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 still controversial. Nonetheless, a review of TLP data shows regularities in the observations; a key question is whether this structure is imposed by human observer effects, terrestrial atmospheric effects or processes tied to the lunar surface.

I interrogate an extensive catalog of TLPs to determine if human factors play a determining role in setting the distribution of TLP reports. We divide the sample according to variables which should produce varying results if the determining factors involve humans e.g., historical epoch or geographical location of the observer, and not reflecting phenomena tied to the lunar surface. Specifically, we bin the reports into selenographic areas (300 km on a side), then construct a robust average count for such "pixels" in a way discarding discrepant counts. Regardless of how we split the sample, the results are very similar: roughly 50% of the report count originate from the crater Aristarchus and vicinity, ∼16% from Plato, ∼6% from recent, major impacts (Copernicus, Kepler and Tycho - beyond Aristarchus), plus a few at Grimaldi. Mare Crisium produces a robust signal for three of five averages of up to 7% of the reports (however, Crisium subtends more than one pixel). The consistency in TLP report counts for specific features on this list indicate that ∼80% of the reports are consistent with being real (perhaps with the exception of Crisium).

Some commonly reported sites disappear from the robust averages, including Alphonsus, Ross D and Gassendi. TLP reports supporting these sites originate almost entirely after year 1955, when TLPs became more popular targets of observation and many more (and inexperienced) observers searched for TLPs.

We review non-lunar hypotheses discussed to explain TLP, and find conflicts with the data involving nearly all of them. Furthermore, in a companion paper, we compare the spatial distribution of robust TLP sites of transient outgassing (seen by instruments on Apollo and *Lunar Prospector*). To a high confidence against the random hypothesis, robust TLP sites and those of lunar outgassing correlate strongly, further arguing for the reality of TLPs.

1. Introduction

TLPs (Transient Lunar Phenomena, called LTPs by some authors) as we are describing 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 at all. 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 2007a.)

On the timescale of a 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 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, but via a robotic imaging monitor that will be much more objective and probably more sensitive than historical means (Crotts 2007b, Crotts et al. 2007).

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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.

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 UFOs (Unidentified Flying Objects). 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 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 three. It is the primary task of this work to answer the question if TLPs are at least consistently tied to specific sites on the lunar surface, so that one can then ask if the appearance or physics of these sites might explain TLP reports.

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 May 1977), and Barbara Middlehurst (1977a, primary from the TLP event catalog of Middlehurst, Burley, Moore & Welther 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 darkside 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 Jocelyn 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 §2.4. At times when the Moon has been an attractive target of forefront 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.) Wilhelm Herschel, the only human to discover a planet on the basis of solely visual telescopic observation, reported TLPs on at least 6 occasions between 1783 and 1790, primarily bright, point-like spots, many of them red in color (Middlehurst 1968). Clyde Tombaugh, discoverer of the dwarf planet 134340 Pluto, along with at least five other observers spread across the United States, reported on 1963 November 28 "reddish-orange and sparkle" activity on the rim of Aristarchus, which some observers saw followed by a faint blue glow on the crater floor (Cameron 1978). Charles Messier, discoverer of 19 comets and author of the famous catalog of nebulae, saw TLPs on one occasion ("moving glows" during a lunar eclipse: Cameron 1978) in 1783, and Ernst Tempel (discoverer of 20 or more comets) at four epochs from 1866-1885. TLPs were also reported by noted observers Edward Barnard (in 1889-1892), Edmond Halley (in 1715), Johann Bode (in 1788-1792), George Airy (in 1877, and confirmed independently), Heinrich Olbers (in 1821), Dominique Cassini in 1671-1673 (Paris Observatory director and grandson of Jean-Domenique Cassini), Camille Flammarion (in 1867-1906), William Pickering (perhaps the first to place a tight astrophysical limit on the Moon's atmospheric mass) in 1891-1912, Johann Schröter in 1784-1792 (first to notice the phase anomaly of Venus), Friedrich von Struve (in 1822), Francesco Bianchini (in 1685-1725), Etienne Trouvelot (in 1870-1877), and more recently Zdeněk Kopal (in 1963) and in 1948-1967, Sir Patrick Moore (Middlehurst 1977a, Cameron 1978). Of course, in 1821-1839 Franz von Gruithuisen reported luminous and obscured spots on the Moon, yet also wrote about the Moon being inhabited and dotted by cities! (He was also first to conclude that lunar craters result from meteorite impacts.)

