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ABSTRACTS
for
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on
Recent Activity in The Moon

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"RECENT ACTIVITY IN THE MOON"

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Lloyd Berkner Room

Lunar Science Institute, Houston, Texas

Organizing Committee

S. K. Runcorn  R. R. Hodges
G. V. Latham  R. O. Pepin
B. Middlehurst  L. J. Srnka
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The Apollo seismic network detects several thousand deep moonquake signals annually. Repetitive signals from 60 deep moonquake hypocenters can be identified. The occurrence characteristics of the moonquakes from individual hypocenters are well-correlated with lunar tidal phases of the anomalistic and nodical months and display tidal periodicities of one month, $7\frac{1}{2}$ months, and six years. With one exception, the deep moonquake foci located to date occur in three narrow belts on the nearside of the moon, and are concentrated at depths of 800 to 1000 km. The locations of 17 shallow moonquake (HFT) foci, although not as accurate as those of the deep foci, show fair agreement with the deep moonquake belts. Six shallow moonquake epicenters are located on the surface traces of deep moonquake belts and 15 of the 17 shallow epicenters are located within about 30° of a deep moonquake epicenter. Focal depths calculated for the shallow moonquakes range from 0 to 300 km. The deep moonquakes of a moonquake belt, or a region within a belt, occur near the same tidal phase suggesting similar focal mechanisms. Shallow moonquakes occur at tidal phases that can be correlated with those of the deep moonquakes. Deep moonquake magnitudes range from about 0.5 to 1.3 on the Richter scale with a total annual energy release estimated to be about $10^{14}$ ergs. The largest shallow moonquakes have magnitudes of 4 to 5 and release about $10^{15}$ to $10^{18}$ ergs each. The smallest shallow moonquakes have magnitudes of about 1.5. Calculations of the tidal deformation of a rigid lunar lithosphere overlying a reduced-rigidity asthenosphere show that concentrations of strain energy occur near the base of the lithosphere. Although tidal strain energy can account for the energy released by the deep moonquakes, it is insufficient to account for the shallow moonquakes. This implies that the shallow moonquakes release a significant amount of tectonic strain energy. The tidal correlation between the shallow and deep moonquakes suggests that the shallow moonquakes are triggered by lunar tides. The calculated magnitudes of tidal stresses within the lunar lithosphere range from about 0.1 to 1 bar. This low level of tidal stresses suggests that lunar tides act as a triggering mechanism for the deep moonquakes with tidal strain energy contributing to the energy released by these events. A secular accumulation of strain energy is implied by the uniform polarities of the deep moonquake signals. This dominant source of deep moonquake energy probably results from weak convection. A convective mechanism would explain the distribution, occurrence characteristics, and energy release of deep and shallow moonquakes, the lunar earth-side topographic bulge, the distribution of filled mare basins, and the ancient lunar magnetic field.
Among thousands of natural seismic events detected yearly by the Apollo lunar seismic network, there are a few distant events of distinctly high signal frequency. These are designated HFT (high-frequency teleseismic) events. Though they constitute a very small fraction of the total number of the observed events, they are quite significant because they include some of the largest natural seismic events ever observed on the moon.

Some of the principal characteristics of the HFT events and signals are the following: (a) The frequency content of the signals is distinctly higher than that of deep moonquakes and meteoroid impacts at comparable distances, attributed either to higher-frequency sources or to low attenuation of high-frequency signals throughout the transmission path. (b) P and S arrivals are relatively well defined, as in deep moonquakes, suggesting either that the sources are located below the surface scattering zone, or that the scattering zone is absent near the source region. (c) Sources are located at or near the surface of the moon, though whether or not they are at a finite depth cannot be determined. There is no doubt, however, that there exists a large gap in seismic activity between the zones of HFT sources and deep moonquakes. (d) The spatial distribution of the epicenters does not show any significant concentrations. Though the activity is low in the SE quadrant, as for deep moonquakes, there certainly is no concentration into narrow belts like earthquake belts, suggesting that they are not caused by relative movements of large plates. (e) The temporal distribution of occurrences, has no apparent regularity, suggesting that, in contrast to deep moonquakes, their occurrences are not strongly controlled by the tides. (f) One estimate assigns Richter bodywave magnitude 4 for a large HFT event, or equivalent seismic energy release of about $10^{15}$ ergs. (g) A small 'b-value' of the amplitude distribution is indicated, suggesting relatively high stress concentrations in the source regions.

