Imaging Exoplanets from the Moon

By A. B. SCHULTZ[1], R. G. LYON[1], I. JORDAN[2], M. KOCHTE[3], F. BRUHWEILER[4], M. RODRIGUE[5], D. BENNUM[5], P. CHEN[6], D. GEZARI[1], D. FRAQUELLI[2], AND K.-P. CHENG[7]

[1]NASA/Goddard Space Flight Center, Greenbelt, MD 20771

[2]Computer Sciences Corporation and The Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

[3]Computer Sciences Corporation and The John Hopkins University, 3400 N. Charles Street, Baltimore MD 21218

[4]Department of Physics, Catholic University of America, Washington, DC 20064

[5]Department of Physics, University of Nevada, Reno, NV 89557

[6]Catholic University of America and NASA/Goddard Space Flight Center, Greenbelt, MD 20771

[7]Department of Physics, California State University Fullerton, Fullerton, CA 92634

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 remotely-operated 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.

1. 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 advantage, over ground-based or low Earth-orbit telescopes, of uninterrupted hours-long integration times. 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.

1.1. *Science*

There are compelling arguments for establishing a lunar observatory to seek out and study extrasolar planets. (1) Fainter target stars need to be observed from space. The high resolution spectroscopy used to detect exoplanets indirectly (by measuring the Doppler shift of the parent star's spectral lines caused by the gravitational pull of the orbiting planet) limits ground based observations to large telescopes and bright targets. (2) The atmospheres of transiting planets need to be studied at higher spectral resolution than is possible from the ground to fully characterize the planetary atmosphere. (3) High contrast imaging from space is needed to image exoplanets. HST NICMOS coronagraphy

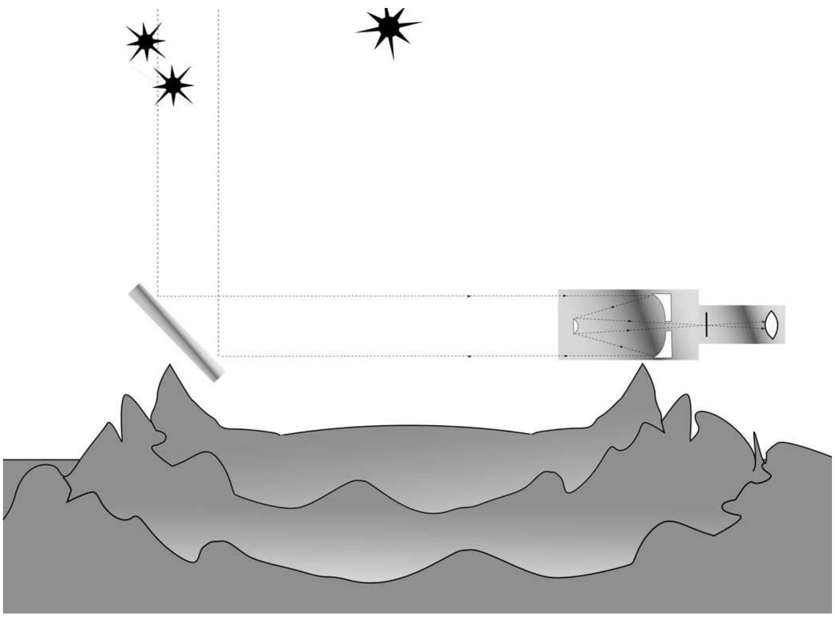

Figure 1. An idealized representation of a lunar telescope and steerable mirror on opposite sides of a lunar crater, i.e., Tsiolkovsky, Joliet, or possibly Sklowdowska.

was used to image the planetary size companion (2M 1207b) to the brown dwarf 2MASSW J1207334-393254 (aka 2M 1207) (Song et. al 2006). But to date, no planetary size object has been imaged about a solar-type star.

We will show that an external occulter coronagraph on the moon could provide a means to image exoplanets.

2. 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 (Schultz et al. 2003a, Jordan et al. 2004). For external occulters the detection contrast for exoplanets is dependent on the Fresnel number (F_N) defined by $F_N = W^2/2\ \lambda\ z$ where W is the width of the occulter, λ is the wavelength, and z is the distance between the occulter and telescope (Schultz et al. 2003b).

In space an occulter may be at large distances ($\geqslant$ 20,000 km) from the telescope. On the moon an occulter is limited to be at some fixed, finite distance, likely no more than 200-300 km. One possible configuration for the telescope and occulter might be on opposite rims of a large crater (Figure 1). Additional mirrors would be needed to increase the apparent occulter-telescope separation.

