# TRANSIENT LUNAR PHENOMENA: REGULARITY AND REALITY

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## ABSTRACT

Transient lunar phenomena (TLPs) have been reported for centuries, but their nature is largely unsettled, and even their existence as a coherent phenomenon is controversial. Nonetheless, TLP data show regularities in the observations; a key question is whether this structure is imposed by processes tied to the lunar surface, or by terrestrial atmospheric or human observer effects. I interrogate an extensive catalog of TLPs to gauge how human factors determine the distribution of TLP reports. The sample is grouped according to variables which should produce differing results if determining factors involve humans, and not reflecting phenomena tied to the lunar surface. Features dependent on human factors can then be excluded. Regardless of how the sample is split, the results are similar: ∼50% of reports originate from near Aristarchus, ∼16% from Plato, ∼6% from recent, major impacts (Copernicus, Kepler, Tycho, and Aristarchus), plus several at Grimaldi. Mare Crisium produces a robust signal in some cases (however, Crisium is too large for a "feature" as defined). TLP count consistency for these features indicates that ∼80% of these may be real. Some commonly reported sites disappear from the robust averages, including Alphonsus, Ross D, and Gassendi. These reports begin almost exclusively after 1955, when TLPs became widely known and many more (and inexperienced) observers searched for TLPs. In a companion paper, we compare the spatial distribution of robust TLP sites to transient outgassing (seen by *Apollo* and *Lunar Prospector* instruments). To a high confidence, robust TLP sites and those of lunar outgassing correlate strongly, further arguing for the reality of TLPs.

*Key words:* catalogs – methods: statistical – Moon

*Online-only material:* color figure

## 1. INTRODUCTION

Transient Lunar Phenomena (TLPs, called LTPs by some authors), as we describe them, are seen at optical wavelengths, typically during visually observations through a telescope (sometimes photographically, discussed below). There is no commonly accepted physical explanation for TLPs, and some authors even question if they are due to processes local to the Moon. Cameron (1972) divides TLPs (from a catalog of 771 reported events) into four categories: "brightenings": white or color-neutral increases in surface brightness; "reddish": red, orange, or brown color changes with or without brightening; "bluish": green, blue, or violet color changes with or without brightening; and "gaseous": obscurations, misty, or darkening changes in surface appearance. Nearly all TLPs are highly localized, usually to a radius much less than 100 km, often as unresolved points (corresponding to roughly 1 km or less).[1]

Several kinds of experiments on *Apollo* lunar missions, both orbiting and on the surface, as well as on *Lunar Prospector*, were designed to detect and identify gasses in the tenuous lunar atmosphere, both ions and neutral species, plus decay products from associated 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. (We analyze these in Crotts 2008: "Paper I.") One key finding that I will use below is the strong geographical correlation of TLP activity to episodic lunar outgassing of $^{222}$Rn, as well as to $^{222}$Rn's decay product, Po$^{210}$. Both of these are particularly strong for Aristarchus and vicinity.

On the timescale of the next decade, numerous spacecraft and 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 upon them rapidly to exploit our upcoming opportunity to explore the Moon in its still pristine state and perhaps even exploit these still poorly understood resources. We would like to evaluate if TLPs might be elevated into a tool which can be used to study other events on the Moon, including outgassing, and thereby do so from the Earth, before the return to the Moon of large spacecraft and their human crews. If TLPs are real, we can study them using modern technology without depending on human event selection, rather via a robotic imaging monitor that will be much more objective and probably more sensitive than historical means (A. P. S. Crotts et al. 2009, in preparation).

## 2. TRANSIENT LUNAR PHENOMENA

### 2.1. The Troublesome Nature of TLP Observations

With the sensitivity of the human eye peering through an optical telescope, the detection of a TLP is evidently a rare event. Heretofore, this has put TLP reporting largely into the category of anecdotal evidence, which in many minds makes them "irreproducible." The harshest critics of the field have likened them to Unidentified Flying Objects (UFOs). This is not to say that rare sightings and anecdotal evidence cannot turn into real phenomena and important science e.g., meteorites, ball lightning, the green flash, and many species of rare and interesting fauna.

The debate as to the reality of TLPs unfortunately has taken place in the unrefereed scientific literature. Additionally, in

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[1] We disregard phenomena involving the whole Moon (e.g., see Spinrad 1964; Sanduleak & Stocke 1965; Verani et al. 2001, and events tied to solar eclipses, or poorly localized).

recent years there have been examples of published, apparently positive evidence that has been later retracted. A positive treatment is found in Cameron (1991). Sheehan & Dobbins (1999) present a condemning case. Also see Haas (2003) and Lena & Cook (2004). In this paper, we intend to give a fair evaluation of this situation, as quantitatively as possible given the state of the data.

Some systematic searches have heretofore yielded few reliable detections; we will raise the question whether these surveys were sufficiently comprehensive to have produced a non-null result. The power of the heterogeneous sample is the much greater coverage over years and centuries compared to in situ spacecraft studies or even programmed Earth-based, telescopic surveys. For now, we will consider the nature of the bulk of these reports, and evaluate their utility in understanding physical phenomena.

One must assume one of the following: either TLPs are in part tied to physical processes local to the vicinity of the lunar surface, or they are "false," either due to human misinterpretation of normal lunar appearance due to physical effects tied to terrestrial phenomena or even the delusion or fabrication of the observer. Given the complexity of the data base, we are considering, one might even consider a combination of all these. The primary task of this work is to determine if TLPs are at least consistently tied to specific sites on the lunar surface, so one can ask if the appearance or physics of these sites might explain TLP.

### 2.2. The TLP Observers

The compilation and cataloging of TLP reports is due largely to the massive efforts of two dedicated investigators, Winifred Cameron (1978; with 1463 events through 1977 May), and Barbara Middlehurst (1977a, primary from the TLP event catalog of Middlehurst et al. 1968, of 579 events up to 1968 October, with another 134 added by Patrick Moore through 1971 May). All but seven of Cameron's were seen after the invention of the astronomical telescope, and virtually all reports after the year 1610 were telescopic (at least 1446 of the 1456, not counting several naked-eye observations by *Apollo* astronauts from lunar orbit).

Most of the naked-eye reports (without telescope) describe bright spots on the daylit or dark side Moon, often seen by several observers, and these seem possibly consistent with particularly bright examples of the kinds of spots seen in profusion with the aid of telescopes. None of these events was reported by observers in widely separated locations, and seem to be recorded only a few times or less per century. (An example: Boston, Massachusetts, the evening of 1668 November 26; several naked-eye observers report a bright, star-like point on the dark side: Middlehurst 1977a, from Josselyn 1675.) An exceptional case is the report from 1178 June 18 by at least five observers in Canterbury, England (Newton 1972; Stubbs 1879), an event which Hartung (1976) speculates might be the impact formation of the young crater Giordano Bruno, as supported by Calame & Mulholland (1978) searching for a source of the anomalous lunar libration, but seriously challenged by Gault & Schultz (1991), Withers (2001), and unpublished work.

The overwhelming majority of TLP reports involve telescopic observations, and most of these were made by amateur astronomers. During the years of the first lunar surface exploration efforts, many sightings were made by mixed teams of professionals and amateurs, detailed in Section 2.4. At times when the Moon has been an attractive target of forefront, ground-based research, some of the most noted and experienced observers have reported TLPs. (Middlehurst 1977a gives a separate summary of this early period of TLP reports.) Reports by noted observers include those by Dominique Cassini (in 1671–1673), Francesco Bianchini (in 1685–1725), Edmond Halley (in 1715), Wilhelm Herschel (six times over 1783–1790), Charles Messier (in 1783), Johann Schröter (in 1784–1792), Johann Bode (in 1788–1792), Heinrich Olbers (in 1821), Franz von Gruithuisen (in 1821–1839), Friedrich von Struve (in 1822), Ernst Tempel (in 1866–1885), Camille Flammarion (in 1867–1906), Etienne Trouvelot (in 1870–1877), George Airy (in 1877, confirmed independently), Edward Barnard (in 1889–1892), William Pickering (in 1891–1912), and more recently Sir Patrick Moore (in 1948–1967 and thereafter), Zdeněk Kopal (in 1963), and Clyde Tombaugh (in 1963).

Several reports by simultaneous but geographically well-separated observers of the same events on the lunar surface are recorded e.g., 1895 May 2, for 12–14 minutes on the floor of crater Plato, Brenner reported a streak of light, while (independently?) Fauth reported bright, parallel bands. Cameron (1991) describes the observations by Greenacre and Barr on 1963 October 30 of several reddish spots that appeared for several minutes in Aristarchus and near Schröter's Valley, and were also seen by other observers. Similar events occurred one month later in the same vicinity. Both cases roughly coincident with local sunrise. *Apollo* astronauts Evans, Schmitt, Mattingly, Aldrin, Collins (and Armstrong?) all reported TLPs from lunar orbit on four occasions. Three of these were rapid flashes that have been hypothesized to result from cosmic rays entering their visual system, but on *Apollo 11*, Aldrin and Collins reported a strange dark side surface appearance during a 1–2 minute period in which ground-based observers saw a similar phenomenon at likely the same location (Cameron 1978). We discuss this singular case in detail in Appendix A, along with the three flashes.