Three working hypotheses for the identity of the HFT sources have been postulated: (I) ordinary meteoroid impacts on an unusually competent surface zone; (II) some impacting objects that achieve unusually deep penetration into more competent material beneath the heterogeneous surface zone; and (III) shallow moonquakes. Many of the characteristics described above favor the third hypothesis, but the evidence is not conclusive.

The determination of the true identity of HFT events will be greatly facilitated by simultaneous observations by other, independent techniques. Spatial correlation of HFT epicenters with locations of lunar transient phenomena (LTP) is difficult owing to the uncertainty of epicenter determinations. The increased Ar in the lunar atmosphere observed following the two strongest HFT events in 1973 might be interpreted as representing diffusion of Ar from some depth, providing strong evidence for the shallow moonquake hypothesis. Long-term observation of gaseous emissions at multiple stations is necessary to provide more positive data on the possible correlation.
"CORRELATION BETWEEN PERIODIC LUNAR PHENOMENA: AN INTERPRETATION". B. Middlehurst, Nassau Bay.

A survey is made of reports of lunar transient surface phenomena. The results of statistical studies by the present author and others have suggested statistical properties, such as periodicity, and preferred sites of occurrence. The importance of the periodicities has been that lunar transients were the first to show apparently tidally related triggering; their study has been followed by the discovery of other tidally related phenomena, both on the Earth and on the Moon. Spatial and temporal correlations between various types of tidally related lunar phenomena, and some difficulties in the interpretation of such correlations, are discussed. In summary, the reality (or otherwise) of these elusive surface phenomena is considered, and attempts to assign them to oblivion, or to endogenic or exogenic causes are discussed.

References


Manifestations, Site Distribution, Possible Causes and Correlations of LTP

by

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My catalog containing 1345 observations, of which 1248 have ancillary data, were analyzed with respect to several hypotheses. These were for tidal, low illumination/thermoluminescence, magnetic tail, and solar flare effects. There were 242 sites reported at least once. About \( \frac{1}{2} \) had two or more. One dozen sites compose 70% of all observations. One site, Aristarchus provides 1/3 of all observations. Of the dozen most reported sites, \( \frac{1}{2} \) are rayed and \( \frac{1}{2} \) are dark, flat-floored craters. The distribution of all strongly favors the borders, both highland and marial, of the maria. Many are within the maria and a very few are inland yet most of these are associated with dark flat areas.

The phenomena manifest themselves in five categories, viz. brightenings, darkenings, gaseous, reddish and bluish. Several hypotheses were proposed for their causes and analyses were conducted to see if different phenomena had different causes. There is some evidence that they do. The strongest peaks are at 0.5 (apogee) for gaseous, 0.6 for reddish and 0.7 for brightenings. Reddish have the strongest correlation with sunrise and Aristarchus brightenings, in an earlier analysis, had the strongest correlation with solar flare activity when earth experienced magnetic storm. All observations, the selected best observations, and Aristarchus, showed minima in the first half and maxima in the last half of the anomalistic (tidal) period. Histograms of several
individual sites, including neighboring ones, behave differently, e.g. Aristarchus and Herodotus. When observed data are compared with those expected if they were evenly distributed, show various correlations. For the best data, 11% and 10% fall close to perigee and apogee respectively and 10% would be expected for each. Nineteen per cent occur within 1 day after sunrise when 3.5% would be expected, 22% occur while the moon is in the earth's magnetopause where 14% would be expected, and 15% occurred the same day the earth had a magnetic storm where 3.5% would be expected.

For the ALPO observing program for LTP, observers send in all observations so that now we know how many observations were made and what percentage result in LTP's. Charts of albedos vs. age of several points for about a dozen features with fair completeness have been compiled. From these we obtain the normal behavior of the features throughout a lunation. If measures depart 2 or more full steps in Elger's albedo scale, I consider it an anomaly. Very few phenomena have been reported. Several cases of anomalous albedo measures show up in the charts, e.g. for points on the north and south walls of Calippus albedos of 7.25 were reported at age 9d while for ages 8d and 10d the average albedos were 2.5 and 3.25 respectively. I think the 7.25 was an anomalous brightening but unnoted by the observer. Most of the features remained stable. A few exceptions were found in the charts, with Dawes showing the most anomalies and these are about 8% of the time. Others will be demonstrated. Thus, monitoring the moon may give an LTP once out of twelve observations.
It would appear that the Apollo crews in lunar orbit have observed several instances of solar light scattering by a transient lunar "atmosphere," probably composed of sub-micron dust, over the terminator regions (1). The crew of Apollo 17 in particular recorded sketches of the appearance of the solar corona/zodiacal light (CZL) as it appeared to them above the lunar horizon while approaching orbital sunrise. These sketches (Fig. 1) included distinct "streamer" features which displayed time variations on the scale of seconds to minutes, incompatible with the time scale of any physical process occurring in the corona itself. Evaluation of various possible sources of such light distributions lead to the conclusion that they were produced by light scattering from a population of small particulates above the lunar terminator, extending back along the lunar shadow boundary.

