APOLLO 15 AND 16 SUBSATELLITE MAGNETOMETER MEASUREMENTS OF THE LUNAR MAGNETIC FIELD

C. T. Russell\textsuperscript{a}, P. J. Coleman Jr.\textsuperscript{a,b}, B. R. Lichtenstein\textsuperscript{b}, G. Schubert\textsuperscript{b} and L. R. Sharp\textsuperscript{b}

\textsuperscript{a} Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Calif., USA
\textsuperscript{b} Department of Planetary and Space Science, University of California, Los Angeles, Calif., USA

Measurements with the UCLA fluxgate magnetometers on the Apollo 15 and 16 subsatellites have been used to map the lunar magnetic field. The strongest magnetic fields found to date occur between 165° and 175° east longitude at about 20° south latitude near the crater Van de Graaff. The measurements place an upper limit of $3 \times 10^{15} \text{ fT cm}^2$ on the dipole moment in the plane of the subsatellite orbit. Assuming that the total dipole moment lies parallel to the lunar rotation axis, an upper limit of $7 \times 10^{18} \text{ fT cm}^2$ results. This is $8 \times 10^{-8}$ of the earth's dipole moment.

1. Introduction

Lunar magnetic investigations, initiated on the Luna spacecraft, were extended significantly with the Explorer 35 lunar orbiter, and have been continued during the Apollo program both on the surface and in orbit. These measurements have been recently reviewed [1], and we will only briefly summarize previous findings here. During the lunar month the moon is immersed in three distinctly different plasma environments. For about five days around full moon the moon is enveloped in the rather steady field of the geomagnetic tail and shielded from the solar wind flowing from the sun. Mapping of the lunar magnetic field is carried out at this time. Orbital studies reveal a lunar field of up to about 1\gamma at 100 km [2]. Surface measurements reveal fields of up to 300\gamma [3]. For about three days on either side of the geomagnetic tail, the moon is immersed in the shocked magnetosheath plasma, a turbulent region with large amplitude fluctuations. These fluctuations are useful in lunar sounding studies from which the electrical conductivity of the lunar interior is inferred [4]. During the rest of the lunar month, the moon is in the comparatively steady solar wind flow. The solar wind, for the most part, directly impacts the lunar surface on the sunward side of the moon, leaving a void behind the moon into which the solar wind expands with increasing distance downstream. When certain lunar regions appear at or near the lunar limbs, compressional disturbances are generated in the solar wind above the terminator. These limb compressions appear to be the result of the deflection of part of the solar wind by the lunar magnetic field [5].

In this paper we discuss first some recent results on mapping the lunar magnetic field using the Apollo 15 and 16 subsatellite magnetometers. Then, we use these measurements to deduce an upper limit on the lunar magnetic dipole and discuss the implication of these results.
2. Instrumentation

The Apollo 15 and 16 particles and fields subsatellites are essentially identical small satellites placed in lunar orbit from their respective command modules at an altitude of about 100 km. Each carried a biaxial magnetometer which returned a measurement of the magnetic field amplitude and phase in the spin plane and the component along the spin axis every 24 seconds at the lowest data rate. Since the orbital period was just under 2 hours, there was approximately one vector sample per orbit of the magnetic field every degree of lunar longitude. Magnetometer observations continued on the Apollo 15 mission for seven months until a telemetry failure terminated transmission of the magnetometer data. Apollo 16 subsatellite operations ceased after only 35 days when the subsatellite crashed into the moon. More extensive descriptions of the subsatellite and the magnetometers can be found in [6, 7].

3. Data Reduction Technique

When the moon is in the lobes of the geomagnetic tail, the non-lunar magnetic contribution to the magnetometer measurements is relatively steady and variations in the data due to the motion of the subsatellite through lunar magnetic features are more readily discernable than in other regions. Furthermore, in the near vacuum conditions of the lobes there is little plasma to distort the lunar magnetic field. In this study we have attempted to separate the contribution of the geomagnetic tail to the measurements from that of the moon in two ways. First, for each orbit we have subtracted the average vector magnetic field in inertial coordinates from the individual measurements and rotated the residual fields into a local lunar coordinate system consisting of the local radial, east and north components. Second, we have removed the average field and the linear slope of the data for each orbit and then proceeded as in the first case. We will refer to these latter data as the detrended data. Both these data processing procedures attenuate the low-order harmonics of the lunar field somewhat but in a readily calculable manner.

In the present analysis we have used 70 orbits of Apollo 15 data in contrast to our previous work with 48 orbits. This increase is due to the processing of additional orbits of tail data. Orbits were selected on the basis of our judging the satellite to be in the lobes of the tail for the entire orbit. This judgment is based on magnetic field direction, magnitude and variability.

In the analysis presented here we have not corrected for any altitude dependence of the data. In part this is because we are studying the body-centered dipole field for which we do not expect the altitude dependence to be discernable over the range of altitudes of the subsatellite orbit. Fig. 1 shows the altitude dependence of the radial component for each of four longitudinal quadrants using the Apollo 15 detrended data and some similarly treated Apollo 16 data at low altitudes. (Positive and negative values have been averaged separately.) The altitude dependence above 80 km where most of our data lie is at best weak. Since lunar magnetic features, such as in the Van de Graaff region, have a measurable altitude dependence, the lack of one here is merely a reflection of the fact that over most of the lunar surface mapped to date, the lunar field is much
weaker than in the Van de Graaff region. It also suggests that the noise level of an individual measurement is about $0.4\gamma$. We note, however, that in our maps, which are constructed from many orbits, the noise level is reduced below this value at some cost of spatial resolution by averaging independent samples over the same region.