### 2.3. Photographic Evidence

There are at least nine events noted by Cameron (1978) as having been photographed, the earliest from 1953 November 15. Many of these are unpublished, but there are some dramatic exceptions. On 1956 October 26, Alter (1957) took a careful sequence of photographs on Mt. Wilson Observatory 60 inch of the craters Alphonsus and Arzachel, in infrared (Kodak I-N emulsion) and blue-violet (II-O) light, which allow a differential measurement of the imaging properties in time and wavelength between the two craters. There is a perhaps convincing, apparent obscuration of the floor of Alphonsus not seen later in time or in Arzachel, and that is apparent in the violet but not infrared as if some scattering cloud is present. A similar effect in crater Purbach was photographed on 1970 April 14 by Osawa but not published (Cameron 1978). On 1959 January 23, Alter recorded (but never published) a photograph of a bright blue glow on the Aristarchus floor, which then turned white. Two unpublished event photographs (No. 876 and 1145 in Cameron 1978) are claimed to show red spots in craters Aristarchus and Maskelyne, respectively, with the former event apparently confirmed by separate visual observers. Two other unpublished photographs involve brightenings of Aristarchus. More recently Cameron (1991) presents fairly dramatic photographs of a glowing, reddish-gray patch moving on the floor of crater Piticus, as observed by G. Slayton on 1981 September 5. Finally, during a polarimetric program at l'Observatoire de Paris for lunar surface texture analysis, Dollfus (2000) caught on 1992 December 30 a brightening in the center of crater Langrenus, and with it

an associated increase in the degree of polarization. Similar polarimetric changes were recorded on at least two occasions in Aristarchus, but the timescale is unclear (Dzhapiashvili & Ksanfomaliti 1962; Lipsky & Pospergelis 1966). We discuss several probable meteoritic impact photographs in Section 2.5, and will discuss spectroscopic and polarimetric observations in Crotts & Hummels (2007; Paper II, which discusses theoretical implications and follow-up observations based on this paper and Paper I).

### 2.4. Patrols and Systematic TLP Searches

Several programs, primarily by groups of amateur astronomers but sometimes involving professional researchers, have made organized observations of the Moon with the goal of constructing scientifically more useful data sets in attacking the TLP problem. Several of these have been organized by D. Darling and collaborators, often in connection with Association of Lunar and Planetary Observers (ALPO)[2] and now with the British Astronomical Association (BAA).[3] A summary of activities until fairly recently is found at http://www.ltpresearch.org/. (Other groups can be found at http://www.glrgroup.org/.) An informal appraisal of the information from these groups indicates that they patrol for TLPs of order 100 hr yr$^{-1}$. Historically, several larger surveys have been conducted. These are summarized in Appendix A, and appear in Section 3, where we discuss some of these in more detail.

### 2.5. Description and Distribution of TLP Reports

As summarized above, Cameron (1972) splits TLPs into brightenings, red-, and blue-colored events, and dimmings plus obscurations. Of 113 reports in Middlehurst (1977a) involving enhanced brightness in blue and/or violet, 101 of them involve J.C. Bartlett, composing most of his total of 114 reports (between 1949 and 1966), most of those (108) involving Aristarchus. In contrast only nine of 12 total non-Bartlett blue/violet events occur in the same years (during which 47% of all reports occur). We must correct for this somehow, either by rejecting all blue/violet events or all reports by Bartlett; we choose the latter.

#### 2.5.1. Timescale Distribution

Seventy one reports in Middlehurst et al. (1968) include duration estimates interpretable to better than a factor of 2. This is not a statistical sample, but gives some measure of event duration; binned in $\sqrt{10}$ intervals from 60 s to 19000 s (with the longest event being 18000 s and the shortest 60 s) the duration distribution is 60–190 s: 7 reports; 191–600 s: 9; 601–1900 s: 27; 1901–6000 s: 23; more than 6000 s: 5. These effects are sufficiently prolonged to allow reinspection (albeit by the same observer in most cases). Nonetheless, during the observations, internal changes are often seen on rapid timescales (selected from Cameron 1978; Middlehurst et al. 1968: "abrupt flash of red settling immediately to point of red haze," "a series of weak glows; final flash observed at 04h18m," "white obscuration moved 20 mph, decreased in extent, phenomenon repeated," etc.).

If TLPs are caused by impacts, they are caused by phenomena at the lunar surface, but will be largely uncorrelated with lunar location. There are four cases in Middlehurst et al. (1968)

described as sudden, isolated flashes of light, and these are not correlated with meteor showers (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 in 1955.) Suggestions for other mechanisms for short-lived TLPs include piezoelectric discharge (Kolovos et al. 1988, 1992—which also includes an interesting recorded TLP observation).

How does a meteorite impact appear on the surface of the Moon? Several of these events have probably been observed recently (since the Cameron and Middlehurst TLP catalogs), although some have not yet been published. (See Cudnik et al. 2003 for some interesting discussion, Cudnik 2007 for a recent summary, and Hunton et al. 1991 for another lunar impact detection idea.) Five Leonid events were reported by Ortiz et al. (2000), three of them confirmed by simultaneous observers. A patrol using a double-detector coincidence system detected three probable meteorite hits (Anoshkin et al. 1978; also see Arkhipov 1991), and events have been caught by Dunlop (1999), Suggs & Swift (2005), and Suggs et al. (2006). While the latter have not been published, the available data show that meteorite impacts tend to be rapid, with an exponential decay times of about 0.1 s. Other works include Ortiz et al. (2007), Volvach et al. (2005), Chandrasekhar et al. (2003), and Cooke et al. (2007). Multiple observer confirmation of a small Perseid meteorite impact (Yanagisawa et al. 2006) indicates a timescale about three times shorter, whereas the possible photographic record (Stuart 1956) of a large impact on 1953 November 15 (near 5°N, 3°W on the Moon) lasting at most 8 s (emitting electromagnetically $3 \times 10^{18}$ erg s$^{-1}$ and perhaps as massive as $10^{13}$ g: Buratti & Johnson 2003) was at one time thought to have been confirmed by the coincidence of a fresh crater seen by *Clementine* (Buratti & Johnson 2003) but was contradicted by pre-event photographs (Beatty 2003). Some impacts might involve space debris (see Maley 1991; Rast 1991).

We have one unquestionable detection of a "meteorite" hit on the Moon in the form of the spacecraft *SMART-1*'s impact on 2006 September 3. *SMART-1* at the time had a total[4] mass of 280 kg and was moving at 2 km s$^{-1}$. This is the kinetic energy of a typical meteoroid measured in the lunar frame (30–40 km s$^{-1}$) of about 1 kg, several times smaller than what models indicate was required for the Suggs et al. (2006) events above. Indeed, an array of telescopes with optical CCD imagers and diameters up to 1 m observed the impact with negative results (P. Ehrenfreund 2006, private communication). In the near IR, however, the situation was much different: as yet unpublished results (Veillet 2006) from a 10 s exposure using the WIRCam infrared imager on the 3.6 m Canada–France–Hawaii Telescope (CFHT) at the time of impact show a signal so bright that it saturated the detector in a 32 nm band at the 2.122 $\mu$m molecular H$_2$ S(1) 1$\rightarrow$0 transition. The signal detected was at least $3 \times 10^6$ e$^-$ and probably many times more, which corresponds to at least $8 \times 10^{-15}$ erg cm$^{-2}$. From stars in the field beyond the Moon at the same time, one can estimate the seeing at about 1″.5 FWHM, indicating that the flux is probably about five times higher at least (which cannot be fully estimated without careful nonlinearity tests or models), meaning that the energy output in this band was at least about $10^9$ erg, about $2 \times 10^{-7}$ of the

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**Table 1**
Number of TLPs Reported, by Feature

| Raw Report Count | Feature (Latitude, Longitude) |
| --- | --- |
| 122 | Aristarchus (24N 48W) |
| 40 | Plato (51N 09W) |
| 20 | Schroter's Valley (26N 52W) |
| 18 | Alphonsus (13S 03W) |
| 16 | Gassendi (18S 40W) |
| 13 | Ross D (12N 22E) |
| 12 | Mare Crisium (18N 58E) |
| Six each | Cobra Head (24N 48W); Copernicus (10N 20W); Kepler (08N 38W); Posidonius (32N 30E); Tycho (43S 11W) |
| Five each | Eratosthenes (15N 11W); Messier (02N 48E) |
| Four each | Grimaldi (06S 68W); Lichtenberg (32N 68W); Mons Piton (41N 01W); Picard (15N 55E) |
| Three each | Capuanus (34S 26W); Cassini (40N 05E); Eudoxus (44N 16E); Mons Pico (B) (46N 09W); Pitatus (30S 13W); Proclus (16N 47E); Ptolemaeus (09S 02W); Riccioli (03S 74W); Schickard (44S 26E); Theophilus (12S 26E) |
| Two each | 1ʹ3 S. E. of Plato (47N 03W); Alpetragius (16S 05W); Atlas (47N 44E); Bessel (22N 18E); Calippus (39N 11E); Helicon (40N 23W); Herodotus (23N 50W); Littrow (21N 31E); Macrobius (21N 46E); Mare Humorum (24S 39W); Mare Tranquilitaties (08N 28E); Mons La Hire (28N 26W); Montes Alps, S. of (46N 02E); Montes Teneriffe (47N 13W); Pallas (05N 02W); Promontorium Agarum (18N 58E); Promontorium Heraclides (14N 66E); South Pole (90S 00E); Theaetetus (37N 06E); Timocharis (27N 13W) |
| One each | Agrippa (04N 11E); Anaximander (67N 51W); Archimedes (30N 04W); Arzachel (18S 02W); Birt (22S 09W); Carlini (34N 24W); Cavendish (24S 54W); Censorinus (00N 32E); Clavius (58S 14W); Conon (22N 02E); Daniell (35N 31E); Darwin (20S 69W); Dawes (17N 26E); Dionysius (03N 17E); Endymion (54N 56E); Fracastorius (21S 33E); Godin (02N 10E); Hansteen (11S 52W); Hercules (47N 39E); Herschel (06S 02W); Humboldt (27S 80E); Hyginus N (08N 06E); Kant (11S 20E); Kunowsky (03N 32W); Lambert (26N 21W); Langrenus (09S 61E); Leibnitz Mt. (unoffic.: 83S 39W); Manilius (15N 09E); Mare Humorum (24S 39W); Mare Nubium (10S 15W); Mare Serenitatis (28N 18E); Mare Vaporum (13N 03E); Marius (12N 51W); Menelaus (16N 16E); Mersenius (22S 49W); Mont Blanc (45N 00E); Montes Carpatus (15N 25W); Montes Taurus (26N 36E); Peirce A (18N 53E); Philolaus (72N 32W); Plinius (15N 24E); Sabine (01N 20E); Sinus Iridum, S. of (45N 32W); Sulpicius Gallus (20N 12E); Taruntius (06N 46E); Thales (62N 50E); Triesnecker (04N 04E); Vitruvius (18N 31E); Walter (33S 00E) |

**Note.** Not counted: 4 (global lunar changes), 14 ("cusp" events), 43 (events with unknown coordinates).

total energy and probably two orders of magnitude more than the limits that will be derived from the optical nondetections, if as reported. There is also a luminous debris cloud spreading elongatedly starting at ∼1 km s$^{-1}$ (even though the bright impact source was nearly point-like), as evident on the subsequent images, and which likely carried a large fraction of the energy and largely disappeared over 150 s.

