Advances in Lunar Polar Exploration: Postprint

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Abstract

Since the 20th century, lunar exploration has become a significant component of human space exploration, characterized by increasingly diversified methodologies, higher resolution, and a gradual shift from global to regional coverage. The lunar north and south polar regions, due to their unique geographical conditions featuring extensive permanent shadow areas, have consistently attracted substantial attention from scholars worldwide. This paper introduces important scientific achievements in lunar polar exploration from domestic and international efforts in optical imagery, digital elevation models, water ice detection, and brightness temperature measurements, along with the parameters of exploration instruments, providing references and recommendations for China' s ongoing lunar exploration missions.

Full Text

Abstract

Since the 20th century, lunar exploration has become an important component of human space exploration. The means of lunar exploration have become increasingly diversified, spatial resolution has improved, and the exploration focus has gradually shifted from global coverage to specific regions. Due to their special geographical conditions, the lunar polar regions contain large areas of permanently shadowed regions, which have attracted significant attention from scholars both domestically and internationally. This paper reviews important scientific achievements in lunar polar exploration, including optical imaging, digital elevation models, water ice detection, and brightness temperature measurements, and introduces the parameters of detection equipment, providing references and recommendations for China' s ongoing lunar exploration activities.

Keywords: Lunar polar exploration; Permanently shadowed regions; Water ice; Illumination conditions; DEM

1. Introduction

The Moon is the primary target for human space exploration. While early exploration activities focused on the mid-low latitude regions of the near side, a new round of lunar exploration has intensified investigations of the lunar poles, particularly the permanently shadowed regions. The main scientific objectives concentrate on geological landforms, water ice, and illumination conditions.

The orbital plane of the Moon around Earth is inclined by approximately 5.145° relative to Earth's orbital plane around the Sun, while the lunar equatorial plane is inclined by about 6.69° relative to the Moon's orbital plane. Consequently, the angle between the lunar equatorial plane and the ecliptic plane is approximately 1.54°. This geometry results in consistently low solar incidence angles at the poles, with sunlight arriving nearly parallel to the lunar horizon. At polar latitudes between 85° and 90°, the percentage of illumination time calculated from observation periods reaches 2,000 days [Figure 85: see original paper]. Due to this unique topographic configuration, impact craters in polar regions may contain dark areas that never receive sunlight, known as permanently shadowed regions. These regions have been a major focus of lunar polar exploration for decades.

2. Optical Imaging of Polar Regions

Optical imaging has consistently been one of the most important exploration methods, providing the most intuitive reflection of lunar topography and illumination conditions. The U.S. Clementine mission, launched in 1994, carried a high-resolution camera that captured high-definition images of the lunar poles, clearly revealing the topography and distribution of permanently shadowed regions. Since these areas receive no solar illumination year-round, optical photos show them as completely dark.

In 2003, the European Space Agency launched SMART-1, whose Advanced Moon Imaging Experiment (AMIE) captured 2.5 million high-definition photos with a maximum resolution of 50 m/pixel, primarily of the lunar south pole region. The Aitken Basin, located on the lunar far side with a diameter of 2,500 km, is the largest and oldest known impact crater in the solar system.

Japan' s Kaguya mission, launched in 2007, carried a Terrain Camera (TC) that obtained observation data of Shackleton crater near the lunar south pole. Shackleton crater is a permanently shadowed region where, due to extremely low temperatures, water ice deposits are thought to possibly exist. However, albedo analysis from the camera suggested that Shackleton crater' s floor does not contain exposed pure water ice—any ice may have volatilized, mixed with lunar soil, or never existed at all.

China' s Chang' e-1 (CE-1), launched in 2007, carried a three-line array CCD stereo camera. At an orbital altitude of 200 km, it achieved a surface spatial resolution of 120 m and an imaging swath width of 60 km, with positioning accuracy slightly better than Clementine (2.0 km). It completed the most comprehensive, highest quality, and most accurately positioned global lunar image to date. Chang' e-1 also captured detailed images of both polar regions [Figure 2: see original paper].

