POSSIBLE EXTRA-SOLARY-SYSTEM CAUSE FOR CERTAIN LUNAR SEISMIC EVENTS. Yosio Nakamura and Cliff Frohlich, Institute for Geophysics, John A. and Katherine G. Jackson School of Geosciences, University of Texas at Austin, 4412 Spicewood Springs Road, Bldg. 600, Austin, TX 78759-8500, U.S.A. (yosio@ig.utexas.edu, cliff@ig.utexas.edu).

Introduction: A rare category of seismic events among more than 12,500 seismic events observed and catalogued during eight years of operation (1969-1977) by the Apollo lunar seismic network consists of 28 events originally called high-frequency teleseismic (HFT) events [1]. HFT events are distinctly different in character from all other lunar seismic events: they are rich in high-frequency content and produce clearly identifiable P- and S-wave arrivals, each with a distinct long coda, suggesting that they originate at some depth below the surface. Although they were extremely rare, they included some of the most energetic events we observed on the Moon. The origin of the HFT events was puzzling [2, 3], but we tended to think that they probably were tectonic, i.e., lunar analogues of shallow intraplate earthquakes that occur on Earth, and thus they are often called ‘shallow moonquakes’ even though some doubts remained of their true identify.

A recent reexamination of these events, however, has revealed that 23 of the 28 HFT events occurred during one-half of the sidereal month when the seismic network on the Moon’s near side faced towards a certain fixed direction on the celestial sphere. This suggests that a yet unknown source outside the solar system might be responsible for causing or triggering HFT events.

Occurrence Times of HFT Events: Our principal observation is that there is a significant correlation between the occurrence times of HFT events and the sidereal phase of the Moon (Fig. 1).

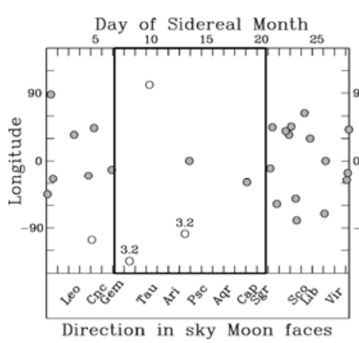

Fig. 1. Sidereal day and longitudes for HFT events. Thick lines show half of sidereal month where HFT events are rare. Abbreviations near the bottom of the diagram indicate zodiac constellations faced by the front side of the Moon at indicated days.

All but five of the 28 HFT events occurred within 1/4 month (~7 days) of the time when the Moon was at right ascension of 0 hours, i.e., when the Moon was facing towards right ascension of 12 hours, in the general direction of constellation Virgo. If we exclude four events with epicenters on the far side of the Moon, 22 of the 24 front-side events occurred within the above specified time interval. This means that they tend to occur when the Moon faces a particular direction relative to the stars. This, therefore, suggests that they are not of internal, tectonic origin but instead are caused by or triggered by objects originating outside the solar system.

Statistical Tests: We have conducted several statistical tests, and they indicate that the probability is 1-2% or less that these events’ seismic origin times are random occurrences. For the 27.32-day sidereal month, the Rayleigh statistic [4] *D* is 11.5 for all 28 events and 13.8 for the 24 front-side events (Fig. 2a); these statistics are significant at the 99% and 99.9% levels, respectively. Application of the Rayleigh test for a range of periods from 22 to 32 days (Fig. 2b) demonstrates that the only peaks in *D* significant at the 99% level occur near 27.32 days and have widths at half-maximum of about 0.37 days.

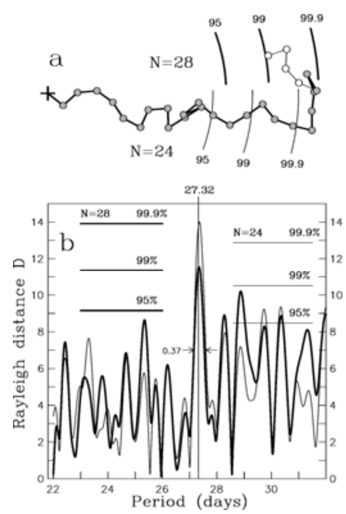

Fig. 2. Rayleigh’s test for periodic behavior. (a) Sum *D* of unit vectors with phase angle of lunar sidereal month (27.32 days) for near-side (solid circles and thick lines) and far-side (open circles and thin lines) HFT events. Labeled arcs indicate significance percentiles for *N*=28 (thick lines) and *N*=24 (thin lines) for *D* significant at 99% and 99.9% levels, respectively. (b) Variation of sum *D* as period changes from 22 to 32 days for all HFT events (thick lines) and near-side events only (thin lines). Note that *D* for both groups peaks at periods near 27.32 days, and that the half-width of these peaks is approximately 0.37 days.

