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Indirect Solar Wind Measurements Using Archival Cometary Tail Observations

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Abstract This paper addresses the problem of the solar wind behaviour during the Maunder minimum. Records on plasma tails of comets can shed light on the physical parameters of the solar wind in the past. We analyse descriptions and drawings of comets between the eleventh and eighteenth century. To distinguish between dust and plasma tails, we address their colour, shape, and orientation. Based on the calculations made by F.A. Bredikhin, we found that cometary tails deviate from the antisolar direction on average by more than 10°, which is typical for dust tails. We also examined the catalogues of Hevelius and Lubieniecki. The first indication of a plasma tail was revealed only for the great comet C/1769 P1.

Keywords Solar wind · Comets

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1. Introduction

In addition to spacecraft measurements, plasma tails of comets are natural probes of interplanetary space. Physical parameters of the solar wind during the so-called grand minima are still a great puzzle (Eddy, 1976). For the Maunder minimum (hereafter MM) from 1645 to 1715, Parker (1976) conjectured whether a fast and persistent solar wind emanated from a coronal hole, entirely covering the Sun, or if the solar wind just did not blow.

Bessel (1836) suggested that cometary particles move under the action of an effective repulsive force. This idea formed the basis of the mechanical theory of cometary shapes. Bredikhin (1879a,b, 1880, 1886) revised Bessel's calculations and created the well-known classification of cometary tails. This classification was further developed by Orlov (1935) and Wurm (1954). However, the mechanical theory could not explain the large acceleration of cloud masses observed in type I tails. Biermann (1951) showed that the acceleration of the ionised particles in cometary tails cannot be explained by the repulsive force of light pressure. He suggested that the ions are accelerated by the flow of the electrically charged particles emanating from the Sun, referred to as the solar wind. The mathematical theory of these particles was developed by Parker (1958).

Suess (1979) proposed that during the MM, the solar wind speed or the interplanetary magnetic field or both were low and not irregular. Mendoza (1997) evaluated average velocities of the solar wind using the proxy aa index and obtained 194.3 $\mathrm{km\,s^{-1}}$ from 1657 to 1700 and 218.7 $\mathrm{km\,s^{-1}}$ from 1700 until now. Cliver, Boriakoff, and Bounar (1998) extrapolated observed solar wind variations to the MM conditions and suggested that average velocities have an upper limit of 340 ± 50 $\mathrm{km\,s^{-1}}$, and the upper limit of the interplanetary magnetic field is 0.3 ± 0.1 nT. The idea of a lowest conceivable solar wind magnetic field (the floor) was developed by Svalgaard and Cliver (2007) and Cliver (2012).

The scenario of a giant coronal hole over the entire solar disc at the MM might imply a solar wind speed of 800 $\mathrm{km\,s^{-1}}$ (Steinhilber *et al.*, 2010). Wang and Sheeley (2013) simulated the axial solar dipole during grand minima and concluded that a factor of 4 – 7 decrease in the total open flux should result in a similar suppression in the solar wind densities, but should not affect the solar wind speeds. Using geomagnetic indices as a proxy for the solar wind speed, Lockwood and Owens (2014) conjectured that solar wind speeds would have been relatively uniform in the MM (between 250 and 275 $\mathrm{km\,s^{-1}}$). Riley *et al.* (2015) argued that disappearance of the solar wind during the MM is not compatible with the presence of geomagnetic activity and aurorae, which did not cease. Owens, Lockwood, and Riley (2017) noted that during the MM, a solar maximum regime prevailed, with a short-lived fast wind at high latitudes. The results agreed with the MM coronal magnetic field configuration constructed in the global magnetohydrodynamic (MHD) model by Riley *et al.* (2015).

Gulyaev (2015) analysed historic drawings of comets using the mechanical classification of cometary tails. He concluded that straight type I tails depicted by observers in the MM correspond to plasma tails, which in turn indicates that the solar wind is a persistent phenomenon.

In this article, we study whether observers reported the plasma tails of comets in the distant past. In Section 2 we describe the main parameters of a cometary tail, which may help specify its nature (dust or plasma). In Section 3 we analyse colour, shape, and orientation of the cometary tails based on historic archives. The catalogues of Hevelius and Lubieniecki are also discussed. Section 4 presents our conclusions.