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 min 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 (see above) in the same vicinity; both cases roughly coincident with local sunrise. Apollo astronauts Cernan, Schmidt, 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 darkside surface appearance (Jones 1969) 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 I.

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, D. 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 (#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 will discuss spectroscopic and polarimetric observations in Paper II, and several probable meteoritic impact photographs in §2.5 below.

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 datasets in attacking the TLP problem. Several of these have been organized by D. Darling and collaborators, often in connection with ALPO (Association of Lunar and Planetary Observers: http://labbey.com/ALPO/Lunar.html and http://www.lpl.arizona.edu/rhill/alpo/lunar.html) and now with the BAA (British Astronomical Association: http://www.britastro.org/baa/ and http://www.cs.nott.ac.uk/acc/). A summary of activities until fairly recently is found at http://www.ltpresearch.org/. (Other groups can also be found at http://www.glrgroup.org/.) An informal appraisal of the information from these groups indicates that observers in these programs are patrolling for TLPs at the level of order 100 h per year. A summary follows of some of these past efforts bearing on the purposes of this paper.

Operation Moon Blink (August 1964 - April 1966): W. Cameron (1966; Cameron & Gilheany 1967) of NASA Goddard SFC organized a network of professional and amateur observatories spanning the contiguous United States and provided 12 of them with an instrument designed to be particularly sensitive to transient sources, particularly anomalously-colored ones, on the lunar surface. Several more observers were engaged in an alert follow-up network using more conventional visual and photographic techniques. The Moon-Blink apparatus consisted of an S-20 photocathode image tube with a rotating filter wheel cycling between a red filter (similar to Wratten 29) and blue (like Wratten 44a) at an adjustable rate of 4-12 Hz. The video output was then monitored visually for any blinking sources. This device was particularly sensitive to color changes, shown by tests to be limited at the 0.02 mag level to changes in color index, but relatively insensitive to color-neutral brightenings, dimmings and obscurations. During the survey 25 events were reported, 14 of which were detected as color changes. No total observing time estimate was published, but of order 1000-2000 hours was devoted to the blink portion (Cameron 2006). Eight of these were actual color blink events. Two of these (one of the blink events) were confirmed by other means, but most events were reported by a team of observers at a single site. Observations were concentrated on small areas, particularly Aristarchus, and the fields of view varied with a selection of different telescopes above 15-inch diameter. The investigation produced no strong conclusions regarding TLPs.

Corralitos Observatory L.T.P. Monitoring Program (October 1965 - April 1972): J.A. Hynek et al. (1976; Dunlap & Hynek 1973, Hynek & Dunlap 1968) conducted a monitoring program for TLPs using a 62 cm telescope and an S-20 image tube cycling through three bands spanning the optical spectrum in a “blink” mode, and logged 3000 h of observation by 1968 and 8000 h by 1972. The field-of-view was 0.1 degree. (There is a reference to “man-hours” of observation, so perhaps the time coverage is two or three times less than this.) During this time, there was only one transient event reported in their publications, a large-scale violet excess just prior to the lunar eclipse of 1967 April 24, not even classified as a TLP for the purposes of this paper. Several TLP alerts by outside observers were transmitted to Corralitos Observatory during the events, and apparently most of these were negative confirmations. Cameron (1978) lists 25 events that were apparently negative (four where this is stated explicitly in terms of the data), and two (#1119 and #1150) where apparently Cameron disagrees with Hynek et al. and concludes there was a positive confirmation. Dunlap & Hynek (1973) claim a sensitivity limit of better than 5% change in intensity in a 100Å band. Hynek et al. speculate that some TLPs are actually due to observers’ misinterpretation of rapid seeing in changes.

Lunar International Observing Network (during Apollo missions 8 & 10-12, 1968-1969): B. Middlehurst (1970) organized LION, consisting of 216 observing stations in 30 countries effectively covering all longitudes. LION performed systematic observations at preselected times of lunar features with a history of TLP reports. This produced 169 reports for 31 lunar areas from 28 observing stations located in 19 countries, during Apollo missions 10-12. In particular a special campaign produced the confirmation including the *Apollo 11* event described above. This one effort involved the crater Aristarchus on 19 July 1969, from 18:45 to 24:00 U.T. Twelve observers in six countries and two continents made simultaneous or overlapping observations of the Aristarchus crater covering a 5.25 h time interval.

