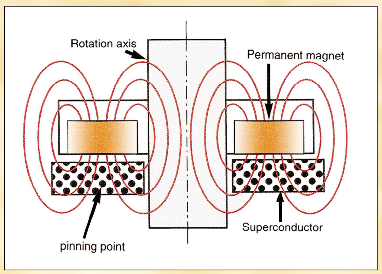
Imaging Exoplanets From the Moon

A.B. Schultz (NASA/GSFC), R. Lyon (NASA/GSFC), I. Jordan (CSC/STScI), M. Kochte (CSC/FUSE), F. Bruhweiler (CUA), M. Rodrigue (UNR), D. Bennum (UNR), P. Chen (CUA/GSFC), Dan Gezari (NASA/GSFC), K.-P. Cheng (CSUF).

ABSTRACT: Current ground-based and low Earth orbit coronagraphic techniques have not been able to directly image an exoplanet about a solar-type star. An external occulter combined with a moderate size telescope on the moon could image expolanets about solar-type stars. The advantages of the moon as a platform for coronagraphic exoplanet observations include stability and an absence of significant atmosphere, allowing the instrumentation to be pushed to the limit. A heliostat-like design, with a steerable flat mirror reflecting light into a fixed telescope and with an occulter inserted in the beam between the siderostat and the telescope would solve many of the technical and operational problems of placing a telescope on the moon. The flat, steerable mirror would be easier to control and to replace, while allowing more complex telescope and instrumentation to remain stationary within a protective facility. A moon-based design might be less complex than building, flying and operating a second occulter spacecraft to support coronagraphy with a space-based telescope. When not used for coronagraphy, the lunar telescope could support other observing projects.



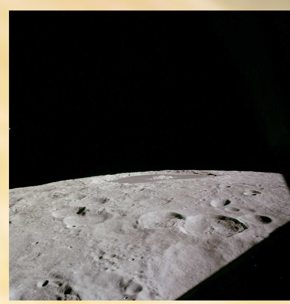
Above, conceptual design for a high temperature superconducting bearing.

Introduction: The surface of the moon provides an unprecedented "seeing" environment for very high sensitivity and resolution observing across the entire electromagnetic spectrum with the added advance of uninterrupted hours-long integration times over ground-based or low Earth orbit telescopes. The location provides a stable optical bench environment for specialized instrumentation and sensitive observations such as for coronagraphy with possible reduced cost for achieving high degrees of stabilization and pointing control as compared with formation control in free space.

Science: There are compelling arguments for establishing a lunar observatory to seek out and study extrasolar planets. High resolution spectroscopy was used to detect exoplanets indirectly by measuring the Doppler shift of the parent stars spectral lines caused by the gravitational pull of the orbiting planet. Fainter target stars need to be observed from space. The atmospheres of transiting planets need to be studied at higher spectral resolution to fully characterize the planetary atmosphere. Ground-based and HST coronagraphs do not have the high contrast imaging capability or sensitivity to directly image exoplanets about solar-type stars. An external occulter coronagraph on the moon provides a means to do so.

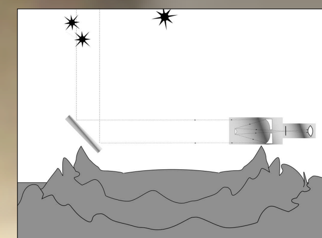
Observatory Construction: Similar to construction of the International Space Station, observatory modules (telescope, relay mirrors, mounts, instruments, communications etc.) could be ferried to the lunar surface to be assembled by astronauts from a nearby lunar base once a suitable site for the observatory has been selected and prepared. Roll away shelters could protect the telescope and mirror sites from excess thermal loading during sunlight hours and from dust kicked up by astronauts or from micrometeoroid hits and ejecta from impacts.

Above, Apollo 15 image of Tsiolkovsky Crater on the far side of the Moon. Below, Apollo 12 image of Tsiolkovsky Crater on lunar horizon.