The U.S. Lunar Reconnaissance Orbiter (LRO), launched in 2009, carried optical cameras with the primary mission of obtaining polar images and illumination environment data to identify permanently shadowed and partially illuminated regions. LRO' s optical cameras include two Narrow Angle Cameras (NAC) and one Wide Angle Camera (WAC). The NAC can capture 0.5 m/pixel panchromatic images at 60 km altitude, while the WAC can obtain 100 m/pixel seven-color images. Using polar stereographic projection, the images cover latitudes from 60° to 90°. The WAC images show significantly better quality than those from Clementine [Figure 3: see original paper].

3. Digital Elevation Model Detection

The polar regions have unique geographical characteristics. The south pole region is particularly complex topographically, with higher elevations. Major craters such as Cabeus, Shoemaker, and Shackleton are elevated compared to surrounding terrain. The highest point in the south pole region exceeds the lunar mean radius. The Shackleton crater rim is significantly higher than its surroundings, receiving sunlight for extended periods. In contrast, the north pole region is relatively flat, transitioning from maria to highlands, with relatively smaller impact craters.

Kaguya' s laser altimeter provided topographic mapping hundreds of times more detailed than previous USGS data, with a resolution of 50-150 km. India' s Chandrayaan-1, launched in 2008, carried the Lunar Laser Ranging Instrument (LLRI) with a laser wavelength of 1,064 nm and vertical resolution of 20-70 km, primarily for precise elevation measurements of polar regions. The data could be used to generate quantitative lunar gravity models.

LRO' s laser altimeter emits laser pulses that simultaneously produce five beams pointed at the lunar surface, receiving reflected signals separately. Compared to single-beam laser detection, this obtains more elevation data and enables calculation of finer three-dimensional terrain models, with vertical resolution up to 10 cm [Figure 4: see original paper].

China' s Chang' e-1 also carried a laser altimeter with a primary mission to obtain three-dimensional stereo images of the lunar surface. Its operating range was 200 $\pm$ 25 km, about twice that of Kaguya' s laser altimeter, with vertical measurement resolution of 240 m. Topographic mapping is one of the main scientific objectives of lunar exploration, as lunar surface rocks and impact craters are major obstacles for rovers and crewed missions. High-resolution cameras and laser altimeter measurements are crucial for obtaining 3D terrain models, and for polar regions, topographic detection is particularly important for studying illumination conditions.

4. Water Ice Detection

Water ice detection is a hot topic in lunar polar exploration. Due to the permanent absence of sunlight in shadowed regions, surface and subsurface temperatures remain at -233°C (40 K). The hypothesis of water ice on the Moon was proposed by Watson et al., suggesting that water from primordial lunar degassing and cometary impacts could be preserved as ice at low temperatures.

To search for water ice in polar permanently shadowed regions, the Clementine bistatic radar experiment mapped the lunar polar surface. Results showed no water ice deposits larger than 1-2 km, with high radar backscatter cross-section and high circular polarization ratio—features not characteristic of dry lunar soil [13]. However, some scientists argued that radar anomalies could result from surface roughness. Considering Earth-Moon motion causing image blur and reduced resolution, bistatic radar data processing algorithms are more complex, and observations are only possible when the lunar target, ground receiving station, and spacecraft orbital plane are aligned with a bistatic angle of 90° [15].

The U.S. Lunar Prospector, launched in 1998, carried a Neutron Spectrometer (NS). When fast-moving neutrons collide with hydrogen atoms of equivalent mass, they decelerate. The NS detected significantly reduced fast neutron count rates at the lunar poles, caused by collisions with hydrogen atoms, indicating enhanced hydrogen abundance likely due to water molecules. The results suggested lunar water ice exists as small crystals with a mixing ratio of 0.1%-0.3% across large areas [17]. Compared to radar, neutron spectrometer results have generated less controversy, although solar wind also contains abundant hydrogen, and debates continue about whether hydrogen exists as water ice, hydroxyl, or other hydrogen compounds.