2. Parameters of Cometary Tails

In the mechanical theory, the ratio of the outward radial force $\boldsymbol{F}_r$ to the gravitational force $\boldsymbol{F}_{\mathrm{g}}$ given by $|\boldsymbol{F}_r/\boldsymbol{F}_{\mathrm{g}}| = R$ (the effective repulsive force) is used to divide the cometary tails into three types. Type I tails have $R > 12$, type II tails have $2.2 < R < 0.9$, and type III tails have $0.75 < R < 0.2$ (Bredikhin, 1879b). In different editions, these values vary slightly. Type I tails are narrow, nearly straight, and point almost directly away from the Sun. Type II tails are smooth, curved, and distant from the prolonged radius-vector of a comet. Type III tails are short and broad.

Figure 1a shows the classification of the tails according to Bredikhin (1879b). Blue denotes the type I tail, which consists of hydrogen. Yellow denotes the type II tail, which is composed of medium-heavy elements. Pink corresponds to the heavy metals of the type III tail. $\boldsymbol{\xi}$ is the prolonged radius-vector, and ϵ is the angle between the observed tail and the antisolar direction. The lighter the chemical element, the closer its path to the prolonged radius-vector, and the greater R for this element. Here, we emphasise that this classification is no longer valid.

Modern theory distinguishes two basically different types of tails, which are composed of either plasma or dust. Figure 1b schematically illustrates the transit of a comet in the solar system. The yellow decagon depicts the Sun. The dashed curve with arrows denotes a cometary orbit. A white circle is a coma complemented by a wide and curving dust tail and a thin and straight plasma tail. $\boldsymbol{V}_{\mathrm{c}}$ is the comet's orbital speed; γ is the angle between the cometary speed $\boldsymbol{V}_{\mathrm{c}}$ and the antisolar vector $\boldsymbol{\xi}$. Simple calculations give that deviation of the plasma tail from the prolonged radius vector is defined as $\epsilon \approx \arctan(|\boldsymbol{V}_{\mathrm{c}}|\sin\gamma/|\boldsymbol{V}_{\mathrm{sw}}|)$, where $\boldsymbol{V}_{\mathrm{sw}}$ is the radial component of the solar wind flow (Mendis, 2007). Figure 1b shows values of ϵ and $\boldsymbol{V}_{\mathrm{sw}}$ for typical values of the transverse component of the comet's orbital speed $|\boldsymbol{V}_{\mathrm{c}}|\sin\gamma \approx 20\ \mathrm{km\,s^{-1}}$. Because of the retrograde orbit, Halley's comet has one of the highest velocities $|\boldsymbol{V}_{\mathrm{c}}| \approx 70\ \mathrm{km\,s^{-1}}$. Sophisticated calculations yield a typical value of $\epsilon < 6^\circ$ for the plasma tails (Brandt, 1967; Mendis, 2007). The deviation of the dust tail from the antisolar direction amounts to a few tens of degrees. For historic observations, the magnitude of ϵ was restored by Bessel and revised by Bredikhin. In order to specify the nature of the tails reported by observers in the distant past, we rely on this parameter.

Another feature of the dust tail is its curvature. In other words, if an observer writes that the cometary tail became curved, this denotes a dust tail. However, in the case of non-stationary outflow of cometary particles and at a short distance from a nucleus, the dust

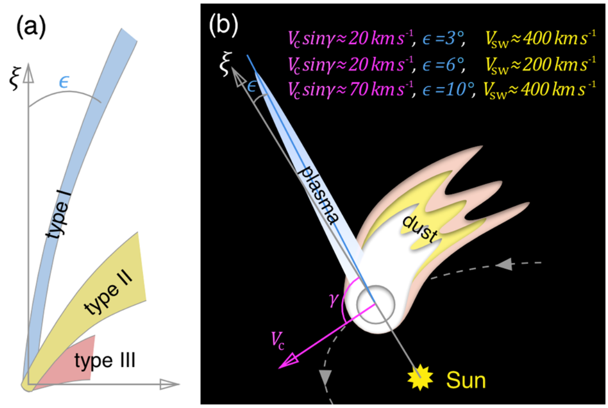

Figure 1 (**a**) Mechanical classification of cometary tails according to Bredikhin (1879b). $\boldsymbol{\xi}$ is the prolonged radius-vector, and ϵ is the angle between the observed tail and the antisolar direction. *Colours* denote types of tails. (**b**) Schematic illustration of the transit of a comet in the solar system.

tail may appear to be straight. For an observer to discover the curvature of a tail, its length should be at least 6 – 7°.