4. The Van de Graaff-Aitken Region

We have used the residual detrended data to construct average radial, east, and north components of the lunar field in boxes one degree in latitude by one degree in longitude. Fig. 2 shows contour maps for each of the three components between $130^\circ$ and $210^\circ$ east longitude, which includes the Van de Graaff anomaly. Shaded regions denote negative fields. The fields here are the strongest encountered in the regions mapped thus far. In the radial component, the strongest fields are $1\gamma$ into the moon in the Van de Graaff region and $1\gamma$ out of the moon just west of Van de Graaff. A strong, $1.2\gamma$, eastward field is observed between these two regions suggesting that many of the field lines leaving the positive anomaly enter the Van de Graaff region. The southward component observed in the bottom panel in this same location is consistent with this interpretation. Most of the features which appear to parallel the orbit tracks occur in regions where there is little coverage, and should be viewed with some suspicion.
Fig. 2. Contour maps of the radial, east and north components of the lunar field in the Van de Graaff region using the detrended data with no altitude dependence. Positive fields point outward, eastward and northward respectively in the three maps.

5. The Lunar Dipole Field

The magnetic field of a body-centered lunar dipole would be constant and perpendicular to the orbit plane if its dipole moment were perpendicular to the orbit plane, but would have a sinusoidally varying radial component if it lay in the orbit plane. In the inertial coordinate system the former field would be constant and would be removed in our creation of the residual fields. The latter field, however, consists of two parts in the inertial system, one constant and one
varying at twice the orbital frequency. The former part is removed but the latter is unattenuated by the subtraction of either the average or the trend.

Fig. 3 shows the radial component averaged as a function of distance along the orbit track from the 0° selenographic meridian using the detrended data. Both

![Graph showing the average radial component as a function of angle in the orbit plane using the detrended data.](image)

Fig. 3. The average radial component as a function of angle in the orbit plane using the detrended data.

sets of residuals have been averaged in this way and their first 19 Fourier harmonics are shown in Fig. 4. As expected both sets of data give the same dipole field. We note that a constant radial field would be sinusoidally varying at the orbital frequency in the inertial coordinate system and quadrupole variation would have components at both the orbital frequency and three times the orbital frequency, all of which would be attenuated by detrending. As expected, this is observed.

The first harmonic variation of 0.05\gamma is not much different from some of the neighboring harmonics and thus may represent simply the noise level of our analysis; in other words, we may be measuring only an upper limit to the first

![Graph showing Fourier amplitudes of the radial components variation for both sets of data.](image)

Fig. 4. Fourier amplitudes of the radial components variation for both sets of data.
harmonic variation. A 0.05\gamma variation would be caused by a magnetic moment in the orbit plane of \(3 \times 10^{18} \ \mu\text{cm}^3\). Assuming a remanent magnetization of \(10^{-5} \ \mu\text{emu cm}^{-3}\), this moment could be produced by a uniformly magnetized lunar surface layer 5 km thick. If we assume that the overall dipole moment is parallel to the lunar rotation axis, then a total dipole moment of \(7 \times 10^{18} \ \mu\text{cm}^{-3}\) would be required to give the observed projection in the subsatellite orbit plane. This is \(8 \times 10^{-5}\) of the earth’s magnetic moment.

The ancient magnetic fields which magnetized the lunar rocks may have been of external or internal origin. If they were of internal origin a magnetic moment of at least \(1.1 \times 10^{23} \ \mu\text{cm}^3\) was once present [8]. The ratio of the present to this hypothesized ancient magnetic moment is less than \(6 \times 10^{-5}\). If it were due to an overall remanent magnetization of the whole moon this remanent magnetization has disappeared. If this was due to an internal dynamo, this dynamo has stopped. We note if a present-day lunar dynamo were operative we would not have expected such low levels of seismic activity as are presently observed. Our analysis to date does not distinguish between the various theories of the source of this magnetizing field. An ancient lunar dynamo could have stopped as the moon’s rotation rate dropped. A remanent field would disappear as the moon warmed up due to radioactive heating. If the source were the earth’s geomagnetic field as the moon orbited close to the earth during the often hypothesized capture of the moon, then the field would not so much have disappeared but, rather, the moon had simply moved out of it.

Finally, we note the possibility of an early dynamo in a melted outer layer of the moon [9]. It has been proposed that this mechanism could explain the hypothesized low magnetic field strength at high selenographic latitudes deduced from Explorer 35 observations of limb compression occurrence rates [10]. While the subsatellite measurements indicate that limb compression formation is related to lunar magnetic regions [5], the low latitude orbits of Apollo 15 and 16 do not cover this interesting region. Such measurements must await a polar orbiting lunar satellite.

**Acknowledgments**

This work was supported by the National Aeronautics and Space Administration under contract NAS 9-12236.

**References**