Supplementary material to the poster

Astronomy from the Moon: Solar System & Exoplanets

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Advantages of the Moon

Progress on the big questions in astronomy, such as life on certain exoplanets or dark matter, will ultimately require high angular resolution, a large collecting area and access to the full optical spectrum.

The Moon offers unique conditions with its lack of atmosphere, access to the entire spectral band, its position relative to Earth and its low gravity.

More precisely, it combines three advantages:

- its lack of atmosphere allows access to the entire UV/Vis/IR spectrum and avoids atmospheric turbulence
- its low gravity and absence of wind make it possible to install extremely large telescopes with very large instruments, which is impossible for satellites in orbit
- it allows the instruments to be upgraded and to have a very long lifetime, which is impossible for satellites due to their limited amount of fuel.
- from the Moon, the sky seen under a different angle than from Earth, allowing to access to more targets

Large instruments will be installed not before a decade or two. In the meantime instrumental technologies will make in parallel significant progress.

Science cases

● Observation toward the Earth

● Observations of the Earth as an exoplanet : the LOUPE photometer (aperture 2 cm, 1 litre volume - Klinczik et al. 2021) will observe the Earth in a singe pixel from multiple phase angles, and its variations over the seasons and the reflection of the Sun by the oceans [41]. Exoplanets will initially be seen only as a point, just as LOUPE will see the Earth. The comparison of LOUPE results with images of the Earth from a 30 cm - 1m telescope will validate the conclusions drawn from a single pixel image and applied to single pixel observations of exoplanets.

● Sun eclipsed by the Earth : the Earth being 4 timess larger than the Moon, a soler eclipse by the Earth seen from the Moon would last 4 times longer than a solar eclipse by the Moon senn from Earth.

● Some stellar rays through the Earth atmosphere converge exactly on the Moon's surface (Kipping 2019)

When a star is on the line going from a lunar telescope to the centre of the Earth, or close to it, the Earth's atmosphere acts as an Earth-sized converging lens [2]. The light rays coming from the star are refracted at different angles depending on their wavelength and the height of their path through the Earth's atmosphere. Some of them will converge exactly on the lunar surface (Figure 1), resulting in a magnification of up to 50,000 |2]. This type of lens is not suitable for imaging, but its magnification can make it useful for rapid photometric observations of optical pulsars for example.

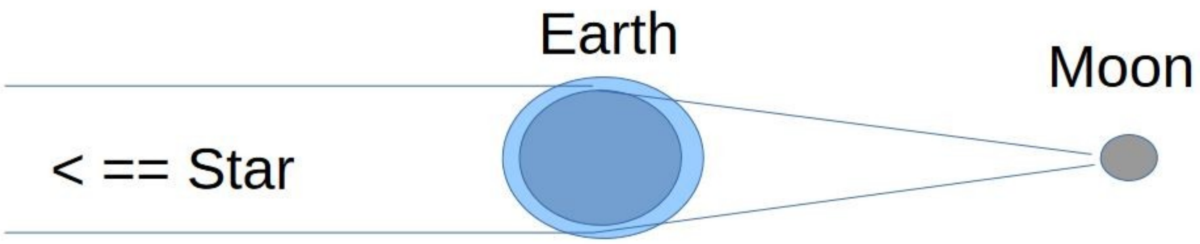

Figure 1 Stellar light rays converging at the Moon surface.

- Solar System
  - Stellar occultations by small bodies : new detections

  Solar system planets will be better investigated with in situ missions. But, with stellar occultations by solar system bodies from the Moon, one benefits from paralactic effects compared to terrestrial observations. From the Moon one can observe occultations that are not visible from Earth. So one will get more stellar occultations. And compared to ground-based observations, they will add constraints on the shape of the solar system body, rings and orbits. An unexplored area, the occultation of binary stars by asteroids, is in preparation (D. Souami, private communication). A lunar telescope can observe those occultations which are missed from Earth. They will constrain

- Exoplanets
  - Imaging of exoplanet transits by interferometric stellar surface imagers.

  When the angular resolution R_{Δ} is of the order of R_{pl} some pixels can focus on the planet's atmosphere. They then receive essentially the stellar light, with some molecular absorption lines from the planet atmosphere, leading to a better knowledge of their molecular composition. (Figure 2).

