Evidence of Eta Aquariid Outbursts Recorded in the Classic Maya Hieroglyphic Script Using Orbital Integrations

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Abstract

No firm evidence has existed that the ancient Maya civilization recorded specific occurrences of meteor showers or outbursts in the corpus of Maya hieroglyphic inscriptions. In fact, there has been no evidence of any pre-Hispanic civilization in the Western Hemisphere recording any observations of any meteor showers on any specific dates.

The authors numerically integrated meteoroid-sized particles released by Comet Halley as early as 1404 BC to identify years within the Maya Classic Period, AD 250–909, when Eta Aquariid outbursts might have occurred. Outbursts determined by computer model were then compared to specific events in the Maya record to see if any correlation existed between the date of the event and the date of the outburst. The model was validated by successfully explaining several outbursts around the same epoch in the Chinese record. Some outbursts observed by the Maya were due to recent revolutions of Comet Halley, within a few centuries, and some to resonant behavior in older Halley trails, of the order of a thousand years. Examples were found of several different Jovian mean motion resonances as well as the 1:3 Saturnian resonance that have controlled the dynamical evolution of meteoroids in apparently observed outbursts.

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1. Introduction

1.1. Historical background

Investigating meteor outbursts or even meteor showers at all in the Maya records presents unique problems since a majority of the ancient books known as codices, possibly containing original astronomical observations, were destroyed by the Spanish after their arrival into Maya territory in the 16th century[3]. Surviving tables and almanacs in these books contain astronomical information relating to Venus, solar and lunar eclipses, and seasonal information for agricultural purposes. Stone monuments, panels, painted murals and portable objects such as bones, shells and ceramic vases however still do exist from the Classic Period and contain hieroglyphic inscriptions that record close to an estimated 2000[4] dates in the Maya calendar (Mathews, 2016). Many of the dates carved in stone record dynastic information such as lineage, births, accessions to rulership and deaths, war events such as "axing," "prisoner-capture" and "Star War" victories over rival polities, and dedicatory events such as Period Endings (see footnote 10) and fire ceremonies. Although much of the inital information inscribed on stelae includes lunar information such as the age of the moon, and the number and length of the lunation (see for instance Schele et al., 1992), little else seemed to have been inscribed outright regarding astronomical information[5]. Incredibly, that notion changed in 2012 with the discovery of an early 9th century astronomer's workshop (Saturno et al., 2012) that contained lunar tables and numbered arrays painted on the walls of a small room indicating commensuration applications to various Maya calendrical and astronomical cycles.

Clearly, the Maya had the capability for investigating and recording a phenomenon such as a meteor shower. The question was, was that astronomical information completely lost or merely embedded in the extant inscriptions?

The ancient Maya area covers the northern latitudes from about 14° to 21.5°N and western longitudes from about 87° to 93°W, including the modern Central American countries of eastern Mex-

[3]In 1562 under the direction of Bishop Diego de Landa, a large number of codices were burned in an action known as the *auto de fe* (Landa, 1566, p. 169, 77, 134).

[4]Counts separately dates duplicated at different sites.

[5] One notable exception of a recorded astronomical event during the Classic Period is a solar eclipse of AD 790 found on a monument at the site of Santa Elena Poco Uinic.

ico, Guatemala, Belize, El Salvador and western Honduras. Although the Eta Aquariids are considered primarily a southern latitude shower, the radiant would have been visible to the Maya in the east for more than three hours before morning twilight. Without any known recorded radiant information, the authors' approach in this paper is to compare the date and time of any computed outbursts to events recorded on or near that date[6].

An "event" refers to any recorded information as described earlier in this section. Those events and associated protagonists and dates are the subject of this paper. In addition, results are computed and compared to ancient Eta Aquariid dates in the Chinese record (Table 5) and Vaubaillon's computations (Jenniskens, 2006, table 5e) of possible historic Eta Aquariid outbursts (Table 6).

1.2. Previous attempts at identifying observations of meteor showers

Hagar (1931) wrote that the Mexicans, pre-dating the arrival of the Spanish, commemorated falling stars called "Tzontemocque or Falling Hairs" by the celebration of an annual festival called Quecholli. He maintained that falling figures shown in various Mexican codices such as the Borgia (Borgia) and Vaticanus 3773 (Vaticanus-3773) represent a meteor shower, possibly the Leonids and another figure the Taurids. Kohler (2002) notes that the Aztecs recorded a meteor in 1489 in the Telleriano-Remensis (Telleriano-Remensis, 1901) on page 39V of that codex (see also Taube, 2000, p. 287-290).

By using a one day shift for every 71 years for Earth's axis precession, Trenary (1987-1988, p. 112-3) calculated a possible Leonid shower date in the Maya corpus within a few days of 709 October 28[7], although the precession additionally of Leonid orbits themselves

[6] All dates and times throughout this treatise are in the Julian Calendar, UT. To convert UT to local (Mexican) time, subtract 6 hours. When converting from the Christian calendar to the Maya calendar, the authors used the correlation constant of 584286 (see Martin and Skidmore (2012), Kennett et al. (2013)). The correlation constant represents the Julian Day Number that corresponds to the Maya Long Count of 13.0.0.0.0, referred to as the "Creation Date". 584286 corresponds to 3114 BC September 9, 12:00 UT, Julian Calendar. The day following the creation date would have been written 13.0.0.0.1, a Julian Day Number of 584287. Other commonly accepted correlations are 584283 and 584285. Conversion from Maya calendar to Julian Day Numbers accomplished using online software by Van Laningham. Conversion from Julian Day Number to Julian Calendar accomplished using software by Simulation Curriculum Corp. (2009). Solar longitudes and ΔT (Table 6 only; other tables Meeus (2000, p. 78)) obtained through JPL'S Horizons system (Giorgini et al., 1996)

[7] The date is found on a stone panel known as Lintel 24 at the site of Yaxchilan.

suggests the expected date around AD 709 may be 2-3 weeks earlier than October 28 (Ahn, 2005).

Kinsman (2014, p. 98) calculated that two Perseid meteor shower dates in AD 933 and 775 are possibly recorded in cognate (similar) almanacs found in the codices. The suspected outburst in 933 falls on the same date that China observed a Perseid outburst (Zhuang, 1977, p. 203) (Pankenier et al., 2008, p. 325).

Therefore other than sidereal year calculations to produce dates that would yield solar longitudes associated with applicable showers, prior to our investigation there had been no scientific attempts such as numerical integrations by high-speed computers to correlate any ancient Maya dates with any meteor outbursts from any meteoroid streams.

1.3. Halley's comet and the Eta Aquariids

The authors decided to investigate Eta Aquariid outbursts. One reason is that the orbit of parent comet 1P/Halley, during and for some time before the Maya Classic Period, is well constrained, reliable observations dating back to 240 BC in Chinese records (Kiang, 1972) and 164 BC in Babylonian cuneiform texts (Stephenson et al., 1985). Yeomans and Kiang (1981) showed that their computed orbit is valid back to 1404 BC, but that Halley's very close approach by Earth in that year affected the comet's orbit to the extent that computer models cannot accurately match it at earlier epochs. Since our study depends on the meteoroid particles being ejected at each starting epoch, knowing each exact time is critical in determing the later position of the particles at a Maya year of observation. By correcting their computer model with actual historic observations of Halley's passage by Earth in 837, 374 and 141, Yeomans and Kiang (1981) produced a model with minimum differences in computed and observed times of perihelion passage, noting (p. 642) the extrapolated computed times' likely accuracy to better than a month even as long ago as 1404 BC.

The Halley meteoroid stream produces the Orionids (IAU meteor shower code 00008 ORI) pre-perihelion at the ascending node and the Eta Aquariids (00031 ETA) post-perihelion at the descending node. The reason to focus here on ETA is that 1P/Halley's descending node came closest to Earth's orbit around AD 500 (the ascending node around 800 BC). Although meteoroid orbits over time can precess away from the comet orbit to have nodal intersections at different epochs – after all, both ORI and ETA showers are observable at present – the authors surmised that the chances for the strongest outbursts in the first millennium AD due to meteoroids released at recent revolutions of Halley were best for ETA.

Recent orbital analysis by Sato and Watanabe (2014) showed that enhanced ETA activity in 2013 was due to dust trails produced by Halley ~3 kyr earlier, in 1198 BC and 911 BC. In principle some outbursts observed by the Maya could be due to trails from before 1404 BC, but our current aim is to determine observable ETA outbursts from trails created since then.

2. Methodology

Given a starting epoch when particles are released by the comet and an "end" year, we consider whether particles from that starting epoch can reach Earth intersection in that end year, and if so then at what date and time.

Particles from each return of the comet soon stretch into a trail owing to variations in initial orbital period. Particles undergo planetary perturbations which are a function of where they are along the trail (Plavec, 1956, 1957). If a part of a trail is perturbed to Earth intersection an outburst occurs.

Instead of period we adopt Δa_0, the difference between particle and comet semi-major axis a at ejection time, to parametrize the trail. Similar 1-parameter techniques to identify orbits that intercept Earth at a later epoch have been used to successfully model meteor outbursts in many streams (e.g., Kondrat'eva and Reznikov, 1985; Lyytinen et al., 2001; Maslov, 2011; McNaught and Asher, 1999; Sato and Watanabe, 2010, 2014).

We search for values of Δa_0 corresponding to particles passing Earth at small "miss distance" $\Delta r \equiv r_E - r_D$ (Δr is proportional to orbit–orbit minimum distance and is easier to compute) and for such particles compute also $f_{\mathcal{M}}$ ($|f_{\mathcal{M}}|$ represents the along trail spatial density of particles) and the calendar date when Earth reaches the particles' descending nodal longitude (essentially the peak outburst time); further explanation of these quantities is in Asher (2000).

If a particle is ejected tangentially at perihelion with relative speed ΔV_T, then for 1P/Halley's orbit,

$$\frac{\Delta a_0}{\Delta V_T} \approx 0.04\,\mathrm{au/(m/s)}. \tag{1}$$

Releasing particles in the visual meteor size range 0.5 down to 0.1 cm radius at a density of 1 g/cc (Babadzhanov and Kokhirova, 2009 quote 0.9±0.5 g/cc for Orionids) in tangential positive and negative directions at each perihelion passage of Halley requires velocities ∼ 34 to 76 m/s, taking the comet radius as 4 km in the Whipple (1951) model, i.e., ejection speeds up to ∼76 m/s occur for such particles.[8] This is equivalent to a Δa_0 range of ±3 au from Halley's a of ∼18 au (Equation 1).

Solar radiation pressure increases a particle's orbital period. The parameter β, the ratio of radiation pressure and gravity forces, depends on particle size and density (Burns et al., 1979, pp. 13–14), with a particle of radius 0.1 cm having $\beta \approx 1.0 \times 10^{-3}$. Equation (2) of Asher and Emel'yanenko (2002) following Reznikov (1983) gives

$$\Delta V_T \approx (V_q\beta)/2 = 54.6\,\mathrm{km/s} \times 10^{-3}/2 \approx 27\,\mathrm{m/s}$$

where V_q is Comet Halley's perihelion velocity ∼55 km/s. Since the effect when $\beta = 10^{-3}$ is equivalent to a change in velocity $\Delta V_T \approx 27$ m/s, then from Equation 1 this solar radiation pressure has the same effect on the period as ejecting a particle with $\Delta a_0 \approx 1.1$. Therefore to compensate for solar radiation pressure ∼1 au should be added in the positive tangential direction.

Thus the integrations were carried out over a range of 16 to 22 au, the upper part of the range associated more with smaller meteoroids (larger β). Initially there were 400–600 particles with a typical spacing of 0.01 au or slightly larger. Interesting intervals of Δa_0 parameter space, with particles approaching Earth at $|\Delta r| \leq 0.01$ au, were then expanded, additional integrations with a typical spacing of 0.00001 au in Δa_0 aiming to identify the exact time and date of the outburst. A trail's density cross section is strongly peaked towards the center where Δr=0 (McNaught and Asher, 1999); numerical experiments (cf. Asher, 2008) suggest an ETA trail encounter can still generate significant meteor activity for $|\Delta r|$ up to a few

[8]It can be shown that for isotropic ejection directions at a given single speed, the expected value of the tangential component is half that speed.

times 0.001 au. Further integrations were performed until the particles converged on a solution identifying Δa_0, Δr and $f_{\mathcal{M}}$ showing an outburst at a specific time and date.

