

LUNAR OUTGASSING, TRANSIENT PHENOMENA, AND THE RETURN TO THE MOON. I. EXISTING DATA

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ABSTRACT

Transient lunar phenomena (TLPs) have been reported for centuries, but their nature is largely unsettled and remains controversial. In this Paper I the database of TLP reports is subjected to a discriminating statistical filter robust against sites of spurious reports, and produces a restricted sample that may be largely reliable, and is highly correlated geographically with event catalogs from *Apollo* and *Lunar Prospector* alpha-particle spectrometers for episodic ^{222}Rn gas releases. Both this robust TLP sample and even the larger, unfiltered sample are highly correlated with the boundary between mare and highlands, as are both deep and shallow moonquakes, as well as ^{210}Po , a long-lived product of ^{222}Rn decay and another tracer of outgassing. This offers another significant correlation relating TLPs and outgassing, and may tie some of this activity to sagging mare basalt plains (perhaps mascons). Additionally, low-level but likely significant TLP activity is connected to recent, major impact craters (while moonquakes are not), which may indicate the effects of impact fracturing, or perhaps avalanches, allowing release of gas. Most TLP (and ^{222}Rn) activity, however, is confined to one area likely causing major, recent volcanic effusion, and plausibly connected to the deep lunar interior. Our accompanying paper (Crotts & Hummels) treats likely theoretical implications, plus practical methodologies for remote and in situ TLP and lunar outgassing observations. With the coming fleet of robotic lunar spacecraft, followed by human exploration, the study of TLPs and outgassing is both promising and imperiled. We anticipate a greater burden of anthropogenic lunar gas than ever produced, perhaps outstripping the natural atmosphere itself, but also unprecedented opportunities to study lunar outgassing and its sources if these can be examined promptly, in their pristine state.

Subject headings: Moon — space vehicles: instruments

1. INTRODUCTION

In the minds of many scientists, the Moon is a dead world. Indeed, the Moon shows little activity compared to many bodies of its size or larger. Internal movements tend to be very low amplitude (see Nakamura et al. 1981, for example), and the native atmosphere is typically at total atomic/molecular number density $\lesssim 10^5 \text{ cm}^{-3}$ at the lunar surface (Hodges 1975; Hoffman & Hodges 1974) with a total mass of order 30 tons. A handful of geological features are suggestive of recent activity (e.g., Schultz et al. 2000, 2006; cf. Strain & El-Baz 1980), but not an overwhelming number. As little as 3 Gyr ago, however, the Moon suffered a major fraction of its surface covered by a high-temperature, refractory basalt, with some areas covered as recently as $\lesssim 1$ Gyr ago, e.g., in the vicinity of craters Lichtenberg, Flamsteed, and Aristarchus (Schultz & Spudis 1983; Hiesinger et al. 2003). Cooling models predict that the Moon has evolved a lithosphere of essentially a single crustal plate many hundreds of kilometers thick (e.g., Spohn 2005, and references therein); however, it is natural to wonder what evidence might exist for residual volcanic activity persisting to the present, or at least degassing from previous activity. This might be manifest in the form of volatile release to the surface through partial breaching of the crust's integrity in the form of lithospheric fracturing due to massive impacts, or stresses from tides and/or mascons interacting with the crust (Reindler & Arkani-Hamed 2001). In this paper I consider indications of rapid changes that may occur on the Moon due to internal or intrinsic processes, and relate those to endogenous gas release (whether or not it indicates volcanic activity). In an accompanying paper (Crotts & Hummels 2007, hereafter Paper II) we propose how to advance our understanding of this situation beyond its current ambiguity.

Transient Lunar Phenomena (TLPs, called LTPs by some authors) are predominantly optical wavelength effects, typically reported by observers monitoring the Moon visually through a telescope (with a few exceptions discussed in Crotts [2007]). Their physical nature is unknown, and even their reality is a point of dispute. (I discuss in § 3 episodic lunar gas discharges that I do not call TLPs per se—while some authors do—but their relation to TLPs is a crucial theme of this paper.) TLPs are usually brightenings or dimming/obscurations of the lunar surface, sometimes changing color—usually reddish but occasionally blue or violet. (Some early observers refer enigmatically to TLPs only as lunar “volcanoes”.) TLPs are localized, nearly always to a radius much less than 100 km, often as unresolved points (less than an arcsecond—about 1.9 km at the Earth-Moon distance). There are classes of phenomena that some authors call TLPs that involve the whole Moon, however, and, while interesting, will fall outside our discussion (some examples: Spinrad 1964; Sanduleak & Stocke 1965; Verani et al. 2001). I do not discuss phenomena tied to solar eclipses (but retain a few during lunar eclipses), and will omit events where the particular location is unspecified, including several events involving the extension of the cusps of the crescent Moon. TLPs are reported on timescales from “instantaneous” (probably a few tenths of a second due to small meteorite impacts) to several hours. TLPs are reported for many sites over the lunar surface, but are far from randomly distributed; a key question is whether this is physical or a severe observer bias.

Even casual investigators of TLPs notice something unusual associated with the region around the crater Aristarchus. This includes the adjacent crater Herodotus, and Vallis Schröteri (Schröter's Valley) flowing from “Cobra Head” (or “Cobra's Head”), which together occupy the southeastern quadrant of the compact, raised Aristarchus plateau of $\sim 40,000 \text{ km}^2$ within

the huge (4×10^6 km²) mare region Oceanus Procellarum, but close to the Mare Imbrium boundary. (Vallis Schröteri was once selected as the landing site for *Apollo 18*, later canceled along with *Apollo 19* and *20*.) Aristarchus is one of the youngest near-side lunar craters, and among the brightest, sometimes *the* brightest depending on lunar phase, sometimes visible to the unaided eye from Earth¹ along with perhaps Copernicus and Tycho (which each produce less than 5% of the TLP reports of Aristarchus).

More than Copernicus or Tycho, Aristarchus is distinguished by its stark contrast to the surrounding dark background (but this is unlike other TLP-producing features on the plateau). Once the region was intensely active, with volcanic flows and eruptions, and many sinuous rilles remain, likely old lava channels, including Vallis Schröteri, the largest on the Moon in terms of present-day volume. Not only is this region responsible for ~50% of the visual telescopic TLP reports (but also likely receives a disproportionate fraction of the observing attention), but also undeniably objective lunar anomalies of a transient, physical nature occur in the Aristarchus region, as detailed below.

Several experiments from *Apollo* lunar missions, orbiting and surface, as well as on *Lunar Prospector*, were designed to detect and identify gases in the tenuous lunar atmosphere, both ions and neutral species, plus decay products from gaseous radioactive isotopes. Even though some of these spent only days or weeks operating near the Moon, most observed evidence of sporadic outgassing activity, including events that seem unassociated with anthropogenic effects. This paper treats the correspondence between this activity and TLPs. To establish if TLP behavior is connected with the physics of the lunar environment, in a separate paper we explore ways in which this might be so, and ways in which this understanding can be increased with technologically accessible, systematic observations.

In the next decade, numerous spacecraft and perhaps humans will visit the Moon again. This offers an unprecedented opportunity to study the atmosphere of the Moon, but will also introduce transients from human activity that may complicate our understanding of this gas and what it can disclose regarding the lunar interior's structure, composition, and evolution. We must evaluate the current results now and expand on them rapidly to exploit our upcoming opportunity to explore the Moon in its still pristine state.

2. TRANSIENT LUNAR PHENOMENA

TLPs as observed are apparently rare events, and therefore the TLP database is largely anecdotal. Furthermore, since TLPs are observed for short durations, there is rarely the opportunity to accomplish possibly corroborating observations, such as photography or spectroscopy. For these reasons, primarily, the reputation of TLPs among many scientists is suspect, and also their explanation is largely unsettled. Nonetheless, TLPs represent a large database, cataloged by the great efforts of Winfred Cameron, Barbara Middlehurst, and collaborators, and if the reality of TLPs can be evaluated they might offer a potentially interesting method to study the Moon.

In Crotts (2007), the statistical structure of the TLP database is investigated in terms of the sensitivity of the results (that is, the consistent rate at which specific lunar features produce TLP reports) to parameters that might betray human observer bias or error. This companion paper concludes that, to the extent that one can test the effects of human bias/errors, they appear to dominate only during one historical period (the most recent), and otherwise

the behavior of TLP source features are impressively consistent, qualitatively. These tests imply that $\geq 10\%$ of TLP reports are inconsistent and therefore suspect, but that many, quite possibly the majority, indicate a consistent phenomenon tied to locally lunar effects.

Below I will review the arguments for statistical consistency from Crotts (2007) by considering such a “robustness test,” but first deal with a few auxiliary issues. There are several works which have studied TLPs in terms of the fraction of various kinds of events, e.g., brightenings, dimmings, obscurations, and red- and blue-colored events. Classification and analysis of TLP categories have been discussed at length in the literature; refer to Cameron (1972) for an effective overview. Of 113 reports in Middlehurst (1977a) involving enhanced brightness in blue and/or violet, 101 of them involve observer J. C. Bartlett, composing most of his total of 114 reports (between 1949 and 1966), most of those (108) involving Aristarchus. In contrast only 9 of 12 total non-Bartlett blue/violet events occur in the same years (during which 47% of all TLP reports occur). We must correct for this somehow, either by rejecting all blue/violet events or all reports by Bartlett; I choose the latter.

Seventy-one reports in Middlehurst et al. (1968) include time duration estimates (which can be interpreted to better than a factor of 2, e.g., not instantaneous). Of course this is not a statistical sample, but the reports indicate prolonged occurrences; binned in $\sqrt{10}$ intervals from 60 to 19,000 s (with the longest event being 18,000 s and the shortest being 60 s) the duration distribution is: 60–190 s, 7 reports; 191–600 s, 9; 601–1900 s, 27; 1901–6000 s, 23; and more than 6000 s, 5. These effects are not so rapid as to disallow reinspection (albeit by the same observer in most cases). There are four cases in Middlehurst et al. (1968) described as sudden, isolated flashes of light, and these are not correlated with meteor showers (the TLPs occurring on 1945 October 19, 1955 April 24, 1957 October 12, and 1967 September 11). None of these are well placed with respect to known meteor showers. (April 23 is the peak of the Pi Puppids, but these are strong only near the perihelion of comet 26P/Grigg-Skjellerup, which occurred in 1952 and 1957, not 1955.) Suggestions for other mechanisms for rapid TLPs include piezoelectric discharge (Kolovos et al. 1988, 1992—which also includes an interesting, instrumentally recorded TLP observation). In Crotts (2007) we discuss minimal impacts visible from Earth occurring on subsecond time-scales, while even the brightest and rarest impacts will be visible for only a few seconds.