Review of the mission reports, air-to-ground voice transcripts and conversations with some of the crew members from previous lunar orbital flights indicates that such phenomena may have been observed on several, but not all, of the previous missions. The crew of Apollo 8 reported the CZL appeared as a "very bright glow" with "dimmer streamers fanning out above and away from this point." The crew of Apollo 10 also reported observations of both orbital sunrise and sunset, with visible ray structures during the 4 to 6 minute period before sunrise and after sunset. Cernan has commented that his Apollo 17 observations were also typical of what he saw on Apollo 10. Visual observations of the CZL were not recorded during Apollos 11, 12 or 14.

The Apollo 15 crew observed a couple of streamers along the ecliptic, which Scott attempted to sketch during the post-flight debriefing (Fig. 2). This was also the first of the missions on which good 35 mm and 70 mm dim-light photography was obtained of the CZL from lunar orbit. Photometric analysis of the 70 mm film indicates a progressive increase by more than 100% in the CZL brightness during the period of 17 to 54 seconds after one sunset (2).

T. Mattingly (Command Module Pilot, Apollo 16) was aware of the previous sightings of streamers and attempted several times to detect them while in lunar orbit. He definitely remembered looking for them because of his personal disappointment in not seeing them. He did see and photograph the CZL. (These are the only photos of the CZL from the three missions which show less than 50% variation in brightness approaching the terminator.)

Additional details of the behavior of streamers observed by Apollo 17 are available from the air-to-ground voice transcripts and on-board tapes of crew conversations. Two periods (orbits 61 and 72) of orbital sunset were observed with specific comment on the streamers which seems relevant to the questions of size and visibility. Both descriptions are by Dr. Schmidt and include comments on the pattern formed and changes from previous patterns. Of particular interest, on orbit 71 the two brightest streamers were located along and 10 degrees south of the ecliptic, very bright "right at sunset." "They form two of the major, longer, duller streamers that are streaming out of the sun now. There are some other linear streamers that are still visible, but those are the major ones. Once you get out to the position of Mars, they all have about the same intensity -- which is very low. -- The pattern is
distinctly different from the one I believe I mentioned to you yesterday." (On orbit 61, he described the dominant streamers as two bands diverging by 70 to 80 degrees on either side of the ecliptic.) These observations indicate the angular elongation of the streamers from the sun to exceed 33° (position of Mars). The complete change in location and configuration of the major streamers present from orbit 61 to orbit 72, while not completely impossible for coronal features as in the case of the sunrise streamers sketched by Cernan, Evans and Scott, seems more compatible with the idea of determination by some projection of features on the changing lunar terminator as it moves at the rate of 12 degrees/day.

Figure 1
Solar Corona Sketch
David R. Scott
Commander
Apollo 15
16 August 1971

Figure 2

References
POSSIBLE PHYSICAL PROCESSES CAUSING TRANSIENT LUNAR EVENTS

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Transient lunar events have been observed to involve two main effects: (1) the obscuration of surface detail, and (2) changes in brightness, as could be caused by (a) emission of light, or (b) modification of the way in which incident sunlight is scattered.

(1) It is difficult to explain the obscuration effect in any other way than by assuming that clouds of surface dust are raised by bursts of gas emission from surface fissures, or by impacts. The possible duration and density of such clouds are considered.

(2a) Processes that could emit light include: luminescence or thermoluminescence of the surface; glow discharge in gas clouds, possibly enhanced by charged dust grains; lightning-type discharge in dust clouds; and thermal emission from hot materials. We conclude that lightning-type discharge is the emission process most likely to be capable of producing enough light to be observable from the Earth.

