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The Lyrids meteor shower: A historical perspective

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ABSTRACT

The April Lyrid meteor shower is the oldest meteor shower ever recorded continuously throughout history, dating as far back as 687 BC. Before the 20th century, historical sources only provided reports of two years of strong activity and up to nine possible additional events. Currently, the shower has low activity, but it has had significant episodes that, during the 20th century, seem to repeat at time intervals that are multiples of 12yr or 60 yr. Earlier outbursts may have also occurred with a frequency consistent with this period. Outbursts of activity are also known in other meteor showers. The classical explanation that they are correlated to the close proximity of the parent comet to the Earth was proven wrong in the last years of the 20th century and this is also clear in the case of the April Lyrids, whose parent comet is C/1861 G1 (Thatcher), with an orbital period of about 400 yr. Our previous research has led us to compile an additional list of possible April Lyrids in the last 2000 years. This paper has two objectives. First, to present the list of possible Lyrids that we have compiled that would significantly increase the number of historical observations considered to date. Secondly, to study if the historical data fit well with the main theories and recent studies concerning the Lyrids.

1. Introduction

Few astronomical phenomena are as spectacular to the naked eye as meteor showers, particularly meteor outbursts. It is no surprise that ancient and medieval observers soon began to take records of them, being the oldest known account linked to a modern shower, the Lyrids outburst seen in China on March 16, 687BC (Hasegawa (1993); Pankenier et al. (2008)). Systematic studies of meteors had to wait until the 19th century, with the Lyrids outburst of 1803 and especially the one of the Leonids on November 13, 1833, (see e.g. Kronk, 2014).

Currently, meteor showers are considered to be the result of the stream of debris ejected from comets or asteroids approaching from one direction and colliding with the Earth's atmosphere. The working list of Meteor showers maintained at the IAU's meteor data center (Jopek and Kaňuchová, 2017) has 921 showers, 110 established, and 28 nominated.

Different authors have carried out the work of compiling a catalog of "historical meteors" over the last two centuries, "historical" meaning those seen prior to the 19th century, see, e.g., Chasles (1841), Quetelet (1841) and Newton (1864). A general characteristic of practically all of them is their focus on observations from Far Eastern countries, especially China, and the very low representativeness of the observations from Europe. This fact is understandable since, in those countries, there was a tradition of systematically writing chronicles of the successive reigns, pointing out astronomical events that, according to their traditions and beliefs, would influence the kingdom or the monarch in some way. This was not the case in Western countries, where we find fewer astronomical observations that are much more dispersed in works by different individual authors who often copy each other or, at least, tend to copy from the most prestigious ones. In addition, meteors and meteor showers were generally also regarded as curiosities or omens. For this reason, the observation could not be mentioned in a chronicle, or the copyist could vary its date to coincide with a particular event. Thus, astronomical phenomena observed from Western countries only appeared in the above mentioned catalogs in a residual way. This scarcity of data led to odd results such as, for example, that Perseids seemed not to have been observed in Europe.

The first systematic search for meteors observed in the European zone in the Middle Ages was carried out by Dall'Olmo (1978), focusing on Medieval literary sources. Later, this list was extended by Martínez and Marco (2017). The list of authors who, in recent years, have contributed to expanding the number of historical observations both from those coming from Eastern and Arab countries would be very long, but a summary of the evolution and the most influential authors in this regard can be found in the introduction in Martínez and Marco (2018).

For this paper, we have reviewed eastern (mainly from Pankenier et al. (2008)) and western sources (mainly from Martínez and Marco (2017)), searching for all meteor showers whose dates were approximately compatible with the April Lyrids. After several feedbacks that will be described in the following sections, a set of 59 timed candidates remained. It should be noted that only a few observations before the 19th century are unanimously accepted as corresponding to Lyrids (Jenniskens, 2006), so an increase in this number, no matter how small,

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could provide much information about the evolution of this meteor shower.

The different theories about the origin and formation of the meteoroid streams associated with the Lyrids and its parent comet have the problem, familiar to most established meteor showers, that they cannot be tested in observations before the 19th century. This paper does not aim to offer a definitive answer or validate these theories. Instead, our primary goal is to expand the list of historical observations of Lyrids and, then, to check if these new historical data support existing theories and data.

Throughout the paper, we will use Julian dates for years before AD1582 and Gregorian dates after that.

2. April Lyrids and related historical observations of comet thatcher

The April Lyrids is an established shower numbered as No. 6 in the IAU MDC list. It is commonly considered the oldest observed meteor shower, with the first record dated by Chinese astronomers in 687 BC. As in most records of meteor showers from pre-telescopic times, the need for more information about the radiant makes it difficult to state the link without doubts.

The strong outburst in AD1803, with an estimated ZHR = 860 (Jenniskens, 1995), aroused interest in the Lyrids. In the astronomical literature, there are a few known cases of other great Lyrids outbursts. However, these seem to have ceased in the last two centuries, being nowadays a moderate shower, with a modest ZHR = 20, and lasting about one week. The shower peaks around April 22 ($\lambda_{\odot} = 32^{\circ}$), although observers report activity between April 14 ($\lambda_{\odot} = 24^{\circ}$) to April 30 ($\lambda_{\odot} = 40^{\circ}$).

The proposal of C/1861 G1 (Thatcher) as the parent comet of the April Lyrids was already asserted in the 19th century. Since then, it has been accepted and confirmed by many authors (a complete list would be very long see, e.g., Denning (1878), Lindblad and Porubčan (1991) or Hajduková and Neslušan (2021) for a recent review on the subject)

An issue of interest in the History of Astronomy is the possibility that the comet was detected in one perihelion passage other than the one in AD1861. In the absence of more historical documents, this is a question about which we can only speculate: the calculated perihelion dates and the orbital parameters may be seen in Table 1. Explanations about how they were computed may be seen in the next section.

No historical records match the date for the most ancient perihelion passage. For the second, in 434BC, we have the possibility of a concise record dated 433BC (Pankenier et al., 2008): 8th year of King Kao of Zhou; a broom star appeared, which may or may not refer to this comet, although the computed visibility conditions of the comet for this perihelion passage were not the most suitable for observation with the naked eye. A comet was detected for the perihelion of 45BC, but its trajectory is not compatible with that of Thatcher. There are no records of any comet for AD320. In addition, visibility conditions turn out to be quite negative.

In AD701, there is only a possible record from Korea: between March 14 and April 12*, a broom star entered the Moon* which, despite referring to a comet ("broom star" is a common way of referring to these celestial bodies), could, in fact, describe the occultation of Jupiter, visible in Korea on March 29 that year. Also, although the text describes a nice astronomical event, it must be taken into account that the source, the *Samguk Sagi*, is a text from the 12th century, quite distant from the phenomenon described.

There are no reports of the comet in AD1086 or AD1472. This is no surprise since its position in the celestial sphere was unfavorable, and the magnitude should have been very low, reaching a magnitude of 3.5 at most.

The comet's descending node is responsible for the Lyrids shower, while the ascending node is quite far from Earth's orbit and does not cause any meteor showers. The meteoroid stream and its relationship with the comet have been the subject of numerous studies trying to understand and explain their behavior. Several possible explanations have been proposed, some of them quite early in time: for instance, the dependence of particular strong showers on the positions of Jupiter and/or Saturn was already proposed by Guth (1947).

Regarding the periodicity of the shower activity, several studies have yielded different conclusions. In particular, the 12-year period has merited in-depth studies by Arter and Williams (1995, 1997a, 1997b), who found that the mean position of the node of all the meteoroids which cross the ecliptic in a given year changes annually but repeats after 12 years as a result of minor changes in the meteoroids orbits caused by the perturbations of Jupiter. Some scholars have confirmed this period (see, for instance, Bel'kovich et al. (2011); Sokolova et al. (2016)), while others are more skeptical and propose alternative solutions see e.g., Jenniskens (1995, 1998).

On the other hand, regular outbursts over a 60 yr interval also have deserved studies. Some proposed explanations include a disrupted fragment in a 60 yr orbit (Arter and Williams (1995); Sokolova et al. (2016), who propose two periods of Lyrids activity: one close to 60 years; and other of about 10–12 years), or trapped dust trails in multiple resonances (Emel'yanenko (2001)).