Even if a few large impacts can produce events of sufficiently long duration, it is clear from model computation, e.g., Morrison et al. (1994), that the fresh impact features seen in *Clementine* and other data sets cannot possibly sustain even a significant fraction of the activity reported as TLPs. This leaves open the possibility that their geographical distribution is not random. The spatial distribution might be expected to carry detailed information about the TLP mechanisms, assuming observer selection effects can be removed. We refine this below, but first note the results from the raw catalogs.

Table 1 and Figure 1 are derived from reports listed by Middlehurst et al. (1968), sometimes with additional information (but not additional reports) drawn from Cameron (1978).²

² After the present paper was written, Cameron released via Internet in 2007 an addendum catalog of TLP reports (<http://users.aber.ac.uk/atc/tlp/cameron1978.pdf>), but negligibly few of these (nine) originate before 1956 when observer predisposition toward particular targets might not predominate. The distribution of additional reports (either before or after 1956) is nearly identical to the sample used here in terms of “robust” sites of TLPs, as explained below. This new catalog is treated in more detail in Crotts (2007).

¹ One even finds reference to Aristarchus in Tang Dynasty (618–907 AD/CE) writings (Mayers 1874).

TABLE 1
NUMBER OF TLPs REPORTED, BY FEATURE

Feature	Lat. (deg)	Long. (deg)	No.	Feature	Lat. (deg)	Long. (deg)	No.
Aristarchus	24N	48W	122	Archimedes	30N	4W	1
Plato	51N	9W	40	Arzachel	18S	2W	1
Vallis Schroteri	26N	52W	20	Birt	22S	9W	1
Alphonsus	13S	3W	18	Carlini	34N	24W	1
Gassendi	18S	40W	16	Cavendish	24S	54W	1
Ross D.	12N	22E	13	Censorinus	0N	32E	1
Mare Crisium	18N	58E	12	Clavius	58S	14W	1
Cobra Head	24N	48W	6	Conon	22N	2E	1
Copernicus	10N	20W	6	Daniell	35N	31E	1
Kepler	8N	38W	6	Darwin	20S	69W	1
Posidonius	32N	30E	6	Dawes	17N	26E	1
Tycho	43S	11W	6	Dionysius	3N	17E	1
Eratosthenes	15N	11W	5	Endymion	54N	56E	1
Messier	2N	48E	5	Fracastorius	21S	33E	1
Grimaldi	6S	68W	4	Godin	2N	10E	1
Lichtenberg	32N	68W	4	Hansteen	11S	52W	1
Mons Piton	41N	1W	4	Hercules	47N	39E	1
Picard	15N	55E	4	Herschel	6S	2W	1
Capuanus	34S	26W	3	Humboldt	27S	80E	1
Cassini	40N	5E	3	Hyginus N	8N	6E	1
Eudoxus	44N	16E	3	Kant	11S	20E	1
Mons Pico	46N	9W	3	Kunowsky	3N	32W	1
Pitatus	30S	13W	3	Lambert	26N	21W	1
Proclus	16N	47E	3	Langrenus	9S	61E	1
Ptolemaeus	9S	2W	3	Leibnitz Mt. (unoffic.)	83S	39W	1
Riccioli	3S	74W	3	Manilius	15N	9E	1
Schickard	44S	26E	3	Mare Humorum	24S	39W	1
Theophilus	12S	26E	3	Mare Nubium	10S	15W	1
Plato, 1.3' SE of	47N	3W	2	Mare Serenitatis	28N	18E	1
Alpetragius	16S	5W	2	Mare Vaporum	13N	3E	1
Atlas	47N	44E	2	Marius	12N	51W	1
Bessel	22N	18E	2	Menelaus	16N	16E	1
Calippus	39N	11E	2	Mersenius	22S	49W	1
Helicon	40N	23W	2	Mont Blanc	45N	0E	1
Herodotus	23N	50W	2	Montes Carpatu	15N	25W	1
Littrow	21N	31E	2	Montes Taurus	26N	36E	1
Macrobius	21N	46E	2	Peirce A	18N	53E	1
Mare Humorum	24S	39W	2	Philolaus	72N	32W	1
Mare Tranquilitatis	8N	28E	2	Plinius	15N	24E	1
Mons La Hire	28N	26W	2	Sabine	1N	20E	1
Montes Alps, south of	46N	2E	2	Sinus Iridum, south of	45N	32W	1
Montes Teneriffe	47N	13W	2	Sulpicius Gallus	20N	12E	1
Pallas	5N	2W	2	Taruntius	6N	46E	1
Promontorium Agarum	18N	58E	2	Thales	62N	50E	1
Promontorium Heraclides	14N	66E	2	Triesnecker	4N	4E	1
South Pole	90S	0E	2	Vitruvius	18N	31E	1
Theaetetus	37N	6E	2	Walter	33S	0E	1
Timocharis	27N	13W	2	(unknown)	...	...	43
Agrippa	4N	11E	1	(cusps)	...	...	14
Anaximander	67N	51W	1	(global)	...	...	4

There is a tendency for TLP reports to favor the western half of the near side (106 in the east, 166 in the west, in addition to 144 on the Aristarchus plateau), which runs counter to the usual preference of casual observers to observe earlier in the night. (Reports for Aristarchus greatly favor evening over morning times, for instance; Cameron 1993.) Instead, this may be due to the greater extent of maria (and mare boundaries; see the following) on the western side. The primary spatial modulation of the report rate, which has been noted previously, beyond just the frequency at specific sites, is the tendency of reports to avoid the deep highlands and to some degree the mid-mare plains, but

instead to congregate in the vicinity of the maria/highland interface (Cameron 1967, 1972; Middlehurst & Moore 1967; Buratti et al. 2000). Even Aristarchus/Vallis Schröteri/Cobra's Head/Herodotus in the midst of Oceanus Procellarum rests on a giant highland-like block of about 40,000 km² (probably raised by the Imbrium basin impact; Zisk et al. 1977) elevated 2 km above the mare plain, although this might easily be a special case.

How do we deal statistically with the horrendous selection effects introduced into this data set by the patterns and biases of the observers, most of whom never intended that their reports form part of a statistical database? This is as much a historical

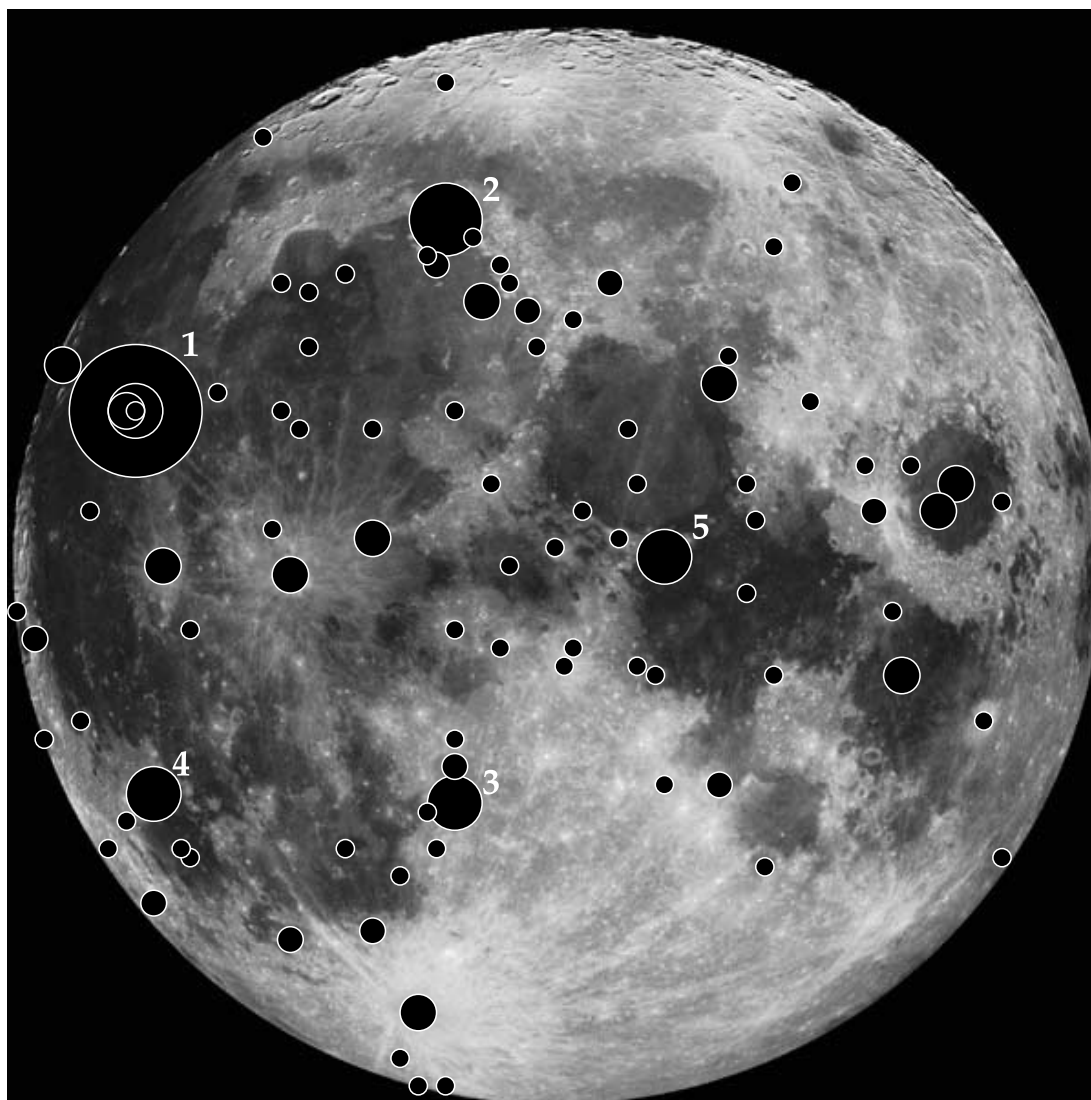


FIG. 1.—Distribution of TLP report loci as cataloged in Middlehurst et al. (1968), with the exception of a minority of cases that are rejected for the reasons detailed in the text. The size of the symbols encodes the number of reports per features, as listed in Table 1. Note that the four symbols for features on the Aristarchus plateau overlap, with the crater Aristarchus being the largest in the figure. Marked features include: (1) Aristarchus (enclosing Vallis Schröteri, Cobra's Head, and Herotus, in decreasing order), (2) Plato, (3) Alphonsus, (4) Gassendi, and (5) Ross D. (Photo credit: NASA)