Orbits for 1P/Halley's perihelion returns were from Yeomans and Kiang (1981, table 4) and initial state vectors of eight planets from JPL Horizons (Giorgini et al., 1996). Computations used the RADAU algorithm (Everhart, 1985) implemented in the MERCURY integrator (Chambers, 1999). The authors verified Sato and Watanabe's (2014) predictions for the ETA outbursts in 2013 with similar integrations, and using the same technique considered in detail 55 different "end" years found in the data base of the Maya corpus of inscriptions wherein a possible ETA outburst might have been recorded.

3. Results

3.1. Maya events

The most common event and one that could easily be planned to coincide on or near a meteor shower that occurred in our data set was the royal accession, a king or queen's assuming rulership over a polity ("taking the royal throne"). There were 14 accession events in the time frame under investigation:

967 BC (*U Kokan Chan* from *Palenque*)(5.8.17.15.17)[9],
484 (*Yajaw Te' K'inich I* from *Caracol*)(9.2.9.0.16),
511 (*Lady of Tikal* from *Tikal*)(9.3.16.8.4),
531 (*K'an I* from *Caracol*)(9.4.16.13.3),
553 (*Yajaw Te' K'inich II* from *Caracol*)(9.5.19.1.2),
572 (*Kan Bahlam I* from *Palenque*)(9.6.18.5.12),
636 (*Yuknoom Ch'en* from *Calakmul*)(9.10.3.5.10),
639 ("Ruler 2" from *Piedras Negras*)(9.10.6.5.9),
640 ("Ruler A" from *Coba*)(9.10.7.5.9),
662 (accession 2 of *Muwan Jol? Pakal*)(9.11.9.11.3),
686 (*Yuknoom Yich'aak K'ahk'* from *Calakmul*)(9.12.13.17.7),

[9]Maya Long Count date, typically composed of 5 digits in a modified vigesimal system where the 3rd digit from the right counts in units of 360 days. See Van Laningham for instance. The Long Count keeps track of numbers of days in a manner similar to the Julian Day Number. 967 BC is likely a mythological date and *U Kokan Chan* likely a mythological ruler

752 (*Bird Jaguar IV* from *Yaxchilan*)(9.16.1.0.0),
781 (unknown ruler from *Los Higos*)(9.17.10.7.0),
802 (*Lachan K'awiil Ajaw Bot* from *La Amelia*)(9.18.11.12.0).

The data set also included rare events such as:

644 (*jatz'bihtuun*, "strike the stone road" at *Naranjo*)(9.10.11.6.12),
790 (*jatz'bihtuun*, "strike the stone road" at *Naranjo*)(9.17.19.9.1),
849 (*u-pataw kab'aj*, "forms the earth"? at *Caracol*)(10.0.19.6.14).

The "strike the stone road" event is unique because there are only four such occurrences of this event currently known in the corpus of inscriptions and one incidence of the "forms the earth"? event.

Outbursts occurring on Period Ending dates[10] would be coincidental. Period Endings found in our data set included the years 480 (9.2.5.0.0), 618 (9.9.5.0.0), 687 (9.12.15.0.0), 752 (9.16.1.0.0) and 756 (9.16.5.0.0).

Four royal births occurred within the constraints of our data set: 566 (*Lady B'atz' Ek'* from *Caracol* on 9.6.12.4.16), 588 (*K'an II* from *Caracol* on 9.7.14.10.8), 606 (*Hix Chapat* from *Tonina* on 9.8.12.14.17) and 750 (Ruler 7 from *Piedras Negras* on 9.15.18.16.7). A birth occurring near the time of an outburst would likely be coincidental.

Altogether we have a data set comprising 55 different years, each with one or more recorded Maya events (Appendix A). To investigate outbursts, all years were checked in conjunction with all possible 1P/Halley starting epochs back to and including the 240 BC return, 46 of them back to 616 BC, 36 to 911 BC and 29 to 1404 BC. Tables 1 (Early Classic) and 2 (Late Classic) list the 30 end years having the best possibility of strong outbursts based on the solution parameters Δa_0, Δr and $f_{\mathcal{M}}$, and observable time within the Maya's visual range. Apart from the computed outburst in 572 due to the 911 BC trail listed in Table 1 there were only 3 somewhat successful solutions involving trails from earlier than 616 BC, none with good enough parameters to warrant inclusion in Tables 1 and

[10] Period Ending (*pe*) dates are typically separated by 360 day (*tuun*) intervals where the day or *K'in* position, the most right placed digit, and the month or *Winal* position, the second most right position, would both be zero. Higher *pe* dates involving 7,200 and 144,000 day intervals in a similar scheme are also possible.

2.

Tables 3 and 4, which collectively list the same end years as Tables 1 and 2, show that there may have been two categories of Eta Aquariid outbursts that were noted by the Maya, one involving outbursts that occurred near the time of a particular event by plus or minus five days and secondly whereby an outburst preceded an event by approximately one week up to three weeks. The second category presents a more difficult problem of connecting the ETA outburst to that particular event because of the possibility of an intervening shower – for instance, an outburst noted (Zhuang, 1977, p. 200),(Pankenier et al., 2008, p. 311) on AD 461 April 20 could have been one such shower if 461 was a year of interest.

The best cases among these 30 identified years during the Maya Classic Period are discussed individually in Section 4.

3.2. Historical Eta Aquariid outbursts observed from China

Our integrations of recorded observations in the Chinese record during the years parallel to the Maya Classic Period showed a high correlation to those dates and times and validated our model. Table 5 shows computed results for ancient observations that are all attributed to China (Zhuang, 1977, pp. 199-200)(Imoto and Hasegawa, 1958, p. 134, table 1) (Pankenier et al., 2008, pp. 309-325, 648-659). Comet Halley input parameters were the same as for the Maya end years.

Several integrations, 401, 443, 466, 530, 839, and 905 correlated directly to the associated dates of the observed outbursts; 401, 443, 530 and 839 showed computed outburst times either within or within a few minutes of the visual range while computed times in 905 and 927 were slightly over an hour outside the visual range. The 927 return differed by one day from the recorded observation. There was a very strong 443 return on April 8 one day prior to the reported outburst followed by another outburst on April 9, the recorded date. Similarly, in 905 a moderate outburst occurred two days prior to the recorded outburst on April 13. The historical record for a 461 outburst is not classified as an ETA by Zhuang (1977) or Imoto and Hasegawa (1958), however integrations showed strong outbursts visible from China on both April 8 and 9. Therefore it is possible that there actually was an ETA outburst in 461 where the date registered was in error.

Table 1: Possible Eta Aquariid outbursts during the Early Classic Period (AD 250–600). Solar longitude in J2000.0, date in Julian calendar, TT converted to UT using Meeus (2000, p. 78). Tr = Year of Halley perihelion passage. For negative years, add (−1) to convert to BC, i.e., (−239) + (−1) = 240 BC. Positive/negative $f_{\mathcal{M}}$ is mean anomaly $\mathcal{M}$ at end date decreasing/increasing function of Δa_0. Final quoted decimals are of no significance, accuracy being limited by comet input data and by knowledge of the meteoroid ejection model, but are retained to enable reproducibility of results if the same data and model are used. Visibility considers whether the computed peak time is within the range of possible visual observation (after radiant rise and at least half an hour before sunrise); there may be increased activity for up to a few hours around this.

Yr	$\lambda_\odot$	Date Time	Tr	Δa_0 (au)	Δr (au)	$f_{\mathcal{M}}$	Visibility
328	42.727	Apr 9 04:19	−239	+0.932	−0.00057	−0.009	−3h 41m
	42.682	Apr 9 03:12	−239	+0.931	−0.00099	+0.003	−4h 48m
480	43.983	Apr 11 10:54	−86	+1.089	−0.00545	−0.019	vis rng
484	42.045	Apr 9 11:28	218	+1.730	+0.00280	+0.162	+0h 13m
511	42.879	Apr 11 06:18	141	+2.578	+0.00273	−0.010	−1h 47m
531	41.962	Apr 10 10:39	451	+0.075	+0.00081	+1.008	vis rng
	41.899	Apr 10 09:05	295	+0.048	−0.00155	+0.666	vis rng
	41.884	Apr 10 08:42	374	+0.052	−0.00089	+0.759	vis rng
556	41.332	Apr 9 04:50	374	+2.039	+0.00215	+0.464	−3h 14m
562	43.011	Apr 11 11:21	−163	+1.967	+0.00022	+0.001	+0h 1m
	42.991	Apr 11 10:51	−163	+1.967	−0.00022	−0.002	vis rng
	42.958	Apr 11 10:02	−163	+1.967	−0.00096	+0.013	vis rng
	42.951	Apr 11 09:51	−163	+1.967	−0.00111	−0.004	vis rng
	41.950	Apr 10 09:00	−239	+3.368	+0.00347	−0.015	vis rng
	41.947	Apr 10 08:57	−239	+3.367	+0.00365	+0.008	vis rng
	41.907	Apr 10 07:57	−239	+3.376	+0.00252	+0.012	−0h 12m
	41.901	Apr 10 07:47	−239	+3.372	+0.00265	+0.011	−0h 21m
	41.898	Apr 10 07:44	−239	+3.375	+0.00253	+0.007	−0h 25m
	41.895	Apr 10 07:39	−239	+3.372	+0.00264	−0.006	−0h 30m
566	41.963	Apr 10 09:59	−239	+2.098	−0.00131	−0.074	vis rng
	41.806	Apr 10 06:06	−239	+2.111	−0.00412	+0.069	−2h 3m
572	42.348	Apr 10 08:24	−910	−1.414	−0.00167	+0.002	vis rng
	42.307	Apr 10 07:23	−910	−1.413	−0.00234	−0.007	−0h 42m
	42.302	Apr 10 07:15	−910	−1.412	−0.00236	−0.001	−0h 50m
	42.274	Apr 10 06:34	−910	−1.412	−0.00238	−0.006	−1h 31m
588	43.311	Apr 11 10:47	−11	−0.096	+0.00506	−0.017	vis rng

Table 2: Possible Eta Aquariid outbursts during the Late Classic Period (AD 600–909).