ALPO Clementine Campaign (1994 February 19 - May 3): The Association of Lunar and

Planetary Observers (Darling 2006) organized 47 observers during the 71-day Clementine multispectral mapping mission, producing five probable event detections (according to a weighting scheme developed by W. Cameron), some seen by over 40 observers at a time. There are four instances in which Clementine multispectral images were acquired both before and after one of these reports (Buratti et al. 2000). Despite initial indications to the contrary (Buratti et al. 1999), none of these four sets of images shows clear changes (that would be of a semi-permanent nature) that could be attributed to these TLPs.

2.5. Description and Distribution of TLP Reports

As we have said, 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 9 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 two. This is not a statistical sample, but give some measure of event duration; binned in $\sqrt{10}$ intervals from 60s to 19000s (with the longest event being 18000s and the shortest 60s) the duration distribution is: 60-190s, 7 reports; 191-600s: 9; 601-1900s, 27, 1901-6000s, 23; more than 6000s: 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 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 et al. 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, Petrov & Mench 1978, also see Arkhipov 1991), and events have been caught by Dunlop (1999) and Suggs et al. (2005, 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 0.1s. 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 seconds (emitting electromagnetically 3×10^{18} erg s^{-1} and perhaps as massive as 10^{13} g: Buratti et al. 2003) was at one time thought to have been confirmed by the coincidence of a fresh crater seen by *Clementine* (Buratti et al. 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[2] mass of 280 kg and was moving 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. events above. Indeed, an array of telescopes with optical CCD imagers and diameters up to 1 m observed the impact with negative results (Ehrenfreund 2006). 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 at the time of impact show a signal so bright that it saturated the detector in a 32 nm band at the 2.122 μm molecular H_2 S(1) 1→0 transition. The signal detected was at least 3×10^6 e^- and probably many times more, which corresponds to at least 8×10^{-15} erg cm^{-2}. From stars in the field beyond the

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[2] Foing, B. (2006), personal communication, although the dry mass of *SMART-1* is listed as 305 kg: http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=2003-043C

Moon at the same time, one can estimate the seeing at about 1.5 arcsec FWHM, indicating that the flux is probably about 5 times higher at least (which cannot be fully estimated without careful non-linearity tests or models), meaning that the energy output in this band was at least about 10^9 erg, about 2×10^{-7} of the total energy and probably two orders of magnitude more than the limits that will be derived from the optical non-detections, if as reported. There is also a luminous debris cloud spreading elongatedly starting at $\sim$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 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, Berezhnoy 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 3.9×10^{15} erg. D. Allen used the AAT to observe the impact at 2.16 μm wavelength and recorded an event fluence corresponding to 6.7×10^{12} erg in a 1% wavelength band, appearing 6-16 s after impact No immediate optical flash was seen and later optical signals (15 min after impact) were unclear, and not near the original impact point. Svedhem 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. (1993) that the fresh impacts 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 information (but not additional reports) drawn from Cameron (1978). This information is summarized in Figure 1.

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)
6 each	Cobra Head (24N 48W); Copernicus (10N 20W); Kepler (08N 38W); Posidonius (32N 30E); Tycho (43S 11W)
5 each	Eratosthenes (15N 11W); Messier (02N 48E)
4 each	Grimaldi (06S 68W); Lichtenberg (32N 68W); Mons Piton (41N 01W); Picard (15N 55E)
3 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)

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2 each   1.3’ 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)

1 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);

Not counted: 4 (global lunar changes), 14 ("cusp" events), 43 (events w/
unknown coordinates)
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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 make further progress in understanding the spatial distribution of TLPs, we must deal statistically with the horrendous selection effects introduced into these data by the patterns and biases of the observers, most of whom never intended that their reports form part of a statistical database. Our task is not modest; we are basically trying to calibrate for this purpose all of the observations made (or not made) of the Moon by all of the human eyeballs over a period of centuries. How do we possibly deal with the historical and even psychological issues that these effect imply, as well as the physical/mathematical ones? This is the major burden of the current paper; nonetheless, there are some regularities that we might exploit.

There are many works on selenography, but in general, there were some systematic naked-eye observations of the Moon starting in Europe in the 1400–1500's, and much earlier in China (but I find no early chinese reports of TLPs). Observations greatly increased in number and detail in the mid 17th century after the invention of the telescope, and early in the next century it was appreciated that the Moon needed to be observed more often due to the effects of libration. Still, it does not seem that attention focussed solely on the limb regions, as mapping the Moon increased in detail generally, with the adoption of lunar coordinates by mid-to-late 18th century. From late-1700's to early 1900's, visual mapping of the entire Moon was an active science, perhaps with some concentration on terminator regions in order to better sense relative elevations of lunar features. By the turn of the 20th century, visual observation was increasingly replaced by photography, which had the unfortunate effect of suppressing sensitivity to TLPs due to the decreased observational sampling cadence of photographic plates with respect to the human eye, as well as the loss of prompt color information. I speculate that for this reason, reports of TLPs by professional astronomers began to die out. It is not the purpose of this paper to dwell on the history of TLP observations beyond gaining some insight into the statistical sampling structure and false report rate of the catalogs. Shortly, we will move on to questions more objectively dependent on the physics of the lunar surface.