The *SMART-1* impact was very atypical of a meteoroid impact, since not only was it much slower but impacted at an angle of only 3° with respect to the horizon. Furthermore, the impactor consisted not only of a spacecraft structure but significant amounts of hydrazine, which probably broke down immediately into atomic and molecular N and H (and perhaps NH$_3$) and charged states thereof, possibly adding considerably to the specific wavelength band chosen for the CFHT detection (but also possibly to Balmer and Paschen lines in the optical and near IR accessible to Si CCDs, and even compounds with regolith material, predominantly O, e.g., near IR/optical Meinel bands of OH). Note as well that the impact at 1.7 km s$^{-1}$ of the 158 kg *Lunar Prospector* into a permanently shadowed polar crater produced no unambiguous detection in the optical or radio (Barker et al. 1999; Berezhnoi et al. 2000). These suggest that further studies of meteoritic impacts on the Moon might benefit from use of an IR camera system.

This is supported by the recent presentation (Svedhem 2006) showing similar results for the impact of the spacecraft *Hiten* near crater Stevinus on the daytime nearside highlands. The spacecraft of mass 143 kg struck at 2.323 km s$^{-1}$ at 48° from vertical, with kinetic energy of $3.9 \times 10^{15}$ erg. The Anglo-Australian Telescope (AAT) was used to observe the impact at 2.16 $\mu$m wavelength and recorded an event fluency corresponding to $6.7 \times 10^{12}$ erg in a 1% wavelength band, appearing 6–16 s after impact. No immediate optical flash was seen and later optical signals (15 minutes after impact) were unclear, and not near the original impact point. Svedhem (2006) likewise concludes that emission from the 1 kg of hydrazine onboard is likely an important part of the infrared source; this may be a key difference between these spacecraft impacts and meteoritic impacts in the infrared.

Regardless of the details of the above, it is clear that the great majority of TLP reports are not impact events. Even if very 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 craters seen in *Clementine* and other data sets cannot sustain such activity.

### 2.5.2. Spatial Distribution

Since meteoritic impact cannot be the cause of transient on the timescales seen in the great majority of TLPs, we can expect that the spatial distribution might be expected to carry detailed information about the TLP mechanisms (if observer selection effects can be removed). How are TLPs localized on the lunar surface? Table 1 is derived from reports listed by Middlehurst et al. (1968), sometimes with additional
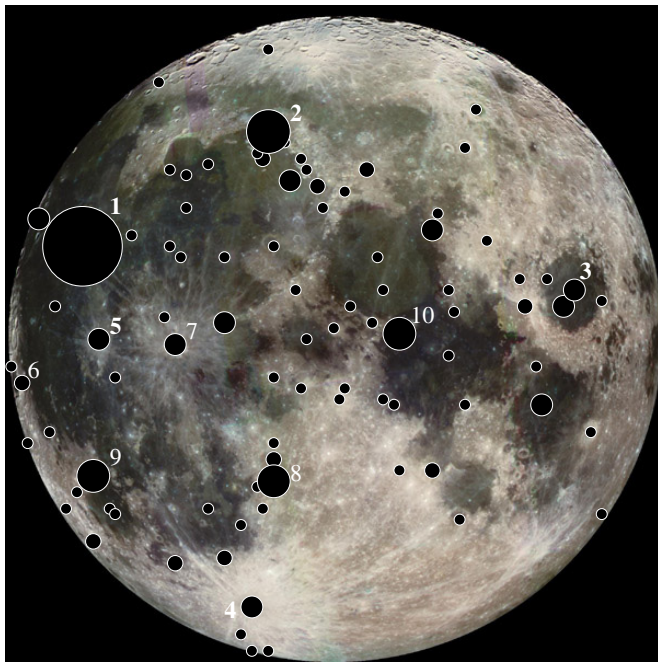
**Figure 1.** Distribution of TLP report loci as catalogued in Middlehurst et al. (1968), with the exception of a minority of cases that are rejected for the reasons detailed in the text. The size of the symbols encodes the number of reports per features, as listed in Table 1. Marked features include: (1) Aristarchus (including Schröter's Valley, Cobra's Head and Herotus), (2) Plato, (3) Mare Crisium, (4) Tycho, (5) Kepler, (6) Grimaldi, (7) Copernicus, (8) Alphonsus, (9) Gassendi, and (10) Ross D. The first seven features on the list survive with their samples nearly intact the various robustness tests imposed, while the last three disappear nearly completely. (Photo credit: NASA)

(A color version of this figure is available in the online journal.)

information (but not additional reports) drawn from Cameron (1978). This information is summarized in Figure 1.

The spatial modulation of the report rate, beyond just the frequency at specific sites, is dominated by the tendency of reports to avoid the deep highlands and to some degree the mid-mare plains, congregating instead near the maria/highland boundary (Cameron 1967, 1972; Middlehurst & Moore 1967; Buratti et al. 2000). Even Aristarchus in the midst of Oceanus Procellarum rests on a giant block (probably from a previous mare basin impact) elevated 2 km above the mare plain. TLP reports favor the western half of the near side (106 in the east longitude, 166 in the west not counting an additional 144 in the west on the Aristarchus Plateau), counter to the usual preference of casual observers to observe earlier in the night, perhaps due to the greater extent of maria (and maria boundaries) on the western side. We will return to this discussion after we deal with at least some aspects of observer selection effects.

### 2.6. Observer Selection Bias and Correlation Effects

To understand the spatial distribution of TLPs, we must deal statistically with the horrendous selection effects introduced by observers, most of whom never intended their reports for a statistical database. This task is not modest; we need to calibrate all of the observations of the Moon made (or not made) by all of the human eyeballs over several centuries. How do we possibly deal with historical and even psychological issues that these effects imply, as well as the physical/mathematical ones? This is the major burden of this paper; nonetheless, there are regularities that we can exploit.

Many works review the history of selenography: there were systematic naked-eye lunar observations starting in Europe in the 1400–1500's, and much earlier in China (but I found no early Chinese reports of TLPs). Observations increased greatly in intensity in the mid 17th century after the invention of the telescope, and early in the next century it was appreciated that libration effects required more observation of the lunar limb. Mapping the Moon increased in detail, with lunar coordinates adopted by the mid-to-late 18th century. From late 1700's to early 1900's, visual mapping of the entire Near Side was active, with some concentration on terminator regions to better sense features' relative elevations. By the early 20th century, visual observation increasingly lost out to photography, suppressing sensitivity to TLPs due to decreased sampling cadence of photographic plates versus the eye, and lost prompt color information. TLP reports by professional astronomers began to die out for this reason, I speculate. This break in TLP reports appears both in the Cameron (1978) and Middlehurst et al. (1968) catalogs; indeed, the 1927–1931 gap divides the Middlehurst catalog at its median report epoch. For the post 1930 half of the reports, 2/3 come after 1955, after which TLPs become commonly known and observing patterns change, as described below. For now I concentrate on the pre-1956 and particularly the pre-1930 period.

For now, rather than studying observer effects for all TLP sites, I concentrate on the Aristarchus Plateau, the most active TLP site by far, including the craters Aristarchus and Herodotus, plus Vallis Schröteri (Schröter's Valley) flowing from "Cobra's Head," together occupying the southeastern ~10,000 km$^2$ of the ~50,000 km$^2$ Plateau. (Vallis Schröteri was once selected as the landing site for *Apollo 18*, later canceled along with *Apollos 19* and *20*.) Aristarchus is among the brightest lunar craters, sometimes *the* brightest, sometimes visible to the unaided eye from Earth, as noted as early as the Tang Dynasty (618–907 A.D./CE; Mayers 1874). It is also one of the freshest: ~500 Myr old, along with Copernicus, Kepler and Tycho (each producing less than 5% of the TLP reports of Aristarchus). The region was once intensely active with volcanic flows and eruptions, and many sinuous rilles remain, likely old lava channels, including the most voluminous on the Moon, Schröter's Valley.

Aristarchus is extreme in maintaining stark contrast to surrounding dark mare, although this is untrue of Vallis Schröteri, Cobra's Head or Herodotus. The Aristarchus region is responsible for ~50% of the visual TLP reports (but also likely receives a large fraction of the observing attention). We see in Paper I that the Aristarchus Plateau is also responsible for undeniably objective transient anomalies associated with lunar outgassing. I will use Aristarchus as a proxy to trace how astronomers have observed TLPs, and whether these observations have influenced each other during different historical periods thereby producing correlated observations, rather than reports that can be counted individually.