and even a psychological question as a physical/mathematical one; however, there are some regularities that we might exploit. First, the pattern of TLP observer behavior seems to have changed significantly in the mid-twentieth century, when well-publicized reports such as Alter (1957) drew attention to TLPs and particular locations such as Alphonsus and Aristarchus. Many observers after that era concentrated specifically on sites such as these in an effort to maximize success in detecting a TLP. Prior to this era, I see little evidence (see Crotts 2007) that observers were drawn a priori to specific sites to find TLPs. Middlehurst (1977a) has reviewed historical reports extensively and comes to a similar conclusion. Indeed, many reports from previous centuries neglect to fully specify the site of their TLP.

I cannot fully appreciate the observing motivations of astronomers from so long ago, but there is little written indicating special sites such as Aristarchus as targets of propagating popular or professional attention in terms of TLPs (see Crotts 2007). Aristarchus did receive wider scrutiny in 1911 when R. Wood indicated that it might contain high concentrations of sulfur, but this did not produce a spate of Aristarchus TLP reports. Indeed, Wood dis-

cusses volcanism in the context of Aristarchus (sometimes known as “Wood’s Spot”)³ and seems unaware of the number of TLP reports in the vicinity (Wood 1910). In Crotts (2007), earlier works by W. H. Pickering (1892, 1904) on Aristarchus and lunar activity are detailed, but these show no evidence of having inspired later TLP reports. Furthermore, Birt (1870) and Whitley (1870) provide a historical overview (1787–1870) of visual observations of Aristarchus (and Herodotus) while conducting a spirited debate about the nature of features including possible changes in their appearance. They mention small, possible changes, but give them no special significance, nor mention anything that today we might refer to as recognized TLP events (or at least a human tendency to report TLPs). A different statement is made by Elger (1884), who again reviews Aristarchus, Herodotus, and the surrounding plateau. While mentioning nothing like TLPs, he makes a telling statement: “Although no part of the moon’s visible surface has been more frequently scrutinized by observers than the rugged

³ For example, Whitaker (1972), or <http://www.lpod.org/archive/archive/2004/01/LPOD-2004-01-17.htm>.

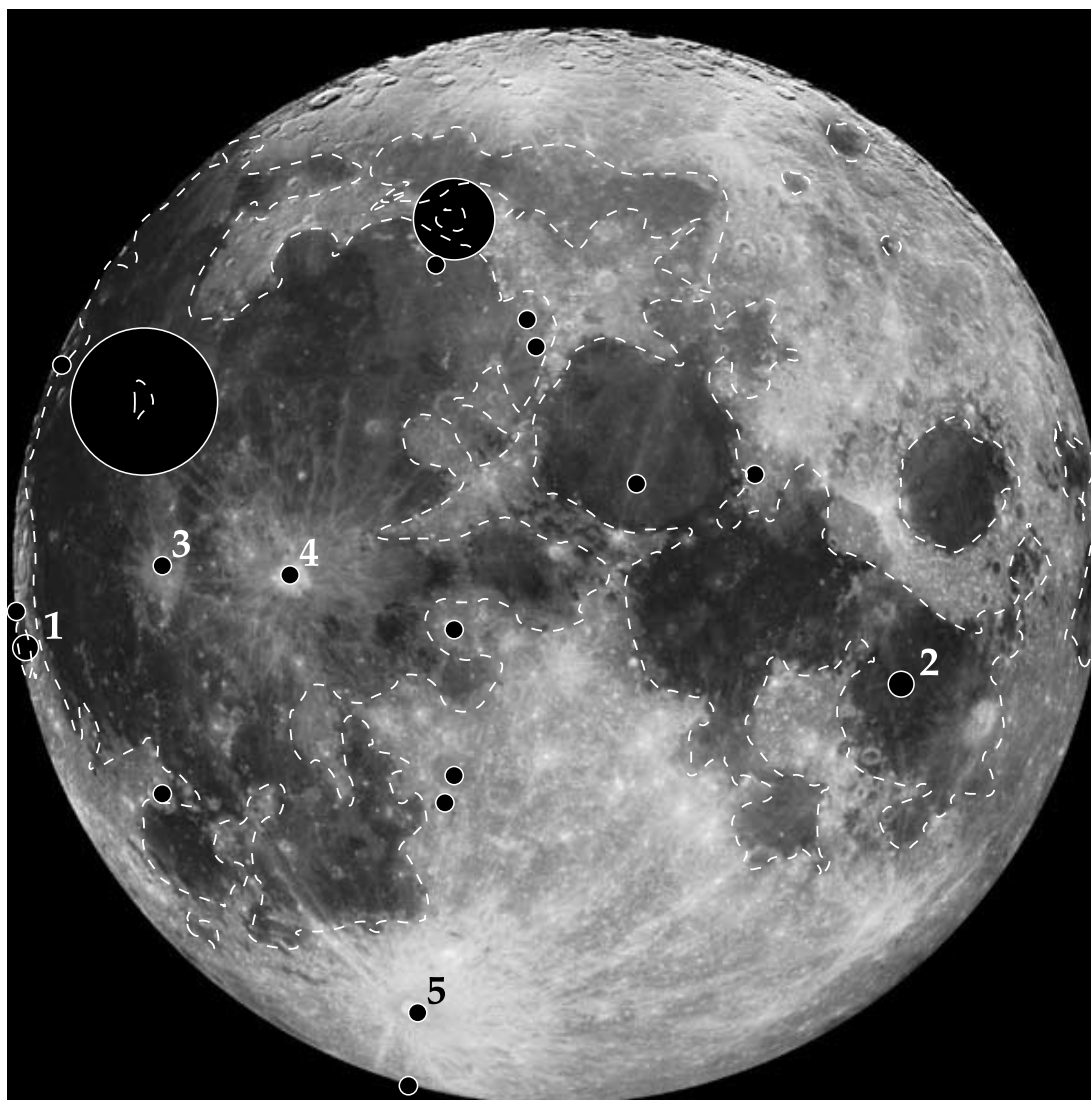


FIG. 2.—Distribution of TLP report loci that survive the robustness filter detailed in the text, taken from those reports portrayed in Fig. 1. The size of the symbols encodes the number of reports per features, as listed in Table 2. Note that reports for the four features on the Aristarchus plateau overlap are merged into a single symbol (the largest). Marked features include several of note not marked in Fig. 2: (1) Grimaldi, (2) Messier, (3) Kepler, (4) Copernicus, and (5) Tycho. The dashed curves represent the locus of the mare/highland boundary adopted for the calculations in the text. (Photo credit: NASA)

and very interesting region which includes these beautiful objects, selenographers can only give an incomplete and unsatisfactory account of it . . .”

Crotts (2007) also contains a more quantitative treatment of the extent to which observations of transients in Aristarchus might be significantly causally correlated; suffice it here to say that there is little evidence of this, before 1956. This lack of significant correlation can also be considered an “integral constraint” on the importance of observer preconception as to the existence of TLPs as an important factor (for Aristarchus, at least) in determining the observation selection function; furthermore, they provide no evidence for a “hysteria signal” of false reports due to special attention. Elger’s statement above implies that the ratio of observing time for Aristarchus and the plateau versus equal areas not near the limb is at least of order unity, and probably more. We will see on the basis of ^{222}Rn alpha-particle measurements from Apollo and *Lunar Prospector* in sections below that this cannot with any reasonable probability imply that TLPs occur all over the Moon at a rate close to that reported near Aristarchus

(and hence we are not simply being fooled because human observers spend more time looking at the Aristarchus plateau).

There is a pause in the frequency in TLP reports in both the Cameron (1978) and Middlehurst et al. (1968) catalogs, and indeed the break in reports 1927–1931 divides the Middlehurst sample at the median epoch in the catalog. I will exploit this to compare both halves of the sample and eliminate over-reporting artifacts by rejecting the higher of the two counts for a given lunar feature in the manner that one can use to remove artifacts from two exposures in a sequence of the same picture with a poorly defined, non-Poisson noise component. Specifically, I bin the counts seen in Figure 1 into 300 km square “pixels” and take the smaller of the two counts for each pixel from before and after 1930, producing Figure 2. Since each pixel can be labeled with the name of the feature(s) identified by the observers in the reports that filled that pixel, I list the corrected count for each feature or group of features (Table 2). Within each pixel, I reevaluate particular features to see if TLPs from the two samples truly correspond geographically. If TLPs occur in the same named feature (and I

TABLE 2

NUMBER OF TLPs REPORTED PER FEATURE, CORRECTED FOR POSSIBLE ARTIFACTS

Robust Report Count	Feature(s)
66.....	Aristarchus/Vallis Schroteri
15.....	Plato
2.....	Grimaldi
2.....	Messier
1 each.....	Alphonsus, Bessel, Cassini, Copernicus, Gassendi, Kepler, Lichtenberg, Littrow, Mare Humorum, Mare Nubium, Mons Pico, Pallas, Picard, Ptolemaeus, Riccioli, South Pole, Theaetetus, Tycho

include any positional information available), or within a 50 km radius of each other, or within 1.5 times the radius of the named crater, whichever is larger, I retain this as a match. The latter is a rejection consideration in less than 10% of the cases. This resulting count from this entire procedure is likely to be much more robust against selection biases than the distribution shown in Figure 1, or for that matter similar plots shown by previous authors who did not impose an artifact rejection algorithm. I am assuming in effect that there are quantitatively different observing strategy results during these two time periods, which are capable of producing spurious peaks in the geographic distribution of reports, but do not completely neglect any area of the near-side Moon, excepting geometric effects such as limb foreshortening or lunar phase selection due to evening/morning viewing times, which are independent of time when averaged over the libration cycle. My appraisal of the literature is that this is probably a good assumption.