There is a pause in the frequency in TLP reports in both the Cameron (1978) and Middlehurst (1968) catalogs, and indeed the break in reports 1927-1931 divides the Middlehurst catalog at the median epoch in the catalog. For the post-1930 half of the sample, 2/3 of the reports come after 1955, at which time TLPs become much more commonly known and observing pattern appear to change, as we will describe later. For now we will concentrate awhile on the pre-1956 and particularly the pre-1930 period.

It is obvious in regard to TLPs that a most unusual area is the Aristarchus Plateau, including the crater Aristarchus itself, the adjacent crater Herodotus, and Vallis Schröteri (Schröter's Valley) flowing from "Cobra's Head" ("Cobra-Head"), together occupying the southeasternmost ∼10,000 km^2 of the ∼50,000 km^2 Plateau in the midst of the huge (4×10^6 km^2) mare region Oceanus Procellarum. (Vallis Schröteri was once selected as the landing site for Apollo 18, later cancelled 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 far in the past as the Tang Dynasty (618 – 907 A.D./CE) (Mayers 1874). It is also one of the freshest: ∼ 500 My old, along with Copernicus, Kepler and Tycho (each producing less than 5% of the TLP reports of Aristarchus. At one time the region was 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.

Even more than Copernicus, Aristarchus is singular in standing in such contrast to the surrounding dark mare background, although this is not true of Vallis Schröteri/Cobra's Head or Herodotus also on the Plateau. The Aristarchus region is responsible for ∼50% of the visual TLP reports (but also likely receives a large fraction of the observing attention). As reviewed in (Crotts 2007a), however, the Aristarchus Plateau is also responsible for undeniably objective lunar anomalies of a transient nature associated with lunar outgassing. We 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 centuries, but prior to the year 1956 there appears to be little writing labeling special sites such as Aristarchus as targets of particular popular or professional attention in terms of TLPs. Aristarchus received closer scrutiny in 1911 with R. Wood indicating that it might contain high concentrations of sulfur, but this did not produce a spate of Aristarchus TLP reports. Indeed, Wood discusses vulcanism 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 1911). Furthermore, Birt (1870) and Whitley (1870) provide a historical overview (1787–1880) of visual observations of Aristarchus (and Herodotus) while conducting a

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[3] e.g., Whitaker (1972), or http://www.lpod.org/archive/archive/2004/01/LPOD-2004-01-17.htm

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 a recognized TLP phenomenon (or at least a human tendency to report TLPs). A different statement is made by Elgers (1884), who again reviews 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 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 twenty 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" (citing Fauth 1909.[4])

The periods covered by these papers are particularly telling in understanding the nature of human behavior over the changing technological state-of-the-art in the historical course of selenography. A paper by W.H. Pickering (1892) asks "Are there present Active Volcanos 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. While Aristarchus is mentioned, it is discounted as being a non-volcano, while several other features are taken much more seriously (Bessel, Linné and Plato), and there is *no* discussion of any activity that we would call TLPs today, only the long-timescale appearance or permanent changes. Pickering described several TLP reports shortly before and then after submitting this paper — statistically marginal in themselves, 14 in our sample, and 9% of Aristarchus and vicinity — but I see no significant evidence that these induced a spate of further Aristarchus reports, at least until publication of his book [1904a], and probably not even then. This was rather late in the pre-1930

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[4] This skepticism of Fauth's was despite his defense in 1912, to his scientific disgrace, of the Austrian engineer Hanns Hörbiger's curious notion that the Moon's "ice-like" appearance implies that it and other celestial objects must be composed of ice! (Hörbiger & Fauth 1913)

period, anyway (which we investigate more quantitatively below).