The next circumstance that has to be taken into account is the projection effect. The closer Earth is to the comet's orbital plane, the straighter the dust tail.

Finally, a bright comet often exhibits a white dust tail that may assume a yellowish or reddish tint, accompanying the dim bluish plasma tail. For a naked-eye observer, a dust tail shining by reflected sunlight is much brighter than a plasma tail, whose light is caused by the fluorescence of ionised gases. Their bluish radiation is located at the edge of the visual spectrum, to which the human eye is poorly sensitive. Therefore, historic reports on bright light emanating from a cometary head also indicate the dust tail.

3. Results

3.1. Colour of the Cometary Tail

We analysed text descriptions of comets from the eleventh to eighteenth century. The older reports often mention the colour of a comet. To find observations of bluish cometary tails, we studied Svyatsky (2007), who collected astronomical events from the complete collection of Russian chronicles; Williams (1871), who translated the Chinese annals; catalogues of Kronk (1984, 1999), and other numerous reports of individual European observers.

In 11 volumes of the complete collection of Russian chronicles, we did not find a single mention of the bluish tint of comets. Conversely, the red colour of comets is often mentioned, usually as an omen of bloodshed. We note that a significant portion of comets were observed at sunset or at sunrise, when the sky is painted with orange and red light. In European reports, we did not come upon the bluish colour of tails either. In Eastern chronicles (Chinese, Korean, and Japanese), luminous envelopes and tails of comets are usually reported as white-light objects. We would like to point out two translations of the report on comet C/1462 M1 from the Chinese annals. Williams (1871) wrote that the colour of a star (comet) was bluish white, while Kronk (1984) reported that the colour was darkish white.

To conclude, we did not find robust support of the hypothesis that observers saw bluish tails. Below we list comets whose observations were detailed.

3.2. Great Comet C/1471 Y1

The comet was reported by Toscanelli (Uzielli and Celoria, 1893), who drew a comet with a short tail. Bredikhin (1886) defined $R = 6.5$ (and proposed type I). Perihelion of the comet was on 1 March 1472. On 20 January 1472, $\epsilon = 6°$, and on 2 February, $\epsilon = 18°$, which indicates the dust tail. However, the comet was near the ecliptic plane, therefore projection effects were significant, and this results in large calculation errors.

3.3. Great Comet C/1577 V1

On 23 November 1577, the cometary tail was pointed west. The head of the comet was above the front of the Equiculi constellation (modern Equuleus). The tail was curved, the convex part at the zenith. The tail ends in front of the Pegasi constellation (modern Pegasus). The head of the comet was white, but not as bright as the starlight. The tail was dim and reddish, especially near the head, like a flame breaking through the smoke, as we translate it from Brahe (1610): "Caudam porrigebat hoc vespere, in eam Stellulam, quæ est superior in

Figure 2 (**a**) Drawing of the great comet C/1577 V1 by Hayck (1578). (**b**) Fragment of the drawing of the great comet C/1618 W1 by Montl'hery (1619).

fronte Equiculi... Erat autem, à capite versus dictam Stellam, paulum more solito incuruata, conuexam partem in Zenith tollens, adeò, ut si à capite per dictam Stellam ulterius protrahi fingeretur, suo ductu obliquo versus eam pertingeret, quæ est in fronte Pegasi. Color autem capitus Cometæ suit albus, non tam clarus, sed pallidior, neque ita lucidus, ut Stellarum lumen. Cauda verò obscuram rubedinem, praesertim quo erat capiti vicinior, ostendebat, qualis ferè solet esse flammæ alicujus, per fumum densum eluctantis…". Numerous engravings by Hayck (1578, see here Figure 2a), Bazelio (1578), Busch (1577), Graminaeus (1578), Mæstlino (1578), and others describe a long and curved cometary tail, which corresponds to the dust nature of the tail.