In some cases reports are tied only to individual mare as features, which are larger than a pixel. The impact of this systematic uncertainty is small, only two cases with one report apiece, which I do not plot in Figure 2. These correspondences are probably spurious, and I do not include them in our mare/highland boundary discussion below, although I include them in Table 2.

Note that the Aristarchus plateau persists as the prime TLP site with 63% of the corrected report count total (of 104), but Alphonsus and Gassendi have virtually disappeared (with one), and Ross D and Mare Crisium are gone altogether. Alphonsus in particular involved reports (except one) only since the Alter (1957) report, which precipitated a great deal of amateur interest. Beyond Aristarchus, Plato is still a prominent feature with 15 counts, but besides these two craters only Grimaldi and Messier survive with more than one count (having only two apiece). If the frequency of TLPs at a given site varies radically on the timescale of centuries down to a few decades, features might drop from Table 2. This selection filter is meant to sacrifice completeness in this case for reliability. Depending on the long-term fluctuations in TLP behavior, there may be additional, active TLP sites beyond what appears in Table 2. For the sake of further discussion in this paper, I assume the rates are constant on these timescales.

Plato is a distinct, flooded crater on the northwestern edge of Mare Imbrium, and hence is about 3.5 Gyr old or older. It is associated with several volcanic rilles, sits near mountainous regions such as Montes Alps, appears very dark in comparison, and is very different than Aristarchus in visual appearance. It can be striking in its long shadows stretching across its face when near the terminator. Some observer descriptions sound suspiciously like reports of this normal activity, but most do not correspond to

normal appearance (see Haas 2003). In 1854–1889 there were four reports involving at least some experienced observers noting extremely bright point sources that appeared for 30 minutes up to 5 hr (the longest duration report considered here); it is unclear if these reports might have influenced each other. There are few reports involving red sources (three not during eclipse); there are many reports of cloudlike appearance.

In detail, if a feature is reported in an unbiased way, one should expect the count N_1 in Table 1 related to N_2 in Table 2 by $N_1 = 2[N_2 + (N_2/3)^{1/2}]$ on average, for the case of taking the lowest of two values deriving from the same Poisson distribution. For Aristarchus + Vallis Schröteri + Cobra Head + Herodotus, the total in Table 1 is $N_1 = 150$, whereas $2[N_2 + (N_2/3)^{1/2}] = 137.4$; hence, the comparison is consistent with a fraction 0.916 ± 0.078 of reports being real. This is 86% for Plato, and essentially 100% for Grimaldi and Messier (within the limits of small number statistics).

This implies that approximately 70 events should have been detected in the Aristarchus plateau before 1930 at the intensity at which the Moon was observed during that interval. Since this represents approximately half of the TLP reports during this time, during which most reports occurred between 1700 and 1930, it seems consistent with approximately one TLP per 2 yr across the sample. The rate since 1930 for the Aristarchus region is about 4 times the report rate prior to this, and it is unclear how much of this is real increase in event coverage versus false detections. It may be simply the effect of the production of many, inexpensive telescopes. Taking the pre-1930 rate just inferred as a lower bound and adjusting for the fact that the Moon is only observable about 20% of the time from the places where observers were posted (accounting for Sun/Earth/Moon position and weather), it seems TLPs occur at least twice yearly on average, approximately. The corresponding rate after 1930, which might have an observing duty cycle closer to unity, but might still suffer from residual spurious reports, is about once per month.

In Crotts (2007) I perform additional robustness tests largely independent of this one, requiring consistency by (1) taking the median of four comparably sized historical subsamples (before year 1877, 1877–1930, 1930–1956, and after 1956), or by taking the median of just the first three subsamples; (2) taking the median over the season of year of the TLP report, before 1956; and (3) the median over subsamples grouping the reports by geographical location of the observer, before 1956. Despite these tests being different in their sensitivity to observer bias and error, they nonetheless give similar results: Alphonsus, Ross D, and Gassendi largely disappear; Aristarchus remains by far the strongest signal, followed by Plato (about 3 times weaker). To a slight degree recent impacts Tycho, Kepler, and Copernicus become stronger signals in these other tests. Even most of the weak features in Table 2 remain; Eratosthenes occasionally appears at a slightly stronger level. Mare Crisium is the only signal to vary significantly in strength between the different robustness estimates, in some cases reaching half the strength of Plato. Since it is actually 2 pixels in diameter, I am unsure that this should even be included as a feature in this analysis. On the whole, however, the consistent behavior of the main features in the sample lends credence to the notion that this approach has some validity. We are testing whether given features are robust either in human observing behavior, or in the long-term variability (of order 100 yr) of the actual physical processes producing TLPs at given sites. At least I have varied the former in several significant ways and find its effects to be consistent for most features, and inconsistent primarily in those features where history casts some suspicion.

Figure 2 as well as Figure 1 appears to retain the property that the points are clustered around the mare/highland interface. To develop the locus for this boundary is a challenge, but guided by the observation by Li & Mustard (2000) that the highlands and maria have distinct compositions and that this is immediately apparent in UV/visible flux ratio maps such as those available from *Clementine* (see also Whitaker 1972; Lucey 2004). Such an analysis tends to smear the boundary on scales less than tens of kilometers due to lateral transport of material by impacts, etc., whereas the standard boundary (Wilhelms et al. 1987) can be detailed on small scales to an extent exceeding the purpose here. We would like to develop a statistical test exploiting the separation between a given TLP site and the closest boundary segment. This depends on not only the length of this curvilinear boundary but also its Hausdorff index (as in a Mandelbrot set) and flux ratio threshold, somewhat arbitrarily (see the Appendix). I intend to explore this further, but for now a simple hand-drawn curve based on *Clementine* maps indicates that the points in Table 2 (weighted by report count) are about 7 times closer to the boundary than random points, which is a statistically significant result (at the $\sim 99.999\%$ level). This TLP correlation still suffers from the objection that some observer effect might manufacture reports at the mare/highland boundary, however, even after circumvention of the fractal/threshold problem. In the Appendix we show why this objection fails quantitatively. When I remove the points in Table 2 from Table 1 and correlate the residuals, I get a 2.5 times greater closest boundary separation, but this is for more points than in Table 2, and hence significant at a very high level. Whatever is causing the TLP/boundary correlation appears to survive even when the points that did not pass the more robust TLP report filter are included, so there appears to be a residual effect of such a mechanism in the rejected points. A natural explanation might be that many of the less active points are real, but create a TLP sufficiently rarely so as to not repeat over decades or even centuries, in which case the total TLP rate might be doubled or more in Table 2.

We explore in § 4 below the connection between outgassing and the mare/highland interface.

2.1. Controversy over the Reality of TLPs

Paper II deals with several works considering explanations for TLPs as nonlunar or nonphysical (usually observer effect) mechanisms. To summarize here, none of these seem to explain more than a small minority of TLP reports, although one or two issues are left as loose ends.

A scientist should be skeptical of any conclusion based solely on the existing optical database of TLP reports, absent independent verification. Most of them are anecdotal, not independently verified, and involve no permanently recorded signal that did not pass through the human visual cortex. Some of the observers are not even very experienced, whether professional or amateur. Our results above indicate that a significant number are of inconsistent rates, and might be spurious.

The onus of the argument must burden those who would convince us that TLPs are real. When it comes to locating a spurious effect that might explain the bulk of TLP reports as unrelated to the vicinity of the Moon, absence of evidence is not evidence of absence. Given the inability heretofore to test a reported TLP in a timely manner with sufficiently complementary measurements, we must ask if any other physical effects firmly tied to the lunar environment are correlated with TLPs.

An investigation by Cameron (1967, 1972) and Middlehurst (1977a, 1977b) into correlations with several possible lunar time parameters turns up primarily null relations, e.g., lunar

anomalistic period (time between perigees), and lunar age (phase), and finds some correlation with perigee and crossing of the Earth's magnetopause and bow shock, plus a strong correlation with local sunrise which might be a selection effect based on observers' attraction to this area of higher contrast. Middlehurst (1977a, 1977b) also claims a statistically significant positional correlation between TLPs and shallow moonquakes (from Nakamura et al. 1974). Note that moonquakes separately have been tied to episodic ^{40}Ar release (Hodges 1977; Binder 1980).

One transient phenomenon which occurs on a regular basis is the elevation of a tenuous dust layer at the local shadow terminator as observed by *Lunokhod-2* (Severnyi et al. 1975) and *Surveyor 7* (Gault et al. 1968a, 1968b; Rennilson 1968) (and perhaps detected extending to high altitudes by astronauts on *Apollo 10*, *17*, and perhaps *8* and *15*; Criswell & Freeman 1975), which Criswell (1972) ties to electrostatic dust elevation at the terminator caused by photoelectric ejection in daylit areas creating a voltage up to 550 V within about 1 cm of a shadow's edge. Few TLPs are consistent with this mechanism, however, since the majority occur far from sunrise/sunset. For the remainder we need to find some mechanism⁴ to create such a disturbance near the lunar surface if TLPs are to be believed. Our next companion paper (Paper II) will deal with the details of such candidate mechanisms. There are other transient processes occurring on the Moon, and it is the primary purpose of the present paper to ask if there is any such tie-in to TLPs.