Yr	$\lambda_\odot$	Date Time	Tr	Δa_0 (au)	Δr (au)	$f_\mathcal{M}$	Visibility
614	44.320	Apr 13 03:57	−86	+0.363	+0.00467	−0.009	−3h 55m
	43.624	Apr 12 10:40	530	+1.137	+0.00575	+1.090	vis rng
	43.346	Apr 12 03:46	−465	−1.189	+0.00360	−0.051	−4h 10m
	43.341	Apr 12 03:39	−465	−1.192	+0.00341	−0.306	−4h 17m
618	41.644	Apr 10 10:02	−390	+0.670	+0.00138	−0.006	vis rng
	41.574	Apr 10 08:18	−390	+0.694	−0.00239	+0.088	vis rng
636	42.712	Apr 11 03:22	530	+4.531	−0.00117	+1.282	−4h 40m
639	43.923	Apr 13 03:58	−239	+1.979	−0.00335	−0.027	−3h 54m
644	43.900	Apr 12 09:54	−86	+2.420	+0.00549	−0.016	vis rng
	42.981	Apr 11 11:05	374	+1.945	−0.00008	−0.003	vis rng
662	42.294	Apr 11 09:02	−465	+2.635	+0.00579	−0.037	vis rng
	42.279	Apr 11 08:40	−465	+2.637	+0.00557	+0.020	vis rng
663	43.929	Apr 13 07:47	−465	+0.262	−0.00333	−0.092	−0h 10m
	43.896	Apr 13 06:57	−465	+0.261	−0.00374	+0.018	−1h 0m
675	44.915	Apr 14 10:05	−239	−0.465	+0.00341	+0.008	vis rng
	44.781	Apr 14 06:48	−239	−0.460	+0.00193	+0.018	−1h 8m
687	43.677	Apr 13 05:16	218	+3.369	+0.00001	+0.002	−2h 44m
	40.708	Apr 10 03:37	−163	−1.302	+0.00024	+0.120	−4h 23m
691	43.691	Apr 13 06:05	−314	+0.534	−0.00181	−0.002	−1h 49m
716	43.496	Apr 12 10:56	141	+2.714	+0.00071	+0.042	vis rng
	43.487	Apr 12 10:42	141	+2.715	+0.00048	−0.016	vis rng
	43.429	Apr 12 09:16	141	+2.691	+0.00251	−0.577	vis rng
721	43.139	Apr 12 08:59	−86	+3.794	+0.00362	−0.005	vis rng
	43.128	Apr 12 08:42	−86	+3.794	+0.00344	+0.007	vis rng
750	42.782	Apr 12 10:35	−465	+2.578	−0.00306	+0.004	vis rng
752	42.125	Apr 11 06:37	141	+1.616	−0.00435	−0.088	−1h 23m
	42.120	Apr 11 06:30	141	+1.610	−0.00431	+0.427	−1h 30m
	42.115	Apr 11 06:22	141	+1.599	−0.00411	−0.678	−1h 38m
756	42.165	Apr 11 08:10	218	+1.785	−0.00521	−0.094	vis rng
	41.315	Apr 10 11:05	218	+3.901	−0.00019	−0.015	vis rng
781	45.619	Apr 15 07:53	−239	+1.974	−0.00042	+0.033	vis rng
790	41.601	Apr 11 11:33	218	−1.304	+0.00075	+0.211	+0h 21m
	41.598	Apr 11 11:29	218	−1.304	+0.00071	−0.137	+0h 17m
802	40.388	Apr 10 07:17	218	+0.482	−0.00148	+0.002	−1h 1m
820	42.863	Apr 12 11:18	−86	+3.795	+0.00018	+0.002	vis rng
849	44.303	Apr 14 09:36	−465	+0.638	−0.00027	−0.022	vis rng
	44.279	Apr 14 09:00	−465	+0.638	−0.00040	+0.022	vis rng

Table 3: Outburst within ±5 Days of Event. Moon = moon age in days, r or s = rise or set, unk = unknown, acc = accession, pe = Period Ending, *pat* = *pat-kab* = "to form the Earth". Sites: WAX = Waxactun, CRC = Caracol, PAL = Palenque, ALS = Altar de Los Sacrificios, PNG = Piedras Negras, MRL = Moral-Reforma, TZE = Tzendales, NAR = Naranjo, AML = La Amelia, HIG = Los Higos. Diff = number of days different.

Yr	Outburst	Moon	r or s	Event	Date	Site	Diff
328	Apr 9	13.4	10:58s	unk	Apr 11	WAX	+2
484	Apr 9	27.3	10:08r	acc	Apr 13	CRC	+4
531	Apr 10	7.8	06:54s	acc	Apr 14	CRC	+4
556	Apr 9	13.5	10:52s	axe	Apr 10	CRC	+1
572	Apr 10	11.1	09:44s	acc	Apr 7	PAL	−3
614	Apr 13	28.3	10:42r	tomb	Apr 12	CRC	−1
	Apr 12	27.4	10:07r	tomb	Apr 12	CRC	0
618	Apr 10	10.0	08:22s	pe	Apr 14	ALS	+4
639	Apr 13	3.8	03:27s	acc	Apr 13	PNG	0
644	Apr 12	29.4	11:59r	strike	Apr 9	NAR	−3
	Apr 11	28.2	11:16r	strike	Apr 9	NAR	−2
662	Apr 11	16.5	13:21s	acc	Apr 6	MRL	−5
687	Apr 13	24.8	08:45r	pe	Apr 12	PNG	−1
	Apr 10	21.6	06:15r	pe	Apr 12	PNG	+2
691	Apr 13	9.4	08:00s	tomb	Apr 12	TZE	−1
750	Apr 12	1.8	12:37r	birth	Apr 8	PNG	−4
756	Apr 11	6.2	05:49s	pe	Apr 9	PNG	−2
	Apr 10	5.4	05:01s	pe	Apr 9	PNG	−1
781	Apr 15	17.4	13:29s	acc	Apr 18	HIG	+3
790	Apr 11	22.5	06:49r	strike	Apr 12	NAR	+1
802	Apr 10	4.3	15:19r	acc	Apr 8	AML	−2
820	Apr 12	25.1	08:38r	tomb?	Apr 13	CRC	+1
849	Apr 14	17.5	13:47s	*pat*	Apr 15	CRC	+1

Table 4: Outburst Preceding or Following Event by Seven Days or More. Events: pe = Period Ending, star = Star War (a conquering of one polity over another), acc = royal accession, ded = dedicatory event, arr = arrival, Sites: QRG = Quirigua, TIK = Tikal, CRN = La Corona, CLK = Calakmul, YAX = Yaxchilan, DPL = Dos Pilas.

Yr	Outburst	Moon	r or s	Event	Date	Site	Diff
480	Apr 11	15.6	12:20s	pe	Apr 18	QRG	+7
511	Apr 11	26.9	10:22r	acc	Apr 20	TIK	+9
562	Apr 11	21.5	05:54r	war	Apr 30	CRC	+19
	Apr 10	20.3	04:57r	war	Apr 30	CRC	+20
566	Apr 10	5.0	05:23s	birth	Apr 23	CRC	+13
588	Apr 11	8.8	07:57s	birth	Apr 19	CRC	+8
636	Apr 11	28.4	11:01r	acc	Apr 29	CLK	+18
663	Apr 13	29.3	11:44r	ded	Apr 23	CRN	+10
675	Apr 14	13.3	10:58s	emerge	Apr 26	CRN	+12
716	Apr 12	15.5	12:29s	war	Apr 4	NAR	−8
721	Apr 12	10.0	08:50s	arr	Apr 27	CRN	+15
752	Apr 11	21.8	06:17r	acc	Apr 30	YAX	+19

Integrations for the years 466 and 934 showed outbursts outside of the visual range by over 4 hours and 7 hours respectively, and no result was found for the 74 BC outburst so it is possible that those outbursts originated prior to 1404 BC.

3.3. Comparison with table 5e of Jenniskens (2006)

The authors ran integrations for the trail/year combinations listed in Jenniskens (2006, table 5e, p. 666). Results are also included in Table 6 from different trails that produced outbursts in the same end years as listed in Table 1. The results with date and times were similar where heavy outbursts were noted, such as in the years 531, 539 and 964. Compared to the intense outbursts in 531 from three different trails (Section 4.2), the 218 trail would have produced a very light outburst in our model. The outburst in 511 computed by the authors and possibly noted by the Maya in their inscriptions would have been due to a different trail other than was reported in table 5e; also the 511 outburst as shown in table 5e would not have been observed in the Maya area as noted by the time of outburst. The strong outburst in 964 has not been noted in any of the extant inscriptions so far in the Maya record, but 964 is later than the Classic Period by over 50 years, so this would not be a surprise. The only other time of outburst noted in table 5e that might have been visible to the Maya was 692. The authors' model however shows a

Table 5: Data for Historically Observed Eta Aquariid Outbursts (China). Observed outbursts compared to integrations. Visible range from radiant rise to one half hour prior to sunrise, approx. 18:20 to 21:10 UT, but computed outburst time vs. actual visual range is calculated from the geographical coordinates of the capital city of the ruling dynasty (Pankenier et al., 2008, p. 468). See also caption to Fig. 1. Year 461 results shown for informational purposes only (i.e., historical record described an outburst on April 13 but not as ETA, however either the month or day was inscribed in error).

Yr		$\lambda_\odot$	Date Time	Tr	Δa_0 (au)	Δr (au)	$f_\mathcal{M}$	
74	Ob	41.3	Apr 6.0					
BC	Int	none						
401	Ob	41.5	Apr 8.7					
	Int	41.733	Apr 8 20:37	−390	+0.427	−0.00508	+0.032	vis rng
443	Ob	42.0	Apr 9.9					0, +1d
	Int	40.917	Apr 8 18:50	295	−0.890	+0.00009	+0.653	vis rng
	Int	41.929	Apr 9 19:57	−163	+1.604	−0.00044	−0.006	vis rng
	Int	41.950	Apr 9 20:28	66	−0.102	−0.00023	+0.001	vis rng
	Int	41.959	Apr 9 20:41	66	−0.102	−0.00011	−0.006	vis rng
461	Ob	46.142	Apr 13 19:30					
	Int	41.274	Apr 8 18:33	374	+1.532	−0.00228	+1.134	vis rng
	Int	42.301	Apr 9 20.02	141	−1.998	+0.00295	+0.250	vis rng
466	Ob	41.0	Apr 8.8					
	Int	40.817	Apr 8 13:48	295	+0.905	−0.00244	+0.751	−4h 35m
530	Ob	41.5	Apr 9.7					
	Int	41.690	Apr 9 21:34	−465	+0.075	+0.00312	+0.204	+0h 2m
839	Ob	43.2	Apr 13.7					
	Int	43.269	Apr 13 18:30	141	+1.736	−0.00085	−0.144	−0h 20m
905	Ob	43.3	Apr 13.7					0, +2d
	Int	41.432	Apr 11 18:56	−11	+0.901	+0.00231	−0.007	vis rng
	Int	41.432	Apr 11 18:56	−11	+0.935	−0.00348	+0.030	vis rng
	Int	43.527	Apr 13 22:54	−163	+1.930	+0.00226	+0.003	+1h 15m
927	Ob	42.7	Apr 13.7					−1d
	Int	43.877	Apr 14 22:57	−314	+0.568	−0.00105	−0.005	+1h 52m
	Int	43.894	Apr 14 23:21	−314	+0.570	−0.00093	+0.005	+2h 16m
934	Ob	42.9	Apr 13.7					
	Int	43.290	Apr 14 03:41	−465	+2.909	+0.00476	none	+6h 41m

Table 6: Comparison of this work (K-A) with Vaubaillon's results in Jenniskens (2006, table 5e).