As is the case for the whole sample, we should search the Aristarchus reports for observers e.g., Bartlett, who produce obvious statistically descrepant results. With 150 reports total for Aristarchus, Pickering should be considered as a marginal candidate for this. His series of 14 reports from 1891-1898 refer to mists or nebulosity in the Herodotus/Cobra Head vicinity east and north of Aristarchus (Pickering 1900). Personally, I suspect that at least some of these reports were erroneous, due Pickering's tendency to overinterpret observations according to his lunar world view. If these were inconsistent with other observers' body of reports and the catalog as a whole, and might be considered a candidate for exclusion. In truth 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. Strictly speaking we cannot exclude the Pickering observations because of an inconsistency. Pickering exhibited a tendency to interpret changes in the lunar surface in terms of weather and biology, but his statements regarding these issues indicate that his statements are not motivated ideologically, but by the best description of observation e.g., Pickering (1904b, 1916).[5] In the end the Pickering subsample has little effect on the overall qualitative behavior of the Aristarchus dataset anyway, so I leave it intact.

To consider the questions above more systematically, I make use of abstract/article search engines. 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 4 matches (not counting the ancient greek astronomer Aristarchus!) and "volcano" alone produces 13 relevant to the Moon. Note that this search does not go into the body (versus the abstract) of the text of some longer articles, for example Wood 1911, but perhaps this is a satisfactory reflection of the amount of attention that a TLP-like claim might attract. Similarly results are found for "gas," "atmosphere," "eruption," "flash," "cloud," "nebulosity," "mist," "geyser,"

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[5] From Pickering (1916): "The writer has sometimes been asked, 'What reason is there to believe that there is ice upon the moon?' The answer is: 'For the same reason that we believe there is ice upon Mars, because the phenomena observed can be more readily explained that way than any other.'" From Pickering (1904b), commenting on his interpretation of mists over the surface of the Moon, which he had established by occultation studies to be at very low atmospheric pressure: "It seems to the writer that the merit of this explanation lies not so much in its novelty, but rather because it is founded so largely upon the observed facts." W.H. Pickering is an interesting case!

[6] The Smithsonian/NASA Astrophysics Data System: http://www.adsabs.harvard.edu/ - which covers a great many journals into the 19th century and even earlier e.g., Lind & Maskelyne 1769, or Street et al. 1671

and “vapo(u)r,” with no matches for any of these with “aristarchus.” These results are summarized in Table 2. Likewise, replacing “aristarchus” with “herodotus” or various versions of 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.

Table 4: TLP-related Terms Correlated with Terms “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
"vapo(u)r"	514	0	0
"transient"	9	0	0
"change"	893	38	0
No First Term	----	2930	7

I think that all of the above this is compelling evidence that the great majority, perhaps all, pre-1930 selenographers did not place any special importance on possible, specifically-localized TLP activity, particularly in Aristarchus as examined here.[7]

Again, we must search the 1930-1955 database for any observer correlation effects visible in the literature, again using ADS Astronomy/Physics searches on key terms (Table 3). The only citation involving “change” AND “aristarchus” is Haas (1938) referring to

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[7] Let me say as a personal statement that the degree of quantitative specificity and careful language by many of the professional selenographers of these times is what made this investigation possible. In contrast, consider data like Bird’s (1870) description of daytime meteors: “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.

periodic changes appearance of the inner eastern wall of Aristarchus over nine-day intervals, hence not TLPs in any regard. 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 these involved TLPs.

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
"vapo(u)r"	698	2	0
"transient"	112	1	0
"change"	2050	26	1
No First Term	----	1124	3

During 1930-1955, of the 26 citations involving “moon” AND “change” there are six articles that actually deal with changes in lunar appearance, all on time scales of days or weeks, spread over many lunar features, not concentrating on any strong TLP sites (except for Haas [1938]). These sites 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 is significant because it delineates the period after which large number of TLP reports appeared, starting with Alter (1957) and followed soon thereafter by publications of Kozyrev (1959, 1962), inspired further observations in a cascade through the catalog. This wreaks havoc with our ability to evaluate TLP observational biases. Citation correlation data for the period after 1955 is shown in Table 4.

Table 4: TLP-related Terms Correlated with References to “Aristarchus” and “Moon”, 1956-1968

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
"vapo(u)r"	1154	8	0
"transient"	458	15	3
"change"	4836	61	0
No First Term	----	2440	10

In contrast, during 1956-1968 there are 10 references to Aristarchus, seven involving TLPs, all of which lead back to the Kozyrev reports. Of these seven, five involve some of the TLP-related search terms that we have used. During this period TLPs are firmly fixed in many people’s minds when discussing particular lunar features, such as Aristarchus.