(2b) Modification of the albedo of a dust surface by agitation has been demonstrated in laboratory experiments, eg by Garlick and Steigmann, and by Mills; under certain conditions the albedo may increase. The most likely lunar process of this type seems to be agitation of surface dust by gas emitted from surface fissures.

It is concluded that all the observed transient lunar events can best be explained by various processes that may occur in gas-borne dust clouds.

The Apollo orbital observations of the uranium series daughters $^{222}\text{Rn}$ and $^{210}\text{Po}$ resulted in the detection of a number of significant features in their spatial distribution. The major results were:

1) There exists a pronounced enhancement of $^{210}\text{Po}$ at the edges of many lunar mare and a general non-uniform surface distribution of $^{210}\text{Po}$.

2) The edges of Mare Fecunditatis had the highest $^{210}\text{Po}$ activity of the regions covered by the Apollo 15 and Apollo 16 orbits.

3) The level of activity of $^{210}\text{Po}$ at many sites and on the Moon as a whole exceeds that of its progenitor $^{222}\text{Rn}$ whereas it would be less than one-half of $^{222}\text{Rn}$'s activity if radon were emanated from the lunar surface uniformly in time.

4) There exists a significant correlation of $^{222}\text{Rn}$ activity with the sunrise terminator.

5) There is a tendency for the $^{222}\text{Rn}$ levels to be highest over the lunar quadrant containing Mare Imbrium and Procellarium and lowest over the farside highlands.

6) The spatial distributions of $^{222}\text{Rn}$ and $^{210}\text{Po}$ are different from each other and from the original member of the decay series, $^{238}\text{U}$, as seen in orbital gamma-ray measurements.

7) There apparently exists both $^{222}\text{Rn}$ and $^{210}\text{Po}$ hot spots that may be associated with well known lunar craters such as Aristarchus and Grimaldi which have been frequently mentioned in historical records as sites of "transient lunar phenomena".

8) There is a more general correlation of high $^{210}\text{Po}$ or $^{222}\text{Rn}$ levels with reported visual sightings of transient phenomena.

These results require that radon be emitted very non-uniformly in time. Sporadic venting of small quantities of gases at or near mare edges is a mechanism that can explain these results. Support for this hypothesis comes from the well known presence of radon as a trace component in terrestrial outgassing events.

Based on the Apollo results a radon monitoring experiment was proposed for the Lunar Polar Orbiter as a means of observing the consequences of internal activity from lunar orbit. The experiment can measure secular changes in the level of radon outgassing from the Moon over a one year period. The proposed investigation can detect episodic changes, in $^{222}\text{Rn}$, the total rate of $^{222}\text{Rn}$ emanated over a month by observing the terminator and can detect changes of five percent which occur over a year.
Perhaps the most significant results of the lunar atmospheric measurements made during the Apollo program are the high rate of escape of $^{40}$Ar from the moon and the time variation of the argon source. Virtually all of the $^{40}$Ar on and in the moon has been formed by radioactive decay of $^{40}$K within the moon. The rate of effusion of argon from the moon to the atmosphere has several important implications on the present state of the lunar interior.

What is known about argon escape from the moon has been deduced from data from the mass spectrometer at the Apollo 17 landing site. These measurements give argon concentration as a function of time. The average of all measured diurnal variations has been used as a basis for a model atmosphere. Subsequent application of the model atmosphere results to individual argon concentration measurements has provided the time variations of both the atmospheric rate of photoionization and the rate of supply of argon to the atmosphere. (1)

Briefly, the rate of escape of $^{40}$Ar from the moon is variable, implying an episodic process of release of this radiogenic gas from the interior of the moon. The average rate of loss of argon from the lunar atmosphere is about $2 \times 10^{21}$ atoms/sec, which is about 8% of the present argon production rate for the entire moon ($2.4 \times 10^{22}$ atoms/sec) if the average lunar potassium abundance is about 100 ppm. (2) To put these rates in planetologic perspective, the present rate of release of $^{40}$Ar needed to account for its 1% abundance in the terrestrial atmosphere should be about $1.1 \times 10^{24}$ atoms/sec if the fraction of total production effusing into the atmosphere has remained constant over geologic time. For a lunar equivalent mass of earth this rate amounts to $1.4 \times 10^{22}$ atoms/sec.