Other explanations include large cloud particles (Porubčan et al., 1992) or filamentary structure of small particles in the Lyrid meteoroid stream (Lindblad and Porubčan (1991)), or Porubčan and Kornos (2008) who described two distinct filaments in the Lyrids stream: one with a shorter period of about 40 years, which should correspond to the outburst peak, and the second one with a period of about 600 years. Also, Tóth et al. (2011) described a short period filament of about 55 years period and another long period of 385 years. However, Ye and Jenniskens (2022) have pointed out that the required ejection speed for these scenarios (on the order of several 100 m/s) is unrealistic. For his part, Jenniskens (1997) suggested that the outbursts could be explained by the reflex motion of the Sun due to Jupiter (and, to a lesser extent, Saturn).

In the next section, we will proceed to describe the selection of historical showers, and then we will see if the new data is compatible with current theories and observations.

Table 1

Computed perihelion dates and orbital elements of comet C/1861G1 (Thatcher) at the past seven perihelion passages. P is the observed interval in years between two successive passages, and P_C is the period calculated from the orbital elements of the comet's previous perihelion passage. The estimated P_C from the data of the AD1861 perihelion is 415.49 years. Notice the significative differences with the dates obtained by Arter and Williams (1997a).

Perihelion date (±0.5d)	e	q	i	Ω	ω	Tp	P	P_C
−871 Aug 19	0.984200	0.917178	79.6920	31.7758	214.0044	1403520.5	–	–
−435 Jul 29	0.984205	0.914445	79.6949	31.8139	214.0246	1562748.5	436	442
−46 Dec 2	0.982946	0.920465	80.0122	31.8965	214.0758	1704956.5	389	440
320 Nov 22	0.982550	0.921224	80.1292	31.9113	213.8303	1838263.5	365	396
701 Nov 2	0.982855	0.922637	80.0569	32.0048	213.7409	1977403.5	381	383
1086 Jun 18	0.982917	0.915745	79.9865	31.9646	213.7553	2117887.5	385	395
1472 Oct 9	0.983184	0.917293	79.8940	31.9776	213.6465	2258987.5	386	392
1861 June 3	0.983465	0.920700	79.7733	31.8674	213.4496	2400930.3899	389	403

3. Selection of historical showers

In order to enlarge the sample of Lyrids historical showers, we have started from the list of eastern meteor observations published by Pankenier et al. (2008), punctually completed by those of other authors such as Hasegawa (1993). For the European reports, we have taken into account those compiled by Martínez and Marco (2017) for the Middle Ages, as well as those from the Arab world (Stephenson and Rada (1992) and Basurah (2012)). For later times (until the 20th century), we have considered those listed in Jenniskens (1995, 2006).

The usual way to establish whether an observed meteoroid belongs to a given meteor shower is to consider the period in which the meteor shower takes place and establish a limit of 5° between the theoretical radiant and the actual observation, and ten days in peak time. For long-period comet showers, the probability of a chance association is about one in 1000 (Jenniskens et al., 2021). However, this method cannot generally be applied to historical observations before the 19th century since most reports only indicate the date when the shower or the meteoroids were detected. In some cases, the time of the day also appears, and very rarely, the part of the sky or the constellations or asterisms the meteoroid crossed is indicated. As a general rule, the older the observations, the less data they provide.

To overcome this situation, we have used a procedure similar to the Nodes Method (for a review of this and other methods, see Egal (2020)), currently employed to link a meteoroid stream to a tentative parent body. In the first place, we calculated for each year between 1000BC and AD2000 the dates when the position of the Earth and the comet descending node were the closest (see Table 2). To this aim, we have integrated backwards (and forward) the orbits of comet Thatcher and the Earth from 1000BC to 2000AD. See Fig. 1 for the spatial position of the nodes with respect to a mean Earth orbit and the next section for details about the integration.

First, we disregarded those historical records that mention a single meteor since we are not interested in studying isolated meteors or fireballs. Bearing in mind that the typical activity of the April Lyrids occurs in an environment of 5 days before and after the passage of the Earth near the descending node of the comet, we considered the dates from Table 2 as the potential peaks of the meteor shower for the given year and we have considered as possible Lyrids all those records that were ±5 days from these dates. In some specific cases, we have considered longer time intervals because the description of the phenomenon fitted well to later Lyrids. Historical records not meeting this characteristic were rejected. Other reports were also dismissed because they seemed to refer to meteorological phenomena. Consider, for instance, the record from AD582 that has sometimes been taken as a Lyrids shower (Gregorii *Episcopi Turonensis Historiarum* L. VI.: MGH, SS. rer. Mer,i, p 284) where two “burning fires” lasting 2 h and forming a “great beacon” are mentioned. This record is ambiguous and seems to correspond better with a phenomenon related to an aurora.

This procedure provided a total of 59 timed and untimed observations for the Asian zone and 120 for the European zone (from now on, we will include in the "European observations" the very few from the Arab world). We consider timed reports those that explicitly indicate the day, month, and year of the observation and untimed those that do not specify the exact day.

Table 2
Dates of the closest distance of the Earth to the descending node of the comet. In parentheses, the corresponding solar longitudes in degrees for the epoch J2000. For intermediate years an error of ±1 day is assumed.

Year	700BC	300BC	AD100	AD300
Min dist.	March 22 (31°)	March 25 (32°)	March 26 (32°)	March 29 (32°)
Year	AD500	AD1000	AD1400	AD1800
Min dist.	March 30 (32°)	April 2 (32°)	April 5 (32°)	April 19 (31°)

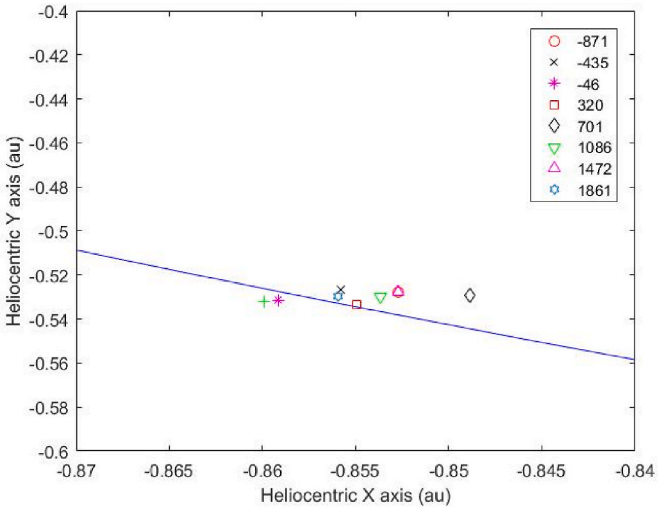

Fig. 1. Projection on the XY axes in heliocentric coordinates of the positions of the descending nodes corresponding to the different perihelion passages of Comet Thatcher between 1000BC and AD2000. The blue line corresponds to the Earth’s orbit for 2000AD, which we have included only as a relative orientation.

It should be noted that in the month of April, other meteor showers occur that can cause spectacular phenomena. Hence, in doubtful cases, we took special care to choose only those records that allowed us to discern that Lyrids were involved, mainly because the place in the sky where they were observed was explicit, but sometimes other considerations played a role. In each case, we explain this consideration in Annex 1.

There is always the possibility of the existence of an already extinct meteor shower in past times, but currently at the end of March-mid-April, there is no significant meteor shower with which the Lyrids can be confused, except for the η -Aquarids, associated with comet 1P/Halley. However, this shower is not so easy to see from the northern hemisphere, which is from where all the observations come.

Among this first selection of candidates, some had previously been associated with other annual April–May meteor showers, particularly with the η-Aquariids or a yet unidentified shower (Jenniskens, 2006) because the variations in the node seemed to be too large for a long-period comet dust trail, and a shorter orbital period of around 5.9 yr was considered more likely. In the same way, some observations previously regarded as possible Lyrids have been eliminated.

Then, we separated timed and untimed reports, and later we analyzed each of them individually. We paid particular attention to the untimed reports that did not specify the year but did specify the month in which the meteors were observed. Although these observations do not have the same relevance, they can give an idea of time intervals in which particularly abundant showers were observed.

Finally, we obtained 43 possible timed and 25 untimed Lyrid meteor showers. They are listed in Annex 1. In these observations, it is challenging to distinguish whether they are regular or outbursts. However, some descriptions include terms such as "innumerable" and "like rain" that seem to refer to the latter phenomenon. In this case, we have marked them with an asterisk. These reports are represented in Fig. 2, together with the distance of the nucleus of the parent comet to the Earth.