I cannot presume to appreciate the observing motivations of astronomers from previous centuries, but prior to 1956 little is written identifying sites e.g., Aristarchus, as targets of particular popular or professional attention in terms of TLPs. Aristarchus received closer scrutiny in 1910 with R. W. Wood indicating that it might contain high concentrations of sulfur, but this did not produce a spate of Aristarchus TLP reports. Indeed, Wood discusses volcanism in the context of Aristarchus (sometimes known as "Wood's Spot"[5]) and seems

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[5] For example, Whitaker (1972), or
http://www.lpod.org/archive/archive/2004/01/LPOD-2004-01-17.htm.

unaware of the number of TLP reports in the vicinity (Wood 1910). Furthermore, Birt (1870) and Whitley (1870) provide a historical overview (1787–1880) 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 call a TLP. A statement is made by Elgers (1884), reviewing Aristarchus, Herodotus and the surrounding plateau. While he does not mention anything 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 and very interesting region which includes these beautiful objects, selenographers can only give an incomplete and unsatisfactory account of it. . . ." By 1913, however, there appears to be some scholarly awareness of reported activity at Aristarchus; witness the summary (Maunder 1913) of reports by Herschel that he "thought he was watching a lunar volcano in eruption," and by Molesworth and Goodacre who "each on more than one occasion, observed what seemed to be a faint bluish mist on the inner slope of the east wall... for a short time. Other selenographers too, on rare occasions, have made observations accordant with these, relating to various regions on the Moon." Maunder balances this with skepticism e.g., "one of the most industrious of the present-day observers of the Moon, M. Philip Fauth, declares that as a student of the Moon for the last 20 years, and as probably one of the few living investigators who have kept in practical touch with the results of selenography, he is bound to express his conviction that no eye has ever seen a physical change in the plastic features of the Moon's surface" (Fauth 1907).

Another telling summary from this period by Pickering (1892) asks "Are there present Active Volcanoes upon the Moon?" and does a quantitative study of candidate volcanoes on the Moon, merging two lists with a total of 67 craters, and then discussing in turn many of the 32 craters common to both lists. Most of these are then eliminated for various reasons, then he starts discussing the rest in turn. Aristarchus is mentioned, but dismissed as nonvolcanic, while some features are taken much more seriously (Bessel, Linné, and Plato). There is *no* discussion of activity that we would call TLPs, only the long timescale or permanent changes. Pickering reported several TLP shortly before and then after this paper—statistically marginal in themselves, 14 in our sample, and 9% of Aristarchus and vicinity—but I see no evidence that these induced a spate of further Aristarchus reports, at least until publication of his book (Pickering 1904a), and probably not even then. This was late in the pre-1930 period, regardless (which we investigate more quantitatively below).

As for the whole sample, I search Aristarchus reports for observers e.g., Bartlett, producing obviously discrepant subsamples. With 150 reports for Aristarchus, Pickering might marginally play this role. His 14 reports from 1891–1898 refer to mists and nebulosity in the Herodotus/Cobra Head vicinity east and north of Aristarchus (Pickering 1900). Personally, I might suspect some of these as erroneous, due Pickering's tendency to overinterpret observations. If these were inconsistent with others' reports and the catalog as a whole, they might be excluded. There are contemporaneous reports e.g., Molesworth and Goodacre in 1895–1897 (Goodacre 1899, 1931) describing mists and darkening nebulosities around Aristarchus. Goodacre and Molesworth were based in Britain and what was then Ceylon, and it is not apparent that they were influenced by Pickering

in the USA. I cannot exclude Pickering's observations because of their inconsistency. Pickering often interpreted changes in the lunar surface in terms of weather and plant life, but his statements on these indicate that he was not motivated ideologically, but by the best observational description e.g., Pickering (1904b, 1916). Pickering's subsample has little effect on the qualitative behavior of the Aristarchus data set, so, with no convincing reason to exclude it, it remains intact.

To investigate correlated observations statistically, I use an abstract/article search engine. A search of the Astrophysics Data System (ADS)[6] Astronomy and Physics archive before 1930, in the title or abstract, for "volcano" and (not or) "aristarchus" produces no matches, whereas "aristarchus" alone produces four matches (not counting the ancient Greek astronomer Aristarchus) and "volcano" alone produces 13 relevant to the Moon. Note that this does not search the body (versus the abstract) of some longer articles, for example Wood (1910), but perhaps satisfactorily reflects the attention that a TLP-like claim might attract. Similarly results are found for "gas," "atmosphere," "eruption," "flash," "cloud," "nebulosity," "mist," "geyser," and "vapor," with no matches for any of these with "aristarchus." These results are summarized in Table 2. Likewise, replacing "aristarchus" with "herodotus" or various terms for Schröter's Valley or Cobra's Head produce no matches with the above terms for potentially TLP-like phenomena, or any articles which described TLPs. There is significant evidence that the majority, perhaps all, pre-1930 selenographers placed no special importance on possible, localized TLP activity, particularly in Aristarchus.[7]

I also search the 1930–1955 database for observer correlations in the literature (Table 3). The only citation involving "change" AND "aristarchus" is Haas (1938) referring to periodic changes appearance of the inner eastern wall of Aristarchus over nine-day intervals, hence not a TLP. The two other Aristarchus citations (Barcroft 1940; Barker 1942) concern the same subject and were evidently written in reaction to Haas (1938). This is the type of statistical correlation between events we would guard against if they involved TLPs.

Over 1930–1955, the 26 citations involving "moon" and "change" include six dealing with lunar appearance changes, all over days or weeks, over many lunar features, not concentrating on any strong TLP sites (except Haas 1938). These include Atlas, Billy, Crüger, Endymion, Eratosthenes, Eudoxus, Furnerius, Grimaldi, Hercules, Linné, Macrobius, Mare Crisium, Messier, Phocylides, Pickering, Pico/Pico B, Plato, Riccioli, Rocca, Snellius, Stevinus, and Theophilus. The only citation involving "moon" and "transient" is irrelevant.

The date 1956 delineates the period after which many TLP reports appear, starting with Alter (1957), then Kozyrev (1959, 1962), inspiring further observations in a cascade through the catalog. This wreaks havoc with our ability to evaluate TLP observational biases, and implies that later reports cannot be considered as isolated entities. Citation correlations after 1955 are shown in Table 4. During 1956–1968, of all 10 references to Aristarchus, seven involving TLPs, all lead back to the Kozyrev reports. Of these seven, five involve TLP-related search terms

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[6] The Smithsonian/NASA Astrophysics Data System: http://www.adsabs.harvard.edu/, which covers many journals into the 19th century and even earlier, e.g., Lind & Maskelyne (1769), or Street et al. (1671).
[7] The careful and quantitative specificity of professional selenographers of these times made this investigation possible. In contrast, consider the description of daytime meteors in Bird (1870): "they sail across the field of view like feather in the wind" would be very difficult to convert into a selection function or error rate.

**Table 2**
TLP-related Terms Correlated with "Aristarchus" and "Moon," Before 1930

| Search Term | Number of Citations | "Moon/Lunar" Cross Citations | "Aristarchus" Cross Citations |
|---|---|---|---|
| "Volcano" | 38 | 14 | 0 |
| 'Gas" | 1194 | 0 | 0 |
| "Atmosphere" | 599 | 22 | 0 |
| "Eruption" | 52 | 1 | 0 |
| "Flash" | 89 | 0 | 0 |
| "Cloud" | 192 | 3 | 0 |
| "Nebulosity" | 45 | 0 | 0 |
| "Mist" | 2 | 1 | 0 |
| "Geyser" | 3 | 0 | 0 |
| "Vapor" | 514 | 0 | 0 |
| "Transient" | 9 | 0 | 0 |
| "Change" | 893 | 38 | 0 |
| No First Term | ⋯ | 2930 | 7 |

**Table 3**
TLP-related Terms Correlated with Terms "Aristarchus" and "Moon," 1930–1955

| Search Term | Number of Citations | "Moon/Lunar" Cross Citations | "Aristarchus" Cross Citations |
|---|---|---|---|
| "Volcano" | 29 | 6 | 0 |
| 'Gas" | 2214 | 3 | 0 |
| "Atmosphere" | 2234 | 47 | 0 |
| "Eruption" | 119 | 2 | 0 |
| "Flash" | 99 | 3 | 0 |
| "Cloud" | 1036 | 9 | 0 |
| "Nebulosity" | 81 | 1 | 0 |
| "Mist" | 5 | 0 | 0 |
| "Geyser" | 1 | 0 | 0 |
| "Vapor" | 698 | 2 | 0 |
| "Transient" | 112 | 1 | 0 |
| "Change" | 2050 | 26 | 1 |
| No First Term | ⋯ | 1124 | 3 |

**Table 4**
TLP-related Terms Correlated with Terms "Aristarchus" and "Moon," after 1955

| Search Term | Number of Citations | "Moon/Lunar" Cross Citations | "Aristarchus" Cross Citations |
|---|---|---|---|
| "Volcano" | 196 | 54 | 4 |
| "Gas" | 5881 | 24 | 1 |
| "Atmosphere" | 4797 | 47 | 0 |
| "Eruption" | 120 | 7 | 1 |
| "Flash" | 262 | 1 | 0 |
| "Cloud" | 1850 | 20 | 0 |
| "Nebulosity" | 80 | 1 | 0 |
| "Mist" | 5 | 0 | 0 |
| "Geyser" | 5 | 0 | 0 |
| "Vapor" | 1154 | 8 | 0 |
| "Transient" | 458 | 15 | 3 |
| "Change" | 4836 | 61 | 0 |
| No First Term | ⋯ | 2440 | 10 |

that we have used. During this period TLPs become firmly fixed in peoples' minds in connection with particular lunar features such as Aristarchus.

These papers (or lack thereof) are an "integral constraint" on the importance of observer preconception of TLPs as an important factor (for Aristarchus, at least) in determining the observation selection function; also, before 1956 they betray no "hysteria signal" of false reports due to special attention. Before 1956 TLP reports can be considered single, largely uncorrelated events, and this partially justifies treating them with Poisson statistics.