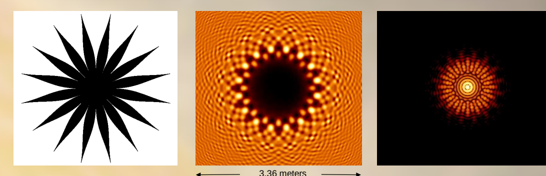


External Occulter Coronagraphy: Previous studies have shown that free-flying occulters in combination with an apodized space-based telescope are a promising means to image and study exoplanets. For external occulters, the detection contrast for exoplanets is dependent on the Fresnel number (F_N) defined by $\mathbf{F_N = W^2/2\lambda z}$ where W is the width of the occulter, λ is the wavelength, and z is the distance between the occulter and telescope.

In space, an occulter may be at large distances (> 20,000 km) from the telescope. On the moon, an occulter is limited to be at some fixed, finite distance, ~200-300 km. One possible configuration for the telescope and occulter is on opposite rims of a large crater. Additional mirrors may be needed to increase the apparent occulter-telescope separation.



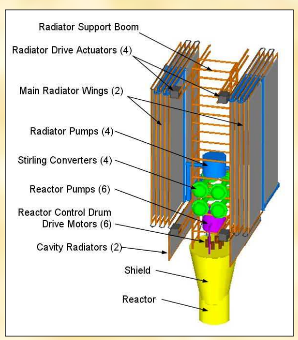
At left, an idealized representation of a lunar telescope and steerable mirror on opposite sides of a lunar crater; i.e., Tsiolkovsky, Joliot-Curie, or possibly Sklowdowska.



The above figures illustrate an optical simulation for a 1.8 m circular aperture telescope and a multi-petal occulter at a separation of 200 km. Above left, a 16 petal occulter, 2 m in diameter. Above middle, is the relative intensity pattern at the aperture plane. Above right, the model PSF at the focal plane is shown. The analytical and computational modeling were performed at NASA/GSFC using the Optical Systems Characterization and Analysis Research (OSCAR) software package.

Telescope and Instruments: The telescope may be of Cassegrain design. The mirrors could be fabricated from silicon carbide (SiC), a material with low thermal expansion and low density. The telescope will be fixed, mounted horizontally. A remote optical flat, steerable with a high temperature superconducting (HTS) bearing (eliminating the need for lubricants) placed at a distance will direct light into the telescope aperture. Similar to instruments on board the Hubble Space Telescope (HST), telescope instruments will be mounted in a bay for easy installation and replacement by astronauts. Instruments will be designed to be fully contained requiring only removal of a lens cap and covers from electrical contacts before installation. Electrical connections may be achieved by insertion of instruments into the appropriate instrument bay slot.

The primary instruments will be an imaging camera and an imaging spectrograph similar to the STIS onboard HST, a heritage design. An optical echelle spectrograph (R~100,000 for a 1-arcsec slit) for radial velocity studies could also be mounted at the Cassegrain focus. Coronagraphy could be achieved by inserting an occulter into the beam between the siderostat and the telescope. An external-type occulter needs to be at a large distance from the telescope.



Observatory Power: The power production and storage system for the observatory will depend strongly upon site selection. We presume the site must operate during lunar night largely due to the horizontal layout of the observatory components and the need to suppress scattered light. Conventional battery storage to operate during the lunar night may not be practical (~ 10 tonnes/kW), and so a site far away from the lunar pole might instead use Radioisotope Thermal Generators (RTGs) (~150 kg/kW).

If the site can be placed within a lunar crater near one of the poles--or in a lunar shadow such that the observatory optical path clears the terrain, a sun-tracking solar array could be mounted near the appropriate crater rim, gathering power while the telescope is in lunar night. Power to support the observatory could also be supplied from a lunar base by cable.

If a human habitation module is nearby, there is a possibility that the base may be supplied with power from a fission reactor. The Los Alamos National Laboratory (LANL) has developed a fission reactor concept for potential robotic missions to Mars called the Heatpipe-Operated Mars Exploration Reactor (HOMER). The HOMER-15 is a 15 kW reactor design that could potentially supply the needed power for a lunar observatory. Shown to the left is a HOMER-type fission power unit design with fin-type radiators in a stowed position (courtesy Glenn Research Center).

Summary and Conclusions:

A lunar-based external occulter-type coronagraph has several important advantages when compared to a space-based external occulter/telescope system:

1) higher control/knowledge of occulter w.r. optical axis,
2) occulter shape/size can be interchanged,
3) higher precision for occulter manufacture/deployment,
4) if necessary, astronaut performed maintenance,
5) installation of new instruments, and
6) large-angle slews between targets do not require weeks to execute.