An issue that other authors had already observed and seems to have been confirmed with the addition of new observations is the relatively high amount of meteor showers that occur when the nucleus of the parent comet is in a position far from Earth’s orbit, even with the comet at aphelion (See Fig. 2) The characteristics of the comet can explain this, as we will see later, but it seems in contradiction with other conclusions that suggest that especially strong meteor showers are related to the

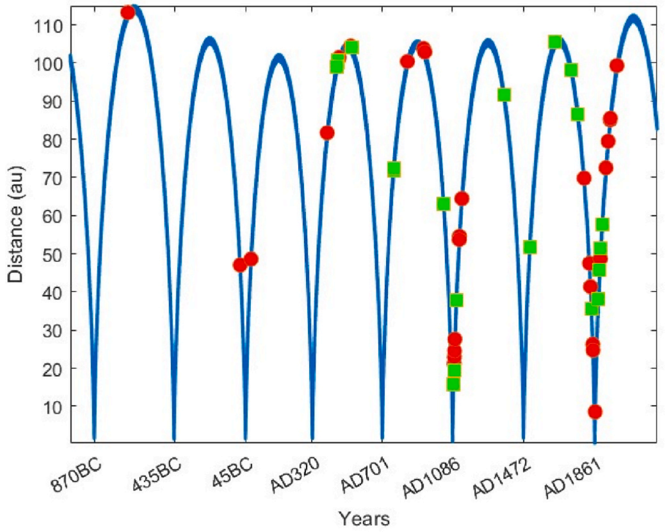

Fig. 2. Distance of the nucleus of C/1861G1 (Thatcher) to the Earth and possible ancient Lyrids outbursts. Red circles represent timed and green squares untimed Lyrids reports.

proximity of the parent comet nucleus to Earth (Wu and Williams, 1992, 1995). As can be seen in Fig. 3, the minimum orbit intersection distance (MOID) ranges from 0.004 to 0.24 au, which means that the comet is expected to generate observable meteor showers (Jenniskens et al., 2021), but it does not seem to be a direct relationship between the distance to the node and the number of observed meteoroids, either.

Always aware that we are working with historical data, which implies unexpected problems such as lost data or copyist errors, we can observe another feature from the data in Annex 1: periods between rains seem to repeat themselves in periods of approximately 12 (or multiples) and 60 (or multiples) years. These repetitions are more evident if we consider the timed and untimed observations. We can also find periods in which many meteor showers occurred within a few years, such as AD453–466 or AD1091–1098. In the latter case, it does coincide with the proximity of the comet's nucleus to Earth and a remarkably reduced distance to the node, although this explanation would not be valid for the first date when a completely inverse situation would occur.

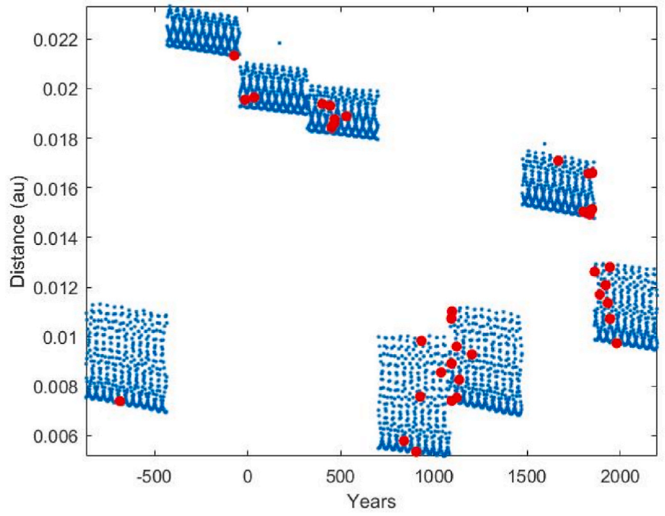

Fig. 3. Minimum distances to the node for each year in au. The red circles represent observed showers.

4. Theoretical meteoroid stream and numerical integrations

Comet C/1861G1 (Thatcher) is one of the few long-period comets (LPC) with an associated meteor shower. In this kind of comet, gravitational perturbations on the orbital period prevent capture in mean motion resonances with the orbital motion of the giant planets (Jenniskens et al., 2021).

Comet Thatcher is supposed to decompose in the vicinity of the sun, leaving a trail of debris behind which, is widely dispersed after a second evolution because of the induced changes in the orbital period (Jenniskens, 2006). As a result, a broad distribution of dust called "Filament" is formed when parts of the trail catch up on each other. These filaments are considered by some authors to be the responsible of the behavior of the Lyrids. Further information about the filaments and their behavior relating to the Lyrids may be found in, for example, Kresák (1993) and Arter and Williams (1997a, 1997b). LPCs differ from shorter-period comets because a "Filament" may already be formed after one revolution. It is also worth noticing that the outbursts for meteoroid showers associated to TPC do not correlate with the return of the parent comet to perihelion, which is verified in the case of the Lyrids, as expected (see Fig. 2).

Jenniskens et al. (2021) obtained some properties that meteor showers from LPC are expected to meet: Meteoroid streams are expected to disperse over time, resulting in showers that last longer and have a more diffuse radiant. In particular, their obtained range for the solar longitude of the Lyrids is $\Delta\lambda_{\odot} = 10.8^{\circ} \pm 1.17$; Over time, precession and other secular dynamical processes may cause the streams to change their mean orbital elements (Jenniskens, 2006). In our case, the high inclination of the comet's orbit makes it less susceptible to large gravitational perturbations from the more massive planets.

It is unclear that Poynting-Robertson drag plays a significant role in the Lyrids shower evolution unless a very long period of time such as the whole range of age for the April Lyrids is considered (see Jenniskens (2006)). This value was estimated as 1.5×10^6 years by Arter and Williams (1997b).

To carry out our study, we will need to integrate the parent comet's orbit and its meteoroid stream over relatively long periods. Many scholars have carried out such numerical simulations according to different models. For example, Kornos et al. (2015) showed that the number of short-period orbits rose with an increasing evolutionary period of the simulation and concluded that the occurrence of the short-period orbits of the Lyrids is caused by the perturbations of the planets influencing the meteoroids for at least 40 kyr. To carry out the calculations, they employed Everhart's integrator RA15 from the package Mercury 6 (Chambers, 1999). The accuracy of the calculations over such long periods of time was also questioned. They found that the results in a long integration were disturbed not only depending on the method used but also on minor variations in the perihelion passage dates that were considered, concluding that only the general features of comet Thatcher's may be reproduced for long periods of time but in the period of ±4kyr the comet's orbit parameters can be recovered quite accurately.

A recent paper by Hajduková and Neslušan (2021) modeled parts of the stream of C/1861G1 with various values of evolutionary times and different intensities for the Poynting-Robertson effect with the primary aim to study whether C/1861 G1 is the parent body of other meteor showers than the April Lyrids. They concluded by denying this possibility and showing that for long periods of time, no clustering of the meteoroids in the stream due to the gravitational perturbations could explain the observed outbursts: the stream of C/1861 G1 remained compact, with no alternative filament evolved, during a long time (several tens of millennia), and found no accumulation of meteors in some intervals of mean anomaly, nor chunks of meteors in the stream which could explain the observed outbursts of the Lyrids. They found the April Lyrids to be a compact shower, with no sub-structures.

In addition, Hajduková and Neslušan (2021) also reviewed the main current proposed explanations for the behavior of the Lyrids: the dependence on the positions of Jupiter and Saturn, with several proposed periodicity in the periods of activity. (in particular, the previously mentioned 12 years period), and the fragmentation of the parent comet suggested by Porubčan et al. (1992) that could have caused the 1982 outburst.

All the studies mentioned are very ambitious in that they involve studying the meteoroid stream over very long periods of time, of the order of 40–100 kyrs. Our intention in this paper is much more modest since we only intend to carry out the study throughout the historical period in which we have records of the meteor shower to check if the calculations of the comet's orbit and its meteoroid stream are associated can explain the reported observations. Occasionally, we will carry out integrations over more extended periods, not exceeding 30 kyr. In this case, we will be aware that the results only represent the main characteristics of the calculated orbits.