These papers (or lack thereof) can 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, before 1956 they provide no evidence for a “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 also implies that there must be some other reason that reports occur 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 6×10^6 km^2 would imply. The Elgers statement above implies that the ratio of observing time per area for Aristarchus and the Plateau versus other areas not near the limb is at least of order unity, and probably more. However, in Crotts (2007a) we will see on the basis of alpha particle transients from outgassing seen by Apollo and *Lunar Prospector* that TLPs are correlated with ^{222}Rn production and that this cannot with any 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). Aristarchus is intrinsically more prone to TLPs, for some reason other than how often people observe it.

2.7. Statistically Consistent TLP Spatial Distribution

While TLPs at Aristarchus events seem to be uncorrelated at least for Aristarchus and for the period 1956 and before, we do not have sufficient statistics for lesser TLP sites to perform the same tests. I will simply assume that all events are Poisson.

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 variable? We will choose variables which should be entirely unrelated to the conditions of the lunar surface, but might 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-labelled "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× 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 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 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.

Table 5: Number of TLPs Reported Per Feature, Median of Three Historical Periods

Robust Report Count	Feature(s)
46	Aristarchus/Schroter's Valley
13	Plato
3	Kepler
2 each	Alphonsus, Eudoxus, Grimaldi, Mare Crisium, Posidonius
1 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

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To within 1σ 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 4σ 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 targetting 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. 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 min up to 5 h (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 multipled 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 is included in a robust (but non-median) average, as we present in Table 7 and explain below (and in Crotts 2007a), the results are qualitatively similar. Even if pre-1956 data is time-sliced not in historical epoch, but time of the year (January-April, May-Auguest, September-December), which would smooth out any long-term fluctuations, the results are similar.

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
1 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

The two-sample robust estimator (Table 7) is constructed by taking the minimum of the two values in equal-total 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.

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
2 each	Grimaldi, 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

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

Median Report Count	Feature(s)
25	Aristarchus/Schroter's Valley
13	Plato
5	Mare Crisium
2 each	Copernicus, Eratosthenes, Kepler, Tycho
1 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

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

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

Median Report Count	Feature(s)
37	Aristarchus/Schroter's Valley
15	Plato
6	Mare Crisium
4	Tycho
2	Eratosthenes
1 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

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 undoubtably 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 σ. 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.

Table 10: Relative Frequencies of Robust TLP Reports by Feature

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

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 fractions for Alphonsus is 2/22, Ross D: 0/13, and Gassendi: 1/18. Taken together, $\sim$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 stucture, at least, is fairly consistent. Now the question of the TLP mechanism must be addressed. There are hypotheses as to possible non-lunar 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. Undoubtably 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 nighttime 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), Greenacre (1963) & Barr, 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 treated above, any reasonable test of the Bartlett sample against the larger TLP data base is likely to conclude that they are not both 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. We will not consider here the first two cases in (1), since they 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 applies the effects of dispersion to the particular case of Greenacre & Barr, but it is unconvincing since (a) the same candidate event was reported by observers two time zones away, where the airmass was much different, and (b) 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 (7000Å) relative to the eye's sensitivity peak ($\sim$5000Å) 1.4 arcsec 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 5000Å and 7000Å 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 hours, 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" in the north-central Andes). Also, Sheehan & Dobbins (1991) argue against a symmetric production by atmospheric dispersion of blue TLPs, which should be displaced even more (by about 20%); I do not find their argument convincing but will not pursue this here.

This leaves objection #5: effects of seeing in high contrast source distributions, and #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 III.

The Corralitos Observatory TLP survey spent some 8000 hours (10.9 months at full duty cycle) observing, and was capable of covering the whole Moon in 15 min (although it is unclear if it always did), hence should have produced some 3×10^4 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 $\sim 3\sigma$ 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 100Å 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. 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 (#1119 and #1150) where apparently Cameron disagrees with Hynek et al. and concludes there was a positive confirmation. This fraction of non-confirmation 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 (April 1966 - June 1969).

Despite the dedicated and laudable progress made by Cameron, Middlehurst, Moore, Darling and centuries of researchers and observers, the current state of the dataset 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

A investigation by Cameron (1967, 1972) and Middlehurst (1977a, b) into correlations with several possible lunar parameters turn 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, b) 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 might 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 Crotts (2007a), however, we analyze the spatial distribution of non-optical 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*, all correspond to 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 (also in Crotts 2007a). 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.

Considering that 1) the spatial distibution 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) and Crotts (2007b) we pursue this connection by showing how outgassing from the lunar surface with 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 techiques which can further illucidate 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.

5. (Appendix I) - A TLP Report Spanning Cislunar Space

Transcript of communications between *Apollo 11* and Capsule Communicator, 1969 July 19.

