Summary: Recently restored Apollo magnetic field data have revealed ion cyclotron waves on the lunar surface. Enhancements on these data can foster further discoveries.

Introduction: Immersed in the solar wind or the Earth’s magnetosphere, the Moon has an conducting core and remnant magnetism in the lunar crust that interact with the external magnetic field. Measurements of the magnetic field on or near the Moon have been found valuable in understanding the lunar interior, the history of lunar crust, the interaction between the solar wind and crustal magnetic field. They also provide specifications of the space weather environment at the Moon for human exploration.

Among the series of lunar missions that carried magnetometers since the 1960s, the Apollo missions in the early years of the space era have made unique contributions to the measurements of the lunar magnetic field environment. The Lunar Surface Magnetometer (LSM) installed by Apollo 12 astronauts on November 19, 1969 marks the first magnetic field measurements on the surface of the Moon [1]. The Apollo 15 Subsatellite Biaxial Magnetometer (SBM) provided the first orbital measurements of the magnetic field surrounding the Moon [2]. As of today, the Apollo 15 and 16 missions are still the only lunar missions that carried both surface and orbital magnetic field experiments [2-5].

Data Restoration: After the conclusion of the Apollo Program, the format in which the Apollo magnetic field data were stored gradually became obsolete, and for several decades the data could not be understood easily. An effort restoring the Apollo magnetic field data started in 2008. The NSSDC read out all the archived magnetic tapes for the Apollo magnetic field experiments. The digital data include the 0.3-s data from the Apollo 12, 15 and 16 LSMs and the 24-s data from Apollo 15 and 16 SBMs. After a lengthy process of identifying legitimate data structures in the binary data stream [6], all the SBM data have now been restored. The restoration of the LSM data has been slower due to the irregular pattern of time words, but the data during April-July 1972 when both Apollo 15 and 16 LSMs were operational have been recovered. More details and future updates of the restoration of Apollo magnetic field data are available online at http://aplunar.igpp.ucla.edu/.

New Results from Apollo Data: An unexpected discovery in the restored Apollo LSM data is the ion cyclotron waves on the lunar surface [7]. A class of narrowband waves with frequencies ranging from 0.04 to 0.17 Hz were found only when the Moon was in the terrestrial magnetotail, including regions in and near the current sheet. The wave properties are consistent with those of ion cyclotron waves: A wave frequency at or slightly lower than the local proton gyrofrequency, a dominant transverse component, and left-hand polarization. Figure 1 shows an example of the narrowband waves simultaneously observed at the Apollo 15 (26.1°N and 3.7°E) and Apollo 16 (8.9°S and 15.5°E) sites for a 3.5 hours on 26 April 1972. The two LSMs detected the same narrowband wave activity in this event as well as in all other wave events during April-July 1972.

Figure 1. (a) A series of narrowband waves observed by the Apollo 15 Lunar Surface Magnetometers (LSM). The white trace indicates the local proton gyrofrequency at the Apollo 15 site. (b) Similar narrowband waves simultaneously observed by the Apollo 16 LSM. The magenta trace shows the proton gyrofrequency inferred from the magnetic field measured by the Apollo 16 sub-satellite orbiting the Moon. (c) Ellipticity of the narrowband waves observed by the Apollo 15 LSM. (d) Angle between wave propagation and the ambient magnetic field. (From [7])
Despite the high conference in the wave observations between the two Apollo sites, the differences in wave amplitude are noticeable and persistent – the Apollo 16 LSM always observed weaker ion cyclotron waves. The most likely reason is the stronger remnant magnetic field (~234 nT) at the Apollo 16 site. Mini-magnetospheres can form above regions of strong crustal magnetization when the Moon is in the solar wind [9-10], and their sizes are expected to be greater in the magnetotail where the dynamic pressure of the ambient plasma is much lower. As an ion cyclotron wave travels to the high-field region, the wave velocity rises, and the wave amplitudes decreases to preserve the Poynting vector. Another mechanism that may alter the wave amplitude and phase on the Moon is the magnetic induction from an electrically conductive interior. In this scenario, the larger wave amplitude observed by the Apollo 15 LSM may imply a greater subsurface electrical conductivity ($\sigma$) at or near the site. If we speculate that $\sigma$ is between $3 \times 10^{-4}$ and $5 \times 10^{-5}$ S/m, the skin depths for a 10-s wave range from ~100 km to ~250 km. These ranges of $\sigma$ and depths agree with our current understanding that $\sigma$ undergoes a sharp transition from extremely low values to above $10^{-3}$ S/m in the upper mantle [10].

Two scenarios have been proposed to explain the existence of ion temperature anisotropies in the vicinity of the Moon that can excite the ion cyclotron waves as observed at the lunar surface [7]:

1. **Absorption of ions at the lunar surface.** The ions on the field lines connected to the Moon are in gyration motion either toward the Moon or away from it. Once Moon-bound particles reach the lunar surface, almost all of them are expected to be absorbed [11]. As a result, few particles traveling away from the Moon exist, creating an asymmetry in the velocity distribution and hence a temperature anisotropy (Figure 2a).

2. **Pickup ions.** When the plasma convection flow exists and is perpendicular to the ambient magnetic field, the pickup ions originating from the lunar exosphere can travel along cycloid trajectories resulting in a ring distribution in the velocity space (Figure 2b). This is how ion cyclotron waves are generated near comets, Venus, and Mars, in the Io torus, or in the Saturn E-ring. Because the lunar exosphere is tenuous, pickup ions from the Moon may not represent a significant amount of particles in the solar wind plasma where a typical density is 5 cm$^{-3}$. When the Moon is in the terrestrial magnetotail, however, the ambient plasma density is at the order of 0.1 cm$^{-3}$ or less, and the pickup ions can be much more noticeable and form an unstable ring-type distribution.

![Figure 2](image.png)

**Figure 2.** Two possible scenarios that create temperature anisotropy near the Moon: (a) Anisotropic particle distribution as a result of the absorption by the lunar surface. (b) Ring-type distribution formed by pickup ions. The diagram is plotted in the V-$B_{\perp}$ plane. (From [7])

**Further Data Enhancements:** In many possible uses of the lunar magnetic field measurements, an important scientific objective is the magnetic sounding of the lunar interior. The most careful analysis on this subject to date was derived from the Apollo 12 (surface) and Explorer 35 (orbital) measurements [12]. Attempts to use the Apollo 15 LSM data, which have a longer duration and were collected at a site almost free of crustal magnetic field, have been hampered by the lack of usable data. Further efforts to complete the restoration of the LSM data and calibrate the Explorer 35 and Apollo 15 orbital measurements can bring in more data for new science on this important subject.

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**References:**