This implies that there must be another reason for reports more frequently at Aristarchus, by several orders of magnitude above what the area ratio of $10^4$ km$^2$ to the near side surface of $1.9 \times 10^7$ km$^2$ would indicate. Elgers implies that observers before 1884 (as well as now, perhaps) are drawn to Aristarchus, so selection bias favors this site: the ratio of observing time per area for Aristarchus and the Plateau versus other areas not near the limb is probably more than unity. However, in Paper I we see from transient outgassing detections by alpha particle spectrometers on *Apollo* and *Lunar Prospector* that TLPs are correlated with $^{222}$Rn outburst events. These events are localized to within about 100 km due to limited gas migration over the short (3.8 days) half-life of $^{222}$Rn. Two or more of these events occur at Aristarchus, whereas two are seen on the entire remaining lunar surface. Scaling the Aristarchus rate to the entire surface predicts $1900 \pm 1300$ events over the Moon; obviously more than observed. To the extent that

**Table 5**
Number of TLPs Robust Reports, by Feature

| Robust Report Count | Feature |
| --- | --- |
| 46 | Aristarchus/Schroter's Valley |
| 13 | Plato |
| 3 | Kepler |
| Two each | Alphonsus, Eudoxus, Grimaldi, Mare Crisium, Posidonius |
| One each | Alpetragius, Peak S. of Alps, Bessel, Calippus, Cassini, Carlini, Copernicus, Daniell, Gassendi, Godin, Hercules, Kant, La Hire, Littrow, Manilius, Mare Humorum, Mare Nubium, Messier, E. of Picard, SW of Pico, Proclus, Promontorium Heraclides, Ptolemaus, Riccioli, South Pole, Tycho |

$^{222}$Rn and optical transients are correlated, a selection bias towards Aristarchus cannot with reasonable probability imply that TLPs occur over the entire Moon at the rate reported near Aristarchus (and hence we are not simply being fooled because human observers spend more time looking at the Aristarchus plateau), since this would imply orders of magnitude more $^{222}$Rn outgassing than seen on the Moon. Aristarchus produces a large fraction of all $^{222}$Rn and must be assumed to be intrinsically more prone to TLPs, for some reason other than how often people observe them.

A statement of caveat is needed; the TLP/$^{222}$Rn result is still a statistical correlation, not an established causal relation. While in Paper II we discuss how this might be causal, one might hypothesize ways in which TLPs and $^{222}$Rn might be associated independently to Aristarchus but not necessarily implying the objective reality of TLPs.

### 2.7. Statistically Consistent TLP Spatial Distribution

From the analysis above, TLPs at Aristarchus seem to be uncorrelated reports at least for the period before 1956. For other TLP sites the sample size is too small for a significant test of report correlations; I will simply assume that all events are Poisson. The reader should be aware of this caveat.

I have not addressed how many reports are erroneous, and cannot without more information about the TLP mechanism. What I can address, however, is whether TLP report rates for various features behave in statistically consistent manner. In other words, what fraction of all reports is most justified for a particular lunar feature, and is this fraction robust against changing a particular observer variable? We will choose variables which should be entirely unrelated to the conditions of the lunar surface, but might be tell-tale of other influences, for example: "irrelevant" observer characteristics e.g., where they live, or when they live. If the TLP rate for a lunar feature depends on the location of the observer, this may say more about the observational process than the physics of the Moon. If the TLP rate for a feature depends on the historical period of observation, this may imply changing influences on the observer (or it may indicate simply that certain sites are more active at some time than at other, on historical timescales). Nonetheless, it may be instructive to construct a "robust" map of where on the Moon TLPs are reported to originate.

Such a robust fraction for a feature is constructed by picking an ostensibly random parameter (as it relates to lunar surface behavior), and then grouping TLP reports according to various ranges in this parameter's value. The robust fraction is computed by an average (usually not the mean) according to some robust estimator e.g., the median.

The simplest robust estimate to construct is perhaps the median over historical periods. One-third (137, exactly) of unculled reports occur during the period 1892–1955, with a roughly equal number before (134) and then after (145). The resulting count as a function of feature-labeled "pixel," analogous to Table 1 (except that on average the current values are three times smaller), is given in Table 5. Specifically, we bin the counts seen in Figure 1 into 300 km square "pixels" and take the median count for each pixel from the three epochs. Since each pixel can be labeled with the name of the feature(s) identified by the observers in the reports that filled that pixel, we can list the corrected count for each feature or group of features. Within each pixel, we re-evaluate particular features to see if TLPs from the two samples truly correspond geographically. If TLPs occur in the same named feature (and we 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, we 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 in Table 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 while there may be 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 nearside 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 period (between one day and one sidereal month). My appraisal of the literature is that this is probably a good assumption; there is no evidence above of any campaign or motivation that draws observers to any feature (before 1956) to any feature more at one time than another. Let us explore this further.

To within $1\sigma$ Poisson errors, the contributions from the Aristarchus region and Plato remain the same, at about 47% and 13% of the total. Taken as a group, the large, young impact craters (Copernicus, Kepler, Tycho) compose 5%, consistent with the raw counts. What is highly significant (at about the $4\sigma$ level apiece) is the disappearance of features Alphonsus, Gassendi and Ross D. All of these were very prominent in post-1955 reports, but disappear in the fraction of the robust count by factor of an order of magnitude or more. Alphonsus, in particular, was one of the features that attracted greatest attention following the report of Alter (1957) and Kozyrev. Many of the observers in these latter reports were obviously aware of previous observations, and in many cases were specifically targeting the crater because of this.

Plato is a distinct, flooded crater on the northwestern edge of Mare Imbrium, near mountainous regions such as Montes Alps, and appears very dark in comparison. It can be striking in its long shadows stretching across its face when near the terminator.

**Table 6**
Median Number of TLPs Reported Per Feature, Over Historical Periods Pre-1956

| Median Report Count | Feature(s) |
|---|---|
| 29 | Aristarchus/Schroter's Valley |
| 12 | Plato |
| 5 | Mare Crisium |
| 4 | Tycho |
| 2 | Kepler |
| One each | Alphonsus, Peak S. of Alps, Bessel, Calippus, Cassini, Copernicus, Eudoxus, Gassendi, Godin, Grimaldi, Kant, Lichtenberg, Taurus Mountains, Macrobius, Messier, Picard, Pico, Posidonius, Proclus, Promontorium Heraclides, Ptolemaus, Riccioli, South Pole, Theaetetus |

**Table 7**
Number of TLPs Reported Per Feature, Comparing Pre- and Post-1930 Samples

| Robust Report Count | Feature(s) |
|---|---|
| 66 | Aristarchus/Schroter's Valley |
| 15 | Plato |
| Two each | Grimaldi, Messier |
| One each | Alphonsus, Bessel, Cassini, Copernicus, Gassendi, Kepler, Lichtenberg, Littrow, Mare Humorum, Mare Nubium, Mons Pico, Pallas, Picard, Ptolemaeus, Riccioli, South Pole, Theaetetus, Tycho |

**Table 8**
Median Number of TLPs Reported Per Feature, Over Seasons of the Year

| Median Report Count | Feature (Latitude, Longitude) |
|---|---|
| 25 | Aristarchus/Schroter's Valley |
| 13 | Plato |
| 5 | Mare Crisium |
| Two each | Copernicus, Eratosthenes, Kepler, Tycho |
| One each | Atlas, Bessel, Cassini, Grimaldi, Hansteen, Helicon, Herschel, Humboldt, Hyginus, Kant, La Hire, Lichtenberg, Messier, Picard, Pickering, Pierce A, Pico, Posidonius, Proclus, Promontorium Heraclides, Ptolemaeus, Riccioli |

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 we consider 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 cloud-like appearance.

Mare Crisium varies significantly in strength between this and the raw result, and as we will see, between the different robustness estimates. Since it is actually two "pixels" in diameter, I am unsure that this should even be included as a feature in this analysis.

To illustrate the independence of the results on choice of historical period, we consider other time intervals. For instance, if we exclude the post-1955 period and slice the remaining sample into three intervals (dividing the sample at 1877 and 1930), the median count per 300 km square pixel, labeled by its primary feature, is shown in Table 6.

The values in Table 6 should be multiplied by 4/3 in order to scale to Table 5. There is little statistically significant change between the resulting report counts, despite the complete exclusion of the post-1955 data. Even if post-1955 data are included in a robust (but nonmedian) average, as we present in Table 7 and explain below (and in Paper I), the results are qualitatively similar. Even if pre-1956 data are timesliced not in historical epoch, but time of the year (January–April, May–

August, September–December), which would smooth out any long-term fluctuations, the results are similar.

The two-sample robust estimator (Table 7) is constructed by taking the minimum of the two values in equally sized samples. This is useful in rejecting discrepant positive-going signals in cases where one has only two copies of what should be otherwise identical images or maps, but no good noise model (as is definitely the case here). The fact that it rejects the same features as the all-history median (Table 5) or the pre-1956 median (Table 6) suggests that the signals for Alphonsus, Gassendi, and Ross D might be systematic noise spikes that ride on an otherwise roughly consistent data set for post-1955. The lack of strong disagreement between the seasonal cut (Table 8) and all others (Tables 5–7) might indicate that there are no strong historical episodes of TLP activity for any of the strong features, since taking a timeslice uniformly across the three centuries or more in data (by the seasonal selection) yields the same result as slicing by historical period. The only exception is the tiny interval 1956–1968 in which observational biases are demonstrably different based simply on the correlations in the citation record alone. This explanation for the change in behavior is much easier to accept than a sudden, simultaneous increase in lunar activity at Alphonsus, Gassendi, and Ross D.