Although the rates of effusion of $^{40}$Ar from the moon and earth are comparable, their total atmospheric abundances differ by more than 15 orders of magnitude. On earth the escape of argon ions is inhibited by the geomagnetic field, so that almost all of the argon ever released is now present in the atmosphere. However, the lack of both a lunar magnetic field and an ionosphere allows the solar wind to impinge directly on the planet, and hence, to accelerate any ions formed near the moon. As a result the average lifetime for lunar argon is only about 80 to 100 days. The product of lifetime and loss rate gives the atmospheric argon content to be only about $10^6$ gm. At any instant most of this gas resides on the nighttime surface as a result of adsorption.

The source of atmospheric $^{40}$Ar is clearly potassium, but the magnitude and time variability of the argon escape rate have nontrivial implications on the internal structure of the moon. What is uncertain is the means by which
about 8% of the lunar argon production has access to the atmosphere. In sub­sequent discussion various depth intervals of the moon are examined in terms of argon production and release mechanisms.

Lunar Surface - Trapped argon in the surface layer of the soil must be re­leased by a solar wind weathering process in a manner similar to the release of implanted solar wind helium. (3) Typical abundances of trapped ⁴⁰Ar in returned soil samples are within an order of magnitude of 5 x ¹⁰⁻⁵ cc STP/g. If this number is taken as an estimate of the average abundance of argon in the entire regolith, then the release of the 2 x ¹⁰²¹ argon atoms/sec needed to supply the atmosphere would require a weathering process which removes about 75 cm of soil from the moon per million years. Since this erosion rate is several orders of magnitude greater than the soil escape rate determined by Fireman (4) it is not reasonable to consider surface weathering to be an im­portant source of atmospheric argon.

Regolith to 25 km Depth - A monotonic increase in seismic velocities with depth to about 25 km has been explained by Toksöz et al. (5) to indicate a pressure effect on soils and broken rocks near the surface, changing to rocks having micro and macro cracks at greater depth. Argon which has diffused from within rocks to surface or fracture boundaries should be an atmospheric source. The Apollo 15 and 16 orbital gamma ray spectrometer data suggests that the average potassium abundance of the surface lunar soil is about 1000 ppm (6), while geochemical models of Taylor and Jakeš (2) indicate a crust average of 600 ppm. Accepting these as representative estimates of the po­tassium abundance in the upper 25 km of the moon, the rate of argon production there is in the range of 3-5 x ¹⁰²¹ atom/sec. Release of 2 x ¹⁰²¹ atom/sec (the atmospheric escape rate) would imply loss of about half of the argon pro­duction. Returned regolith samples do not generally exhibit a depletion of ⁴⁰Ar that would confirm this loss process. More important, there is no time dependent phenomenon which would vary the argon release rate.

Lower Crust and Lithosphere (25 km to 1000 km) - Seismic data reveal the beginning of a competent rock layer at about 25 km depth and an apparently petrological discontinuity at about 65 km, marking the upper boundary of the mantle (5). Nearly constant seismic velocities suggest a lack of rock frac­turing. Taylor and Jakeš (2) estimate that about 70% of the moon's potassium has been captured in this region mainly above 300 km depth. However, the re­lease of enough argon from this solid rock to supply escape is not a practical postulate, even if increasing temperature with depth is considered to increase the argon diffusion velocity. Again there is no practical mechanism to cause temporal changes in the release rate.

Asthenosphere (Below 1000 km) - The central part of the moon is thought to be semimolten because seismic shear waves are attenuated below 1000 km (6). Two alternate models of this asthenosphere have been proposed by Taylor and Jakeš (2). One is a conventional Fe-FeS core formed early in lunar evolution. If the process of formation of such a core should have fractionated the entire moon, displacing all potassium from the core, then there is no apparent ex­planation of the atmospheric argon. However, a core in which potassium has been concentrated is a plausible source of argon.
The alternative asthenosphere model of Taylor and Jakeš (2) is a region of primitive undifferentiated material. The present partially molten state of the asthenosphere commenced after fractionation of the lithosphere, and is maintained by radioactive decay of K, Th and U. About 8% of the moon's potassium should be trapped below 1000 km if the whole moon average potassium abundance is 100 ppm. This is sufficient to supply the atmosphere provided that all of the argon escapes, which in turn seems to imply that either the semimolten state is pervasive of the entire asthenosphere, or that the asthenosphere has gradually fractionated to form pockets of material rich in K, Th and U, which are naturally hot and from which argon can readily escape.