Bredikhin (1886) also defined that the comet had a dust tail with $0.02 < R < 2.8$. From 13 November 1577 to 12 January 1578, the angle of the asymptote deviation of the cometary tail hyperbola from the antisolar direction varied from 12.5° to 33.5° and on average was 20° (Bredikhin, 1879a). Here, we may conclude that observers reported a dust tail.

3.4. Comet C/1580 T1

The comet was reported by Graminaeus (1581). Bredikhin (1886) defined $R = 1$ and $\epsilon = 15°$, which indicates a dust tail. However, since there is only one observation of the tail, the inaccuracy of the estimates is large (Bredikhin, 1862).

3.5. Great Comet C/1582 J1

Based on three observations by Tycho Brahe on 12, 17, and 18 May 1582, Bredikhin (1879b, 1886) defined $R = 0.2$ and $\epsilon = 37.5°$ (dust tail). Note that the orbital elements are uncertain because there were only a few observations.

3.6. Great Comet C/1618 W1

There are numerous drawings of this comet by Bainbridge (1619), Cysato (1619), Kepler (1619), Montl'hery (1619, see here Figure 2b), *etc*. Bredikhin (1886) calculated $0.6 < R < 2.1$. From 30 November 1618 to 16 January 1619, ϵ varied from 16° to 41.6° and on average was 25° (Bredikhin, 1879a), indicating a dust tail.

3.7. Comet C/1652 Y1

The comet was observed more than a month after perihelion. According to the reports of Hevelius (1668) and Weigel (1653), on 20 December 1652 (10 December, old style) the

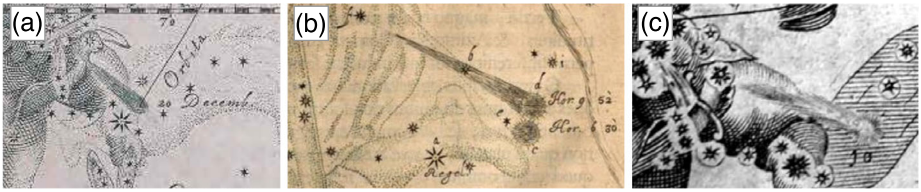

Figure 3 Fragments of drawings of comet C/1652 Y1 by Hevelius (1668) (**a**) and (**b**), and Weigel (1653) (**c**).

comet passed through the foot of Orion and its tail had the largest size in the entire observation set (Figure 3). Hevelius drew a straight tail 5° in length, and Weigel plotted a slightly curving tail 6° in length. We recall that a short tail (shorter than 6 – 7°) for a visual observer appears to be almost straight.

Of particular interest is the dynamics of the cometary tail in Figure 3b. Hevelius (1668) described his observations as follows: "At half past six, the comet was visible in position *c*, tail passed through star *e* and star *b*, which is above the foot of Orion in Eridan. Moreover, Regel (modern Rigel), star *b*, and the comet form an almost equilateral triangle... Distance between the comet and the star *b* was 3° 25″... At 9 hours 52 minutes, the comet was already slightly higher at position *d*. The tail was still located along the foot of Orion in Eridan and pointed toward the star *f* in the hilt of the sword..." ("Horâ dimidiâ circiter septimâ, Cometa in *c* primùm nobis illuxit, caudam extendens per *e* Stellulam ... & Stellulam *b*, supra pedem Orionis in Eridano, *b* supremam cinguli circiter versùs. Atq́; tum Trianqulum ferè æquilaterum, cum Regel, & dictâ Stellâ supra pedem Orionis constituebat... Distantia autem... inter Cometam & stellam *b*, 3 grad. 25 min... At horâ 9 52′, Cometa jam paulò altiorem occupaverat locum, nempe *d*... Cauda verò adhuc per stellam pedis Oriones in Eridano, usq́; ferè stellam *f* in Ensis manubrio..."). Thus, in three and a half hours, the position angle of the tail changed by 18°. Such dramatic changes are hardly probable even under the influence of the local inhomogeneity of the solar wind.

Bredikhin (1879b) defined an average $R = 1.5$. On 20 December, $\epsilon = 15°15'$; on 23 December, $\epsilon = 13°$; and on 26 December, $\epsilon = 7°$. As only three observations were available, the uncertainty is high. However, all these findings indicate that observers reported a dust tail.