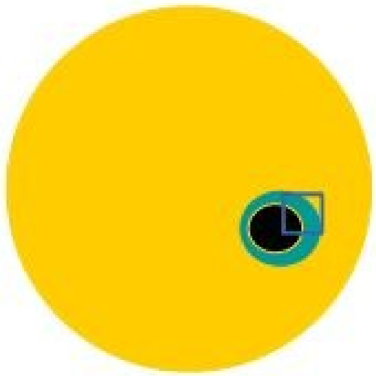

Figure 2 Imaging of an exoplanet atmosphere transit with R Δ= R pl . The square symbolizes a telescope pixel

2.2.2 Imaging of stellar glint on exo-oceans

Just as terrestrial oceans (gaidos et al. 2008) and Titan lakes (Jauman et al.2020) reflect the Sun (Figure 3 from Gaidos et al. 2006), oceans on exoplanets reflect the light of the parent star (McCummough 2006). It is a direct confirmation of liquid water on the planet. Note nevertheless that glaciers and high-altitude cirrus clouds produce a similar glint, but the la tter changes in time with the planet meteorology.

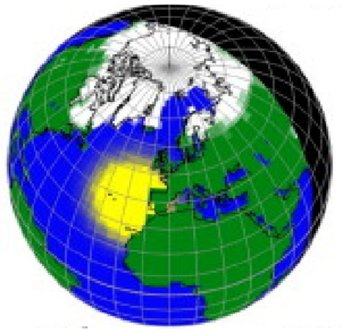

Fig. 3 Simulation of the Sun glint by terrestrial oceans (Credit Williams & Gaidos 2008)

The planet rotation will modulate the planet specular reflection. This modulation is different from the modulation due to albedo difference from oceans (A < 0.1) and land (A > 0.3). The latter is strictly periodic, with the period of the planet rotation.

Figure 4 A real Sun glint.

For a known planet radius, the angular angle of the glint gives the height of waves of the exo-ocean (Fig. 5)

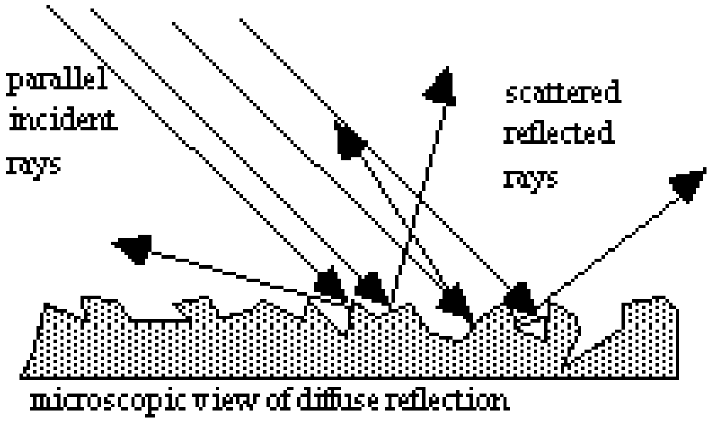

Figure 5 Diffuse reflection

Instrumental approaches

● 2cm photo-polarimeter : observing the Earth as an exoplanet
● 30 cm – 1m telescopes : follow-up of quasar variability, microlensing, stellar occulatations by solar system bodies
● 10 – 50 m telescope : spectro-imaging of exo-earths, imaging of arcs of lensed quasars
● Interferometer (Kervella 2023) : structure of AGNs

Issues
● Lunar dust from micrometerites seems not be a problem. But dust produced by in situ activities will be. One can for instance mitigate it electrostatically
● Meteorites : one will have a better statistics with the LUMIO detection project (Taputo et al. 2023.
● Seismic activity : can be from internal lunar activity or crash of meteorites. Seismology measurements are planed to measure this activity. It will be a problem for large interferometers (Bely et al. 2023). One can suppress it by antiseismic damping
● Regolith mechanical properties : one will have to choose sites where the regolith is mechanically sufficiently strong to support heavy and stable structure. One can also reinforce it by cement.
● Day/Night thermal shock : sunshade
● Robotisation or human assistance ? Robotisation is permanently in progress, but some delicate operations needing a human judment will require a human presence.

More details
Schneider J., Kervella P. & Labeyrie A. 2024 Astronomy from the Moon : From Exoplanets to Cosmology in Visible Light and Beyond. *Phil. Trans. Roy. Soc.* **382** 20230071 and references therein