3. LUNAR OUTGASSING

3.1. Geological Evidence of Trapped Lunar Gas

Lunar sample evidence, including basalt vesicles and volatile coatings, indicates that the eruption of mare lavas came with the release of copious amounts of gas, although the nature of such gas is still somewhat mysterious. Mare basalts brought near the surface during formation are riddled with a large volume filling factor of voids or vesicles (for a review, see O'Hara 2000; some examples are *Apollo 15* sample 15556 and *Apollo 17* sample 71155). The volatiles whose pressure produced these vesicles are unknown; some candidates have been modeled based on lunar petrology and knowledge of terrestrial basaltic volatile content: CO, COS, Na, SO₂, S₂, in decreasing order of likely concentration (Sato 1976), and probably CO₂. Wilson & Head (2003) discuss possible concentration levels of various gases, but with considerable uncertainty. Unfortunately, measuring the amount of gas once trapped in the vesicles or inferring its density and content is difficult (O'Hara 2000). If volatiles were trapped in the basalt, they most likely escaped (although even this is controversial; cf. Taylor 1975). Circumstantial evidence has been found recently for endogenous water in some lunar minerals (McCubbin et al. 2007) and definitive evidence for water endogenous to fire-fountain glass from deep, picritic magma (Saal et al. 2007).

In lunar fines carbon/nitrogen compounds are found primarily as CO, but also CO₂, CH₄, and traces of HCN, C₂H₂, and N₂, as well as trace O₂, cumulatively at about 200 ppm (Burlingame et al. 1970, which did not treat N compounds explicitly). Most of this gas might be due to reactions of solar-wind-implanted atoms (Hodges et al. 1973b).

One must consider the actions of fire fountains driven by gas into the vacuum (see Biggar et al. 1971, 1972). Evidence for such fire fountains is found in the orange glass and crystallized black beads in *Apollo 17* samples (Elkins-Tanton et al. 2003). Inclusions in these beads offer one way of sampling the ancient

⁴ See Hughes (1980) for a short review.

volatile content of the magma (Ebel et al. 2005). One recent paper gives convincing evidence that highly volatile substances were contained in the formation of fire-fountain glasses (Saal et al. 2007), including H_2O , F, S, and in most cases Cl (but not CO_2), with H_2O being detected at levels of $\sim 4\text{--}50$ ppm (± 1 ppm). The possible connection between former lunar activity and possible transients observed now has not been ignored (Friesen 1975; Classen 1974). The outgassing/TLP connection has not been established on the basis of the petrological record, but outgassing has been suggested to explain recently formed geological features (Schultz 1976; Schultz et al. 2000, 2006).

3.2. *Apollo Mass and Ion Spectrometers*

The tentative but intriguing nature of our knowledge of lunar outgassing is summarized by Srnka (1979), and its ambiguity is impressed by Freeman & Benson (1977). It is reasonably clear that ^{40}Ar is released by moonquakes (Hodges 1977; Binder 1980), not predominantly solar wind implantation (Hodges et al. 1974a). Also, bursts of gas, from neither artificial nor extralunar sources, have been recorded coming from near the lunar surface. Hodges et al. (1973a, 1973b, 1974b) report a burst recorded by the *Apollo 15* orbital mass spectrometer (at UT 1971 August 6, 08:22), showing species of 14, 28, and 32 amu, N_2 , and perhaps O_2 , near the northwest edge of Mare Orientale just on the far side (110.3° west, 4.1° south)—and hence cannot be an Earth-viewed TLP. Hodges et al. rule out many anthropogenic mechanisms for this event. This burst was so rapid that the scanning mass spectrometer was incapable of covering all species, but it is estimated that at least 10 kg of gas was involved. Freeman et al. (1973) report similar bursts of OH^- ions recorded by the *Apollo 14* ALSEP Suprathermal Ion DETector (SIDE). Both the Freeman et al. (1973) and Hoffman et al. (1973c) reports were reevaluated two decades later (Freeman & Hills 1991; R. R. Hodges 1991, private communication), although not in light of new data, and doubt cast on their nonartificial nature.⁵

The ALSEP mass spectrometer at the *Apollo 17* site indicates that radiogenic ^{40}Ar is released episodically, which is puzzling unless it is venting from deep within the Moon (Hodges & Hoffman 1974). Importantly, the ALSEP mass spectrometer provides evidence that the Moon releases CH_4 , and perhaps other molecules, from its surface at a local molecular number density of $\sim 6000\text{ cm}^{-3}$ over a 25 hr period at sunrise (Hoffman & Hodges 1974, 1975). Most of these signals are small, of marginal or slightly higher statistical significance (3σ for CH_4 , 2σ for NH_3 , and $1\text{--}2\sigma$ for H_2O , CO , and CO_2 ; Hoffman & Hodges 1975; N_2 and O_2 as seen in the burst from orbit are at the 1σ level.) The presence of these molecules at all, even if at tiny concentrations, is cause to suspect an outgassing source, since the sum of concentrations of H, N, and C in all forms in the regolith totals only about 200–300 ppm. The question remains whether this gas is endogenous or cometary/meteoritic impact in origin.

3.3. *Orbiting Alpha-Particle Spectrometer: Apollo 15, 16, and Lunar Prospector*

The crust of the Moon contains about 20 ppb of uranium (Drake 1986), mostly ^{238}U , which decays eventually to ^{222}Rn in 4.5×10^9 yr (half-life). Over the thickness of the lunar crust of

64 km (Zuber et al. 1994), this implies that the Moon produces $\sim 10\text{ g s}^{-1}$ of ^{222}Rn , assuming these values pertain homogeneously, which corresponds to a decay rate density of $40\text{ cm}^{-2}\text{ s}^{-1}$, assuming all ^{222}Rn reaches the surface. How much of this escapes to the surface? (Simple diffusion is not important; Friesen & Adams [1976]. Also, see Hodges [1975] for an alternative analysis.)

The way to establish this would be with orbiting alpha-particle spectrometers of the kind that were flown on *Apollo 15* (Gorenstein et al. 1974b), *Apollo 16* (Golub et al. 1973), and *Lunar Prospector* (Lawson et al. 2005). The alpha-particle detector (ARD) currently in lunar orbit on *Kaguya* (SELENE) is very promising in this regard. The global *Lunar Prospector* ^{222}Rn decay map averages about $0.004\text{ cm}^{-2}\text{ s}^{-1}$, which amounts to $2 \times 10^{15}\text{ s}^{-1}$ or $\sim 2\text{ g yr}^{-1}$. Most of the ^{222}Rn produced in the crust does not leak out, but 10^{-4} of it does, within the half-life of 3.8 days. This amounts to the equivalent of the outer 20 m or so of the regolith (roughly its typical highlands depth and close to a global average), which does not bespeak leakage from the deep crust, seemingly. (Either this, or the gas takes typically 50 days to reach the surface from anywhere in the crust.)

In spite of the above calculation, the detailed structure of the ^{222}Rn decay map implies a more complicated situation which does seem to indicate involvement with the deeper Moon. In orbit these instruments will see alpha particles flying in nearly straight-line paths from their decay site (deflected slightly by magnetic fields), with a locational accuracy comparable to the elevation of the spacecraft (for one alpha) but to better accuracy for a point source if it is strong enough to be centroided using multiple detections. The orbiting alpha-particle spectrometer on *Apollo 15* and *16* revealed two types of features, against a nearly constant background level: (1) a consistent enhancement of the alpha particles of ^{210}Po , a daughter product of ^{222}Rn gas, over the maria edges (Gorenstein et al. 1974b); and (2) anomalous outbursts of short-lived ^{222}Rn alpha particles probably tied to recent outgassing, over craters Grimaldi and Aristarchus (Gorenstein et al. 1974a, 1974b; Gorenstein & Bjorkholm 1973), both prime TLP sites. Gorenstein et al. conclude that since ^{210}Po and ^{222}Rn were not in radioactive equilibrium over these sites, radon must have been released sporadically and recently, with large amounts within the past few decades.

Lunar Prospector orbited the Moon during 1998 January 17–1999 October 25, *Apollo 15* during 1971 July 29–August 4, *Apollo 16* during 1972 April 19–25, and all three stayed about within 93–120 km above the surface. *Lunar Prospector* covered the whole lunar surface, whereas *Apollo 15* was confined to a strip within 30° of the equator, and for *Apollo 16*, 12° . (Aristarchus was covered by *Apollo 15* but not *Apollo 16*; neither over Plato). These detectors were sensitive to the decay of ^{222}Rn (half-life of 3.8 days), its daughter ^{218}Po (3 m), half of which will be forced back into the regolith from its recoil from ^{222}Rn gas decay and half lost to space, within the ^{222}Rn migration radius of a few hundred kilometers, and their product ^{210}Po (21 yr, effectively due to the decay of ^{210}Pb). *Lunar Prospector* likewise detected a ^{210}Po mare edge correlation, and two episodic ^{222}Rn releases.