Yr		$\lambda_\odot$	Date Time	Tr	Δa_0 (au)	Δr (au)	$f_{\mathcal{M}}$	ZHR
511	K-A	42.879	Apr 11 06:18	141	+2.578	+0.00273	−0.010	
	K-A	41.151	Apr 9 11:16	374	−1.428	−0.00905	+0.605	
	5e	41.594	Apr 9 23:39	374	−1.4411	−0.00098	-.-	60
531	K-A	41.962	Apr 10 10:39	451	+0.075	+0.00081	+1.008	
	K-A	41.899	Apr 10 09:05	295	+0.048	−0.00155	+0.666	
	K-A	41.884	Apr 10 08:42	374	+0.052	−0.00089	+0.759	
	K-A	41.464	Apr 9 22:07	218	+0.061	−0.00905	+0.002	
	5e	41.935	Apr 10 11:10	218	+0.0472	−0.00109	-.-	900
539	K-A	42.285	Apr 10 19:35	141	+0.412	+0.00145	−0.527	
	5e	42.388	Apr 10 23:27	141	+0.4818	−0.00090	-.-	1200
543	K-A	41.983	Apr 10 12:57	66	+0.526	−0.00486	+0.057	
	5e	42.263	Apr 10 21:12	66	+0.5126	−0.00259	-.-	20
550	K-A	40.907	Apr 9 05:00	451	+2.918	−0.00842	+1.171	
	5e	41.342	Apr 9 17:06	451	+2.8680	−0.00066	-.-	150
601	K-A	41.285	Apr 9 16:25	451	−0.637	−0.00761	+0.434	
	5e	41.713	Apr 10 04:12	451	−0.6420	−0.00122	-.-	470
619	K-A	41.116	Apr 10 03:07	374	+0.670	−0.00599	+0.217	
	5e	41.518	Apr 10 14:13	374	+0.6629	−0.00034	-.-	190
641	K-A	41.529	Apr 10 04:40	374	+1.688	−0.00341	−0.023	
	K-A	41.441	Apr 10 02:30	374	+1.720	−0.00557	+1.210	
	5e	41.827	Apr 10 13:07	374	+1.6986	−0.00043	-.-	60
647	K-A	41.014	Apr 10 04:51	451	+2.743	−0.00692	+1.690	
	5e	41.377	Apr 10 14:53	451	+2.7166	−0.00113	-.-	370
650	K-A	40.841	Apr 9 19:03	66	+0.834	−0.00638	+0.006	
	5e	41.139	Apr 10 03:28	66	+0.8581	−0.00224	-.-	50
672	K-A	none	none	451	−0.854	none		
	5e	41.843	Apr 10 12:17	451	−0.871	−0.00082	-.-	40
692	K-A	43.194	Apr 11 23:46	530	+0.871	−0.00533	+0.665	
	5e	43.604	Apr 12 10:51	530	+0.8601	+0.00024	-.-	20
713	K-A	none	none	141	−0.820	none		
	5e	43.469	Apr 12 16.43	141	−0.8347	−0.00100	-.-	40
719	K-A	40.000	Apr 9 14:53	218	+0.468	−0.00429	+0.022	
	5e	40.263	Apr 9 22:17	218	+0.4707	−0.00068	-.-	410
796	K-A	41.303	Apr 10 16:59	218	+1.306	−0.00434	−0.130	
	5e	41.636	Apr 11 01:54	218	+1.2751	−0.00084	-.-	250
964	K-A	41.888	Apr 12 09:18	218	+0.476	−0.00206	+0.082	
	5e	41.973	Apr 12 11:44	218	+0.4755	−0.00152	-.-	1100

time well outside of the visible range in the Maya area and there was no April date recorded in 692.

4. Discussion of possible sightings

4.1. Ordering of outburst intensity

Among the 30 years in Tables 1 to 4, stronger outbursts will be associated with smaller $|\Delta r|$, higher $|f_{\mathcal{M}}|$, and Δa_0 closer to 0 (or closer to about +1 au for smaller particles). The likelihood of sightings by the Maya also depends on the peak time being within or close to the visible range, and on the phase of the moon if present. Based on these points the five most probable ETA displays are (order of descending intensity):

531, 566, 618, 663, 849.

Outbursts less likely though still with a relative high probability of being observed are (loosely in descending order of likelihood):

756, 790, 644, 721, 562, 572, 675, 752, 484, 781, 716, 511

with others listed in Tables 1–4 having somewhat smaller possibility of being observed.

The following possible sightings of outbursts are described in order of their relative strength or intensity, the strongest being first, then the second strongest and so on.

4.2. Extreme outburst in AD 531

The outburst on 531 April 10, the strongest by far noted by the authors, resulted from particles released by Halley from three different perihelion passages, AD 295, 374 and 451. The parameters from each of these trails, low $|\Delta r|$ and high $|f_{\mathcal{M}}|$, indicate that any one trail would have produced a very strong outburst, all three being within the time the radiant would have been visible. The $f_{\mathcal{M}}$ values close to 1 indicate particles much more compressed in the along trail direction compared to most other cases in Tables 1 and 2. The miss distances $\Delta r = +0.0008$, -0.0009 and -0.0016 au for the 451, 374 and 295 trails respectively were near optimum for a strong outburst. With Δa_0 so close to zero (Table 1), i.e., particle orbits similar to Halley, the particles had not been ejected very far from the comet indicating heavy and densely-packed particles that would cause an intense outburst. The sky was dark since the moon had set a few hours prior to the radiant rise (Table 3) making for even a more impressive display. This shower was likely the most intense that the Maya would have seen during the Classic Period. A ZHR = 900 was post-dicted for this same outburst (Jenniskens, 2006, table 5e), also shown in comparison in Table 6: although both models compare favorably in intensity and time of outburst, they differ in the responsible trail(s).

An accession to the royal throne followed this outburst by 4 days (9.4.16.13.3); the likelihood of the connection of an accession event to this outburst may be strengthened by the fact that the inscribed lunar information supplementing the Maya Long Count indicates a lunar age of 8 days, the actual age of the moon during the outburst on April 10, not the moon age of 12 days required for the actual calendar date; whether a scribal error or a notation made on purpose to indicate the date of an astronomical event is not known at this time.

4.3. Outburst in 566 due to 240 BC trail

From its 240 BC passage Halley produced one relatively moderate outburst on the morning of 566 April 10 at about 10:00. An earlier outburst computed at about 06:00, ∼2 hours prior to radiant visibility was likely not visible. The visible display at 10:00 had a moderate $|f_{\mathcal{M}}| \sim 0.07$ and $|\Delta r|$ was slightly greater than 0.001 au. The moon would not have been a factor since it set a few hours prior to the rise of the radiant. Almost two weeks after this outburst the birth of a princess was recorded on 9.6.12.4.16 at the site of Caracol.

4.4. Outburst in 618 due to 391 BC trail

Two nearby segments of the 391 BC trail reached Earth on the morning of 618 April 10. The first outburst peaked at 08:18 and the second at 10:02. The first may have been stronger due to $f_{\mathcal{M}}$=+0.088 versus $|f_{\mathcal{M}}| \sim 0.006$ for the second even though Δr = –0.0024 for the first versus a closer Δr = +0.0014 for the second. A Period Ending fell on 9.9.5.0.0, four days following the outburst. The age of the moon is inscribed as 11 days which corresponds to within one day of the age of the moon on the outburst, not the age of the moon that would be required for the inscribed Long Count (note similar situation for the 531 outburst).

4.5. Outburst in 663 due to 466 BC trail

The outburst on the morning of April 13 was from two parts of the trail, the first occurring about one hour before radiant rise, and the second at 07:47, a few minutes prior to radiant visibility. The other parameters seem to indicate a moderate outburst, $\Delta r = -0.0037$ and -0.0033, $\Delta a_0 = +0.26$, and moderate $f_{\mathcal{M}}$, although the outburst occurring at radiant visibility had a significantly stronger $|f_{\mathcal{M}}| \sim 0.09$. The moon was not a factor, nearly new and rising slightly after sunrise. Ten days after the outburst there was a house dedication on 9.11.10.12.5 at the site of La Corona (CRN).

4.6. Outburst in 849 due to 466 BC trail

For the outburst that may have been observed by the Maya on 849 April 14 a dual intercept was computed for the 466 BC trail with both solutions close to $\Delta a_0 \sim +0.638$ au. Both outbursts were in the visual range, the first occurring at 09:00 and the second at 09:36, each with a modest $|f_{\mathcal{M}}| \sim 0.02$. Δr was very close to scoring a direct impact, -0.0004 au for the first outburst and -0.0003 au for the second. Although the 13.5 day old moon did not set until about two hours after sunrise and may have affected viewing somewhat, considering the values for all parameters, the dual outburst likely would have been relatively strong. The 849 outburst was significant because the next day on 10.0.19.6.14 a phrase possibly meaning "he/she/it forms the earth," *u pataw kab'aj*, was inscribed on stone monuments Stela 17 and Altar 10 at Caracol (Grube and Martin, 2004, p. 88, 89). The phrase seems to occur only once in the hieroglyphic corpus, although the root of the verb, *pat* is fairly common. The possibility of the action described at Caracol being related to meteors is intriguing and worthy of further investigation.

4.7. Outburst in 756 due to 218 trail

It was possible outbursts occurred both on April 10 and 11. The outburst on April 10 had a very low Δr, -0.0002, but the particles were very small, indicated by $\Delta a_0 = +3.9$ au. Fortunately the sky would have been dark since the moon had set a few hours before radiant rise. The outburst on the morning of the 11th consisted of medium sized particles, $\Delta a_0 = +1.8$ au but the only drawback would have been a value of Δr of just over 0.005 au. The related Maya event was a Period Ending (9.16.5.0.0) that fell one or two days prior to the outburst, with several different polities marking the occasion with elaborate celebrations[11].

4.8. Outburst in 790 due to 218 trail

This possible outburst on April 11 would have been caused by two adjacent segments of Halley's trail from AD 218. The numbers are robust, $\Delta r \sim 0.0007$ au, $\Delta a_0 \sim -1.3$ au and $|f_{\mathcal{M}}| \sim 0.2$; the outburst occurred in the morning twilight and the 22.5 day old moon rose at 06:49 possibly only hampering viewing conditions slightly. The following day (9.17.19.9.1) a "strike the stone road" (*jatz'bihtuun*) (Stuart, 2007), (Grube and Martin, 2004, p. 20, 38, 70) event was recorded at the site of Naranjo.

4.9. Outbursts in 644 due to trails from AD 374 and 87 BC Halley passages

Outbursts in 644 occurred under dark skies (new moon rising) on both April 11 and April 12 due to the dust trails from 374 and 87 BC respectively. Although $|f_{\mathcal{M}}| = 0.003$ was rather modest on the morning of April 11, the stream of medium-sized particles impacted the Earth in a virtual direct hit as $\Delta r = 0.00008$ au. The outburst on the second day, April 12, may have been lighter since $\Delta r \sim 0.005$ au, although $|f_{\mathcal{M}}| \sim 0.02$ somewhat stronger than the day before. The recorded event, again *jatz'bihtuun*, "strike the stone road" was dated 2 days earlier on April 9 (9.10.11.6.12) and was inscribed on the same stone panel as the 790 event (see Section 4.8).

4.10. Outburst in 721 due to 87 BC trail

The 721 outbursts that occurred on the morning of April 12 were light but occurred in a dark sky just as the moon was setting, therefore the display may have been observed by the Maya. Fifteen days later a woman known as *'Ix Ti' Kan Ajaw* arrived at the site of La Corona on 9.14.9.9.14. The question for investigation might be "Did the outburst prompt a departure from some other locale that was a 15 day's walking journey from La Corona?"

[11] Yaxchilan marked the event by a "dance" (Lintel 3) and blood letting (Lintel 54) and Quirigua by a "vision event" (Looper, 2003, p. 100-104) for example.

4.11. Outburst in 562 due to 164 BC and 240 BC trails

Eta Aquariid activity that may have occurred in 562 on two successive days could have been due to no less than 6 intercepts of the 240 BC trail on the morning of April 10 and 4 intercepts of the 164 BC trail with Earth on the morning of April 11. Almost all outbursts were within or very close to the visual time of observation on both days and nominal computed times of some intercepts were in rapid succession, within 10-15 minutes of each other, enough that those outbursts could have combined and thus reinforced their intensity. The last quarter moon may have affected viewing conditions slightly. On the 10th, Δa_0 was around 3.3 au indicating smaller particles and a finer outburst. The outburst at about 10:00 (04:00 AM local time) on April 11 would have likely been the stronger of the two days with $|\Delta r| < 0.001$ au and $\Delta a_0 < 2.0$ au. A war event known as a "Star War" followed this probable outburst by slightly less than three weeks (9.6.8.4.2) so it cannot be said for certain that the two are connected[12]. Martin and Grube (2008, p. 89) note that the defeat of Tikal from this Star War event "would change the course of Early Classic history."

4.12. Outburst in 572 due to 911 BC trail

In 572 there were multiple intercepts from the 911 BC trail on the morning of April 10. Two occurred about 45 minutes prior to the rise of the radiant and although $|f_{\mathcal{M}}|$ was small, the overlapping nature of the intercepts may have produced a combined overall display if seen. All four were in a very small range $\Delta a_0 = -1.412$ to -1.414 au, and Δr was around -0.002 au in all cases. The last of the four intercepts clearly occurred within the visual observation time. The accession of a ruler (*Kan B'ahlam I*) occurred at Palenque on April 7 (9.6.18.5.12), three days prior to the outburst on April 10.