We simulated C/1861G1 Thatcher's orbit using numerical integrations. The tests were made with the JPL Horizon system (https://ssd.jpl.nasa.gov/horizons/app.html#/) and Gauss-Radau integrator (Everhart, 1985) from the package Mercury 6 (Chambers, 1999; Chambers and Murison, 2000). In particular, we tested the output intervals using Bulirsch–Stoer (BS), RA15 (Radau), and the symplectic integrator MVS in the range from every 1 day to the output for each perihelion passage. The model of the Solar System used in the integrations included 8 planets, and the Earth and Moon were considered as a barycenter. The results may be seen in Table 1 for the Radau method and the table in Annex 2 for a comparison among all the methods. The differences when using the Mercury integrators are not significant. However, the JPL yields results that are progressively further away from the previous ones as we consider more distant epochs in time. The date of the earliest historical perihelion passage differs from the other integrators by more than 100 years. For further integrations, we dismissed the JPL integrator and used the Gauss-Radau integrator in the Mercury software package.

On the other hand, we will also simulate meteoroid streams ejected from the parent comet. To this aim, we consider 1000 particles emitted by the comet in a given perihelion. Arter and Williams (2002) derived a range of the meteoroid ejection velocities of 25–150 m/s. We have considered a rate of ejection velocity of 50 m/s following Kornos et al. (2015), but we have made further tests using different ejections velocities, as we will see in the next section.

Considering all the elements that can modify the orbit and the structure of a meteoroid stream, it is virtually impossible to simulate it with total accuracy, which would also require huge calculation capacity. Thus, we will limit ourselves to following a method simplified and similar to that described by Neslušan (1999) and then improved and ultimately used by Neslušan and Tomko (2023). First, we consider the osculating orbit of the comet published in the JPL Small-Body Database (See table 6 in Annex 2), and we integrated it backwards in time to its chosen perihelion. When the integration orbit into the past was finished, we assumed 1000 test particles were ejected from the comet nucleus. These particles represented the meteoroids. We assumed an ejection uniformly in all directions, with a single velocity value as previously stated.

After the ejection of the test particles, we integrated their orbits in time forward until the required date. In this way, we followed the dynamical evolution of the stream. We assumed that the eight major planets gravitationally perturbed the particles in this integration. Finally, we disregarded the non-gravitational Poynting–Robertson (P–R) effect, which is not likely to affect over such a period of time. In this regard, Hajduková and Neslušan (2021) modeled the comet's orbit including values for the P–R forces that ranged from a merely residual value to some very high ones in time periods of up to 100kyr, obtaining that only the latter had a significant influence. In any case, given that we have already commented that numerical integration over long periods of time is not free of errors, and that we are only looking for a general overview, the introduction of this effect seemed irrelevant to us, as it would only contribute more entropy to the simulation. In the next section we will show and discuss the results.

5. Discussion

Having obtained the list of potential historical Lyrids observations, both timed and untimed, we studied if they matched with existing measurements and theories about the evolution of the meteoroid stream. As seen in Annex 1, some intervals multiples of 12 and 60 repeat in the reports of historical Lyrids, but not in such a clear way as to consider them a general pattern. Of course, as these are non-systematic observations, we must take into account the possibility that records have been lost or that the existing ones correspond to observation periods with good atmospheric conditions or other particular circumstances.

Several observers have attempted to estimate the orbital period of this meteoroid stream from visual observations. The early attempts from e.g. Herrick (1841) concluded in a near 27 years period. Denning (1897) obtained 47, and then again in (1914) 16 years. Malzev (1929), a period of 29.70 years. V. Guth (1947) determined 11.965 years.

Later authors used photographic and radar data to obtain p.e. an average period of 131 years (Lindblad and Porubčan (1991)), or 9.58 years (Sekanina (1970)). In the study by Porubčan and Kornos (2008), two distinct groups of orbits, the short-period and long-period, were recognized in the Lyrid meteoroid stream. The groups were probably formed under the gravitational influences of two dominant bodies, Jupiter and Saturn. They obtained two filaments. One of them, Filament 1, had an average period of 40 years and the other of 600 years. Finally, Brown et al. (2010) found 1197 meteor orbits in the data acquired by the Canadian Meteor Orbit Radar (CMOR) system during 2002–2008 and determined the Lyrid period as about 36 years.

Let us consider the orbital elements obtained for the Lyrids by different authors in Table 3. All of them were integrated backwards in time, proving to be very stable regarding their orbital periods, as expected. See the evolution in the periods in Figs. 4 and 5. The density functions of the periods are represented in different colors for the indicated years, and no significant changes are observed in their evolutions. We have carried out this calculation with all the sets from Table 3, and then we have included in some of the graphs the density function of the intervals between observations obtained from the data in Annex 1. In Fig. 4 this line has not been included as the match with the integrated periods is not good. It can be seen in Fig. 5 that the actual observations appear to correspond to what might be expected from the calculated elements.

While the ancient observations appear to agree with the periods calculated from observations of modern Lyrids, another problem is explaining the origin of these meteors, especially those with periods less than 40 years.

In the first place, we wonder if the verified outburst observed in the 19-20th century may have been caused by ejected particles in one of the previous returns of the comet. As explained in the last section, we simulate 1000 particles ejected by the comet in each of the seven previous perihelions using an ejection velocity of 50 m/s.

In the beginning, shortly after the ejection, the fragments would form a spherical cloud around the comet's nucleus, and the orbit of the meteoroids and that of the parent body would not differ too much. In time, the cloud will evolute into a trail. As successive passes through perihelion occur, the difference would be more and more pronounced. As an example, in Fig. 6, we can see the distribution of the particles assuming that they were ejected at the perihelion of AD1086 after the first (left) and the second (right) successive passes through the perihelion of the parent comet. This simulation was carried out for the eight perihelia of the comet in the interval from −871 to the year 1861. The behavior is similar in all cases.

Under the indicated conditions, the meteoroid stream stabilizes with the subsequent period in orbits of an average of 350 years. In Fig. 7

Table 3

Sets of orbital elements obtained from different authors for the Lyrids. T_C is the mean period in years, calculated from the orbital elements.

a	q	e	ω	Ω	i	T_C	References
13.97	0.922	0.934	213.912	32.072	79.095	52	*Set*I. Arter and Williams (1997b)
15.83	0.918	0.942	214.852	32.078	79.351	63	Set II. Arter and Williams (1997b)
11.14	0.914	0.918	216.0	31.6	79.2	37	*Set*I. Porubčan and Kornos (2008)
71.15	0.925	0.987	213.0	31.8	80.4	600	Set II. Porubčan and Kornos (2008)
10.85	0.9149	0.916	215.71	32.0	80.0	36	Brown et al. (2010)
10.8	0.921	0.956	214.0	32.3	79.4	35	Jenniskens et al. (2016)

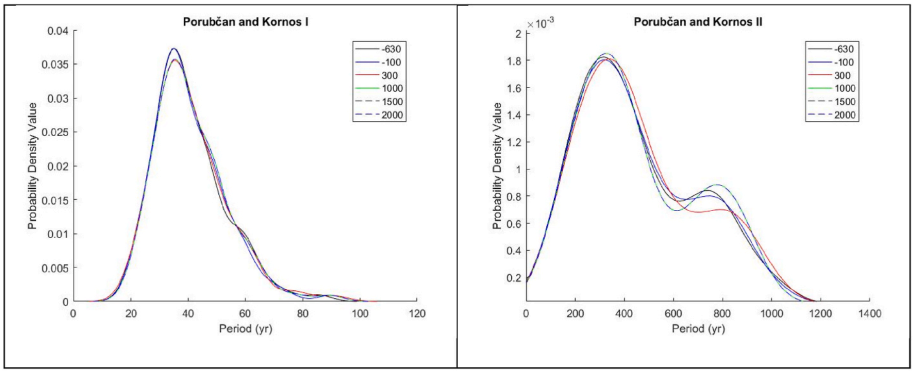

Fig. 4. Density functions for the periods obtained for different epochs using the orbital sets Porubčan and Kornos (2008) I (left) and II (right). In this case, the match with the observed Lyrids is not good and we have not included the comparison with the reports in Annex 1.