The *Apollo 15* and *Lunar Prospector* alpha-particle spectrometers detected at least four signals from recent episodic activity: at Grimaldi, Kepler, and twice from Aristarchus (the *Apollo 15* and *Lunar Prospector* events being sufficiently separate in time to be effectively independent despite their positional coincidence). Note that the *Lunar Prospector* signals were time averaged over the mission, and so may indicate more than one event apiece (for Aristarchus and Kepler). It is notable that all are on the near side, location of nearly all maria. If TLPs were exactly correlated with ^{222}Rn , the results shown in Figure 2 and Table 2 would predict

⁵ On the surface the *Apollo 17* mass spectrometer (Hoffman et al. 1973c) recorded a burst (at UT 1973 February 22, 22:30) which included N_2 , NH_3 , and perhaps ethane. The release is thought to contain 10–50 kg of gas and originate from a source 100–300 km from the *Apollo 17* landing site (Criswell & Freeman 1975; transmitting unpublished report by R. Hodges). Hodges et al. (1973b) do not include this event in their sample, however.

that given four uncorrelated events chosen at random, the most probable result would be two events on the Aristarchus plateau, and two events distributed among other features on the list (favoring Plato, except for the fact that it is too far north to have been seen by *Apollo 15* or *16*). This describes exactly what is observed. A simple nonparametric test comparing the distribution of corrected TLP counts versus alpha episodic activity, such as a two-sided Kolmogorov-Smirnov test, provides a very low degree of rejection of the null hypothesis, indicating that the sample distributions could easily be identical among these features. Furthermore, the fraction of the lunar surface represented by the sites listed in Table 2 is very small, about 11% even if one includes each entire pixel, and several times smaller if one restricts the area to the feature alone or the region actually spanned by TLP reports for each feature. Despite this, all four alpha episodes land within this area. The episodic alpha-particle releases are extensive in area roughly on the scale of a pixel, but they can be centroided better than this. Given the state of the data set, the author will not attempt to compute a realistic correlation coefficient for the alpha versus TLP distributions, but it seems very unlikely that these coincidences are random, at roughly the 10^{-4} probability level. The orbit of *Lunar Prospector* was polar, while that of *Apollo 15* was inclined 26° to the equator (extending to 30° in sensitivity domain for alpha particles given the elevation of the spacecraft's orbit). *Apollo 15* covers 67% of the area of *Lunar Prospector*, but 73% of the TLP sites in Table 2, and 77% of the TLP counts (54% not counting Aristarchus). These fractional differences are not sufficient to change significantly $P \lesssim 10^{-4}$ for random radon/TLP coincidence. If one considers that the four ^{222}Rn events distribute in a manner very similar to the TLPs within the list of sites with detections, the random probability is even lower.

Lower level TLP activity seems to correlate with mare/highland edges, as does the long-term signal for leakage of gas, for which ^{210}Po represents a proxy (see the Appendix). The TLP/mare boundary correlation is very strong, while the ^{210}Po signal is limited by poor statistics to $P \lesssim 10^{-4}$ of being nonrandom. Nonetheless, this provides an independent statistical indication, separate from the ^{220}Rn result, that there is a correlation between TLP activity and radon outgassing, even over long timescales.

If the TLP/ ^{222}Rn correlation is one-to-one, we can use the alpha-particle data to estimate TLP event rates (without knowing how visible these ^{222}Rn events would be). The Apollo and *Lunar Prospector* alpha-particle spectrometers were in orbit for a total of 293 days, compared to ~ 10 days in which an outgassing event might remain within 10 times of full detectability. During the ^{222}Rn event time, the Apollo instruments would pass overhead at least once, but *Apollo 15* and *16* covered only about 45% and 25% of the surface, respectively. For *Lunar Prospector*, on a polar orbit, all points were covered, but roughly 1/3 of the time. This implies that an instrument covering the entire Moon 100% of the time might expect to detect about one every 24 days. Assuming for the sake of simplicity that each of these produce a TLP, and TLPs are only near-side phenomena (due to the far-side paucity of maria), observers should see about one per month at full observing duty cycle.

Since Aristarchus was the site of ^{222}Rn episodes in both *Apollo 15* and *Lunar Prospector* samples, the connection to this most frequent site of TLPs has been noted (Gorenstein & Bjorkholm 1973; Lawson et al. 2005). Uncertainty remained heretofore as to whether this was due to an effect of the extreme selection biases present in the TLP catalogs, but this doubt is diminished for two reasons: (1) the TLP signal discussed above depends entirely on pre-*Apollo 15* TLP sightings, and the alpha

spectrometer surveys were highly unbiased, so there is no observer-based causal link between the data sets; and (2) the fact that as fair as possible treatments of the optical TLP selection effects such as above causes the optical/ ^{222}Rn correlation to become even more evident is a strong indication of their reality and association with outgassing. This paper represents the first time this correlation has been demonstrated statistically. In addition to this, a nearly equally strong correspondence between weaker TLP sites and the long-term ^{210}Po enhancement both tied to the mare/highland boundary provides nearly independent and strong support to the tie-in of TLPs and outgassing.

4. LUNAR SEISMIC DATA AND A DISCUSSION

At the outset, the ALSEP seismic record offers fascinating but confusing insight into the physical nature of TLPs, in that it provides a third spatial dimension and enough information for considering physical mechanisms, and appears to point to at least two. I postpone most discussion of local physical mechanisms (such as changes in albedo during explosive outgassing and coronal discharge) to Paper II, but will touch on possibilities here for explaining the TLP spatial distribution.

Why is gas leaking out of the Moon, preferentially at the mare edges (and around Aristarchus, a recent impact on an elevated region among maria)? The maria/highland boundary signifies several additional geophysical and mineralogical transitions: the change in albedo and UV/IR and UV/optical properties already mentioned—which is tied to composition; an apparent correlation with rille structures from lava flows draining into mare basins, presumably (Whittaker 1972); and even changes in electrical conductivity properties presumably related to deep basalt concentrations and differing structure and cooling due to the ancient presence of lava (Vanyan et al. 1979). The cooling of the maria and highlands were very different (Reindler & Arkani-Hamed 2001), which might lead to a situation in which mascons that tend to underlie the maria that were supported at early times might come to strain the surrounding material as the maria cool. Since the highlands are heavily fractured, while the maria are more “annealed,” the mare/highland boundary might also be the location where basalt-entrained gas might most easily escape.

There are several possibilities plausibly related to TLPs. First and most simply, the mare/highland interface is the one place where the fractured structure of the highlands interacts stratigraphically with more structurally sound mare basalts. This leads to compositional boundaries and fractures in highlands materials acting as channels to the surface for trapped gas related to mare emplacement. In the case of Aristarchus, the pervasive volcanic conduits that fed the materials that created the plateau act as channels for residual gases. A second idea is that ^{40}Ar might derive from high KREEP minerals since buried by mare basalt, and that the quickest way for this gas to escape is via subsurface migration in cracks below the maria, reaching the surface concentrated at mare edges. In this picture outgassing is potentially driven by purely radiogenic production, not requiring recent volcanism. This idea is troubled by the complex nature of igneous highland rock, which presumably underlie the maria, that in some cases are high in KREEP composition, but in many cases KREEP-poor (Simon & Papike 1985). It is uncertain which rock underlies the maria in question. Also, this picture would presumably indicate large amounts of outgassing in the highlands far from mare edges.

Hodges (1977) argues that ^{40}Ar arises many hundreds of kilometers deep below the surface, with the outgassed ^{40}Ar rate amounting to 3 tons yr^{-1} , about 6% of the total internal radiogenic production. (This will be higher if a significant fraction is ionized, consistent with SIDE results; Vondrak et al. 1974.) Runcorn

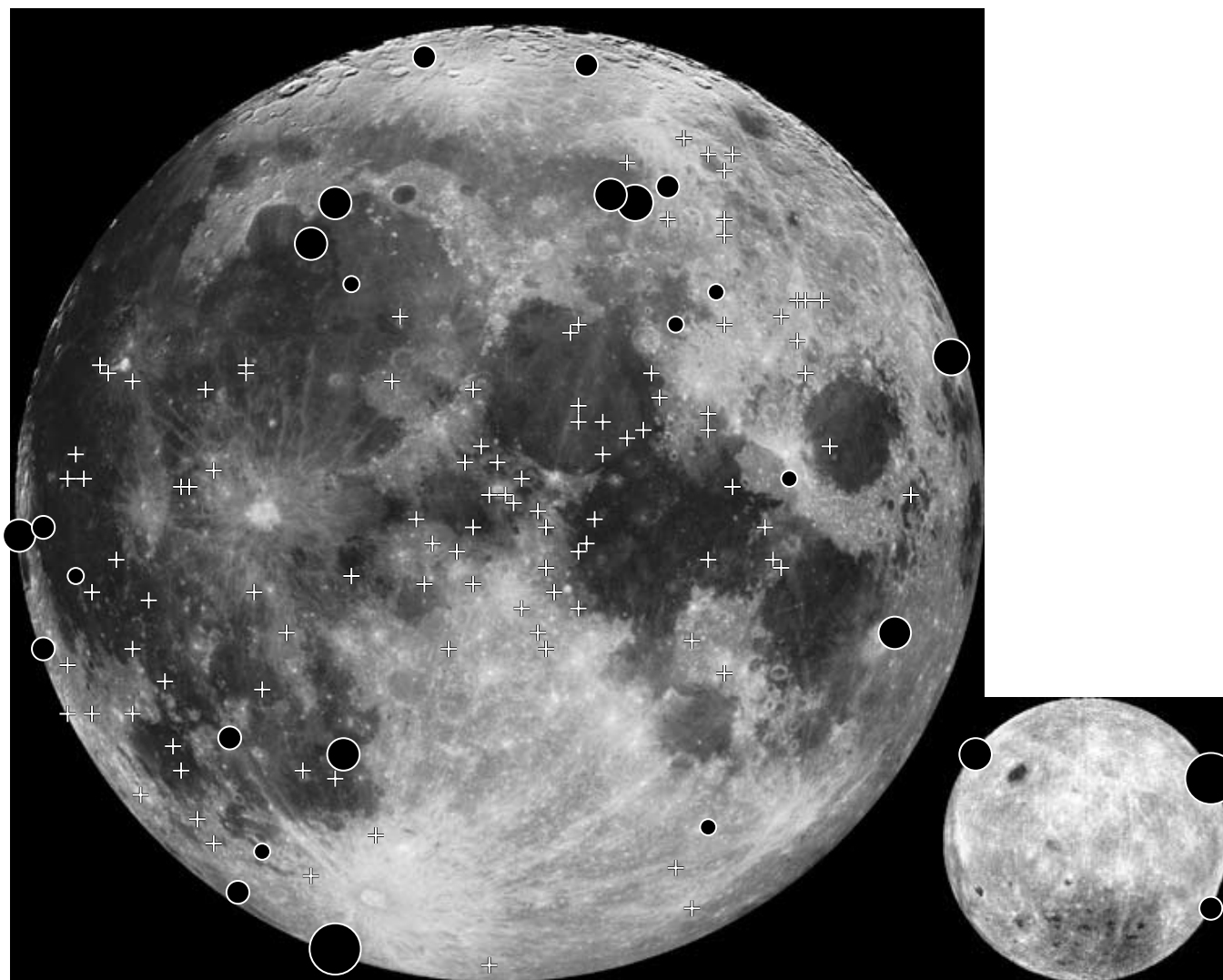


FIG. 3.—Distribution of shallow moonquakes from Nakamura et al. (1979), plotted with circles indicating magnitude (from 0.7 to 3.2 on the high-frequency teleseismic [HFT] scale, with magnitudes ~ 1.0 less than their Richter magnitude; Nakamura et al. 1979). Note the complete absence of a signal from the Aristarchus plateau. The three moonquake locations invisible from Earth are shown by similar symbols on the smaller far-side inset. Most of these and the near-side quakes cluster near edges of maria. The larger sample of deep moonquakes (Nakamura 2005; positions indicated by plus signs, typically accurate to $\sim 7^\circ$) is even more obviously correlated with mare edges. (Photo credit: NASA)

(1974) proposes a model wherein episodic lava effusion can lead to the production of mare mascons in layers denser than a single basalt mass, and that cracks caused by the resulting strain of support can surround the maria and extend through the lithosphere. These can lead to moonquakes and also channels by which gas can escape perhaps to produce TLPs (Friesen 1975; Runcorn 1977). This is supported by the (weak) correlation of TLPs with maximal tidal stress (Middlehurst 1977b).