4.13. Outburst in 675 due to 240 BC trail

A trail encounter was computed in AD 675 around an hour prior to radiant rise and another during the observable time on the morning of April 14; $f_{\mathcal{M}}$ was a modest $+0.02$ and $\Delta r < +0.002$ au for the

[12] A possible explanation may be that the Star War, which usually recorded one polity's defeat of another, began on the day of the outburst and finished on the recorded date. Most of the other Star War dates do not correlate directly to solar longitudes of meteor showers that would have been visible to the Maya (Kinsman, 2014, p. 92) and thus it cannot be determined at this time whether there is a general trend connecting meteor outbursts to Star War events.

first likely outburst if seen and slightly weaker for the second visual display. The nearly full moon set at 10:58 but at least $\Delta a_0 \sim -0.5$ au implies quite bright meteors. The outburst in 675 was possibly noted by the site of La Corona on a carving known as Panel One 12 days later on 9.12.2.15.11 by a departure event.

4.14. Outburst in 752 due to 141 trail

There may have been a significant outburst from particles ejected in AD 141 that appeared on the morning of April 11. The Earth intercepted one particular segment of the trail three times in rapid succession, but all intercepts were about an hour and a half prior to radiant rise. Although $|\Delta r|$ was moderate ~ 0.004 au, $f_{\mathcal{M}}$ was strong for all three segments, and $\Delta a_0 \approx +1.6$ au indicating medium-sized particles. If the display was seen, the moon may have been a slight factor, 22 days old and having risen at 06:17. Although this outburst may be tied to an accession event 19 days later (9.16.1.0.0), there seems to be legitimate rationale for the ruler to have waited that long before taking the throne.[13]

4.15. Outburst in 484 due to 218 trail

The outburst in 484 occurred around daybreak on the morning of April 9, which may have diminshed its viewing. The parameters were moderate $\Delta r = 0.003$ au, $\Delta a_0 \approx +1.7$ au and $|f_{\mathcal{M}}| \approx 0.2$. Four days later on April 13 (9.2.9.0.16) a royal accession took place at the site of *Caracol*.

4.16. Outburst in 781 due to 240 BC trail

The 781 outburst occurred on April 15. The small-to-medium sized particles had good encounter parameters (Table 2) though likely a modest display around the time of radiant rising, being somewhat affected by the gibbous moon (Table 3). A ruler's accession at the minor site of Los Higos followed 3 days later on 9.17.10.7.0.

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[13]The king, *Bird Jaguar IV* of the site of Yaxchilan, may have waited so that he could assume the throne on a “round number” or Period Ending date, Maya Long Count 9.16.1.0.0 (Martin and Grube, 2008, p. 128).

4.17. Outburst in 716 due to 141 trail

The outburst in 716 on April 12 was caused by three separate sections of the 141 trail, the first peak at 09:16, the second at 10:42 followed a few minutes later by the third at 10:56. Although $f_{\mathcal{M}}$ was strong (~ 0.6) with the first intercept, the stream was slightly wide of the mark where $\Delta r \approx +0.0025$. The second two intercepts had weaker $f_{\mathcal{M}}$ but were closer to direct impact, $\Delta r \approx +0.0005$ and $\Delta r \approx +0.0007$. Unfortunately the moon was full and did not set until 12:29, so many of the light particles ($\Delta a_0 \approx +2.7$) may have been washed out. An attack by the site of Naranjo on an unknown opponent is noted to have occurred eight days earlier on April 4 (9.14.4.7.5) (Grube and Martin, 2004, p. II-55).

4.18. Modest outburst in 511 due to trail from Halley's AD 141 return

The outburst on April 11, at 06:18, peaking almost 2 hours before radiant rise, was likely modest if seen, with trail encounter parameters $\Delta r \approx +0.0027$, $\Delta a_0 \approx +2.6$ and $|f_{\mathcal{M}}| \approx 0.01$. The sky would have been dark with the moon almost new. Nine days later on April 20 (9.3.16.8.4) a queen of only six years old assumed the throne[14] at the site of Tikal. A meteoric display may have provided a suitable back drop for the ceremony starring the young *Lady of Tikal*.[15]

4.19. Modest outburst in 639 due to 240 BC trail

This outburst, among our 30 best candidates (Tables 1–4) though not estimated as one of the strongest, is notable as the dynamics involves Saturn (Section 4.20). The outburst was computed to peak almost 4 hours before the radiant was visible and so whether the display was seen depends on its duration; however, the moon had set and if seen the outburst may have been stronger than it appears strictly from the 1-parameter dust trail model since there is a significant Δa_0 range for which particles cross the ecliptic plane at a

[14]Normally a female would only accede in extreme circumstances, for instance if there was no male heir or the failure of the dynasty was imminent; in addition, such an installation of a female required elaborate justification (Martin, 1999).

[15] Numerical integrations also showed an outburst occurring the year before on 510 April 9 at 08:59: this moderate outburst was due to particles ejected by the 374 passage of Halley, where $\Delta r = -0.00239$, $\Delta a_0 = -1.535$ and $f_{\mathcal{M}}$ was fairly strong ~ 0.6. Reflected light from the moon may have washed out some of the display however since the nearly full 13.4 day old moon set at 11:27. How or if this may have affected the coronation the following year would be difficult to assess.

very similar time (albeit not exactly at the dust trail solution time). Numerical integrations also indicated a solution on the morning of April 12 within the visual range, but Δr was greater than 0.006 au, so likely this outburst was low level. A regal accession was recorded the same day as the April 13 outburst at Piedras Negras on 9.10.6.5.9.

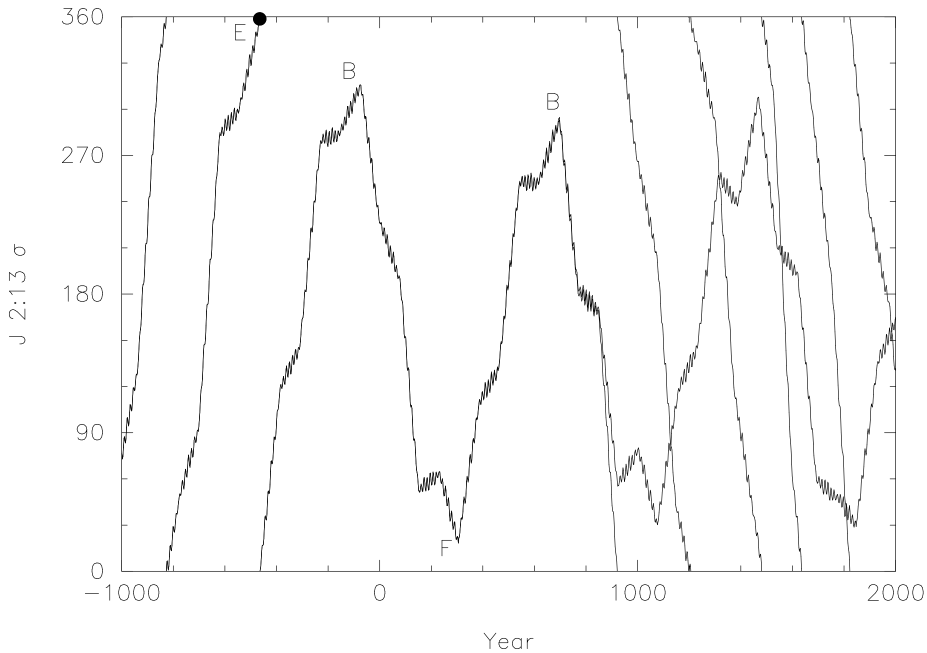
4.20. Mean motion resonances

The natural tendency of gravitational systems to develop synchronicities among bodies that are close enough to perturb one another (see for instance Murray and Dermott, 1999, p. 9-19) has affected the dynamics of many trails described above. Whereas in the absence of resonant perturbations trail particles will start to scatter considerably after several revolutions, particles trapped in resonance by planets could remain for thousands of years in a cluster dense enough to produce an outburst (cf. Emel'yanenko and Bailey, 1996; Asher et al., 1999; Sekhar and Asher, 2013; Sekhar et al., 2016).

In *mean motion resonance* the mean motions of a meteoroid particle and planet are in whole number ratio $p : (p + q)$ and orbital periods in the inverse ratio, neglecting orbital changes in the slowly varying angles. By Kepler's 3rd Law, the particle's semi-major axis a is constrained to remain at a given value, or in practice to oscillate or *librate* about that value. If an idealized point – a *resonance center* – moves around an orbit with orbital period $P_J(p + q)/p$ at all times where P_J is Jupiter's period, then a resonant particle periodically drifts in front of and behind this point as a librates. It can be shown that the maximal extent of this libration, front to back, measured in terms of mean longitude relative to the resonance center, is $1/(p+q)$ of the orbit. It follows that there are $(p+q)$ *resonant zones* around the orbit, in any one of which a particle can librate. A perturbation to a, e.g., from a close approach to a different planet, can send the particle out of resonance, after which it will drift beyond the front or back boundary of the resonant zone. Particles were confirmed trapped in resonance by verifying that the resonance variable (Peale, 1976, section 4; Greenberg, 1977, section 3), also called the resonant argument (Murray and Dermott, 1999, chapter 8) librates (see also Sekhar and Asher, 2014).

The 849 outburst (Section 4.6) involved the 2:13 Jovian resonance and particles released at the 466 BC passage of 1P/Halley. The

Figure 1: Resonant argument of Jovian 2:13 resonance for 2 particles ejected (dot labeled E) in 466 BC; they are imaginary in the sense that their evolution before ejection from 1P/Halley is also shown, this prior behavior indicating that they were not immediately resonant in 466 BC. They evidently enter the resonance between 466 BC and 100 BC after which they rebound between the back (B) and front (F) of their resonant libration as the period varies about its average resonant value. They were separated by just 0.0001 au in Δa_0 and are indistinguishable in this plot before 849, when one approaches Earth and is perturbed out of the resonance while the other misses by 0.1 au and stays resonant.



2:13 produces 13 zones around the 360° mean longitude of the orbit, any resonant particle librating within one zone. Each zone covers ∼28° which is ±14° about the respective resonance center. Figure 1 illustrates resonant trapping, libration vs circulation of the resonant argument σ corresponding to being trapped in that resonance or not; σ effectively amplifies the longitude 13 times so that the full extent of the resonant zone and the maximum possible peak to trough libration amplitude are 360°. Here the resonance center is $\sigma \approx 180°$; Halley in 466 BC (point E in Fig. 1) is near the boundary between two adjacent 2:13 zones at that time.

Selecting a range in Δa_0 encompassing the solution values, reverse integrations of 41 "imaginary" particles were carried out a few centuries prior to their release from the comet and then carried

Table 7: Mean motion resonances, all Jovian except 1:3 Saturnian, causing observable outbursts: a_n nominal resonance location (Murray and Dermott, 1999, sec. 8.4); a_0 osculating semi-major axis at ejection; Diff (Tables 3, 4) in days of recorded Maya event.

Yr	Trail	Reson	a_n	a_0	Diff
562	164 BC	3:23	20.22	20.047	+19
562	240 BC	2:17	21.66	21.423–21.432	+20
566	240 BC	2:15	19.93	20.154, 20.167	+13
572	911 BC	3:17	16.53	16.377–16.379	−3
618	391 BC	1:7	19.03	18.628, 18.652	+4
639	240 BC	1:3 S	19.84	20.035	0
663	466 BC	3:19	17.80	18.225, 18.226	+10
675	240 BC	1:6, 4:23	17.17, 16.69	17.596	+12
721	87 BC	2:17	21.66	21.910	+15
849	466 BC	2:13	18.12	18.602	+1

forward to AD 2000. Particles released directly into the resonance would show σ libration before 466 BC. In fact all these particles were not resonant but soon afterwards became so. Although a few particles fell out of resonance (the particle nearest the solution as a direct result of the 849 Earth encounter: Fig. 1), most stayed in the 2:13 zone through 2000. The action of the 2:13 covering most of the time frame between 466 BC ejection and 849 Earth encounter ensured a sharp outburst can be produced even after >1 kyr.