Chandrayaan-1 carried a Miniature Synthetic Aperture Radar (Mini-SAR) and the Moon Mineralogy Mapper (M3). Mini-SAR, operating with left-circular polarization transmission and reception of both horizontal and vertical polarizations, obtained data covering both poles. It discovered over 40 craters with anomalous echoes, most associated with permanently shadowed regions, suggesting possible water ice presence [18]. M3 obtained near-infrared (0.42-3.0 m) spectra indicating hydroxyl or water signatures in polar regions. However, since M3 only senses depths of a few millimeters, any detected water or hydroxyl exists only in surface dust, possibly as crystalline water strongly bound to minerals.

LRO carries a Lunar Exploration Neutron Detector (LEND), similar to Lunar Prospector' s NS but more sensitive, obtaining epithermal neutron distribution data near the lunar south pole. Analysis shows that regions with low epithermal neutron flux contain abundant hydrogen, suggesting water ice presence [Figure 5: see original paper]. LRO also carries Mini-RF, which, compared to Mini-SAR, adds a higher frequency band and achieves higher spatial resolution due to lower orbital altitude. Mini-RF radar images of Shackleton crater show increased circular polarization ratio on crater walls with fragmented, non-uniform characteristics that weaken with depth. While surface roughness may contribute, water ice presence cannot be excluded [Figure 6: see original paper].

The Lunar Crater Observation and Sensing Satellite (LCROSS), launched with LRO, impacted the lunar south pole' s Cabeus crater in 2009. The impact ejecta plume reached 6-8 km in diameter. LRO' s ultraviolet spectrometer (LAMP) and near-infrared spectrometer detected hydroxyl spectral features in the ejecta, successfully demonstrating water ice in Cabeus crater [24]. However, Mini-RF and Mini-SAR radar images of the LCROSS impact crater show circular polarization ratios similar to or smaller than the southern highlands average, inconsistent with the high circular polarization ratio hypothesis expected from water ice deposits several meters below the surface.

5. Radiation Temperature Detection

Lunar polar temperature studies are crucial for understanding the polar environment and water ice. Surface temperatures in permanently shadowed regions can reach -233°C (40 K). Clementine' s long-wave infrared camera measured radiation temperatures, but its coverage was limited to latitudes below 60° [28].

LRO' s Diviner Lunar Radiometer Experiment (DLRE) measures thermal radiation and solar reflectance data with a central wavelength of 8.75 m. The radiometer has seven channels covering 0.35-400 m, with temperature measurement range of 20-400 K and spatial resolution of 0.2-1.3 km. Diviner measured surface temperature distribution in the lunar south pole region, showing cold traps in permanently shadowed craters [Figure 7: see original paper].

Chang' e-1 and Chang' e-2 carried multi-channel microwave radiometers (CELMS) with frequencies of 3.0, 7.8, 19.35, and 37 GHz, measuring accuracy of 0.5 K, and spatial resolution of 30-50 km. The microwave data covers both polar regions, though the spatial resolution is coarser than Diviner' s, resulting in less detailed brightness temperature maps [32].

6. Summary and Future Prospects

From the 1990s to present, lunar polar exploration has continued with diverse methods. Optical imaging and laser altimetry survey topography and landforms, while infrared and microwave radiometers measure polar radiation temperatures. Radar detection, unaffected by illumination, studies potential water ice in permanently shadowed regions through echo characteristics. Neutron detectors sensitive to hydrogen have also been employed, though enhanced hydrogen content doesn' t necessarily prove water ice existence–it could indicate other hydrogen-bearing compounds.

Although China' s lunar exploration started relatively late, it has developed rapidly. Future polar exploration should focus on illumination conditions, temperature, and water ice presence, requiring higher precision and resolution.

Since direct detection of water molecules in permanently shadowed regions remains impossible, future missions need higher-precision remote sensing methods for mutual verification. The focus could shift from entire polar regions to typical impact craters like Cabeus and Shackleton, which have been intensively studied internationally, including through impact ejecta analysis. Drawing from international experience can help China avoid detours and establish a foundation for future deep space exploration.

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Note: Figure translations are in progress. See original paper for figures.