To study this I look at the compilation of shallow moonquakes (Nakamura et al. 1979) from the ALSEP seismograph array (concentrated on the equatorial near side) and plot their locations (Fig. 3). With only 26 well-localized points, the distribution at first appears random, excepting an overwhelming tendency for events to congregate on the near side (with the greatest angular distance away from Earth being only 11° onto the far side). This is largely just a sensitivity issue. Visual inspection of Figure 3 indicates a tendency for these to favor the maria and even their edges, as Nakamura et al. point out. Again, I will calculate later a mare-edge correlational significance, which depends somewhat arbitrarily on issues discussed in § 2, but for now I take

at face value Nakamura et al.'s statement, which appears secure at the 99.9% level based on the same mare/highland curve drawn in § 2. (See the Appendix.)

Even though the entire sample of shallow moonquake loci is only 26 events over 8 years, one notes the total absence of the Aristarchus plateau from the signal; either it was quiescent during this time, or gas leaks through its cracks without being stimulated by strong moonquakes. Given that this plateau contributes 61% of reports in Figure 2, the spatial distribution of shallow moonquakes differs from this at the level of $\sim 4 \times 10^{-8}$ probability of being random. It may be that the massive impact which occurred at Aristarchus only ~ 450 Myr ago has made the process of gas finding fractures to the surface easier; the same might be said of Tycho, Copernicus, and Kepler, the most prominent, recent, near-side impacts,⁶ none of them on the mare/highland interface but

⁶ The age of Aristarchus is quoted variously as 450 ± 50 Myr (Zisk et al. 1977) and 155 ± 25 Myr (König et al. 1977), compared to Copernicus: 900 Myr (Silver 1971), Tycho: 96 Myr (König et al. 1977; Arvidson et al. 1976), and Kepler: 785 ± 160 Myr (König et al. 1977) and 75 ± 25 Myr (Basilevsky et al. 1977).

nonetheless prime TLP sites that survive the robustness sieve, and with Kepler being a site of detected ^{222}Rn outgassing. This idea is perhaps borne out by the distribution of TLP report locations near Aristarchus, which while not sampled uniformly, nonetheless seems to show a concentration centered around the Aristarchus impact, rather than the whole plateau. (Of the 40 events near Aristarchus localized to within about 10 km, 11 are contained within the 1500 km² of the crater itself, and all are within the southwesternmost 10⁴ km² of the plateau, which totals about 4×10^4 km² in area.) There are no good shallow moonquake matches with any particular TLP sites, beyond the mare edge tendency. (None of the total of 28 moonquakes, localized or not, land closer than 1.5 days to a TLP report:⁷ on 1972 September 16–17 being the closest—not statistically significant.) On the other hand, the rate of moonquakes is very similar to our estimate for mare/highland boundary TLPs, which may not be totally a coincidence.

Somewhat paradoxically, deep moonquakes (Nakamura 2005), which are usually thought to occur at depths (500–1500 km) unassociated with mare basalt plains, e.g., Bulow et al. (2006), are evidently correlated with mare edges as well. This is even a stronger result than for shallow quakes. There are only two (or three) deep moonquakes near Aristarchus, out of a total sample of 98; again the recent impacts Aristarchus, Tycho, Copernicus, and Kepler are not sites of major deep moonquake activity, while they are the sites of TLP reports and ^{222}Rn outgassing. The correlation between the TLP reports shown in Figure 1 (or Fig. 2) and deep moonquakes in Figure 3 is amazing, but there are limits to it: as well as fresh impacts, the correlation around to Plato is diffuse at best, spread over hundreds of kilometers, and includes shallow events.

Moonquakes seem to be correlated with TLPs and presumably outgassing in terms of the large-scale mare/highland boundary pattern, but not on a finer scale (in space or time). The two classes of events appear to be associated, but not directly correlated in detail in a way indicating a prompt causal sequence. A correlation does not guarantee a physical relation. We will ask in Paper II whether this apparent smearing of the correlation might be due to time delay or spatial dislocation, subsurface. The presence of shallow moonquakes and outgassing events on the mare edges may be a sign of the settling of mare basalt plains, as above. This can be studied further by the examination of concentric fault or arcuate graben structures (Wilhelms et al. 1987: Plate 5), and is consistent with it: these are present nearly exclusively in or within near-side maria, sometimes in nearby highlands, and most well defined around mascons, e.g., Serenitatis, Crisium, Imbrium, Humorum (Konopliv et al. 2001), and also regions such as Grimaldi and Tranquilitatis. They are more diffuse but common along western and southern Procellarum, but not strongly clustered near Aristarchus. In this case, typical mare plate edges are settling no more than a few tenths of a kilometer over 3 Gyr (Freed et al. 2001; Watters & Konopliv 2001), or a rate under $1 \mu\text{m yr}^{-1}$ around their circumference.

Is this sufficient to release the observed gas? As a simple model for illustration here, consider that the grinding front of this mare slippage, if as long as the curve in Figure 2 ($\sim 10,000$ km), will pulverize $\sim 10^4$ – 10^5 tons yr^{-1} of rock for each 100 km depth of active fault, depending on the details of the slippage face. From Wilson & Head (2003), a reasonable estimate for the entrained gas content might be 10^{-3} by mass. This may liberate

gas in large quantities; in Paper II, we will discuss how much gas is needed to support the observational signatures discussed above, tending toward 10–30 tons yr^{-1} , depending on how many and which species. The way in which this gas reaches the surface, how long it takes, and how much it spreads from its source in the interior (as well as the total amount of gas and what fraction thereof) will be regulated in part by the nature of this grinding and how deeply it extends.

Of course we could also see gas leaking from elsewhere in the maria, not just along the edges, if the settling (and impacts) cause them to fracture (which they almost certainly do). One final calculation is whether the mare-edge signal simply involves the edge, or might involve fractures throughout, as one might suspect. A glance at the Appendix would indicate that the latter case probably dominates for many of the data sets, although curiously perhaps not for deep moonquakes and definitely not for TLPs that have passed the robustness test. A larger data set for both TLPs/outgassing and deep/shallow moonquakes will help elucidate what mechanisms are in play.

What is the cause of TLP reports in major, fresh impacts Tycho, Kepler, and Copernicus? Certainly they cause extended fractures, but their fractured/breccia lens extends down only about 1/3 of the crater diameter (Hanna & Phillips 2003), and the fractures themselves less than the crater diameter (Ahrens et al. 2002).⁸ These barely penetrate the crust, if at all, but do perforate the mare basalt. Alternatively, Buratti et al. (2000) hypothesize that gas may be released by avalanches down these young surfaces, or the outgassing itself may activate mass wasting.

Aristarchus is unique in being about 30 times more active than any one of the other three young craters; it is also the only such crater that arguably lands on the mare/highlands boundary (the Aristarchus plateau being highland-like both in terms of both elevation and composition—although with differences in mafic concentration; McEwen et al. 1994.) Regardless of this issue, we should not overlook the singular nature of the plateau. This region contains the largest density of sinuous rilles (including Vallis Schröteri, the largest on the Moon in many respects), including large numbers of rilles in the Prinz and Montes Harbinger regions, less than about 100 km away. The Aristarchus impact is likely the largest recent source of fracturing in this region, which might be the operative effect in terms of TLPs.

Is the volcanism in this region connected to TLP activity? The Aristarchus plateau and Harbingers are thought by some to have been a major effusion site (Whitford-Stark & Head 1977, 1980; Garry et al. 2007), but the Aristarchus region's eruption history is highly uncertain. The Aristarchus plateau has undergone several generations of effusion, perhaps highland-like, along with mare, feldspathic, and pyroclastic (the largest exposed pyroclastic lunar deposit; Gaddis et al. 2003), including at least two outflow episodes in Vallis Schröteri itself. It sits near the center of Procellarum KREEP terrane, which according to one hypothesis is intimately connected to deep fracturing caused by an oblique impact which formed the South Pole–Aitken basin on the other side of the Moon (Schultz 2007; Schultz & Crawford 2008). Fractures associated with less catastrophic scenarios for flooding Procellarum are also described by Raitala (1980).

The further study of outgassing and the gas composition might offer many insights into the lunar interior and evolution. For instance, the fact that we see gas derived from heavier elements like uranium bespeaks only partial differentiation of the interior, which might be probed additionally by understanding the behavior of

⁷ Cameron (1991) mentions the observation of the temporal coincidence of a large moonquake and a surface water outgassing event, but this appears to have not entered the refereed literature.

⁸ Diameters—Aristarchus: 42 km; Copernicus: 93 km; Kepler: 32 km; Tycho: 85 km.

very light volatiles, a topic requiring much future work regarding TLPs.