Table 7 lists further examples identified by the authors and indeed four of the best five cases (566, 618, 663, 849: Section 4.1) are resonant. The resonances keep particles compact in space over these time frames, e.g., the particles giving the 572 outburst were strongly trapped in the 3:17 Jovian resonance for over 1 kyr from ejection until perturbed by approaching to a few $\times$ 0.01 au of Earth in 234. When there are only a few centuries between ejection and Earth encounter, particles may ultimately be resonant but the short time scales render the resonances irrelevant, with barely time for a full libration cycle.

The 566 and 639 cases (Table 7) contrast the 2:15 Jovian and 1:3 Saturnian resonances; in the latter the action of another planet than Jupiter inhibits the dispersion of the particles so that an outburst can still occur. The authors verified which resonance operated by plotting the relevant resonant arguments (cf. Sekhar and Asher, 2013, fig. 1). The segment of the Halley trail from 240 BC that reached Earth in 639 was in the Saturnian 1:3 during that interval.

Jovian resonance is well known as a cause for historical outbursts, especially in the Halley stream (cf. Rendtel, 2007, 2008; Sato and Watanabe, 2007; Christou et al., 2008). Comet Halley was in a 1:6 Jovian resonance from 1404 BC to 690 BC, increasing chances that meteoroids released during this epoch could be trapped in the same resonance, and was in a 2:13 resonance with Jupiter from 240 BC until AD 1700 (Sekhar and Asher, 2014).

A very strong resonance such as 1:6 can dramatically affect precession rates which can become much slower. This explains how Orionid outbursts due to 1:6 meteoroids can occur in the present epoch (Sato and Watanabe, 2007), the precession of their nodal distance being hugely different from that of Halley whose ascending node was near 1 au nearly 3 kyr ago. In many cases the authors found that the 1:6 substantially slows the precession of the descending (Eta Aquariid) nodal distance too, potentially making it harder to obtain 1:6 resonant ETA outbursts during the same (Maya) epoch when the comet's descending node is near 1 au.

5. Events that preceded ETA solar longitudes by 2–4 days

The Maya recorded a small group of dates that preceded the likely solar longitude of the ETA's by a few days. Since it is fairly certain that the Maya were able to calculate the length of the sidereal year accurately to at least three decimal places (Grofe, 2011; Kinsman, 2014), it would be unusual for the Maya to fall short of a sidereal cycle by 2-4 days. Therefore it is possible that some rulers were attempting to accede into office a few days prior to a typical ETA shower.

Assuming that the Maya knew that the peak of the most common meteor showers during the Classic Period occurred on a sidereal year basis, especially the Perseids and Eta Aquariids, the Maya knew that it would have been difficult to synchronize a cycle of a specific shower itself with any of their typical integral number day cycles. However, they likely realized that the time between peaks of *different* annual showers was an integral number of days; the peak of an ETA (solar longitude $\lambda_\odot \approx 42.0°$) occurred about 266-267 days following the peak of a Perseid ($\lambda_\odot \approx 139.0°$) the previous year, or in a minimum day scenario, an ETA would arrive about 262 days after the previous year's Perseid. A ruler would add 260 days (the length of the sacred Tzolk'in calendar) to the day that the Perseid

Table 8: Maya Events Occurring prior to Typical Eta Aquariid Showers

Yr (1st column) = year of recorded event. Ev = event. "Long Count" = the date recorded for that particular event. "Perseid" = the base Long Count that the Maya might have used for computation. These Long Count dates are already recorded in the inscriptions and also are consistent with solar longitudes of the Perseids. Yr = year of base computation. (260) + n(365) = number that the Maya would have added to the base LC (Long Count) to arrive at a calculated pre-ETA date. 260 = 13.0, 365 = 1.0.5 in Maya notation. n = number of years. Err = no. of days (d) difference between calculated LC and actual event LC.

Yr	Ev	Long Count (event)	$\lambda_\odot$ (event)	Perseid (base LC)	Yr (base)	(260) + n(365)	LC (calc)	err. (d)
572	acc	9.6.18.5.12	39.84	9.6.16.10.7	570	(1)(1.0.5)	9.6.18.5.12	0
662	acc	9.11.9.11.3	37.82	9.11.5.15.9.	658	(3)(1.0.5)	9.11.9.11.4	1
686	acc	9.12.13.17.7	35.73	9.11.16.0.1	668	(17)(1.0.5)	9.12.13.17.6	1
738	fire	9.15.6.13.1	36.38	9.15.5.0.0	736	(1)(1.0.5)	9.15.6.13.5	4
802	acc	9.18.11.12.0	38.88	9.18.6.16.0	797	(4)(1.0.5)	9.18.11.12.0	0
808	fire	9.18.17.13.10	37.39	9.18.6.16.0	797	(10)(1.0.5)	9.18.17.13.10	0

shower occurred and arrive at a date that would be no closer than about 2-3 days prior to an expected ETA shower the following year. If the ruler did not assume office the following year, he would add 365 days or a multiple of that (the length of the *haab'*), to arrive at the year he expected to take office, to his 260 day calculation. Table 8 shows six examples from dates[16] that are already recorded in the inscriptions wherein the rulers might have applied this simple rule[17]. Future research numerically integrating Perseids could shed more light on the Maya's knowledge of the Perseid meteor shower.

Figure 2 in Section 6 shows how the accession events from Table 8 are grouped in solar longitude prior to the most probable outbursts.

[16]The Long Count 9.18.6.16.0 listed in Table 8 is somewhat of an educated guess since only the Tzolk'in date 8 Ajaw is inscribed (see Martin and Grube, 2008, p. 212, 213) and without the additional *haab'* year supplied the selected Long Count is only one of several Long Count options. However included in the carving of this stone monument (Copan Stela 11) is the phrase "piercing (by) obsidian," and thus a possible connection to meteors; there are only two possibilities of a major shower during the appropriate ruler's reign, the other being an ETA shower. Dates that are used in Table 8 are just possible dates from the corpus of inscriptions. The Maya could have easily used other Perseid dates that have not been found in any extant inscriptions.

[17]The use of combining two cycles is not new, as Powell (1997) has investigated the number 949 days = 584 days (Venus synodic) + 365 days (*haab'*) and the 819 day cycle in relation to (3)(399) days = 819 + 378, where 378 = Saturn synodic cycle and 399 = Jupiter synodic period.

6. Conclusions and Discussion

6.1. Overall conclusion and significant events

The overall conclusion is that in all probability the Maya kept track of and observed Eta Aquariid meteor showers and outbursts.

Significantly, the likely most massive display during the Classic Period, the outburst of 531, apparently was not missed in the Maya record. On a moonless night, three very strong, overlapping, barrages of meteors from the most recent passages of Halley impacted Earth within a two hour period followed four days later by an important Maya royal accession ceremony (*K'an I* on 9.4.16.13.3 at *Caracol*).

Two *jatz'bihtuun*, "strike the stone road" events seem to have recorded the observation of an ETA outburst, one in 644 and another in 790 (9.10.11.6.12 and 9.17.19.9.1 respectively), inscribed on the same monument from the site of Naranjo, Guatemala. There are only two other known records of this event in the hieroglyphic corpus, each possibly recording a numbered shower (Kinsman, 2014, pp. 91-92, figure 4)(Jenniskens, 2006, pp. 601, 608) or in one case, "lost" shower "D" (Imoto and Hasegawa, 1958, p. 136, table 1).

The weather may have been a factor in a few cases but it is doubtful for instance that cloud cover would have prevented the entire Maya population from observing a shower or outburst from every location in the entire Maya area. It seems a safe assumption that at least one site would have had an unobstructed view of the heavens at any time during the year.

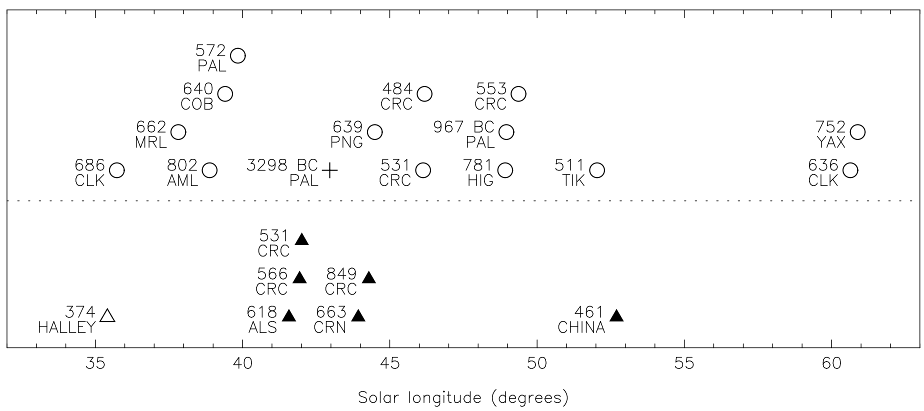
6.2. Events with regard to most probable outbursts

The likely most intense outbursts computed are paired with recorded Maya events as follows. The five most probable ETA outbursts (cf. Section 4.1) are:

531 (royal accession)(Caracol)
566 (royal birth)(Caracol)
618 (Period Ending)(Altar de Los Sacrificios)
663 (house dedication)(La Corona)
849 ("forms the earth"?)(Caracol).

And the next ten are:

Figure 2: Distribution of Most Probable Outbursts in Relation to April Accessions, Primordial 3298 BC Event (12.10.12.14.18)(Stuart, 2005, p. 68-77), 967 BC Accession, and Comet Halley 374 Perihelion Passage. Solid triangles with Maya site identifiers mark the most probable outbursts determined in this treatise. Horizontal scale is J2000.0 $\lambda_{\odot}$. Separation of points on vertical scale is for ease of reading only.



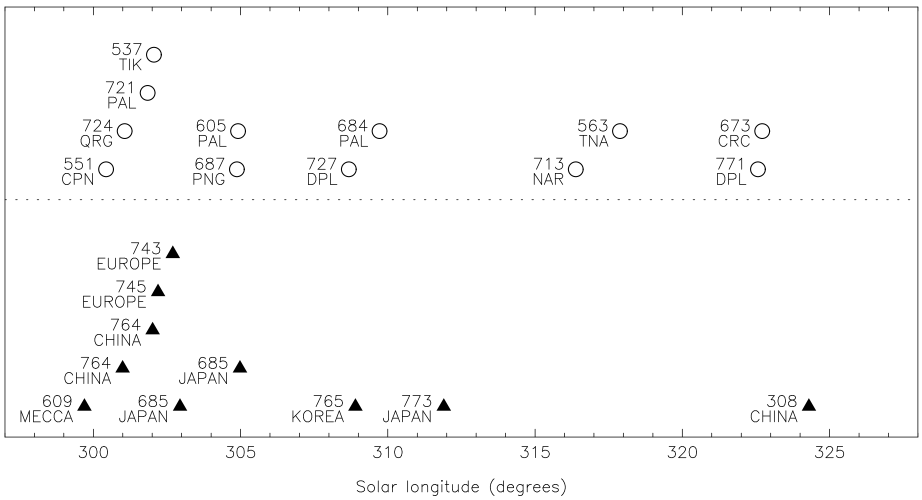
756 (Period Ending with special ceremonies)(multiple sites)
790 (“strike the stone road”)(Naranjo)
644 (“strike the stone road”)(Naranjo)
721 (arrival)(La Corona)
562 (“Star war”)(Caracol)
572 (royal accession)(Palenque)
675 (departure [emerge?])(La Corona)
752 (royal accession)(Yaxchilan)
484 (royal accession)(Caracol)
781 (royal accession)(Los Higos).

Outbursts in 716 (war event, Naranjo), 511 (royal accession, Tikal) and 588 (royal birth, Caracol) would have had some chance of being observed, and still others listed in Tables 1–4 had some albeit small possibility.

6.3. Outbursts and ETA's with regard to royal accessions

Figure 2 shows the distribution of the 14 accession events that occurred during April, a range of about 30 days or 30° in solar longitude, throughout the Classic Period. In a random distribution, there would be slightly less than one accession every two days; the figure, however, shows at least three different groups, with a distinct

Figure 3: Distribution of accessions during the 30 day period covering the end of December and most of January (Maya mid-Classic Period) compared to historically observed outbursts. Horizontal scale is J2000.0 $\lambda_{\odot}$. Vertical separation for ease of reading only.



gap between the early event group and the accessions following the 3298 BC primordial event and the most probable outbursts.