The only apparent, viable explanation of the lunar atmospheric argon is that it effuses from a semimolten asthenosphere. In addition, it is necessary that the potassium abundance in the asthenosphere be at least as great as the whole moon average of 100 ppm. The mechanism of conduction of argon from the asthenosphere to the atmosphere can be conjectured to involve a percolative process in which the gas collects either in bubble-like areas near the 1000 km depth, or in voids nearer the lunar surface. Subsequent increasing pressure could force the opening of deep fissures, causing sudden release of gas to the atmosphere.

A correlation of increases in the atmospheric argon supply rate with the high-frequency lunar teleseismic events reported by Nakamura et al. (8) was discussed earlier (1). Time resolution of the argon source is not sufficiently accurate to establish that this correlation is not fortuitous, but its existence substantiates the above pressure release hypothesis. In addition, the seismic correlation suggests that argon release may be the cause of some moonquake activity. The amount of seismic energy available from this process has an upper bound equal to the stored energy prior to release (i.e. pressure times volume). At 300 K the average argon escape rate could supply about $2 \times 10^{15}$ ergs per year.

REFERENCES

Both lunar transient phenomena (LTP) and $\text{Rn}^{222}/\text{Po}^{210}$ anomalies observed by Apollo 15 and 16 orbital alpha spectrometers display preferences for certain kinds of locations: rims of circular maria and craters with central peaks and/or dark floors. If these classes of observations are due to lunar gas venting, why are these types of locations preferred? The hypothesis offered is that these are locations at which cracks or channels exist extending deep enough into the Moon to tap lunar volatile reservoirs. Possible channels include circumferential cracks around circular maria, old lava tubes for dark floor and volcanic central peak craters, and shattered subsurface rock structure for impact central peak craters.
GASEOUS EMISSION FROM THE MOON; J. W. Freeman and J. L. Benson, Rice Univ., Houston, Texas 77001

The Suprathermal Ion Detectors (SIDEs) deployed on the lunar surface monitor lunar atmospheric ions through three processes: 1) acceleration of ions by the interplanetary (or solar wind) electric field; 2) acceleration by the electric field due to lunar surface charges; and 3) acceleration by an artificial electric field generated by SIDE. All three techniques require the atmospheric atoms to be ionized by the solar 3V or solar.

Techniques 1 and 2 work in the terminator region and Technique 3 on the lunar dayside at solar zenith angles less than about 60°.

An exhaustive survey covering some 20 lunations of choice data and employing Technique 1 has provided no evidence of sporadic gas emissions above the neutral number density characteristic of the ambient lunar atmosphere. Technique 1 regularly allows the monitoring of ions in the mass ranges about 20 amu/q and 40 amu/q, presumably neon and argon. The terminator neutral number densities giving rise to the observed ion fluxes are of the order of 10⁵ and 10⁴ atoms/cm³ respectively(¹). Gases arising from sporadic events would be detectable if their neutral number densities at the Apollo 14 and 15 sites substantially exceeded these values. The only event found to date exceeding or approaching these values and not identified with Apollo mission exhaust products or debris is the event on March 7, 1971 characterized by ions of mass 18 amu/q. The proximity of this event in time to the Apollo 14 mission and the absence of later similar events suggest that this too was mission related although the exact source and intensity of the event cannot be accounted for(²).

Technique 3 above provides the most reliable and continuous monitor of the dayside lunar exospheric ions. A long term secular study of these data is underway. Fluctuations in ion flux exceeding one order of magnitude over a period of several lunations are apparent. Before these can be related directly to the neutral number density, variations in the ionizing processes must be factored out. This work has been hampered by the lack of available solar wind and UV data, however, to date, all variations in the ambient ion flux appear to be explainable in terms of changes in the ionizing fluxes.

AN APPROACH TO A PHYSICAL THEORY OF MOONQUAKES, LTPs AND GAS EMISSIONS FROM THE MOON.
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The moonquakes, lunar transient events and the rare gas emissions have a common spatial characteristic being associated with the mare. They also are time dependent: the latter episodic, the former having tidal correlation. The positions of the L.T.E's, whatever be the phenomena they represent, are known to be quite accurate and the time span over which they have been observed $10^3$ times the tidal period. The moonquake epicentres may still be subject to more error and the time record of their pattern short. If spatial and temporal relationship between these is accepted, they may be related to a common internal activity. It follows that the trace of this on the lunar surface may be best indicated by the L.T.E's: consequently the fact that the majority of these are close to the boundaries of the circular mare is a significant one and is a clue to their relation to deep events.