2.1. *Star Shaped Occulter*

Presented are optical simulations of a star shaped occulter (Figure 2), similar in design to a Marchal-Cash occulter, except a prolate-spheroid function is used to define the star pattern (Marchal, C. 1985, Cash, W. 2006). The occulter blocks light in the center core of radius r_0 and partially transmits light out to a radius of r_1. The PSF at the telescope focal plane is the diffracted star light that leaks around the occulter, collected by the

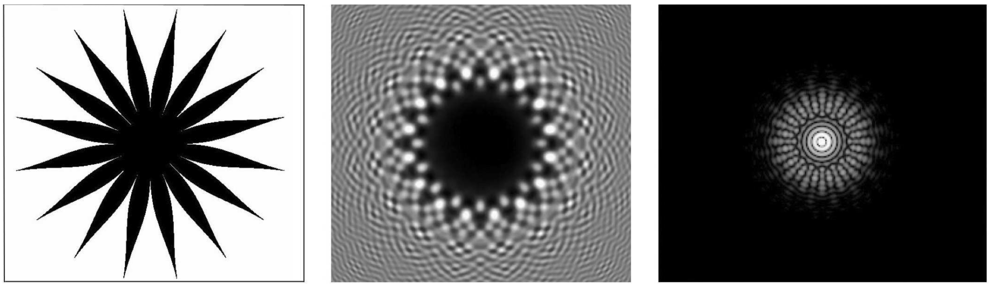

FIGURE 2. The figures illustrate an optical simulation for a 1.8 m circular aperture telescope and a multi-petal occulter at a separation of 200 km. Above left, a 16 petal occulter, 2 m in diameter. Above middle is the relative intensity pattern at the aperture plane. Above right the model PSF at the 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.

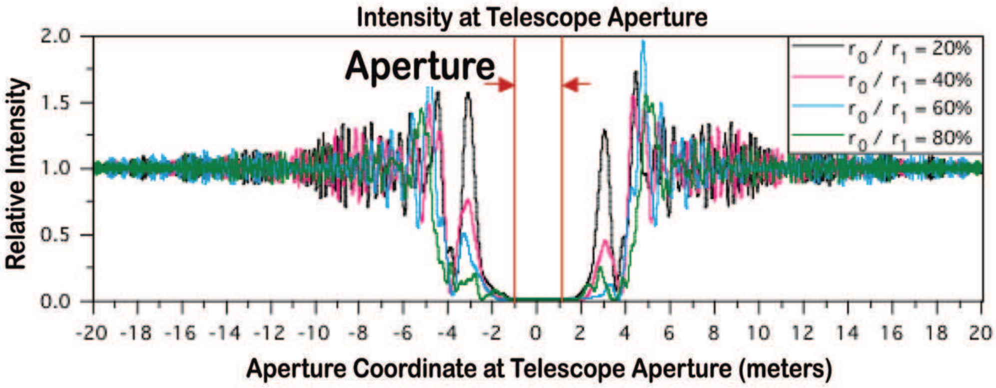

FIGURE 3. The relative intensity at the telescope entrance aperture for different ratios of r_0/r_1. The shadow of the external occulter has very low values in the center. Outside the geometic shadow of the occulter, the relative intensity increases with structure (diffraction) until all light is transmitted.

aperture and brought to a focus. Ideally, it is reduced in intensity significantly and the contrast ratio should be better than 10^{10}. Simulations are on-going.

A prolate-spheroid function is an eigenmode of the wave equation and thus propagates intact, i.e., the wave front has the same functional form, only scaled in coordinates, under a Fresnel propagation. The wave front tends uniformly to zero at the edge - much like a Gaussian beam but with an edge. The "edge" stays quite sharp during propagation to the telescope. The apodizing function goes smoothly to zero at a radius of r_1 and thus, ringing (aliasing) in the numerical simulations is avoided since the function is not truncated. Figure 3 shows plots of the relative intensity at the telescope entrance aperture for different ratios of r_0/r_1.

3. Observatory

We assume a telescope of Cassegrain design with mirrors fabricated from silicon carbide (SiC), a low thermal expansion and low density material (Petrovsky et al. 1994). The telescope is expected to be fixed and mounted horizontally. A remote steerable optical flat is mounted on a high temperature superconducting (HTS) bearing (eliminating the need for lubricants) and placed at a distance from the telescope. The flat is used to direct light into the telescope aperture (Brown, DiRusso, & Provenza 1995, Lamb, M., et al. 1995).

Instruments for the telescope are mounted in bays, similar to the instruments on board the Hubble Space Telescope (HST). This allows for easy installation and replacement by astronauts. The instruments are designed to be fully contained requiring only removal of a lens cap and covers from electrical contacts before installation. Electrical connections are achieved by insertion of the instrument into the appropriate instrument bay slot.

The primary instruments are expected to be an imaging camera and an imaging spectrograph similar to the STIS onboard HST. An optical echelle spectrograph (R$\sim$100,000 for a 1-arcsec slit) for radial velocity studies can be mounted at the Cassegrain focus. Coronagraphy is achieved by inserting an occulter into the beam between the siderostat and the telescope. The occulter will be housed in a structure close to the siderostat at a large distance from the telescope.

3.1. *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.