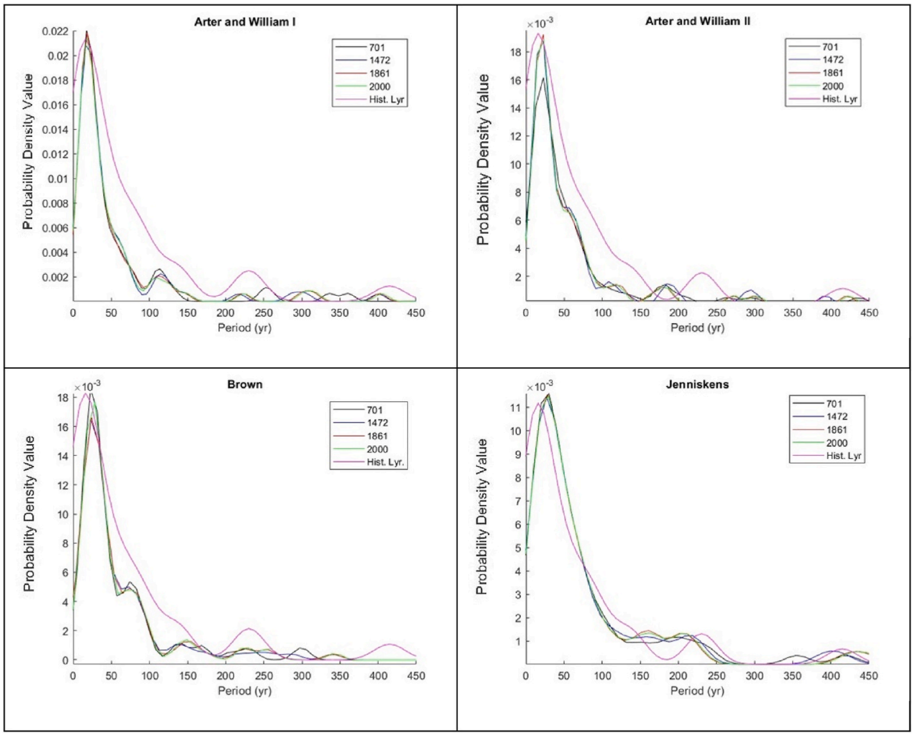

Fig. 5. Density functions for the periods obtained for different epochs using orbital sets from authors in Table 3. The magenta line represents the density function for the interval between observations from Annex 1.

(right), we see the density functions of the periods for the particles after one perihelion passage (in blue) and after a second perihelion passage (in red). We see that, after one perihelion, they present three modes: around 316, 415, and 560 years. Then, after the second perihelion passage, only a mode remains, the one around 330 years. On the right, the same situation, considering the particles ejected during the AD320 passage. We have added a green line to simulate a third period. Similar results were obtained for the other perihelion passages.

After these experiments, we see that meteoroid streams with periods of less than 100 years do not appear, except in a residual way. We obtained similar results by increasing the ejection speed to an improbable 250 m/s.

Subsequently, we performed the same experiment with perihelia close to the years −10,000 and −30,000, obtaining the same result (See

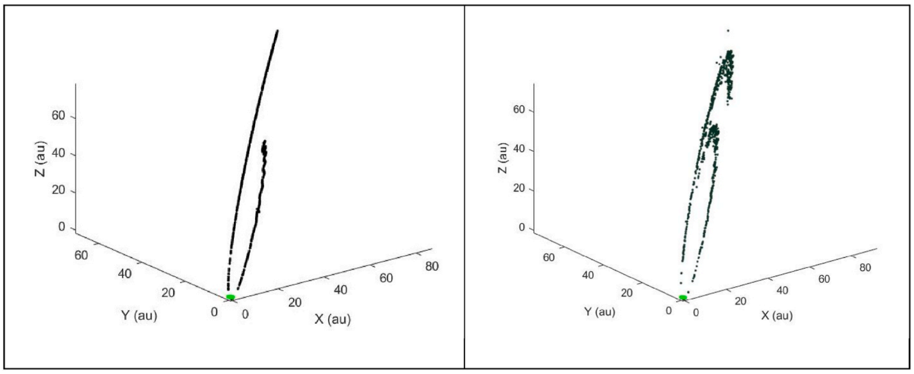

Fig. 6. Distributions of a sample of 1000 fragments ejected in the AD1086 perihelion after one perihelion passage (AD1472, on the left) and after a second perihelion passage (AD1861. On the right). Axes are in ecliptic heliocentric coordinates. Units are in au. The little green circle represents the Earth's orbit.

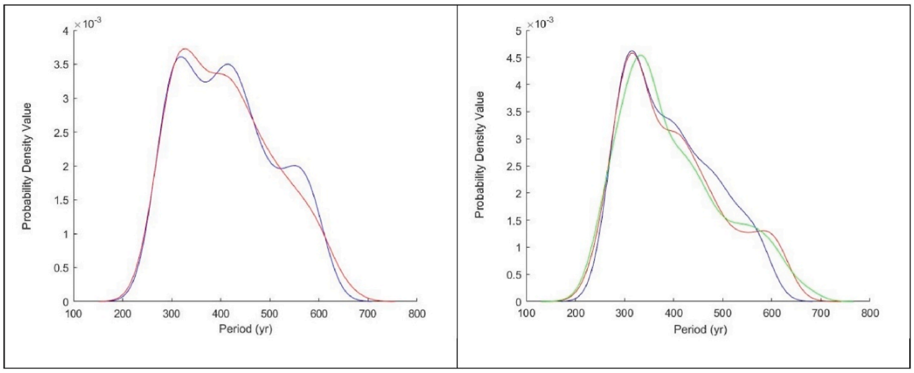

Fig. 7. Density functions for the periods of the fragments in the meteoroid stream ejected in the AD1086 perihelion (on the left) and in the AD320 perihelion (on the right). After one perihelion, three modes appear: around 316, 415, and 560 years. After the second perihelion passage, only a mode remains, the one around 330 years.

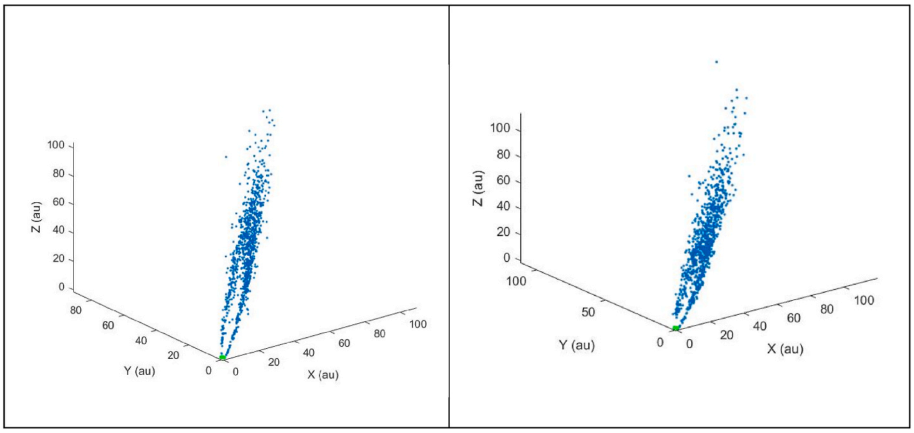

Fig. 8. Distributions of the fragments after 25 (left) and 75 perihelion passages (right). The little green circle represents the Earth's orbit. Axes are in ecliptic heliocentric coordinates. Units are in au.

Fig. 8 for the distribution of the particles after 25 and 75 perihelion passages of the nucleus of the comet and Fig. 9 for the function of density of the periods of the particles in different periods after the ejection). The different lines represent the density functions of the periodic components of the meteoroid stream 5, 20, 25, and 30 kyr after its ejection. Although at first, the periods are close to 400 years, later these are reduced so that the mode stabilizes around 200 years.

Kornos et al. (2015) studied the orbital evolution of the Lyrid meteoroid stream in depth. They considered a simple model in which particles were released from the body only at the moment of the comet's perihelion passage at times approximately 10000, 20000, 30000, 40000, and 50000 years in the past. 900 particles were released from the side facing the Sun, from the cometary equator and latitudes $\pm 10^{\circ}$ and $\pm 20^{\circ}$ and, the ejection velocity of the modeled particles was considered as $50 \mathrm{ms}^{-1}$. They concluded that particles released in the simulated perihelion passages of the comet Thatcher 50000 years ago are most responsible for the occurrence of the short-period orbits of the Lyrids. However, very few of the obtained meteoroids have a semimajor axis smaller than 35 au, and none have a semimajor axis smaller than 20 au.