Eight-digit numerical code: days, hours, minutes, seconds after launch (JD 2440419.0639, geocentric reference). Communicators are:
CC: Capsule Communicator (CAP COMM) Bruce McCandless
CDR: Commander Neil A. Armstrong
CMP: Command module pilot Michael Collins
LMP: Lunar module pilot Edwin E. Aldrin, Jr.

03 04 56 35 CC: Apollo 11, this is Houston. Over.

03 04 56 41 CDR: Go ahead, Houston.

03 04 56 42 CC: Roger. We show you, in the flight plan, staying in orbital rate until about 79 hours 10 minutes. Do you have some particular attitude or reason for wanting to go inertial? Over.

03 04 57 00 LMP: No, that's fine. I just wanted to confirm that. Until 79 10, then we'll breeze around here in orbit.

03 04 57 07 CC: Roger. And we've got an observation you can make if you have some time up there. There's 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 couldn't 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'll get out the map and see what we can find around Aristarchus

03 04 57 54 CDR: We're coming upon Aristarchus right now - -

03 04 57 55 CC: - - Okay. Aristarchus is at angle Echo 9 on your ATO chart. It's about 394 miles north of track. However, at your present altitude, which is about 167 nautical miles, it ought to be over - that is within view of your horizon: 23 degrees north, 47 west. Take a look and see if you see anything worth noting up there. Over.

03 04 58 34 CDR: Both looking.

03 04 58 36 CC: Roger. Out.

03 05 03 01 LMP: Houston, 11. It might help us a little bit if you could give us a time of crossing of 45 west.

03 05 03 09 CC: Say again, please, 11.

03 05 03 23 LMP: You might give us a time of crossing of 45 west, and then we'll know when to start searching for Aristarchus.

[Note: the reader might want to skip this italicized, 9-minute section, during which time the spacecraft approaches Aristarchus.]

03 05 03 32 CC: Roger. You'll be crossing 45 west at 77 04 10 or about 40 seconds from now. Over. Thirty seconds from now.

03 05 03 45 LMP: Okay.

03 05 04 50 CC: Apollo 11, when we lose the S-band, we'd like to get OMNI Charlie from you. And update my last, that 77 04 was the time when Aristarchus should become visible over your horizon. 77 12 is point of closest approach south of it. Over.

03 05 05 14 LMP: Okay. That sounds better because we just went by Copernicus a little bit ago.

03 05 05 18 CC: Roger. We show you at about 27 degrees longitude right now.

03 05 05 25 LMP: Righto.

03 05 07 07 LMP: Houston, when a star sets up here, there's no doubt about it. One instant it's there, and the next instant it's just completely gone.

03 05 07 16 CC: Roger. We copy.

03 05 09 21 CC: Apollo 11, this is Houston. We request you use OMNI Charlie at this time. Over.

03 05 09 29 LMP: Okay. Going to OMNI Charlie.

03 05 09 32 CC: Roger. Out.

03 05 11 57 LMP: Houston, Apollo 11.

03 05 12 01 CC: Apollo 11, this is Houston. Go ahead.

03 05 12 06 LMP: Roger. Seems to me since we know orbits so precisely, and know where the stars are so precisely, and the time of setting of a star or a planet to so very fine a degree, that this might be a pretty good means of measuring the altitude of the horizon ...

03 05 12 32 CC: Roger.

03 05 12 51 CMP: Hey, Houston. I'm looking north up toward Aristarchus now, and I can't really tell at that distance whether I am really looking at Aristarchus, but there's 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'm 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.

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.[8]

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.

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

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.

Note: at the time of the above observation, the Moon's phase was 5.2d past new, with Aristarchus in darkness, 26° from the anti-solar 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 would be significant only for angles of a few degrees.

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 precisely which event previous to this the Capsule Communicator was indicating to *Apollo 11.* He probably refers to a pulsing glow in Aristarchus reported by Whelan from New Zealand some 12.3 h earlier. That night there were nine TLP reports in our sample, primarily from LION (see §2.4), with seven involving Aristarchus over a 14 h 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 h later in its initally wider and as yet uncircularized lunar orbit. (The "LOI 2" burn – Lunar Orbit Insertion – at mission time 03 08 11 36 accomplished this circularization.) 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 to is 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?

Note on "Flashes" Observed from Lunar Orbit: Three instances of very rapid, bright flashes apparently from the lunar surface were observed on *Apollo 16* (by Mattingly) and *Apollo 17* (separately by Schmidt and Cernan). While we do not analyze these in our sample, they are worth some separate mention. 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 reasonably 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 vitrious humour of the eye is somewhat problematic.