3.2. *Observatory Power*

The power production and storage system for the observatory will depend strongly upon site selection. We assume 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 ($\sim$10 tonnes/kW), so a site far away from the lunar pole might instead use Radioisotope Thermal Generators (RTGs) ($\sim$150 kg/kW) (Oleson, S., et al. 2002).

If the site can be placed within a lunar crater near one of the poles or in a lunar shadow such that the 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 shadow and/or lunar night. Power to support the observatory could also be supplied from a lunar base by cable.

If a human habitation module is nearby, the base might be supplied with power from a fission reactor. The Los Alamos National Laboratory (LANL) has developed a Mission reactor concept, called the Heatpipe-Operated Mars Exploration Reactor (HOMER), for possible robotic missions to Mars. The HOMER-15 is a 15 kW reactor design that could potentially supply the needed power for a lunar observatory (Poston et. al 2006).

4. Operations

After construction the observatory would be a remotely controlled facility either from a moon base and/or directly from an Earth-based Operations Center. The facility would require minimal maintenance by astronauts. The science phase will cycle between approved science and calibration observations, as well as target of opportunity (TOO) observations. Data might be stored temporarily at the moon base and/or transmitted directly to the Earth-based Operations Center.

5. 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 with respect to the optical axis, 2) occulter shape/size can be changed, 3) higher precision for occulter manufacture/deployment, 4) if necessary, astronaut performed maintenance, 5) installation of new instruments, and 6) more rapid large-angle slews between targets.

We would like to thank David Poston (LANL) for discussions on the HOMER fission power reactor description.

REFERENCES

Brown, G. V., DiRusso, E., & Provenza, A. J. 1995, An Active Homopolar Magnetic Bearing With High Temperature Superconductor Coils and Ferromagnetic Cores, *NASA*, **TM-1995-106916**.

Cash, W. 2006, Detection of earth-line planets around nearby stars using a pedal-shaped occulter, *Nature*, **442**, 51–53.

Jordan, I. J., Schultz, A. B., Lyon, R. G., Hart, H. M., Bruhweiler, F., Fraquelli, D. A., Carpenter, K. G., Kochte, M., & Hollis, J. M. 2004, Apodized square aperture plus occulter concept for TPF, *Proc. SPIE*, **5487**, 1391–1401.

Lamb, M., BuiMa, K., Cooley, R., Mackey, D., Meng, R., Chu, C.-W., Chu, W.-K., Chen, P. C., & Wilson, T. 1995, High Temperature Superconducting Bearings for Lunar Telescope Mounts, *IEEE Transactions on Applied Superconductivity*, **5**, 638–642.

Marchal, C. 1985, A space telescope able to see the planets and even the satellites around the nearest stars, *Acta Astronautica*, **12**, 195.

Oleson, S., Benson, S., Gefert, L., Patterson, M., & Schreiber, J. 2002, Radioisotope Electric Propulsion for Fast Outer Planetary Orbits, *NASA*, **TM-2002-211893**.

Petrovsky, G. T., Tolstoy, M. N., Lubarsky, S. V., Khimitch, Y. O., & Robb, P. N. 1994, 2.7-meter-dimater silicon carbide primary mirror for the SOFIA telescope, *Proc. SPIE*, **2199**, 263–270.

Poston, D. I., Kapernick, R. J., Marcille, T. F., Sadasivan P., Dixon, D. D., & Amiri, B. W. 2006, Comparison of Reactor Technologies and Designs for Lunar/Martian Surface Reactor Applications, *Proc. ICAPP'06*, **6413**, 1–8.

Song, I., Schneider, G., Zuckerman, B., Farihi, J., Becklin, E. E., Bessell, M. S., Lowrance, P., & Macintosh, B. A. 2006, HST NICMOS Imaging of the Planetary-Mass Companion to the Young Brown Dwarf 2MASSW J1207334-393254, *ApJ*, **652**, 724–729.

Schultz, A. B., Jordan, I. J., Kochte, M., Fraquelli, D. A., Bruhweiler, F., Hollis, J. M., Carpenter, K. G., Lyon, R. G., DiSanti, M. A., Miskey, C., Leitner, J., Burns, R. D., Starin, S. R., Rodrigue, M., Fadali, M. S., Skelton, D., Hart, H. M., Hamilton, R. C., & Cheng, K.-P. 2003a, UMBRAS: a matched occulter and telescope for imaging extrasolar planets, *Proc. SPIE*, **5170**, 262–271.

Schultz, A. B., Lyon, R. G., Kochte, M., Fraquelli, D. A., Bruhweiler, F., Jordan, I. J., Carpenter, K. G., DiSanti, M. A., Miskey, C., Rodrigue, M., Fadali, M. S., Skelton, D., Hart, H. M., & Cheng, K.-P. 2003b, Imaging terrestrial planets with a free-flying occulter and space telescope: an optical simulation, *Proc. SPIE*, **5170**, 262–271.