Finally, I slice the post-1955 sample in a nontemporal parameter, the location of the observer at the time of the report. There are roughly equal number of reports from three groups: Great Britain, continental western Europe, and the rest of the world (smaller by about 30%, and consisting primarily of the

**Table 9**
Median Number of TLPs Reported Per Feature, Varying Observer Location

| Robust Report Count | Feature(s) |
| --- | --- |
| 37 | Aristarchus/Schroter's Valley |
| 15 | Plato |
| 6 | Mare Crisium |
| 4 | Tycho |
| 2 | Eratosthenes |
| One each | Alphonsus, Atlas, Bessel, Calippus, Cassini, Copernicus, Gassendi, Godin, Grimaldi, Hercules, Kant, Kepler, La Hire, Lichtenberg, Macrobius, SW of Pico, Posidonius, Proclus, Promontorium Heraclides, Ptolemaeus, Riccioli, South Pole, Theaetetus |

**Table 10**
Relative Frequencies of Robust TLP Reports by Feature

| Relative Frequency $\pm 1\sigma$ error | Feature(s) |
| --- | --- |
| $46.7\% \pm 3.3\%$ | Aristarchus/Schroter's Valley |
| $15.6\% \pm 1.9\%$ | Plato |
| $4.1\% \pm 1.0\%$ | Mare Crisium |
| $2.8\% \pm 0.8\%$ | Tycho |
| $2.1\% \pm 0.7\%$ | Kepler |
| $1.6\% \pm 0.6\%$ | Grimaldi |
| $1.4\% \pm 0.6\%$ | Copernicus |
| $6.2\% \pm 1.2\%$ | sum of Tycho, Kepler & Copernicus) |
| $1.1\% \pm 0.5\%$ | Alphonsus, Bessel, Cassini, Messier, Ptolemaus, or Riccioli |
| $0.9\% \pm 0.5\%$ | Eratosthenes, Gassendi, Kant, Lichtenberg, (E. of) Picard, (SW of) Pico (B), Posidonius, Proclus, Promontorium Heraclides, or South Pole |
| $0.7\% \pm 0.4\%$ | Calippus, Eudoxus, Godin, La Hire, or Theaetetus |
| $0.5\% \pm 0.3\%$ | Peak S. of Alps, Atlas, Hercules, Littrow, Macrobius, Mare Humorum, or Mare Nubium |
| $0.2\% \pm 0.2\%$ | Alpetragius, Carlini, Daniell, Hansteen, Helicon, Herschel, Humboldt, Hyginus, Manilius, Pallas, Pickering, Pierce A, or Taurus Mountains |

Americas and some reports in Asia and Russia). The median of these, scaled to the same sample size is given in Table 9. It shows qualitatively similar structure to all of the other robustness tests.

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 the actual physical processes producing TLPs at given sites. At least we 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.

Mare Crisium is the only signal to vary significantly in strength between the different robustness estimates. Since it is actually two "pixels" in diameter, I am unsure that this should even be included as a feature in this analysis.

I think that the results are sufficiently robust, even for Mare Crisium, to allow one to average the relative frequencies in Tables 5–9 for various features, summarized in Table 10. A total of 49 features are listed (in order of decreasing statistical significance, assuming Poisson behavior) in the table; many of these are undoubtedly spurious. Somewhat arbitrarily, we will require that the Poisson probability for a feature's relative frequency excluding the value zero be greater than 48/49, hence the detection be greater than about $2.4\sigma$. Features that are at least this significant are Aristarchus/Schroter's Valley, Plato, Mare Crisium, Tycho, Kepler, Grimaldi, and marginally Copernicus, which together compose 74.3% of the robust signal.

It seems fairly clear that the behavior of major features in the distribution is nearly bimodal. Comparing, for instance the median in Table 5 versus the available total counts, which should be three times larger, on average, the major features

in Table 10 maintain nearly the average fraction of counts (one-third): Aristarchus/Schroter's Valley: 46/150, and Plato: 13/45. For the major, young impacts this is not so clear, for Tycho+Kepler+Copernicus: $(1 + 3 + 1)/(6 + 7 + 6)$, and for Mare Crisium there are 15 total counts, which in consistent in some cases of robust counts and in some cases not, marginally (which reduce anywhere from 0 to 6). The maximum fraction of Grimaldi's counts are maintained: 2/4. In contrast, the fraction for Alphonsus is 2/22, for Ross D: 0/13, and for Gassendi: 1/18. Taken together, this is 72/284, or 76% of the expectation if all counts were consistent except for random fluctuations. One might consider this as evidence that most TLP reports are real (or at least consistent), at least for sites with enough statistics to check.

These results show a surprising amount of regularity in the behavior of the TLP sample, consistent at least with the possibility that many reports are real. The spatial structure, at least, is fairly consistent. Now the question of the TLP mechanism must be addressed. There are hypotheses as to possible nonlunar mechanisms that have been advanced, plus reasons for why we should suspect TLPs in general.

## 3. THE TLP CONTROVERSY

Any scientist should be skeptical of any conclusion based solely upon the existing optical data base of TLP reports. Most of them are anecdotal, not independently verified, and involve no permanently recorded signal that did not pass through the human visual cortex. Many of the observers are not professional, and some are not even very experienced. Undoubtedly some, many, perhaps most of these reports are spurious. Are they all spurious? Is there any truth in these catalogs? It is perhaps insufficient that a few special cases seem well documented. When selected from

a huge data set, from all of the observers looking at the brightest and most spectacular night-time astronomical source, over a time interval of four centuries, seemingly convincing random fluctuations will occur. One might despair that even with the robustness sieve implemented above that an attempt to extract real information from this data set is likely to fail.

Perhaps the most condemning treatment of the TLP observations is Sheehan & Dobbins (1999). This is not a scientific investigation but an essay in a popular magazine, and is effective as such. They propose without quantitative evaluation several arguments that cast doubt on the reality of TLP reports: (1) several well known cases of reported TLPs are suspect: Alter (1957), Kozyrev (1962), Barr and Greenacre (Greenacre 1965), plus associated reports by the same observers; (2) atmospheric refractive dispersion will cause red areas to appear shifted with respect to points brighter than portions of the image around them; (3) the Corralitos Observatory TLP survey reported no positive detections; (4) the reports by Bartlett are spurious; and (5) TLPs are caused by transient optical mixing of bright and dark areas due to bad seeing in front of areas of high source contrast. Nonetheless, experienced observers aware of these criticisms are still reporting TLPs and vouch in writing that these points do not explain their observations. Having laid criticism upon the TLP reports themselves, we consider these and other possible objections with an open and critical eye, in order to understand what may be occurring and whether we should believe it involves phenomena arising near the lunar surface.

As started before regarding point (4), any reasonable test of the Bartlett sample against the larger TLP data base is likely to conclude that they are not both chosen from the same parent distribution. One needs to hypothesize a different mechanism to explain this sample than the one for other TLPs, and this cannot possibly be due to processes local to the Moon. The cases in (1) are statistically insignificant.

The effect in (2) is accurately calculated given the report time, and latitude, longitude and elevation of the observer, to a high degree of accuracy. Sheehan & Dobbins (1999) applies the effects of dispersion to the particular case of Barr and Greenacre (Greenacre 1965), but it is unconvincing since (1) the same candidate event was reported by observers two time zones away, where the airmass was much different, and (2) the scale and direction of the dispersive color separation corresponds only loosely to the reported observations. To elaborate on the second point, at the time of observation (1963 October 30, 01:50 UT at mid-TLP), the Moon was approaching full at 11.9 days age, so that Aristarchus was illuminated with the Sun about $16°$ above the horizon producing some shadows, cast to the WNW in lunar coordinates. From the observer's viewpoint the Moon was at $66°$ zenith distance, with a parallactic angle of $-55°$ dispersing red light (7000 Å) relative to the eye's sensitivity peak ($\sim$5000 Å) $1''.4$ to the ENE in lunar coordinates. This is roughly the direction that would be needed to disperse the illuminated rim of Aristarchus into shadow for red wavelengths, in the location observed (to the SW of the crater). What is not apparent is that a $1''.4$ displacement can produce the extended region described, or the flux enhancement noted as "brilliant."

Does this mechanism explain the production of red TLPs, statistically? There are 26 cases describing red or pink color, not during an eclipse, and for which there is sufficiently accurate data to calculate a useable airmass. The zenith distances for these reports, taken at mid-TLP observation, range from $27°$ to $80°$, with a median of $56°$, producing a dispersive displacement between 5000 Å and 7000 Å of $0''.3$ to $3''.0$, median of $0''.8$

(or slightly less since we do not correct for site elevation). Subarcsecond displacements in the red, as most of these are, seem unlikely to produce an observable effect. Since the Moon never reaches more than $28°.6$ from the celestial equator, and most of these observing sites are far to the north ($+34°$ to $+60°$ latitude, with a heavy concentration to larger values), one would expect few observations at zenith distance under $25°$. There is no particular tendency for red events to favor high airmass. This explanation also has an intrinsic timescale of about 1–3 hr, which is much longer then the reported timescale of at least 70% of TLPs. It is difficult to imagine a consistent source of modulation 10–100 times faster. In their book Sheehan & Dobbins (2001) hypothesize a very rare phenomenon relating to winter atmospheric considerations (that I am not sure I have experienced in thousands of hours of observing, both with CCDs and visually), but there is very little seasonal dependence in the red/pink TLP reports (Jan.: 3, Feb.: 7, Mar.: 5, Apr.: 4, May.: 4, Jun.: 5, Jul.: 6, Aug.: 3, Sep.: 6, Oct.: 9, Nov.: 9, Dec.: 7—almost completely in the northern hemisphere, or suffering from "Bolivian winter" which inverts summer/winter behavior in the north-central Andes). Also, Sheehan & Dobbins argue against a symmetric production by atmospheric dispersion of blue TLPs due to the greater extinction of blue light. B-band flux is diminished only 12% relative to the center of the visual band at unit-air mass in standard atmospheric extinction, whereas the blue end of the human optical range is displaced even more than the red by refraction (by about 20%). In light of this they do not explain why most observers recording a color shift report red TLPs.