As we have already stated, Hajduková and Neslušan (2021)

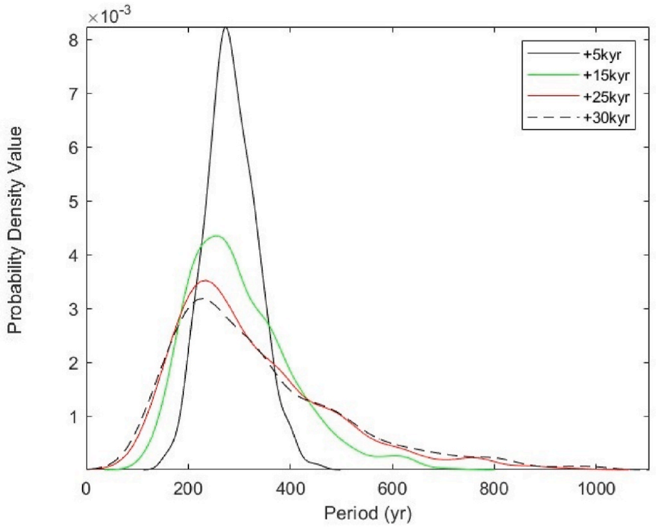

Fig. 9. Density function for the orbits of meteoroids ejected from the nucleus at a perihelion near year −30kty computed at different times after ejection.

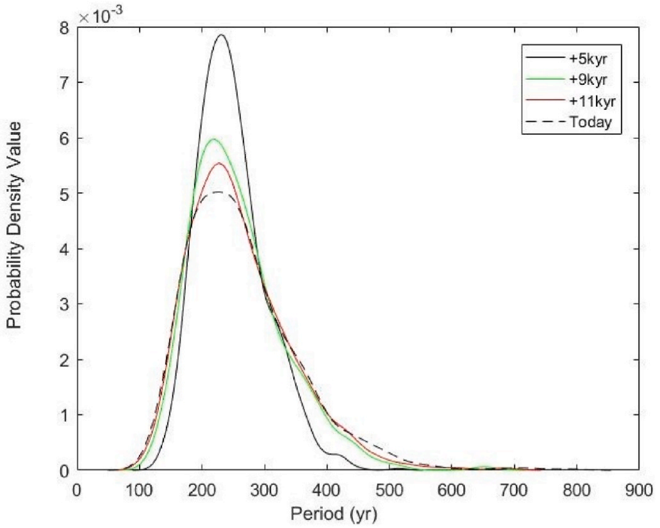

Fig. 10. Density function for the orbits of meteoroids ejected from a secondary nucleus at a perihelion near year −10kty computed at different times after ejection.

disregarded the existence of "chunks" of the particles as the cause of the outburst of the Lyrids. They suggested that the proposed explanation provided by Porubčan et al. (1992), which implied a fragmentation of the nucleus of C/1861 G1, was more reliable. This fragmentation would have separated from the comet about 30kyr ago. In particular, Porubcan and J. Stohl (1992) suggested "a secondary, relatively large body loosed from the parent comet Thatcher at an earlier time, perhaps together with smaller particles that dispersed more quickly along the orbit due to their higher ejection velocities" and then Porubčan et al. (1992) concluded that the secondary nucleus separation from the primary happened sometime between 16 and 136 revolutions ago, with 71 revolutions the most likely, and that the breakup of the secondary nucleus probably happened "about 2 years before the time of the observed shower on the pre-perihelion arc immediately preceding the 1982 Lyrid strong burst".

We have considered the possibility of chain fragmentations similar to those that could give rise to Kreutz Sungrazer comets. All the simulations considered that the fragment separated tangentially from the original nucleus at a speed of 2 m/s and led us to the fact that 20,000 years after the fragmentation, the fragments are set mostly in orbits of periods ranging between 250 and 200 years, with a mean of 224 and std 14. Then, we chose different fragments with these characteristics. We simulated a new fragmentation and observed the evolution, but the expected transition to short period filaments did not occur.

In another experiment, we considered that after the initial partition of the comet in two, the second nucleus ejects fragments in a subsequent passage through perihelion at 50 m/s. In this case, we assume that the fracture of the nucleus of the comet occurred about 30kyr ago, and it is this other comet the one that ejected the meteoroid cloud at a perihelion about 10kyr ago. After different simulations, we consider the second fragment the one whose orbital elements are the average of those mostly obtained. In this case $e = 0.976964$; $q = 0.900019$; $i = 82.4918^\circ$; $\omega = 212.9931^\circ$; $\Omega = 33.0373^\circ$; For this second fragment, we simulate a meteoroid stream generated as we have explained in the previous paragraphs.

The results may be seen in Fig. 10. The orbital period of the meteoroid stream tends to decrease with time, but the elements of the stream with periods less than 100 years are purely residual.

A very similar situation occurs if we consider a fragmentation at the perihelion closest to year −30000, although this time, fragments with orbits smaller than 100 do appear, but again very few.

As an alternative to these models based on the ejection of debris from the comet and its subsequent evolution, Jenniskens (1997) suggested that the outbursts from long-period comet streams can be explained by the reflex motion of the Sun due to Jupiter (and to a lesser extent, Saturn). Considering the displacements of the Sun from the barycenter as (formula (2) in Jenniskens (1997)):

$$\Delta R = -\sum_i \frac{m_i}{M_\odot + m_i} R_i$$

where the summation is over the considered secondary bodies, whose masses and heliocentric distances are given by m_i, and R_i, respectively, and $M_\odot$ is the mass of the Sun. Although we have considered the influence of all the major planets, it is evident that the most significant variations are due from Jupiter and Saturn.

If the influence of all planets is added, meaning that all planets should be aligned, the total motion ranges from −0.01 to 0.008 au. Fig. 11 shows the location of the Sun with respect to the barycenter on the date of the maximum approach of the Earth to the node for all years in the period from AD400 to AD1990, and also for isolated years in which a meteor shower was observed before the 5th century. An open circle marks the position in each year, while solid red circles mark the years when Lyrids outbursts were observed, bigger circles correspond to exceptional outbursts. For historical meteor showers, we have considered that an exceptional outburst occurred when mention is made of "innumerable", "stars that fall from the sky as rain", or similar cases. This consideration implies certain inevitable subjectivity.

In Fig. 11 (upper), all significant showers are represented. In Fig. 11 (bottom), we have only represented those exceptional showers that also took place with a solar longitude less than or equal to 37°. Although the dispersion of the red points in both figures is considerable, three zones in which the density is considerably higher (marked in the upper figure) can be isolated. As the Sun's reflex motion may be a (distorted) image of the relative displacement of a trail of dust with respect to the Earth's orbit as a result of planetary perturbations, the zones could show the existence of several Lyrid trails, perhaps from before and after recent perturbations of the parent come, following the line suggested by Jenniskens (1997). Verification of the latter would require further studies outside this paper's intentions.

In addition, in the table in Annex 1, we have added two columns with the longitudes of Jupiter and Saturn to check if the correlations suggested by Jenniskens (1997) continue to hold with the addition of the new observations. He noticed that the four strongest outbursts of Lyrids (AD1982, 1922, 1836, and 1803) occurred when Jupiter and Saturn were at solar longitude 20 ± 15 and 10 ± 16 respectively, the

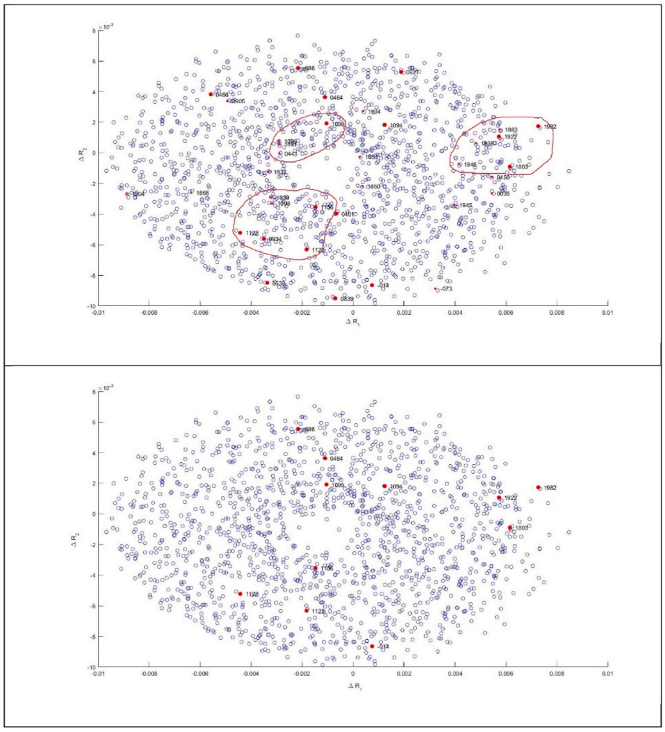

Fig. 11. Displacement of the Sun from the solar barycenter in the plane of the Ecliptic in au with respect to the barycenter on the date of the maximum approach of the Earth to the node for all years in the period from AD400 to AD1990 and also for isolated years in which a meteor shower was observed prior to the 5th century. In the upper figure, significant showers are represented by a larger circle. In the bottom figure, only those exceptional showers that also took place with a solar longitude less than or equal to 37° are represented.

descending node of the stream being at solar longitude of 31°. However, none of the proposed showers verifies these conditions. The assumed correlation with Jupiter and Saturn positions observed in three historic outbursts (582 AD, 464 AD, and 686 BC occurred when Jupiter was in conjunction with the node of the stream. Saturn was, in all cases, close to 180°. In any case, let us remember that we consider the outburst of the AD584 as very doubtful since its description seems to mention some meteorological circumstances) are lost, too, when we add the new reports.