Finally, we generated 1000 sets of 28 random times uniformly distributed within a 5-year interval and applied the tests described above to these sets. For the simulated data sets, the Rayleigh test identified 1% with a 99%-level peak at 27.32 days (as expected); however, 42% have a 99%-level peak at some other period between 22-32 days. Thus observing any 99%-level peak isn't highly significant; rather, the key observations are that we observed such a peak precisely at the period of the sidereal month, and the statistical significance improves when we remove events situated on the Moon's far side. That it, these events occurring on the front side of the Moon around the seismic network mostly occur during the specific half-month when the Moon's near side faces approximately towards the right ascension of 12 hours. Moreover, three of the five events that occurred at other times had epicenters on the Moon's far side; these include the two largest events which were most likely to be observable at far distances.

Possible Causes: HFT events are clearly a seismic phenomenon and not an artifact of the data collection process. Most are observed on all four stations of the Apollo seismic network, exhibiting onset times of P and S that are separated by intervals appropriate for seismic wave transmission through the Moon. The largest HFT events have estimated seismic energy that corresponds to terrestrial earthquakes with magnitude m_b of about 5 [5, 6]. However, the majority of events are much smaller, giving estimated seismic energy release of 10^3 to 10^8 J. These observations cannot be explained by, for example, a shower of cosmic rays that interferes with seismograph electronics or data transmission. A sidereal period may appear with impacts of ordinary meteoroids originating inside the solar system, but their periodicity is more heavily influenced by the synodic period of 29.53 days [7], while no synodic periodicity is observed for HFT events. Some deep moonquake nests may mimic sidereal periodicity for a limited period of time if the two tidal components of close periods, the nodic (27.21 days) and anomalistic (27.55 days), interact at a precise ratio; but this is for very specific locations in the Moon and does not apply to globally distributed events such as HFTs.

If the observed distribution is not a statistical aberration, what explains it? One possibility is that meteoroids from a source outside the solar system cause or trigger these events that tend to be observed when the Moon's front side faces their direction of approach. However, the seismic signature of HFT events is unlike that of ordinary meteoroid impacts. Thus, if extra-solar-system meteoroids cause these events, their composition and/or impact speed must allow them to punch through the lunar regolith and distribute most of their energy at greater depths than ordinary meteoroid impacts. There are reports of meteors possibly of extra-solar-system origin, but their reality is often uncertain and their estimated speed barely exceeds the escape velocity from the solar system [8]. Therefore, they are unlikely to produce seismic signatures significantly different from ordinary meteoroid impacts, even if they exist.

A second possibility is that exotic high-energy particles such as nuggets of strange quark matter (SQM) might cause or trigger HFT events [9, 10]. However, previous calculations using a presumed density in the range of 10^{14} g/cm^3 conclude that nuggets massive and energetic enough to produce observable seismic signals will pass entirely through the Moon or Earth [11]. If they pass completely through the Moon, they would be observable seismically throughout the sidereal month. To produce the observed monthly periodicity, the Moon's interior must have properties that stop SQM, or SQM nuggets must have certain yet-unknown properties that prevent them from passing completely through the Moon.

Final Remarks: With limited observations, the result reported here is far from conclusive. However, it certainly warrants further investigation, considering its potential influence in our understanding of matters in our universe. Statistics would improve if we can identify more HFT events, and thus we should search for them among hundreds of thousands of events recorded with Apollo short-period seismometers. If they are real, we may also find them among seismic activities in stable continental shields on Earth, where ambient seismic noise is low.

Acknowledgements: We thank V. L. Teplitz and P. Schultz for many helpful comments and suggestions concerning impact effects of SQM nuggets and meteoroids, respectively.

References: [1] Nakamura Y. et al. (1974) *Proc. LSC, 5th,* 2883-2890. [2] Nakamura Y. (1977) *Phys. Earth Planet. Inter., 14,* 217-223. [3] Nakamura Y. (1979) *Proc. LPSC, 10th,* 2299-2309. [4] Rayleigh L. (1919) *Philos. Mag., 27,* 278-288. [5] Goins N. (1981) *J. Geophys. Res., 86,* 378-388. [6] Oberst J. (1991) *J. Geophys. Res., 92,* 1397-1405. [7] Obserst J. and Nakamura Y. (1991) *Icarus, 91,* 315-325. [8] Ceplecha Z. et al. (1998) *Space Sci. Rev., 84,* 327-471. [9] Witten E. (1984) *Phys. Rev. D, 30,* 272-285. [10] De Rújula A. and Glashow S. L. (1984) *Nature, 312,* 737-738. [11] Herrin E. T. and Toplitz, V. L. (1996) *Phys. Rev. D, 53,* 6762-6770.