This leaves objection No.5: effects of seeing in high contrast source distributions, and No.3: the absence of positive detections in the Corralitos Observatory survey, the largest, probably most objective TLP search. Considering seeing, this depends on the perception by the human visual system which is hard to quantify without extensive psychological/physiological tests, which are beyond the scope of this paper. From my own observational experience, I think that an experienced human observer would not be fooled by such an effect, whereas a novice observer might be (see also Haas 2003). This is particularly worrisome since this effect might be particularly in play at regions of high surface brightness contrast, like the mare/highland interface, or indeed at the crater Aristarchus. (One might even worry that some inexperienced observers, noticing Aristarchus for the first time, might report a TLP; there appear to be a few reports consistent with this.) This does not explain why TLPs do not tend to be seen associated with many small, bright points, usually fresh impact craters, across the otherwise flatter mare visual field. An electronic survey, using CCD or CMOS imaging detectors, could easily make these effects moot, using established analysis techniques to compensate for seeing variations. We discuss this in detail in Paper II.

The Corralitos Observatory TLP survey spent some 8000 hr (10.9 months at full duty cycle) observing, and was capable of covering the whole Moon in 15 minutes (although it is unclear if it always did), hence should have produced some $3 \times 10^4$ whole-Moon epochs. What intrinsic event rate for TLPs should we assume? As stated above, we might infer a rate of about once per month. Given the structure of the distribution of observed TLP timescales, about 30% of the reports in the catalog would be missed. If the Corralitos setup was equally sensitive as the typical TLP observer at large, the absence of TLPs detected by them in the untriggered survey might correspond to a $\sim3\sigma$ negative fluctuation (about 0.02% Poisson—not Gaussian—

random probability) in the expected counts *if* observations were made at 100% efficiency (which is unrealistic).

How sensitive was the Corralitos survey? This is an important question that would have quantitative implications if we knew the flux distribution function for TLPs, which we do not. Still, the Corralitos was probably at least as sensitive as the typical TLP observer and probably more so, so they should access at least the same event rate. The claimed sensitivity of the survey method seems improbably good: better than a 5% change in intensity in a 100 Å band (Dunlap & Hynek 1973), corresponding to 0.5%–1% in a typical broad band characteristic of a photometric optical color such as those employed, which then is converted to a monochromatic, blinking contrast difference which is monitored by the eye. This seems to be several times more sensitive than the threshold for the eye detecting a constant monochromatic contrast, but the intent was apparently to improve this threshold by causing the spot to blink at rate of a few Hz. This may work for short periods of time, but the response of the eye to such a signal fatigues over time in a manner that is most significant at rates of about 12 Hz (Kanai & Kamitani 2003). Hynek et al. (1976) did their work before this effect had been studied scientifically and it is unclear how they might have adjusted their observing procedure to correct for this or perform tests to gauge the importance of such effects. The likely effects of fatigue would need to be evaluated by reconstructing the original setup of the Corralitos display equipment and this is difficult to pursue. In principle the same evaluation should be made of Moon Blink.

Particularly concerning are the TLP reports promptly transmitted to Corralitos Observatory during the TLP patrol to provide confirmation or lack thereof. Cameron (1978) lists 25 events that were apparently negative (four where this is stated explicitly in terms of the data), two of these originating with Bartlett are not included in our analysis, and two (No. 1119 and 1150) where apparently Cameron disagrees with Hynek et al. (1976) and concludes there was a positive confirmation. This fraction of nonconfirmation might lead one to conclude that many TLP reports are not objectively real, at least in the midst of intensive campaigns like those underway when these reports were produced (1966 April–1969 June).

Despite the dedicated and laudable progress made by Cameron, Middlehurst, Moore, Darling and centuries of researchers and observers, the current state of the data set resists application of the scientific method to the problem of transient lunar phenomena. There are striking examples of several well-documented cases where TLPs are confirmed and suggest connection to physical mechanisms, but the strongest evidence is anecdotal and leaves insufficient permanent records to allow the testing and elaboration of hypotheses. Given the transient nature of TLPs and state of available technology heretofore, this outcome was difficult to avoid.

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.

## 4. DISCUSSION, SUMMARY AND CONCLUSIONS

An investigation by Cameron (1967, 1972) and Middlehurst (1977a, 1977b) into correlations with several possible lunar parameters turns up primarily null relations e.g., lunar anomalistic period (time between perigees), and lunar age (phase), and find 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), which separately have been tied to $^{40}$Ar release (Hodges 1977; Binder 1980).

With the results in Section 2, we seem to have developed a reliable means to compute the spatial distribution of the TLPs, and we should use this as a tool for understanding their nature. The sites of consistent TLP activity are dominated by Aristarchus and vicinity, to a lesser extent Plato, followed perhaps by Mare Crisium, then the recent, large impacts (Tycho, Kepler, Copernicus) and finally Grimaldi. The often-reported sites Alphonsus, Gassendi and Ross D may be spurious. In total, the area that is affected by such activity appears to be a vanishingly small fraction of the lunar surface (at most a few percent, at least on the near side).

In Paper I, however, we analyze the spatial distribution of nonoptical transient events on or below the lunar surface. The robust distribution of TLPs found above corresponds to a striking coincidence: of the four episodes when outbursts of $^{222}$Rn gas were detected by virtue of alpha-particle detection (by detectors on *Apollo 15* and *Lunar Prospector*, each lands in the small minority of the lunar surface responsible for the robust TLP reports (Grimaldi, Kepler, and Aristarchus - twice). Furthermore, there is a significant correlation between TLP loci and the edges of maria, which is similar in description to the significant correlation between maria edges and moonquakes. (This is analyzed in Paper I.) Also, this correlation with mare edges is seen for the density of alpha particles from $^{210}$Po decay, which is a tracer for lunar outgassing as a product of the decay of $^{222}$Rn gas.

Consider that (1) the spatial distribution of TLPs is robust across the lunar near side regardless of various parameters tied to observer characteristics, and (2) this spatial distribution is highly correlated with tracers of lunar outgassing ($^{222}$Rn and, indirectly $^{210}$Po), which we show elsewhere. These two results greatly strengthen the case for the reality of TLPs: they behave in a repeatable fashion, and they are tied to outgassing from the lunar surface.

In Crotts & Hummels (2007), we pursue this connection by showing how outgassing from the lunar surface might produce TLPs and other effects due to volatiles which might be studied to confirm or refute this picture, and we also detail an array of measurement techniques which can further elucidate the TLP mystery, and tell us more about activity of lunar volatiles. A key part of this effort is a robotic lunar imaging monitor, which is practically capable of creating a new TLP data base without the enormous biases present in the powerful but flawed human observer record.

## APPENDIX A

## LARGE, SYSTEMATIC SURVEYS FOR TLPS

*Operation Moon Blink (1964 August–1966 April)*: Cameron (1966) and Cameron & Gilheany (1967) organized professional and amateur observatories in a network spanning the contiguous United States, equipping 12 sites to search for TLPs (particularly

anomalously colored ones), and engaging several follow-up observers. Moon Blink used an image tube with a red/blue filter wheel rotating at an adjustable 4–12 Hz rate, monitored visually via video for blinking sources, detecting changes >0.02 mag in the color index, but only larger color-neutral changes. Of 25 events reported, 14 were color, eight as color blink events. Two of these (one blink event) were confirmed by other means, but most were reported by observer teams at a single site. Observations covered various fields-of-view, concentrated on small areas (particularly Aristarchus). A total observing time of order 1000–2000 hr was devoted to the blink project (W. S. Cameron 2006, private communication[8]). Moon Blink produced no strong conclusions regarding TLPs.

*Corralitos Observatory L.T.P. Monitoring Program (1965 October–1972 April)*: Hynek et al. ([1976](#)), Dunlap & Hynek ([1973](#)), and Hynek & Dunlap ([1968](#)) conducted a monitoring program for TLPs using an image tube over a $0.1$ field, cycling through three bands spanning the optical in a "blink" mode, logging 3000 hr of observation by 1968 and 8000 hr by 1972. (These are quoted as "man-hours" so perhaps covers 2 or 3 times less.) During this time, only one transient was reported, a large-scale violet excess just prior to a lunar eclipse, not even classified as a TLP in this paper. Several TLP alerts by outside observers were transmitted to Corralitos during the events, and apparently most were negatively confirmed. Cameron ([1978](#)) lists 25 events that were apparently negative (four where this is stated explicitly), and two (No.1119 and 1150) where Cameron disagrees with Hynek et al. ([1976](#)) and lists a positive confirmation. Dunlap & Hynek ([1973](#)) claim a sensitivity limit better than 5% change in intensity in a 100 Å band. Hynek et al. speculate that some TLPs are actually due to observers' misinterpretation of rapid seeing changes.

*Lunar International Observing Network (during Apollos 8 and 10–12, 1968–1969)*: LION (Middlehurst [1970](#)) consisting of 216 observing stations in 30 countries effectively covering all longitudes, performing systematic observations at preselected times and features associated with TLPs. This produced 169 reports for 31 lunar areas, during *Apollo* missions 10–12, including confirmation of the *Apollo 11* event described above.

*ALPO Clementine Campaign (1994 February 19–May 3)*: ALPO (Darling [2006](#)) organized 47 observers during *Clementine*'s mission, reporting five probable TLPs (ranked by Cameron's method), some seen by over 40 observers at a time. In four cases, *Clementine* multispectral images were acquired both before and after a report (Buratti et al. [2000](#)). Despite initial indications to the contrary (Buratti [1999](#)), none of these four image sets show clear, semipermanent changes due to TLPs.

## APPENDIX B

## TLPS REPORTED FROM LUNAR ORBIT BY *APOLLO* ASTRONAUTS

*TLP Report Spanning Cislunar Space:* only one case was reported by any astronaut of any event plausibly called a TLP of more than instantaneous duration. This report is special in that discussion around the time were recorded verbatim, so one can understand some of the human factors involved with the report, unlike many in the historical sample.