6. Conclusions

In this paper, we have carried out a historical review of historical Lyrids showers and outbursts with two main goals: to increase the list of possible historical observations of the Lyrids and to study if the historical data fit well with the main theories and recent studies concerning the Lyrids. Our original compilation includes about 200 observations of meteoroids, showers, or outbursts seen in October–November between the 5th and 15th centuries, from a previous search in literary sources coming mainly from Europe. For earlier or later centuries, we have relied on lists from other authors. However, unfortunately, most of them cannot be used astronomically for different reasons. After checking the list of ancient observations of the Lyrids, we have proposed an extended list of timed and untimed observations of meteor showers listed in Tables 4 and 5 in Annex 1. The most valuable for further investigation are those in Table 1 since the original sources provide the exact day they were collected. In the period above, we propose 23 new timed observations and explain why we consider that they should be considered Lyrids and not belong to other meteor showers active in those months. In light of current evidence, we have checked that these reports agree quite well with the observed orbital elements for the Lyrids.

Outbursts of activity are typical in the Lyrids, although they are also present in other meteor showers. In our case, the periodicity or the existence of long and short-period Lyrids and the value of the latter are still in discussion today. The simple explanation that these outbursts are related to the proximity of the nucleus of the parent comet does not hold since the Lyrids have presented periods of high activity even with the nucleus of the comet at aphelion. We have reviewed the main explanations that different authors have given for generating different periods in the Lyrids shower, and we have seen that currently proposed theories do not fully explain the historical observed showers and outbursts. If this is due to a lack of data or because existing theories need to be modified or adapted, it is a study that requires more complete models and deeper analyses that are not within the intentions of this paper.

Author statement

First of all, thank you very much to you and the reviewers for your comments and suggestions. All of them have been taken into account, either by making the corresponding changes (shown in bold in the text). We include a separate response for reviewer 1 since reviewer 2 did not made any suggestion. However, please thank both of them their effort If you have any problem, please feel free to ask us what you need.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

ANNEX 1.

Timed observations from Asian, Arabic, and European sources. In the latter case, the number in parenthesis corresponds to Martínez and Marco (2017) enumeration. Eastern references have been taken from Pankenier et al. (2008), pp. 306–451, further reading on Eastern Astronomy are available on e.g. Pankenier (2013).

Descriptions prior to the 19th century that refer to ”stars falling from the sky as rain”, “countless meteors”, or “hundreds of stars” have been marked with an asterisk as potential exceptional outbursts.

Table 4

List of proposed timed observations for the April Lyrids. Jenniskens (2006) only considers (1), (3) and (33). Bagnall (2021) considers (1), (3), (19)–(22) The Δt column corresponds to the interval in years elapsed between the previous observation of a possible Lyrids outburst. $\lambda_{\odot \mathrm{Jup}}$, $\lambda_{\odot \mathrm{Sat}}$ are the longitudes of Jupiter and Saturn, respectively, and $\lambda_{\odot}$ is the solar ecliptic longitude in the epoch J2000.

	Date	Report	Site	Δt	$\lambda_{\odot \mathrm{Jup}}$	$\lambda_{\odot \mathrm{Sat}}$	$\lambda_{\odot}$
1*	687BC Mar 23	stars fell like rain	China	–	60	160	32
2	74 BC Apr 7	a meteor as big as the Moon, and a multitude of stars	China	613	314	107	43
3*	15BC Mar 27	stars fell like rain	China	59	304	97	32
4	35AD Mar 30[1]	white meteors like the Moon	China	50	349	345	34
5*	401AD Apr 8[2]	a multitude of stars streamed	China	366	299	127	41
6	443AD Apr 9[3]	meteors as big as peaches	China	42	125	289	41
7	450AD Apr 4 (3)[4]	Lines and spears of fire	Europe	7	344	18	37
8*	464AD Apr 1[5]	innumerable meteors	China	14	43	175	34
9*	466AD Apr 8	innumerable large and small meteors	China	2	102	124	40
10*	530AD Apr 9	large meteors in their thousands	China	64	254	269	41
11	750AD Apr 5 (50)	Tres estrellas que se movían de una forma extraña	Europe	220	82	77	35
12*	839AD Apr 10	over 200 meteors	China	89	274	84	39
13*	839AD Apr 13[6]	over 200 meteors	China	–	274	84	42
14	905AD Apr 13	large meteors	China	66	106	164	42
15*	927AD Apr 13	a multitude of small stars streamed	China	22	55	80	42
16*	934AD Apr 13	a multitude of stars streamed	China	7	277	171	42
17	1039AD Apr 6 (167)	plagam ignea trabes mirae magnitudinis	Europa	105	220	15	35
18*	1094AD Mar 31 (186)	Stelle innumerabiles cadere et quasi pluere	Europe	55	81	326	29
19*	1094AD Apr 4 (188)	Stelle a multis vise sunt de celo cecidisse.	Europe	–	81	326	33
20*	1095AD Apr 2 (192)	stellae mixtim ex omni parte Coeli decurrisse, et in terram decidisse.	Europe	1	111	339	31
21*	1095AD Apr 4,5,6 (193), (194), (195)	Stelle de coelo cadere et quasi pluere visae sunt	Europe	–	111	339	33
22	1096AD Apr 4, 5 (200), (201)	nocte stellae, quae ceciderunt de coelo	Europe	1	143	352	33
23	1098AD Apr 4 (210)	Stellae de celo cadere	Europe	2	209	16	33
24*	1122AD Mar 31 (233)	Stellae innumerabiles visae sunt cadere	Europe	24	218	307	29
25*	1122AD Apr 4 (236)	Stelle innumerabiles quasi pluere	Europe	–	218	307	33
26*	1123AD Apr 4, 5 (234), (237)	Stellae de coelo innumerabilis cadere	Europe	1	251	321	33
27*	1136AD Apr 3	a myriad stars streamed	Korea	13	286	112	31
28	1204AD Apr 1 (279)	stellae micantes	Europe	68	183	221	30
29	1503AD Apr 6	tre fiamme di fuoco	Europe	299	264	281	32
30	1520AD Apr 17[6]	several meteors	Korea	17	53	124	42
31	1668AD Apr 21	were meteors as big as peck measures	China	148	231	131	36
32	1803AD Apr 20/21	a great shower in morning	China	135	6	351	33
33	1832AD Apr 16	a scarlet star as big as a peck measure (…) countless smaller stars	China	29	162	345	29
34	1838 Apr 20	Jenniskens (1995)		6	349	57	32
35	1850 Apr 20	Jenniskens (1995)		12	353	193	32
36	1851AD Apr 20[7]	a display of meteors	India	1	21	206	31
37	1863AD Apr 21[8]	meteors were falling at a rate of 40 per hour	Europe	12	23	5	31
38	1891AD Apr 16	stars fell like rain	China	28	151	346	28
39	1922AD Apr 20/21	Jenniskens (1995)		31	16	6	30
40	1934 Apr 22	Jenniskens (1995)		12	20	142	33
41	1945AD Apr 20/21	Jenniskens (1995)		11	356	282	30
42	1946 Apr 22	Jenniskens (1995)		1	24	295	32
43	1982AD Apr 20/21	Jenniskens (1995)		37	35	19	31

Notes.

[1] Dated in the 10th year of the Jianwu reign period of Emperor Guangwu of Han (AD34), 3rd month, day guimao. There was no day guimao in the 3rd month of that year. However, it is possible that the 10th year of Emperor Guangwu's Jianwu reign (建武 AD25–56) was AD35, and that year there was a guimao day in the third month: march 30.