The surfaces of the circular mare are 1-2 km lower than those of the irregular mare, relative to the best fitting ellipsoid, and if hydrostatic head arguments are used to explain the mascons, it must be concluded that these surfaces were once the same height and that the mascons have subsequently subsided by 1-2 km. Because there have been no plate movements on the Moon, the energy released by the Moonquakes must be tidal strain energy, strain energy produced by internal convection or the potential energy of the mascons. The latter is quantitatively adequate ($10^{16}$ erg/yr). The tidal correlation seems easiest to explain if, at the maximum stretching of the lithosphere at apogee and perigee, the mascons have subsided a little along the cylindrical fault system around the circular mare which must be postulated to exist if subsidence is occurring. Features around the peripheries of these mare support the latter hypothesis.

The L.T.Ps must therefore arise from the release of volatiles along these faults which raise dust (obscuration of sharp features) or cause red glows (excitation connected with the solar wind, e.g. Koseryl's spectrum of C₂). Again this release might well occur at times of highest tidal strain. Radioactive products from a considerable volume of lunar material might be swept out during such a process.

The theory is speculative but, because of its precision, invites refutation by observation.
Many high resolution Apollo pictures of the lunar surface show faults that have undergone little modification by mass wasting processes and cratering. The faults cut the youngest geologic units and are therefore interpreted to be the youngest observable features on the Moon except for ongoing cratering. Some of these faults are the loci of dark halo craters and other possible young volcanic features. In some areas the faults and volcanic rocks appear to be related to regional tectonic structures (the lunar grid) and to radial and encircling faults associated with impact features. These young faults cut both young mare material and ancient upland rocks. Because the faults are linear features of small aerial extent, they are difficult to date by conventional crater counting techniques or by the degradation index technique developed for dating Mars channels. Even the second technique has not proved successful when applied to the youngest lunar faults. We are developing other statistical techniques in an attempt to test the appealing hypothesis that lunar transient events can be correlated with active lunar faults and young volcanic events.
TOWARD A THEORY OF MOONQUAKES
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The quadrupolar model for the build-up and release of elastic energy in solid stars and planets (1) will be reviewed and its possible applicability to moonquakes will be discussed. The model explains in a simple way the occurrence of quakes with fixed foci which show a monthly periodicity, and appears capable of explaining as well those "swarms" of smaller moonquakes, which do not have a fixed focus, and which display a semi-monthly periodicity in their occurrence.


Two outstanding aspects of lunar seismicity are: (a) most moonquakes are very deep with focal depths of 600-1000 km, and (b) these deep quakes are periodic with periods corresponding to lunar tidal periods (1). To understand the relationship between tides and lunar seismicity, we calculated the tidal stresses in the moon using a radially heterogeneous model.

For the numerical calculations we use an approach similar to that of (2). The total potential is expressed as the sum of the self gravitational potential and the tidal potential. The latter is calculated as a function of time using Brown's theory of lunar motion. The equilibrium conditions are expressed by three simultaneous differential equations which are solved numerically. In the absence of a liquid core an asymptotic solution is obtained at very small radii. Then the solution is propagated outward using a variable step size for computational efficiency.

For the initial calculations, a lunar model with radially varying shear modulus, constant bulk modulus and constant density were used. The values of the parameters were chosen on the basis of available seismic velocity and density models (3).

The calculated maximum shear stress at 15°S latitude and 25°W longitude is shown in Figure 1 as a function of depth. Also shown on the same figure is the range of focal depths of moonquakes, and specifically, the focal depths of "A1" moonquakes. "A1" is the most active lunar hypocenter with coordinates of approximately 15°S and 25°W.

The tidal shear stresses have a broad maximum at 600-900 km depth range. This is controlled primarily by the shear modulus profile. The maximum shear stress is less than 0.5 bars at all locations.

The stress variation as a function of time at the A1 hypocenter is shown in Figure 2. The variation of the maximum value of shear stress is about 0.1 bar. The occurrence of A1 moonquakes and their amplitudes measured on seismic records are also shown on the same figure. At this site, the time of occurrence of moonquakes corresponds to the maximum of the shear stress.

