A Deep Field Infrared Observatory near the Lunar Pole

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Summary

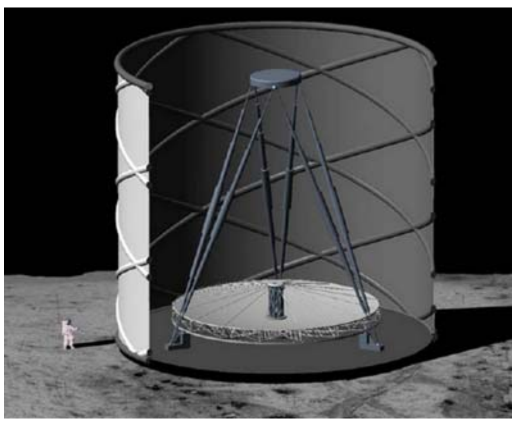
A study has been made of the feasibility and scientific potential of a 20 – 100 m aperture astronomical telescope at the lunar pole, with its primary mirror made of spinning liquid at < 100K. Such a telescope, equipped with imaging and multiplexed spectroscopic instruments for a deep infrared survey, would be revolutionary in its power to study the distant universe, including the formation of the first stars and their assembly into galaxies.

Our study explored the scientific opportunities, key technologies and optimum location of such a Lunar Liquid Mirror Telescope (LLMT). An optical design for a 20 m telescope with diffraction limited imaging over a 15-arcminute field has been developed. It would be used to follow up of discoveries made with the 6 m James Webb Space Telescope (JWST), with more detailed images and spectroscopic studies, as well as to detect objects 100 times fainter, such as the first, high redshift star in the early universe.

A model was made of a liquid mirror spinning on a superconducting bearing, as will be needed for the cryogenic vacuum environment of the LLMT.
Reflective silver coatings have been deposited for the first time on a liquid surface.

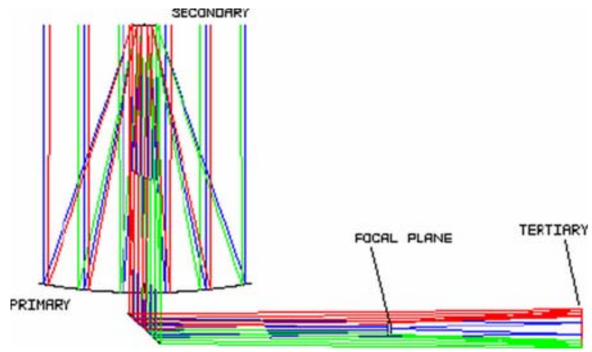
Issues relating to polar locations have been explored. Locations at or within a few km of a pole are preferred for deep sky cover, and allow for long integrations by simple instrument rotation.

This revolutionary mission concept could provide a scientific focus to NASA's planned exploration of the Moon, just as currently HST stands as a major achievement of its Shuttle program



Artist's impression of the 20 m telescope. The secondary mirror is erected by extending the six telescoping legs and the sunshield by inflation. The scientific instruments are below the bearing pier, shielded by lunar soil. (drawn by Tom Connors).
We considered a series of designs beginning with a 2-m precursor telescope, scaling up to 20 m and 100m.

Diffraction-limited corrector



This design achieves the goal of a 15-arcminute field with diffraction limited images at 1 μm wavelength. It is for an f/1.5 20 m parabolic liquid primary, has a 2.4 m Cassegrain secondary and a 4 m tertiary mirror. The final focus is at f/15, for a field diameter of 1.3 m. The imaging array would be a mosaic of 18 x 18 four-megapixel arrays, with
each 18 micron pixel corresponding to 12.4 milliarcseconds. This provides Nyquist sampling of images down to 1.6 μm wavelength. This first optical concept has significant vignetting by the focal plane, and options to reduce this are being explored. This type of design is expandable to larger sizes – perhaps as large as 100m

Superconducting bearing

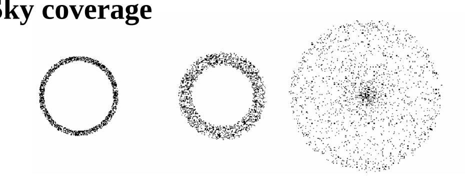
Model of spinning liquid mirror on a superconducting bearing. (a) shows the bearing, with a nitrogen-cooled YBCO superconductor in the upper cup, and a neodymium magnet in the inverted cup below. Hanging on 3 strings below is a 20 cm s pinning dish of black soy sauce with ~ 8" focal length (b). The lettering is the reflection of a screen above. A superconducting bearing for the spinning mirror is an ideal choice, because no lubricant is required and there is a large gap that avoids issues of dust contamination. We conducted a series of experiments with "toy" magnetic suspension bearings

Liquids

Mirror surface of silver on polypropylene

We need a material that is liquid at T< 100K , with very low vapor pressure to prevent evaporation, and either intrinsically reflective or can be metallized to become so. We considered three main classes liquids: eutectics of alkali metals, which have the advantage of high intrinsic reflectivity; low-reflectivity liquids coated with a thin metallic coating produced by sputtering or evaporation; and low-reflectivity liquids coated with self-assembling nanoparticles. We concluded that the most promising approach was to apply metallic coatings to low temperature, low vapor pressure moderate viscosity liquids.

Sky coverage



Effect of location on sky access for a zenith-pointed telescope with 0.2 degree field of view.. *Left* – at the pole, over 18.6 years the field sweeps out an annulus 3.1 degrees in diameter centered on the ecliptic pole, with continuous integration of ~ 5 months on any one spot. *Center* – 0.2 degrees from the pole, the field sweeps out a half degree annulus each month, covering any one spot every month for a year *Right* – 1.55 degrees from the pole. Each month the field sweeps a 3.1 degree annulus, covering any spot for about 15 hours. The ecliptic pole is seen for this time every month, for a total integration time of 5 months over 18 years.

Scientific potential

An enormous investment would be needed to realize a large survey telescope on the moon, justifiable only if the scientific reward were commensurate. The scientific impact would have to be comparable to that of the Hubble telescope.
Our initial conclusion is that there is potentially a superb and unique scientific role in the study of the early universe, because of the potential on the moon of a cooled telescope to reach much deeper in the infrared than is possible from the ground, and to be built at a size that would likely be prohibitively expensive if built from precision panels in free space. The infrared in the wavelength range between 1 and 10 microns is an extremely important region of spectrum because all of the optical and UV processes that dominate the light from galaxies are shifted into the infrared when one looks at galaxies in the early Universe. Notably one can study rest-frame optical and near-infrared properties of galaxies at $1<z<6$ and study UV and optical properties of galaxies at $z>6$.

At 50 m aperture, the diffraction limit at 2 microns is roughly 10 mas.. This means that one can study rest-frame optical properties of galaxies at $z=3$ with resolution equivalent to a ground-based telescope looking at galaxies in the Virgo cluster. Integral-field spectroscopy could open detailed dynamical and stellar population studies of high-redshift galaxies.

High spatial resolution would also be advantageous for investigating supermassive black holes at high redshift. One would separate the nucleus from the stars at resolutions considerably above that of HST. Integral-field spectroscopy would permit spatially resolved line diagnostics. One could see black holes of 100,000 solar masses radiating at their Eddington luminosity out to $z=30$, thereby tracking the growth of black holes along with the growth of galaxies.