Out of about 70[18] events that occurred in the month of April, the 14 accessions constitute about 20%. The 14 occurring in April of all years out of approximately 90 recorded royal accessions that occurred during the Classic Period represent a disproportionate amount of accessions for one month. In another 30 day period approximating the month of January covering numbered shower 32 (Kinsman, 2014, pp. 91-92, figure 4)(Jenniskens, 2006, p. 610), the authors note up to 12 accessions that could be related to these showers (see Figure 3). The binomial probability for 26 or more out of 90 accessions to occur in only two specified months of the year (p=1/6) is 0.0027 (or if multiplied by 66, the number of possible pairs of months, is still below 2%). Therefore it is highly unlikely that the distribution of these 26 accessions within those two months is random.

There were 30 different years during the Maya Classic Period for which integrations revealed that ETA outburst activity may have

[18]A count of individual events in the Maya corpus by the authors otherwise not noted in this study.

occurred. Approximately 18 of those exhibited an especially higher likelihood of actual outbursts being observed in the Maya area. Six of the possible 18 outbursts occurred near the time of an accession event; those years were:

484 (*Yajaw Te' K'inich* from *Caracol*),
511 (*Lady of Tikal* from *Tikal*),
531 (*K'an I* from *Caracol*),
572 (*Kan Bahlam I* from *Palenque*),
752 (*Bird Jaguar IV* from *Yaxchilan*)
781 (unknown ruler from *Los Higos*)

The years 511 and 531 are also analyzed by Vaubaillon in Jenniskens (2006, table 5e), as we described in Section 3.3. These years constitute pairings of recorded accession events with computed meteor outbursts. In the following statistical calculation we impose the condition that the pair should match within ± 4 days which disqualifies 511 (accession followed outburst by 9 days; Table 4).

The year 572 may have been the first year that a ruler attempted to forecast an ETA. Whether expecting an outburst or simply the annual shower is not known, but several other accessions may have attempted similar predictions as shown in Table 8. If this assumption is true, it would connect another three (four if 572 is included in the early group in Figure 2 and not the outburst group) accession events to the ETA's, bringing the total to seven out of 12 accessions connected to the ETA's.

Considering both types of accessions, i.e., those following outbursts and those occurring prior to typical ETA solar longitudes as described in Section 5, both within a ± 4 day period during the month[19], the binomial probability (at least 7 out of n=12 with p=9/30) implies only 4% chance of a random occurrence.

The primordial event (Stuart, 2005, p. 68-77) that the Maya recorded as occurring on 3298 BC March 17 correlates to a solar

[19] Qualifying years for outbursts: 531, 484, 781. Qualifying years for early accessions: 572, 662, 686, 802. Disqualified due to out of ± 4 day criterion: 511. No outburst or too weak outburst to include: 553, 636, 639 and 640. Not included in n: 967 BC, 752. An accession that occurred in 967 BC, was not included in the analysis because there were not enough previous Halley perihelion passages available going back to 1404 BC for a statistically valid analysis of this event. For 752 the possibility exists of the ruler choosing the accession date for a reason other than an outburst.

longitude that is compatible with the ETA's, 43.3° (see Figure 2). For reasons discussed in Kinsman (2015, pp. 44-45, figure 3) the authors believe this primordial event may be linked to the ETA's and thus the events discussed herein are not only related to contemporary ETA's but also the primordial event. In other cases such as the site of Palenque it is believed that some rulers related their accessions to mythological events through sidereal Earth years (Kinsman, 2016).

6.4. Outbursts related to events other than accessions

The variety of events paired with the other 12 of the 18 likely strongest outbursts are:

Royal births (566, *Lady Batz' Ek'*; 588, *K'an II*)(*Caracol*)
Period Endings (618, *Altar de Los Sacrificios*; 756, multiple sites)
War (562, "Star War'," *Caracol* defeats *Tikal*; 716, Naranjo attacks unknown opponent)
Departure (675, *Yuknom Yich'ak K'ahk'* from *La Corona*)
Arrival (721, *Lady Ti' Kan Ajaw* at *La Corona*)
Building dedication (663, *La Corona*)
"Forms the earth(?)" (849, *u-pataw-kab'aj*[20], *Caracol*)
"Strike the stone road" (644 and 790, *jatz' bihtuun*, *Naranjo*)

6.5. Spearthrower Owl and Comet Halley

There may be alternative ways of linking accessions to previous extraordinary events in a sidereal way. Heretofore the visible display of 1P/Halley has not been discussed, yet this comet made its second closest known approach to Earth on 374 April 1 at a distance of 0.09 au (Seargent, 2009; Yeomans and Kiang, 1981). Although the historical description is somewhat mundane, Seargent (2009)(p. 40-41) describes its passage as one of the greatest comets in history:

> On April 1, it appeared in the south as a broom star, and reached an elongation of 166 degrees from the sun on the third of that month. This must have been an incredible

[20] Although the root of the verbal phrase *pat* has several different meanings and the correct meaning has yet to be determined (Grube and Martin, 2004, p. 89), the authors believe the stated meaning fits the context most appropriately.

> sight, but (once again) physical description is lacking. The comet went out of sight sometime during the month of April. Although there is nothing in the very matter of fact description to suggest it, Halley's Comet at this apparition almost certainly deserves a place among the greatest of the greats.

So, were any of the accessions shown in Figure 2 linked to this incredible sight? Possibly, of course, since the Maya must have seen the comet at this passage as the Chinese did (Pankenier et al., 2008, p. 50)(Yeomans and Kiang, 1981). However, there may be a better connection with another accession previously not mentioned, and that is the accession of a remarkable figure known as *Spearthrower Owl* on 8.16.17.9.0 (Martin and Grube, 2008, p. 31)(Martin, 2003, p. 13)(Stuart, 2000, p. 481-490). Long Count 8.16.17.9.0 corresponds to 374 May 5, about one month after Halley's 374 passage by Earth. *Spearthrower Owl*, whose hieroglyph and iconic representations clearly depict an owl, holds in his hand an *atlatl* with stars attached, an overt symbol of meteors or "star darts" (Taube, 2000, p. 298). Amazingly, *Spearthrower Owl* was probably from the distant non-Maya site of Teotihuacan, and was responsible for the establishment of a "New Order" at the site of Tikal in 378 (Martin, 2003, p. 11-15). Therefore, with the connection to meteors, and likely comets as well, it may be that *Spearthrower Owl* based his accession on the passage of Halley in 374, as his accession occurred about one month after the close approach to Earth, or perhaps a few weeks after its disappearance, not unlike some of the Maya accessions discussed in this paper shown in Table 8. This connection of *Spearthrower Owl*'s accession to Comet Halley must nevertheless remain speculative while there is no knowledge of any observations of comets in the Maya hieroglyphic corpus.

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7. References

Ahn, S.H., 2005. Meteoric activities during the 11th century. Mon. Not. Roy. Astron. Soc. 358, 1105–1115.

Asher, D.J., 2000. Leonid dust trail theories, in: Arlt, R. (Ed.), Proc. International Meteor Conference, Frasso Sabino 1999, International Meteor Organization. pp. 5–21.

Asher, D.J., 2008. Meteor outburst profiles and cometary ejection models. Earth Moon Plan. 102, 27–33.

Asher, D.J., Bailey, M.E., Emel'yanenko, V.V., 1999. Resonant meteoroids from Comet Tempel-Tuttle in 1333: the cause of the unexpected Leonid outburst in 1998. Mon. Not. Roy. Astron. Soc. 304, L53–L56.

Asher, D.J., Emel'yanenko, V.V., 2002. The origin of the June Bootid outburst in 1998 and determination of cometary ejection velocities. Mon. Not. Roy. Astron. Soc. 331, 126–132.

Babadzhanov, P.B., Kokhirova, G.I., 2009. Densities and porosities of meteoroids. Astron. Astrophys. 495, 353–358.

Borgia, . Codex borgia. Foundation for the Advancement of Mesoamerican Studies, Inc. Facsimile, Electronic document, http://www/famsi/org/research/codices.

Burns, J.A., Lamy, P.L., Soter, S., 1979. Radiation forces on small particles in the solar system. Icarus 40, 1–48.

Chambers, J.E., 1999. A hybrid symplectic integrator that permits close encounters between massive bodies. Mon. Not. Roy. Astron. Soc. 304, 793–799.

Christou, A.A., Vaubaillon, J., Withers, P., 2008. The P/Halley stream: meteor showers on Earth, Venus and Mars. Earth Moon Plan. 102, 125–131.

Corp., S.C., 2009. Starry night pro plus version 6.4.3. Software.

Emel'yanenko, V.V., Bailey, M.E., 1996. Regular and stochastic motion of meteoroid streams in Halley-type orbits, in: Gustafson, B.A.S., Hanner, M.S. (Eds.), ASP Conf. Ser. Vol. 104, Physics, Chemistry and Dynamics of Interplanetary Dust, Astron. Soc. Pacif., San Francisco. pp. 121–124.

Everhart, E., 1985. An efficient integrator that uses Gauss-Radau spacings, in: Carusi, A., Valsecchi, G.B. (Eds.), Dynamics of Comets: Their Origin and Evolution (Proc. IAU Colloq. 83; Astrophys. Space Sci. Libr. Vol. 115), Reidel, Dordrecht. pp. 185–202.

Giorgini, J.D., Yeomans, D.K., Chamberlin, A.B., Chodas, P.W., Jacobson, R.A., Keesey, M.S., Lieske, J.H., Ostro, S.J., Standish, E.M., Wimberly, R.N., 1996. JPL's on-line solar system data service. Bull. Amer. Astron. Soc. 28, 1158.

Greenberg, R., 1977. Orbit-orbit resonances in the solar system: Varieties and similarities. Vistas Astron. 21, 209–239.

Grofe, M.J., 2011. The sidereal year and the celestial caiman: Measuring deep time in Maya inscriptions. Archaeoastronomy XXIV, 56–101.

Grube, N., Martin, S., 2004. Patronage, betrayal, and revenge: Diplomacy and politics in the eastern Maya lowlands, in: Maya Hieroglyphic Forum at Texas, The University of Texas at Austin. Maya Workshop Foundation. pp. 1–95. Part II.

Hagar, S., 1931. The November meteors in Maya and Mexican tradition. Popular Astron. 39, 399–401.

Imoto, S., Hasegawa, I., 1958. Historical records of meteor showers in china, korea, and japan. Smithsonian Contribution to Astrophysics 2, 131–144.

Jenniskens, P., 2006. Meteor Showers and their Parent Comets. Cambridge University Press.

Kennett, D.J., Hajdas, I., Culleton, B.J., Belmecheri, S., Martin, S., Neff, H., Awe, J., Graham, H.V., Freeman, K.H., Newsom, L., Lentz, D.L., Anselmetti, F.S., Robinson, M., Marwan, N., Southon, J., Hodell, D.A., Haug, G.H., 2013. Correlating the ancient Maya and modern European calendars with high-precision AMS 14C dating. Scientific Reports 3, 1597 EP.

Kiang, T., 1972. The past orbit of Halley's comet. Mem. Roy. Astron. Soc. 76, 27–66.

Kinsman, J.H., 2014. Meteor showers in the ancient Maya hieroglyphic codices, in: Jopek, T.J., Rietmeijer, F.J.M., Watanabe, J., Williams, I.P. (Eds.), Proceedings of the Meteoroids 2013 Conference, Aug. 26-30, 2013, A. M. University, Poznań, Poland, Adam Mickiewicz Univ. Press. pp. 87–101.

Kinsman, J.H., 2015. A rationale for the initial date of the temple xix platform at palenque. The Codex, at the University of Pennsylvania Museum of Archaeology and Anthropology 23, 39–58.

