virtual reality
- Deployment of large infrastructures
- Earth-Moon L1 libration point for transfer
- Coordination humans and robots
- Medical aspects
- Biospheres on the Moon
- Human expansion in solar system

11.2 Astrobiology and Life sciences lab on the Moon:
- Analysis of organics from extraterrestrial samples
- Bacteria and extremes of life
- Survival, replication, mutation and evolution
- Extraterrestrial botanics: Growing plants on the Moon
- Animals: physiology and ethology on another planet
- Closed Ecological Life Support Systems,
- Greenhouses and Food

11.3 Expanding Life & Humans on the Moon:
A Lunar Exploration Roadmap can be given in an broad historical perspective:

1965 First organisms (Luna, Ranger)
1969 First humans (Apollo)
Robotic precursors in orbit
1994 (Clementine, Prospector)
2003 (SMART-1, SELENE)
Penetrators and Landers
(Lunar A, SELENE-B)
Virtual telepresence
2010 Robotic Outposts
Evolving life on the Moon
2012 Sample returns
2015 Ecosystem experiments
Plants, animals
Resource utilization
Robotic village
Short crew missions
Life support systems
2020 Humans and Lunar bases
2030 Expansion
2040 International Lunar Village
2060 Cities on the Moon

11.4 Human aspects of lunar exploration:
- Architecture design and operations of lunar base
- Man/robotics synergies, Life support systems
- Low gravity physiology laboratory, Telemedicine
- Psychology, Social and Multi-cultural Laboratory
- Infrastructures: communication, transport,
- Construction, exploitation
- Commercial development

Fig. 23 An advanced lunar base concept

11.5 Elements for Human Moon/Mars Exploration
New technologies and systems must be developed for future Human Exploration of the Moon and Mars:

- Advanced Launch /access to space
- Orbital Infrastructure
- Transport/ communication
- Habitable Descent / Ascent Vehicle

- Surface Power Generation
- In-Situ Fuel Production
- Robotic outposts and rovers

- Habitation Modules
- Workshop
- Scientific Laboratories
- Greenhouse / Agriculture Module
- Medical Centre

- Pressurized Rover
- Advanced EVA Suit
- Life Support Systems

© European Space Agency • Provided by the NASA Astrophysics Data System
12. THE ESA AURORA INITIATIVE

Having reached maturity in human space-flight with the development and operation of the International Space Station (ISS), the next step for human kind will be to reach out to other planets in the solar system. They will start first as explorers and then spend extended living and working periods on lunar and planetary bases. Precursor missions with soft and precision landing, drilling and sample return, in-situ resource utilisation will also greatly advance our technology capability. Technology spin-offs are expected in spacecraft and crew systems autonomy, communications, navigation for precision targeting to distant places, data transmission technology for large volumes of data, information technologies, non-conventional power and propulsion systems, reliable and efficient thermal control for extreme temperatures, radiation hardened electronics, “self-repairing” and adaptable software, in-situ resources utilisation, and robotics.

In line with the European long-term strategy to explore the Solar System and the Universe and to prepare for the “next step” in human space exploration, a new Programme – Aurora, has been proposed by ESA. The programme proposal, with an initial period of technology studies in 2002-2004 outlines a preparatory framework for robotic and then human exploration missions. Its focus is on Mars, the Moon and Near Earth Objects. It is characterised by a phased scenario with remote sensing first, then automated planetary in-situ reconnaissance, sample return and eventually the transportation and assembly of the necessary infrastructure for human in-situ exploration at the final destination. The scenario will be implemented in full synergy with other planetary missions planned elsewhere. Its science objectives are the search for life in the Solar System, the search for the origin of the solar system and to gain knowledge on Near Earth Objects-NEOs. Apart from its technological challenges, the programme also serves as an exciting and peaceful goal to society. The challenge for future lunar and planetary exploration is about science, technology and innovation; it is about people and cultures and it is about finding our place in the Universe, with the active involvement and excitement of the youth in particular.

13. ACKNOWLEDGEMENTS

We thank the members of ILEWG, the participants of the ICEUM, COSPAR and EGS sessions, for the discussion of ideas that led to this paper. We thank the teams of Clementine, Lunar Prospector, SMART-1, Lunar-A and SELENE for sharing the information on their projects, and for illustrations.

14. REFERENCES

14.1 Links
International Lunar Exploration working Group: http://www.estec.esa.nl/ilewg/
ESA Science web page: http://sci.esa.int
SMART-1 page: http://sci.esa.int/smart-1/
Lunar Explorers Society: http://lunarexplorer.org
Aurora: http://www.esa.int/export/esaHS/future.html

14.2 Publications
http://solarsystem.estec.esa.nl/Moon2000/ilewg4_frame.htm

14.3 Images credits: ESA, NASA, ISAS, ILEWG

Fig. 24: A biosphere on the Moon