The *Apollo 16* event location is more uncertain because it not only occurred on the dark side, hence was difficult to localize visually. Being on the far side, it cannot be tied to TLPs. Nonetheless, it was reported by Mattingly as coming from below the horizon and therefore austensibly 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.

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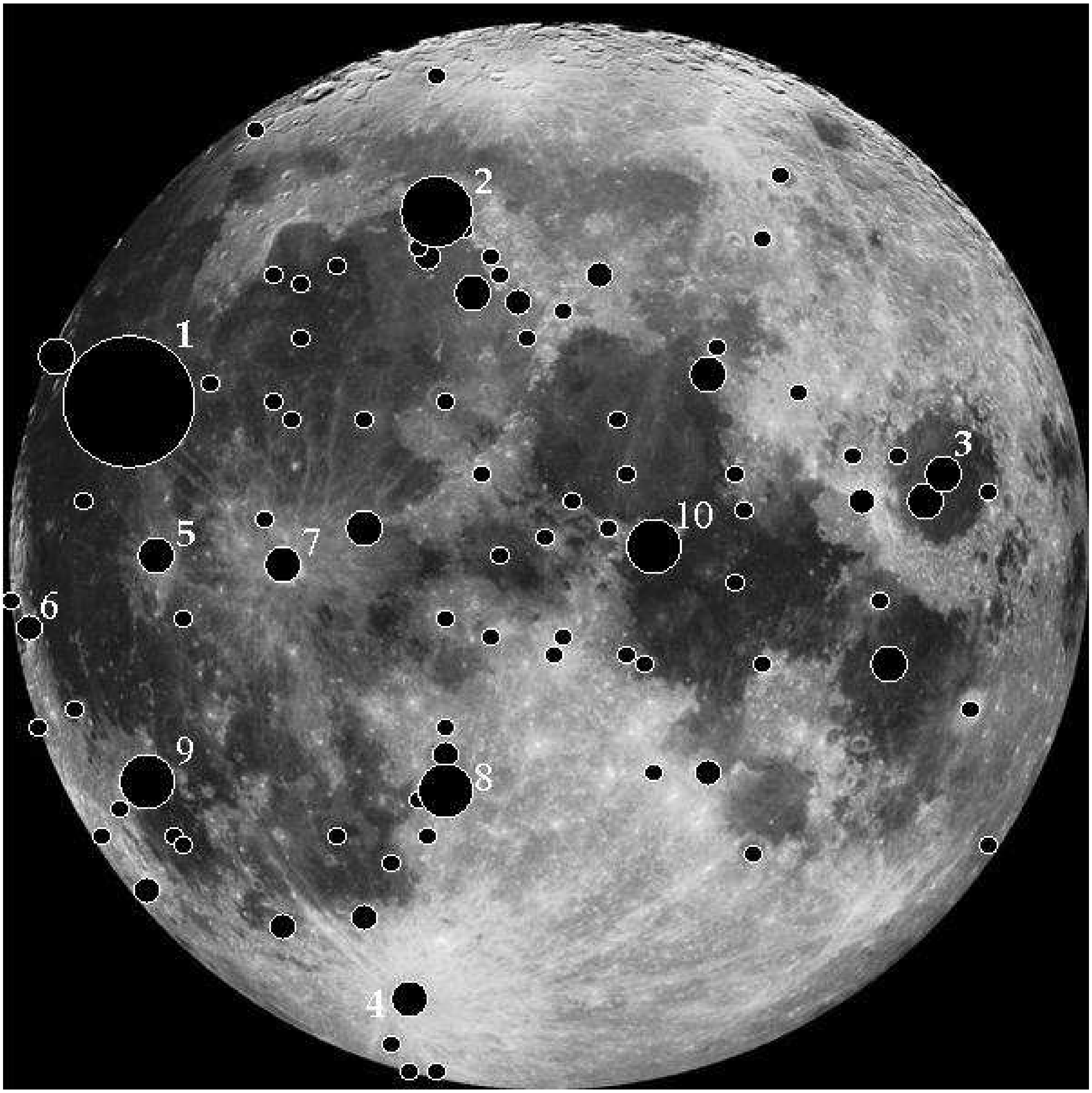

Fig. 1.— Distribution of TLP report loci as catalogued in Middlehurst et al. (1968), with the exception of a minority of cases that are rejected for the reasons detailed in the text. The size of the symbols encodes the number of reports per features, as listed in Table 1. Marked features include: 1) 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)