A longer term variation of shear stress is shown in Figure 3. In this plot the stress variation due to solar perturbation of the orbit is illustrated by the 206-day modulation of the monthly variation of the tidal stresses.

The outstanding question is whether tidal stresses trigger the moonquakes or provide the seismic energy as well. This point is not yet resolved. It appears that stress amplitudes are too small to provide adequate energy for moonquakes.
However, lateral heterogeneities and stress concentrations need to be incorporated into the calculations before the question can be answered.

References


Figure 1 - The variation of maximum tidal shear stress with depth at one location (15°S, 25°W). The distribution of moonquake focal depths is also shown. $A_1$ events are the moonquakes whose epicenters are near 15°S and 25°W.
Figure 2 - (Top) Monthly variation of maximum tidal shear stress with time at 15°S, 25°W and 770 km depth. (Bottom) The occurrence of $A_1$ moonquakes. Height of the bar is proportional to the moonquake amplitude measured on the seismogram.

Figure 3 - Long-term variation of maximum shear stress as a function of time at the point 15°S, 25°W and 830 km depth. Note the solar effects with 206-day period.
DISPERsal OF GASES RELEASED AT THE LUNAR SURFACE, Richard R. Vondrak, Radio Physics Laboratory, Stanford Research Institute, Menlo Park, CA 94025

The rate at which neutral gases spread out from a source on the lunar surface can be computed from collision-free kinetic theory. The dispersal rate is found to be dependent upon the source intensity, duration, and surface adhesion characteristics. Similar results are obtained if the gas dispersal is treated as the free expansion of a collision-dominated compressible fluid, which is a physically more realistic description of both the gas releases that occurred during the Apollo Missions and those that are claimed to occur as transient lunar phenomena.

Gas releases associated with the Apollo missions (LM engine firings, cabin ventings, LM impacts) are of interest because they are the only gas releases at the lunar surface for which the source location, duration, and intensity are known. In principle, ALSEP data for these man-made gas releases could both verify the theoretical modeling of gas dispersal and determine the adsorption properties of the lunar surface, thus aiding the identification and interpretation of any natural ventings which may be detected. Apollo gas releases were observed by the ALSEP Suprathermal Ion Detector Experiment and the Cold Cathode Gauge Experiment. However, it appears unlikely that any definitive conclusions can be made from these observations because of the proximity to the source, source uncertainties, and instrumental characteristics.

The results of gas dispersal models can be used to evaluate the amount of gas which would reach the ALSEP sites if venting occurs at locations suspected to be regions of present lunar activity (e.g. Aristarchus, Alphonsus, etc.). The failure of the ALSEP instruments to detect significant gas enhancements then indicates quantitative upper limits to the amount of gases now being released at those locations.

The length of time that a gas release will be a significant enhancement of the lunar atmosphere can be estimated from a quantitative evaluation of the mechanisms for lunar atmospheric mass loss. Computations indicate that any venting comparable to a terrestrial volcano ($10^{11}$ kg of released gas) must have occurred more than 100 to $10^5$ years ago. Had such activity occurred within contemporary times, the remnants of the gas release would probably be detectable by the ALSEP experiments.
Alfvén (1,2) has proposed that when the relative velocity between a neutral gas and a magnetized plasma exceeds a "critical velocity" $v_c \approx (2e\phi_i/m)^{1/2}$, where $\phi_i$ is the ionization potential and $m$ is the reduced mass of the neutral, the neutral ionization rate would abruptly increase. Many laboratory experiments (3) have verified the existence of this effect, although its theoretical grounding is weak (4). Nevertheless, recent observations (5) by the SIDE and SWS experiments in the Apollo 12 ALSEP suggest that clouds of neutral gas are strongly ionized near the lunar surface at rates much above the photoionization and solar wind coulomb collision rates. Energetic (50eV) electrons were observed during the event, which suggests that some rapid plasma/neutral interaction (such as observed in "critical velocity" laboratory experiments) took place.

Since $v_c$ refers to the component the relative neutral-plasma velocity normal to the local magnetic field, variations in the orientation of the interplanetary magnetic field relative to the solar wind flow velocity would modulate the occurrence of critical velocity interactions between the solar wind plasma and any neutral gas emissions from the lunar interior. If the neutral cloud is sufficiently dense, some of the interaction energy could appear as photons (bound-free transitions, line emission, etc.), and hence produce a short-lived "transient event".

References