5. SUMMARY AND CONCLUSIONS

In this paper, I study and cross-correlate various transient effects occurring on the Moon: radon outgassing, moonquakes, and optical transients. The latter are somewhat problematic because they are the most heterogeneously surveyed. At the same time, this TLP database is much larger, offering the possibility that we might remove the effects of observer selection bias and false reports. This is worthwhile, because lunar outgassing, whether tied to TLPs or not, would be a rare event, and the combined observational survey power of human observers since the invention of the astronomical telescope would be by far the most potent way to study these events if they are optically active. While in the near future, robotic telescopes will supplant this database (see Crofts et al. 2008), it is fortunate that I can produce consistent signals from these data with a variety of robust sieves probing the structure of the database in various ways.

The TLP data set is fraught with selection effects and almost certainly at least some false reports, for which explicit correction is problematic. Nonetheless, the striking spatial correspondence between the distributions of ^{222}Rn episodic release and a sample of TLPs once they are culled of the more obvious selection biases and bad data is strong evidence that lunar outgassing is an important contributor to TLPs, with a probability at the 99.99% level or greater. Since there is little evidence in the TLP database and literature of a hysteria signal before 1956 which might be due to inexperienced or overenthusiastic observers significantly polluting the sample with false reports, the most likely systematic effect that might remain is over-attention to certain features by observers not seeking TLPs. However, this cannot explain the geographical distribution of reports. This is because the TLPs are confined to the same very small area as ^{222}Rn activity (hence they are almost certainly related), but TLPs are also highly concentrated on Aristarchus (as may be ^{222}Rn). If the preponderance of Aristarchus reports were due to an observer selection bias only, the implied amount of outgassing in the rest of the TLP region would be at least 2 orders of magnitude greater than in Aristarchus alone (and more than 3 orders of magnitude if extended to the entire near side). As well as seeming increasingly implausible in terms of observer behavior, this selection bias hypothesis would violate these physical constraints (the number of ^{222}Rn episodes detected being four, not a few hundred or several thousand). At least as it applies to Aristarchus, and presumably the rest of the sample, much of the geographical structure must be due to real variation in TLP rates near the lunar surface, not selection biases.

The related, but independent, correlation between lower level TLP sites and ^{210}Po concentration is nearly as strong, and statistically (although not physically) independent, indicating long-term as well as episodic correlation between ^{222}Rn and TLPs. The

^{222}Rn signal is almost certainly due to outgassing, because none of the known effects associated with the mare/highlands interface listed in § 4 would enhance ^{238}U and therefore ^{222}Rn (and therefore ^{210}Po). The radon must be transported to these regions, presumably mixed with other gas, presumably through subsurface cracks. The same applies to sites such as Aristarchus. There may be other important mechanisms, but the evidence above indicates that gas leaking from the Moon somehow changes the surface appearance in the optical at least for limited periods of time. These events appear to occur around Aristarchus and perhaps Plato, Grimaldi, and recent impact craters, and may well occur at lower rates in a broad distribution of locations. TLPs can be used as a probe of lunar outgassing.

It appears that gas may leak out of the Moon for two reasons: because of the sagging of the mare basalt, and some other mechanism that directs gas out of impact fractures but does not produce detectable moonquakes. Both may be in play at the Aristarchus plateau and the latter at Kepler, Tycho, and Copernicus, all recent, major impacts there and elsewhere. Surprisingly, there is an amazing correlation between the locus of TLPs not including massive, fresh impact craters, and the distribution of deep moonquakes. The production of gas, and perhaps how this differs between these two kinds of sites, has the potential of becoming a new way to dissect the lunar interior structure and composition.

There may be a connection of TLP activity near Aristarchus to the massive eruptions on the Aristarchus plateau and within about 100 km. This outgassing might be a useful probe of this activity, possibly providing a residual mode of sampling the lunar interior.

In Paper II we discuss the likely implications and possible ways to enlarge our understanding of the connection between TLPs and lunar outgassing. We discuss reasonable, simple models that help us understand how gas might leak from the Moon and how that may produce TLPs. I also propose several simple and powerful techniques which might be exploited to learn about the internal structure, composition, and evolution of the Moon employing experiments involving observations from Earth and from the vicinity of the Moon, and how these might relate to human activity there.

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APPENDIX

CALCULATIONS OF PROXIMITY TO THE MARE/HIGHLANDS INTERFACE

As alluded to in the main text, the correlations of different samples with the edges of the maria is an example of a Mandelbrot “coast of Britain” problem (Mandelbrot 1983), and is in particular sensitive to the smoothing scale, which we will see below is a severe consideration in the case of the Aristarchus plateau. I have drawn a mare/highland boundary “by hand” aided by *Clementine* albedo and UV/visible flux maps, as shown in Figure 2. Compared to the locus several point distributions are correlated, and the probability is calculated in two fashions as to the probability of this correlation occurring at random: (1) measure the mean separation d between a given point in the sample distribution to the nearest segment of mare/highland boundary, divide this by mean separation m for a completely uniform distribution of points distributed over the lunar surface, then raise this ratio $R = d/m$ (always less than 1) to the exponent equal to the number of points n , yielding a random probability $P = R^n$. This depends on the approximation that the points are close

compared to the size of the dominant structural scale in the boundary, and hence is one-dimensional. (The alternative, that the points are far away compared to the size of boundary regions, has two-dimensional scaling, hence $P = R^{2n}$, which is an even smaller probability). This prescription is an approximation to a likelihood estimator where $P = \prod_{i=1}^n d_i/m$, where d_i is the distance from the boundary for each point.

Alternatively, (2) I must consider the change in P if the maximum d value is removed (which measures the sensitivity to more such values), and consider this as a 1σ fluctuation in a Gaussian distribution. This is usually the larger of the two probability estimates for the chances of the result being random, and how much it would change the mean for the typical point to be removed from the distribution. I cannot state this explicitly and concisely here, since it depends on the details of the distance distribution, but in all but two cases (F and H, below), this is the larger of the two probabilities.

The several cases of mean closest separations versus the mare/boundary I compute are as follows:

A. *Uniform distribution over near side.*—Mean separation $m_A = 7.9^\circ$ (as measured in a great circle across the lunar surface), which I will use to normalize most results below.

B. *Uniform distribution over both sides.*—Mean separation $m_B = 12.8^\circ$, which reflects the much smaller number of maria on the far side. This will be used in some cases to normalize the moonquake values.

C. *Uniform distribution over maria.*—Mean separation $m_C = 5.4^\circ$, can be used to establish if the correlation is with the edge of the maria versus the entire mare area.

D. *Features in Table 1, weighted “raw” TLP count, uncorrected by robustness filter (and dominated by Aristarchus).*— $n = 412$, $m_D = 1.5^\circ$, much smaller than m_A , leading to a vanishing probability (1) above ($P_1 \approx 10^{-292}$), but a probability (2) corresponding to 25.7σ : $P_2 \approx 10^{-142}$, both ridiculously small and certainly overwhelmed by other effects not treated here. While one might suspect that TLPs cluster around the maria/highlands boundary as the result of a false signal produced by the contrast between the two surface brightnesses exacerbated by seeing effects, the results here and in (E) suggest it is not the latter. The typical distance from the maria/highlands boundary is 47 km, or $\sim 26''$ as seen from Earth, placing the great majority of events beyond the range of seeing effects. A bias attracting observers to maria/highlands boundaries and increasing the probability of detecting TLPs nearby might be considered, but only if the intrinsic TLPs is elevated in nonboundary locations.

E. *Features in Table 2, weighted by robust TLP count.*— $m_E = 1.1^\circ$, $P_2 \approx 7 \times 10^{-6}$, also depending heavily on whether the Aristarchus plateau is counted as highland area. (It has a partially consistent multispectral mineral signal.)

F. *Features in Table 2, unweighted.*— $n = 20$, $m_F = 5.5^\circ$, $P_1 \approx 6 \times 10^{-4}$ is less sensitive to the Aristarchus plateau condition, but effectively reduces n , so gives results only slightly weaker than (E).

G. *Features in Table 1 unrepresented in Table 2, weighted by raw count.*— $n = 130$, $m_G = 3.0^\circ$, $P_1 \approx 10^{-55}$ used to test if residual correlation appears in the nonrobust sample, which it obviously does, indicating some real tendency of the remaining sample to cluster around the mare/highland interface.

H. *Shallow moonquakes, both hemispheres.*— $n = 26$, $m_H = 6.2^\circ$, $P_1 \approx 10^{-8}$, should be compared to m_B and m_C , except for possible shadowing at the ALSEP sites of some far-side events due to a small molten core.

I. *Shallow moonquakes, near side only.*— $m_I = 5.3^\circ$, $P_2 \approx 2 \times 10^{-4}$, but only three events need be dropped.

J. *Deep moonquakes, near side only.*— $n = 98$, $m_J = 5.7^\circ$, $P_2 \approx 10^{-14}$, which recovers the obvious visual impression that deep quake loci follow the mare edges. Note that the typical nearest edge distance is comparable to the median one-dimensional positional error of 4.7° (avoiding the few anomalously large values in the catalog), so the correlation may in reality be tighter.

I also study the distribution of ^{210}Po from *Lunar Prospector* (Lawson et al. 2005). In their paper Lawson et al. prefer to deal with statistically significant potential sources ($2.2\text{--}3.8\sigma$) rather than moments over the entire ^{210}Po distribution map; hence, I will follow their preference in ignoring low signal-to-noise ratio pixels. Note that there are 360 pixels total in this map, so $\sim 1.5\%$ of detections are actually noise (less than 1 for $n = 13$, below).

K. *All ^{210}Po sources.*— $n = 13$, $m_K = 10.6^\circ$, $P_2 \approx 6.3 \times 10^{-5}$. ($P_1 \approx 0.088$ is a problematic overestimate given the size of spatial bins in the ^{210}Po map of Lawson et al. [2005]. Correcting for this gives $m_K \approx 6.1^\circ$, and hence $P_1 \approx 6.5 \times 10^{-5}$.)

L. *^{210}Po sources, $> 3\sigma$ detections.*— $n = 6$, $m_L = 10.2^\circ$, $P_2 \approx 0.028$.

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