Communications transcript between *Apollo 11* and Mission Control[9], 1969 July 19; eight-digit code: days, hours, minutes, seconds postlaunch (JD2440419.0639 geocentric). Speakers are:

**CC:** Capsule Communicator (CAP COMM) Bruce Mc-Candless

**CDR:** Commander Neil A. Armstrong

**CMP:** Command module pilot Michael Collins

**LMP:** Lunar module pilot Edwin E. Aldrin, Jr.

*03 04 57 07 CC:* Roger. And we have got an observation you can make if you have some time up there. There has been some lunar transient events reported in the vicinity of Aristarchus. Over.

*03 04 57 28 LMP:* Roger. We just went into spacecraft darkness. Until then, why, we could not see a thing down below us. But now, with earthshine, the visibility is pretty fair. Looking back behind me, now, I can see the corona from where the Sun has just set. And we will get out the map and see what we can find around Aristarchus.

**Note:** we skip the following 15 minutes and approximately 33 lines of dialog between Aldrin, Armstrong, and McCandless regarding navigation and communications channels. Aristarchus is mentioned only in terms of when *Apollo 11* will be able to view it from orbit.

*03 05 12 51 CMP:* Hey, Houston. I am looking north up toward Aristarchus now, and I cannot really tell at that distance whether I am really looking at Aristarchus, but there is an area that is considerably more illuminated than the surrounding area. It just has—seems to have a slight amount of fluorescence to it. A crater can be seen, and the area around the crater is quite bright.

*03 05 13 30 CC:* Roger, 11. We copy.

*03 05 14 23 LMP:* Houston, *Apollo 11*. Looking up at the same area now and it does seem to be reflecting some of the earthshine. I am not sure whether it was worked out to be about zero phase to—well, at least there is one wall of the crater that seems to be more illuminated than the others, and that one—if we are lining up with the Earth correctly, does seem to put it about at zero phase. That area is definitely lighter than anything else that I could see out this window. I am not sure that I am really identifying any phosphorescence, but that definitely is lighter than anything else in the neighborhood.

*03 05 15 15 CC:* 11, this is Houston. Can you discern any difference in color of the illumination, and is that an inner or an outer wall from the crater? Over.

*03 05 15 34 CMP:* Roger. That's an inner wall of the crater.

*03 05 15 43 LMP:* No, there doesn't appear to be any color involved in it, Bruce.

*03 05 15 47 CC:* Roger. You said inner wall. Would that be the inner edge of the northern surface?

*03 05 16 00 CMP:* I guess it would be the inner edge of the westnorthwest part, the part that would be more nearly normal if you were looking at it from the Earth.

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[8]    See http://users.aber.ac.uk/atc/tlp/cameron2006.pdf

[9]    *Apollo 11* Technical Air-to-Ground Voice Transcription, in *Apollo* Lunar Surface Journal, ed. E. M. Jones of 1969 original report GOSS NET 1 (Houston: NASA JSFC), see http://www.hq.nasa.gov/alsj/a11/a11transcript_tec.pdf

*03 05 16 20 CC:* 11, Houston. Have you used the monocular on this? Over.

*03 05 16 28 LMP:* Stand by one.

*03 05 17 59 LMP:* Roger. Like you to know this quest for science has caused me to lose my E-memory program, it's in here somewhere, but I can't find it.[10]

*03 05 18 08 CC:* 11, this is Houston. We're—we're hearing only a partial COMM. Say again please.

*03 05 18 20 CDR:* I think...

*03 05 18 41 CDR:* Houston, we will give it a try if we have the opportunity on next—when we are not in the middle of lunch, and trying to find the monocular.

*03 05 18 51 CC:* Roger. Copied you that time. Expect in the next REV you will probably be getting ready for LOI 2.

*03 05 19 09 CC:* So, let's wind this up, and since we've got some other things to talk to you about in a few minutes. Over.

At the time of these observation, the Moon's phase was 5.2 days past new, with Aristarchus in darkness $26°$ from the antisolar point and $57°$ from the sub-Earth point on the Moon. The spacecraft was about 245 km in elevation above the lunar mean equatorial surface and some 750 km from the center of Aristarchus, which appeared inclined only $5°$ from edge-on. Only the north–northwestern part of the inner rim would be easily seen. At the time of the observation the phase angle was about $63°$, whereas enhanced backscattering is significant only for angles of a few degrees. Backscatter does not explain these observations.

At mission elapsed time 03 05 14 (accurate to the minute), Pruss and Witte in Bochum, GDR reported independently a 5–7 s brightening in Aristarchus (Cameron 1978—we assign the longer timescale perhaps indicative of the *Apollo 11* report, otherwise the Pruss & White timescale is one of the shortest in the catalog). It is unclear which event previous to this the Capsule Communicator indicates to *Apollo 11*. He probably refers to a pulsing glow in Aristarchus reported by Whelan from New Zealand some 12.3 hr earlier. That night there were nine TLP reports in our sample, primarily from LION (see Appendix A), with seven involving Aristarchus over a 14 hr interval, including independent reports (including photographs) over 03 05 58–03 06 58 of Aristarchus being brighter than normal. There was no apparent attempt on *Apollo 11* to observe Aristarchus on the next revolution, 2.15 hr later in its initially wider and as yet uncircularized lunar orbit. (The "LOI 2" burn—Lunar Orbit Insertion—at mission time 03 08 11 36 accomplished this circularization.) I have discussed point in 2008 with Aldrin and Collins, and neither have any recollection of any such reobservation of Aristarchus. Collins has no clear recollection of the entire Aristarchus event, and Aldrin recalled no attempt to re-observe it. The transcript 2.15 hr later shows the crew engaged in other activities. The astronauts were busy, because the next day two of them would become the first humans to walk on the Moon!

The point of this extensive excerpt is to illustrate a few important issues at play in the data set, particularly in the interval around the *Apollo* era. This is a unique example not only because of the setting, but because of the degree to which the information

flow is documented. Is it a TLP report if observers are told to look at a specific area with special attention? Are the observers trained to distinguish the exceptional crater Aristarchus as a spatial anomaly rather than a temporal one in comparison to other craters? Do perhaps observers sometimes dismiss real temporal anomalies because they have a mental model for normal appearance e.g., variations due to seeing—or in this case, the direct, $180°$ backscatter—that might be caused by less well known effects? To what extent can simultaneous, independent reports differ in description and still be considered a confirmation? Is it significant that many earlier selenographers made careful, repeated observations with written records, or do more incidental observers provide useful reports as well? In the end, this singular case is not a strong TLP report because even while simultaneous to another report for the same feature, it is unclear what the *Apollo* observers saw truly transient activity on relevant timescales.

*Note on "Flashes" Observed from Lunar Orbit.* Three instances of rapid, bright flashes apparently from the lunar surface were observed on *Apollo 16* (by Mattingly) and *Apollo 17* (by Schmitt and Evans). While we do not analyze these in our sample, they are worth mentioning separately. They are documented in the mission transcripts, debriefings, preliminary science reports and in Cameron (1978).

The two *Apollo 17* reports were tied to Grimaldi and Mare Orientale, respectively. The first locus, and even the second (while indistinct), are sites of some of the few outgassing events detected by means other than TLPs (both during *Apollo 15*). Grimaldi is a persistent TLP site, while Mare Orientale is too close to the limb to be relevant. This is interesting because there seem to have been very few if any of these flashes seen *not* coming from the direction of the lunar surface, so perhaps the explanation of them being caused by cosmic ray interactions with the retina or vitreous humor of the eye is problematic.

The *Apollo 16* event is hard to localize because it occurred on the dark side and was purely visual. Being on the far side, it cannot be tied explicitly to TLPs. Nonetheless, Mattingly noted it as coming from below the horizon and therefore ostensibly the lunar surface. As best as I can reconstruct from the available description, Mattingly was looking in the vicinity of crater Korolev, on the far side. This is highly uncertain.

I have discussed these events with Schmitt and Mattingly. (Evans died in 1990.) Both were well aware of cosmic ray-induced flashes within the human eye. Schmitt is nearly certain this is not what he saw; Mattingly is somewhat less sure because he never saw a cosmic ray flash otherwise, but describes the event as completely point-like and instantaneous, which varies with documented description of cosmic ray events. Schmitt also describes his event as point-like and instantaneous, although there is slight reference in contrast to the *Apollo 17* transcript (within 1 minute of the report— "Schmitt: it was a bright little flash right out there near that crater. See the crater right at the edge of Grimaldi. Then there is another one north of it. Fairly sharp one north of it is where there was just a thin streak of light.")

Rather than dwell on the memory of more than three-decade old events, one can make a brief inquiry into whether these events are easily explained by meteorite impacts on the lunar surface. Based on the verbal descriptions, one can localize the Mattingly event to within about $10°$ on the lunar surface versus about $1°$ and $2°$ for the Schmitt and Evans events, respectively. The latter two reports occur during the relatively intense Geminid meteor shower (peaking December 14 versus

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[10] The E-memory was the spacecrafts erasable memory, which held temporarily programs for control of the spacecraft e.g., for guidance.

times for the two reports of UT 1972 December 10 21:11 and 1972 December 11 22:28), and occur only 20° and 18° in longitude, respectively, from the point on the Moon's surface directly below the Geminid radiant. These two events occurred close to the point most likely to have been struck by Geminids. The Mattingly event (at UT 1972 April 21 19:01) occurs 142° in longitude from the leading point of the Moon's motion, in heliocentric coordinates, far from the most likely point for a meteoritic impact, but not conclusively so. (Note that the two *Apollo 17* events were 104° and 99° from the leading point, but could easily be Geminids.)

The two *Apollo 17* reports during the Geminids might be explained by such impacts. The *Apollo 16* report has no such obvious explanation, but might also be due to impact.

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