[2] Jenniskens (2006) includes this record in the η Aquariids, but the translation given by Pankenier et al. (2008) states that the stars "traveled westward" and not that the meteor shower occurred in the west. Sources indicate that a multitude of stars traveled west through a series of Lunar Mansions (LM): QIANNIU [LM 9], XU [LM 11], WEI [LM 12]. They also crossed TIANJIN, GEDAO, and penetrated TAIWEI and ZIGONG. In practice, this implies that the meteor shower produced meteors between the right ascensions of β Cap (18h 49m., epoch of date) and α Aqr (20h 42m epoch of date). The rest of the details indicate that the meteors originated in the circumpolar zone, near γ Cyg and Cas and their trace reached the β Vir zone. Although the constellations are ordered in the opposite direction in the original, the fact that the meteors ran to the west implies that they originated in the circumpolar zone and moved towards Vir, not vice versa.

[3] The sources are specific about the trajectory and the area of the sky in which the meteors appeared: they emerged from TIANJIN and entered ZIGONG; emerged from ZIGONG and entered the bowl of BEIDOU; emerged from the middle of GUANSUO and passed through TIANSHIYUAN. All the meteors traveled northward together; by daybreak, there had been too many to count.

[4] Although the description of the phenomenon speaks of "lines and spears of fire" it probably refers to a shower or an aurora that lasted all night, seen in Galicia, North-West of Spain. It was seen as the omen of an Earthquake.

[5] Originally, the indicated date is the third month (Mar 24-Apr 26), but the paragraph states that the Moon entered YUGUI [LM23], corresponding to the RA from θ Cnc to δ Hya (7h 2m-7h 15m, epoch of date). The Moon reached that position on April 1.

[6] This report provides a list of meteors, including their colors and paths. Among them: a red meteor emerged from BAGU (δ Aur) and entered WUCHE (ι Aur); [another] red one emerged from GUANSUO (β CrB) and entered FANG [LM 4] (RA from 15h30m-16h00m, epoch of date); Other examples follow, not all of them seem to be Lyrids.

[7] Published in the *Bombay Times* (Kronk, 2014).

[8] A small outburst (Kronk, 2014).

Untimed observations from Asian, Arabic, and European sources. In the latter case, the number in parenthesis corresponds to Martínez and Marco (2017) numeration. Again, Eastern references have been taken from Pankenier et al. (2008), pp. 306-451.

Table 5
List of proposed untimed observations for the April Lyrids.

	Date	Report	Site
1	AD453, April (6)	Cruzando por el cielo exhalaciones ardientes	Europe
2*	AD458 Mar 31–Apr 28	several tens of thousands of meteors streamed	China
3*	AD461 Mar 27–Apr 25	a meteor as big as the several tens of millions of meteors	China
4*	AD534 Mar 1–29	a multitude of stars streamed	China
5	AD763, March (54)	Stellae de caelo ceciderunt	Europe
6	AD764, March (55)	Stellae de coelo cadentes	Europe
7	AD905 Mar 9–Apr 7[2]	white meteors like the Moon	Korea
8	AD1038, April (166)	Maxima ignea trabes	Europe
9*	AD1091, April (179)	Stellae innumerabiles de celo quasi pluere	Europe
10	AD1093, April (182)	stellae in occidente cadere de coelo	Europe
11*	AD1094, April[3] (187)	Stellae de Coelo innumerabiles quasi pluere	Europe
12*	AD1095, April[4] (191)	Stellae innumerabiles de caelo quasi pluere	Europe
13*	AD1096, April[5] (199)	stellae noctu, ac si pluvia dense de coelestibus labi	Europe
14*	AD1098, April[6] (209)	Stelle innumerabiles de celo quasi pluere.	Europe
15*	AD1368 Mar 19–Apr 17	stars streamed (…) trailed by a multitude of small stars	China
16*	AD1506 Mar 25–Apr 22	stars fell like rain	China
17*	AD1644 Mar 9–Apr 6	stars fell like rain	China
18	AD1735 Apr 23–May 21	roaming stars flew everywhere	China
19*	AD1770 Mar 27–Apr 25	stars fell like rain	China
20	AD1843 Mar 31–Apr 29	a giant star fell, and countless smaller stars followed it	China
21	AD1881 Mar 30–Apr 27	stars moved without a fixed direction all over the sky	China
22	AD1888 Apr 11–May 10	countless meteors	China
23	AD1891 Apr 9–May 4[7]	the whole sky was full of falling stars	China
24	AD1894 Apr 6–May 4	stars fell like rain	China
25	AD1901 Apr 19–May 17	stars fell like rain	China

[1] This is possibly the same shower that (12, 13) in the previous table.
[2] This is possibly the same shower that (14) in the previous table.
[3] This is possibly the same shower that (18,19) in the previous table.
[4] This is possibly the same shower that (20,21) in the previous table.
[5] This is possibly the same shower that (22) in the previous table.
[6] This is possibly the same shower that (23) in the previous table.
[7] This is possibly the same shower that (38) in the previous table.

ANNEX 2.

Table 6
Different sets of orbital elements of C/1861 G1 Thatcher, listed in the first row, for each perihelion according to the integrator under similar integration conditions and using those given by JPL as initial elements. Notice the almost exact coincidence of the numerical values obtained using the integration with the Mercury package and how these values moved away from those of the JPL as the integration moved away from the date of the comet's last perihelion. The first line corresponds to the original elements of the comet from https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=C/1861+G1

Integrator	e	q	i	Ω	w	Tp
Original	0.983465	0.9207	79.7733	31.8674	213.4496	2400930.3899 1861 Jun 3.8899
Radau	0.984200	0.917178	79.6920	31.7758	214.0044	1403520.5 −871 Aug 19
	0.984205	0.914445	79.6949	31.8139	214.0246	1562748.5 −435 Jul 29
	0.982946	0.920465	80.0122	31.8965	214.0758	1704956.5 −46 Dec 2
	0.982550	0.921224	80.1292	31.9113	213.8303	1838263.5 320 Nov 22
	0.982855	0.922637	80.0569	32.0048	213.7409	1977403.5 701 Nov 2
	0.982917	0.915745	79.9865	31.9646	213.7553	2117887.5 1086 Jun 18
	0.983184	0.917293	79.8940	31.9776	213.6465	2258987.5 1472 Oct 9
BS	0.984199	0.917171	79.6922	31.7758	214.0042	1403524.5
	0.984205	0.914441	79.6949	31.8139	214.0245	1562748.5
	0.982945	0.920465	80.0122	31.8965	214.0758	1704957.5
	0.982550	0.921224	80.1292	31.9113	213.8303	1838263.5
	0.982855	0.922637	80.0569	32.0048	213.7409	1977403.5
	0.982917	0.915745	79.9865	31.9646	213.7553	2117887.5
	0.983184	0.917292	79.8940	31.9777	213.6466	2258987.5
msv	0.984200	0.917175	79.6921	31.7758	214.0044	1403522.5
	0.984205	0.914444	79.6949	31.8139	214.0246	1562748.5
	0.982945	0.920465	80.0122	31.8965	214.0758	1704957.5
	0.982550	0.921224	80.1292	31.9113	213.8303	1838263.5
	0.982855	0.922637	80.0569	32.0048	213.7409	1977403.5
	0.982917	0.915745	79.9865	31.9646	213.7553	2117887.5
	0.983184	0.917293	79.8940	31.9776	213.6465	2258987.5

(continued on next page)

Table 6 (*continued*)

Integrator	e	q	i	Ω	w	Tp
JPL	0.981928	0.914242	80.3182	32.3958	213.6103	1450759.8671 −742 Dec 19.3671
	0.981944	0.909031	80.2589	32.2449	213.6762	1580213.1311 −387 May 22.6311
	0.981792	0.919831	80.2532	32.0667	213.9679	1707123.6141 −40 Nov 7.1141
	0.982388	0.920460	80.0200	31.9463	213.8077	1837759.6123 319 Jul 7.1123
	0.982883	0.922677	80.0508	32.0193	213.7515	1977407.2611 701 Nov 5.7611
	0.982912	0.915794	79.9988	31.9760	213.7643	2117898.9253 1086 Jun 29.4553
	0.983166	0.917112	79.9095	31.9868	213.6455	2258989.9948 1472 Oct 9.4948

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