Kinsman, J.H., 2016. Palenque rulers and mythological time: Evidence of sidereal earth year calculations. Unpublished manuscript in possession of authors.

Kohler, U., 2002. Meteors and Comets in Ancient Mexico. Geological Society of America, Boulder, Colorado. pp. 1–6. Special Paper 356.

Kondrat'eva, E.D., Reznikov, E.A., 1985. Comet Tempel-Tuttle and the Leonid meteor swarm. Sol. Syst. Res. 19, 96–101.

Landa, D.d., 1566. Landa's Relacion de las cosas de Yucatan. Peabody Museum of American Archaeology and Ethnology, Harvard University. Translated by Tozzer, 1941.

Looper, M., 2003. Lightning Warrior: Maya Art and Kingship at Quirigua. University of Texas Press.

Lyytinen, E., Nissinen, M., van Flandern, T., 2001. Improved 2001 Leonid storm predictions from a refined model. WGN, J. International Meteor Organization 29, 110–118.

Martin, S., 1999. The Queen of Middle Classic Tikal. P.A.R.I. Online Publications: Newsletter 27, 1–7.

Martin, S., 2003. In line of the founder: A view of dynastic politics at Tikal, in: Sabloff, J.A. (Ed.), Tikal: Dynasties, Foreigners, and

Affairs of State, Advancing Maya Archaeology. School of American Research Press. School of American Research Advanced Seminar Series. chapter 1, pp. 3–45.

Martin, S., Grube, N., 2008. Chronicle of the Maya Kings and Queens: Deciphering the Dynasties of the Ancient Maya. 2nd ed., Thames and Hudson. (1st ed. 2000).

Martin, S., Skidmore, J., 2012. Exploring the 584286 correlation between the Maya and European calendars. The P.A.R.I. Journal 13(2), 3–16.

Maslov, M., 2011. Future Draconid outbursts (2011 – 2100). WGN, J. International Meteor Organization 39, 64–67.

Mathews, P., 2016. The Maya Dates Project. Ongoing database of dates from Classic Maya monuments and inscriptions. Unpublished.

McNaught, R.H., Asher, D.J., 1999. Leonid dust trails and meteor storms. WGN, J. International Meteor Organization 27, 85–102.

Meeus, J., 2000. Astronomical Algorithms. Second English ed., Willmann-Bell, Inc.

Murray, C.D., Dermott, S.F., 1999. Solar System Dynamics. Cambridge University Press.

Pankenier, D.W., Xu, Z., Jiang, Y., 2008. Archaeoastronomy in East Asia: Historical Observational Records of Comets and Meteor Showers from China, Japan, and Korea. Cambria Press.

Peale, S.J., 1976. Orbital resonances in the solar system. Ann. Rev. Astron. Astrophys. 14, 215–246.

Plavec, M., 1956. On the evolution of the meteor streams. Vistas Astron. 2, 994–998.

Plavec, M., 1957. On the origin and early stages of the meteor streams. Publ. Astron. Inst. Czechosl. Acad. Sci. 30, 1–94.

Powell, C., 1997. A New View on Maya Astronomy. Master's thesis. University of Texas at Austin.

Rendtel, J., 2007. Three days of enhanced Orionid activity in 2006 – Meteoroids from a resonance region? WGN, J. International Meteor Organization 35, 41–45.

Rendtel, J., 2008. The Orionid meteor shower observed over 70 years. Earth Moon Plan. 102, 103–110.

Reznikov, E.A., 1983. Origin of the Bootid meteoroid shower. Trudy Kazanskaia Gorodkoj Astron. Obs. 47, 131–136. In Russian.

Sato, M., Watanabe, J., 2007. Origin of the 2006 Orionid outburst. Publ. Astron. Soc. Japan 59, L21–L24.

Sato, M., Watanabe, J., 2010. Forecast for Phoenicids in 2008, 2014, and 2019. Publ. Astron. Soc. Japan 62, 509–513.

Sato, M., Watanabe, J., 2014. Forecast of enhanced activity of eta-Aquariids in 2013, in: Jopek, T.J., Rietmeijer, F.J.M., Watanabe, J., Williams, I.P. (Eds.), Proceedings of the Meteoroids 2013 Conference, Aug. 26-30, 2013, A. M. University, Poznań, Poland, Adam Mickiewicz Univ. Press. pp. 213–216.

Saturno, W.A., Stuart, D., Aveni, A.F., Rossi, F., 2012. Ancient Maya astronomical tables from Xultun, Guatemala. Science 336, 714–717.

Schele, L., Grube, N., Fahsen, F., 1992. The Lunar Series in Classic Maya Inscriptions. Technical Report 29. The CHAAAC of the Art Department of the University of Texas at Austin. Texas Notes on Precolumbian Art, Writing, and Culture.

Seargent, D., 2009. The Greatest Comets in History: Broom Stars and Celestial Scimitars. Springer.

Sekhar, A., Asher, D.J., 2013. Saturnian mean motion resonances in meteoroid streams. Mon. Not. Roy. Astron. Soc. 433, L84–L88.

Sekhar, A., Asher, D.J., 2014. Resonant behavior of Comet Halley and the Orionid stream. Meteorit. Planet. Sci. 49, 52–62.

Sekhar, A., Asher, D.J., Vaubaillon, J., 2016. Three-body resonance in meteoroid streams. Mon. Not. Roy. Astron. Soc. 460, 1417–1427.

Stephenson, F.R., Yau, K.K.C., Hunger, H., 1985. Records of halley's comet on babylonian tablets. Nature 314, 587–592.

Stuart, D., 2000. The arrival of strangers: Teotihuacan and Tollan in classic Maya history, in: Carrasco, D., Jones, L., Sessions, S. (Eds.), Mesoamerica's Classic Heritage: from Teotihuacan to the Aztecs. 2002 ed.. University Press of Colorado. chapter 15, pp. 465–513.

Stuart, D., 2005. The Inscriptions from Temple XIX at Palenque: a Commentary. The Pre-Columbian Art Research Institute.

Stuart, D., 2007. Hit the road. Electronic document online at decipherment.wordpress.com. Maya Decipherment: Ideas on Ancient Maya Writing and Iconography.

Taube, K., 2000. The turquoise hearth: Fire, self-sacrifice, and the central Mexican cult of war, in: Carrasco, D., Jones, L., Sessions, S. (Eds.), Mesoamerica's Classic Heritage: from Teotihuacan to the Aztecs. 2002 ed.. University Press of Colorado. chapter 10, pp. 269–340.

Telleriano-Remensis, 1901. Codex telleriano-remensis. Foundation for the Advancement of Mesoamerican Studies, Inc. Page 39V.

Trenary, C., 1987-1988. Universal meteor metaphors and their occurrence in Mesoamerican astronomy. Archaeoastronomy 10, 99–116.

Van Laningham, I., . pauahtun.org.

Vaticanus-3773, . Codex vaticanus 3773. Foundation for the Advancement of Mesoamerican Studies, Inc. Facsimile, Electronic document, http://www/famsi/org/research/codices.

Whipple, F.L., 1951. A comet model. II. Physical relations for comets and meteors. Astrophys. J. 113, 464–474.

Yeomans, D.K., Kiang, T., 1981. The long-term motion of comet Halley. Mon. Not. Roy. Astron. Soc. 197, 633–646.

Zhuang, T.S., 1977. Ancient Chinese reports of meteor showers. Chinese Astron. 1, 197–220.

Appendix A. ETA Data Set

967 BC Apr 7	5.8.17.15.17	PAL	acc (U Kokan Chan)
249 Apr 7	8.10.10.10.16	CPN	unk
328 Apr 11	8.14.10.13.15	WAX	unk
480 Apr 18	9.2.5.0.0	QRG	pe
484 Apr 13	9.2.9.0.16	CRC	acc (Yajaw Te' K'inich I)
511 Apr 20	9.3.16.8.4	TIK	acc (Lady of Tikal)
531 Apr 14	9.4.16.13.3	CRC	acc (K'an I)
553 Apr 17	9.5.19.1.2	CRC	acc (Yajaw Te' K'inich II)
556 Apr 10	9.6.2.1.11	CRC	war (axing)
562 Apr 30	9.6.8.4.2	CRC	war (Star War)
566 Apr 23	9.6.12.4.16	CRC	birth (Lady B'atz??? Ek')
572 Apr 7	9.6.18.5.12	PAL	acc (Kan B'ahlam I)
588 Apr 19	9.7.14.10.8	CRC	birth (K'an II)
599 Apr 13	9.8.5.12.19	TNA	unk
606 Apr 14	9.8.12.14.17	TNA	birth (Hix Chapat)
611 Apr 5	9.8.17.15.14	PAL	war (axing)
614 Apr 12	9.9.0.16.17	CRC	tomb
618 Apr 14	9.9.5.0.0	ALS	pe
621 Apr 9	9.9.8.0.11	PNG	unk
634 Apr 9	9.10.1.3.19	DPL	depart (B'alaj Chan K'awiil)
635 Apr 9	9.10.2.4.4	CRN	foundation?
636 Apr 29	9.10.3.5.10	CLK	acc (Yuknoom Ch'en II)
639 Apr 13	9.10.6.5.9	PNG	acc (Ruler 2)
640 Apr 7	9.10.7.5.9	COB	acc (Ruler A)
644 Apr 9	9.10.11.6.12	NAR	strike (stone road)
662 Apr 6	9.11.9.11.3	MRL	acc (2nd, Muwan Jol? Pakal)
663 Apr 23	9.11.10.12.5	CRN	dedication (house)
675 Apr 26	9.12.2.15.11	CRN	depart (CLK king)
686 Apr 4	9.12.13.17.7	CLK	acc (Yuknoom Yich'aak K'ahk')
687 Apr 12	9.12.15.0.0	PNG	pe
690 Apr 9	9.12.18.0.13	CRN	fire
691 Apr 12	9.12.19.1.1	TZE	fire (tomb)
694 Apr 23	9.13.2.2.8	CRN	unk (Chak Ak'ach Yuk)
699 Apr 17	9.13.7.3.8	NAR	dedication (ceremonies)
711 Apr 9	9.13.19.6.3	NAR	unk
716 Apr 4	9.14.3.8.4	NAR	war (attack)
721 Apr 27	9.14.9.9.14	CRN	arrive ('Ix Ti' Kan Ajaw)
723 Apr 24	9.14.11.10.1	YAX	fire

726 Apr 5	9.14.14.9.18	PNG	unk
726 Apr 21	9.14.14.10.14	NAR	war? (star war?)
738 Apr 5	9.15.6.13.1	YAX	fire
738 Apr 24	9.15.6.14.0	QRG	fire
738 Apr 30	9.15.6.14.6	QRG	war (decapitation)
750 Apr 8	9.15.18.16.7	PNG	birth (Ruler 7)
752 Apr 30	9.16.1.0.0	YAX	acc, pe (Bird Jaguar IV)
756 Apr 10	9.16.5.0.0	multiple sites	pe
770 Apr 9	9.16.19.3.12	EKB	arrive (Ukit Kan Lek)
778 Apr 13	9.17.7.5.19	AGT	war (downing of “flint-shield” [army])
778 Apr 17	9.17.7.6.3	ITZ	smoke
780 Apr 13	9.17.9.6.14	IXK	dedication
781 Apr 18	9.17.10.7.0	HIG	acc (unk)
783 Apr 16	9.17.12 .7.8	QRG	unk
790 Apr 12	9.17.19.9.1	NAR	strike (stone road)
790 Apr 26	9.17.19.9.15	QRG	unk
796 Apr 2	9.18.5.10.3	TNA	death (Aj Tolol Te’)
802 Apr 8	9.18.11.12.0	AML	acc (Lachan K’awiil Ajaw Bot)
808 Apr 6	9.18.17.13.10	YAX	fire
808 Apr 10	9.18.17.13.14	YAX	throw
820 Apr 13	9.19.9.17.0	CRC	tomb?
849 Apr 15	10.0.19.6.14	CRC	???form the earth????
863 Apr 12	10.1.13.10.4	Randel Stela	819 day count