3.8. Comet C/1661 C1

The comet was observed by Hevelius (1668), Megerlino (1661), Welper (1661), and others. Welper drew a slightly curved tail. According to Hevelius (Figure 4a), the maximum length of the tail was 5 – 6° on 3 February 1661. Such short tails appear to be almost straight for a observer. Bredikhin (1862) noted the poor quality of the observations.

3.9. Great Comet C/1664 W1

This comet was observed by Cassini (1665), Montanari (1665), and others. According to Hevelius (1665), on 21 December 1664, the comet had the longest and curving tail (Figure 4b). Bredikhin (1879b, 1886) evaluated $R \approx 1.2 – 1.7$ and $\epsilon = 27°$, which corresponds to a dust tail. We also note that at the beginning of the observations, the Earth passed through the plane of the cometary orbit, and then the full Moon interfered with the observations. The cometary orbit was inclined by 21° to the ecliptic, therefore projection effects might be significant, which means that the quality of the observations was poor, and the value of ϵ is inaccurate.

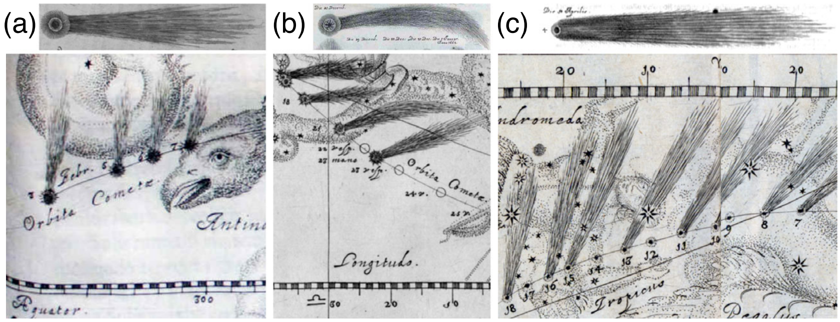

Figure 4 Fragments of drawings of comet C/1661 C1 by Hevelius (1668) (**a**), the great comet C/1664 W1 by Hevelius (1665) (**b**), and the great comet C/1665 F1 by Hevelius (1666) (**c**).

3.10. Great Comet C/1665 F1

The comet was observed in the morning twilight, not far from the horizon. Hevelius (1666) drew a wide, straight tail (Figure 4c). Lubieniecki (1681) also showed a schematic comet with a straight tail. However, we note that Lubieniecki made his drawing based on the words of Thomas Bartholin, who observed in Copenhagen.

Bredikhin (1879a, 1886) wrote that the observation quality was poor. R changed from 2.9 to 115.8; ϵ from -2 to 12.9. Bredikhin (1862) concluded that the large variation of R raises doubts that the comet had a type I tail.

3.11. Great Comet C/1668 E1

Cassini (1730) reported this observation as a meteorological phenomenon similar to that of 1683. In 1702, Maraldi (1743) also reported another similar phenomenon at the same place. Observational data are too poor to define the nature of this object.

3.12. Comets C/1672 E1 and C/1677 H1

Comet C/1672 E1 was drawn by Hevelius (1672) and Weigel (1672), and comet C/1677 H1 was plotted by Honold (1677), Hooke (1678), Voigt (1677). The comet tails were too short to define their nature.

3.13. Great Comet C/1680 V1

The first Astronomer Royal John Flamsteed reported the comet from 10 December 1680 to 5 February 1681. On the first day, he noted that the cometary tail was thin and stood straight up from the horizon, as translated by us from Flamsteed (1725, "Cometæ Caudam prætenuem advertimus, ab Horizonte sursum erectam…"). On the next day, the tail was like a beam standing straight up from the horizon and slightly deviating to the right of the vertical ("Cauda quasi trabs ab Horizonte sursum erecta conspiciebatur, ad dextram etiam parum a perpendiculo declinaris…"). Note that "trabs" may be translated as timber, beam, rafter, or tree trunk. On 21 December (perihelion on 18 December), the tail was located to the right of the Dolphin constellation, slightly curving ("Cauda fixas Delphini à dextra reliquerat, incurvata paululùm…"). On 26 December, the tail was thinner and shorter than

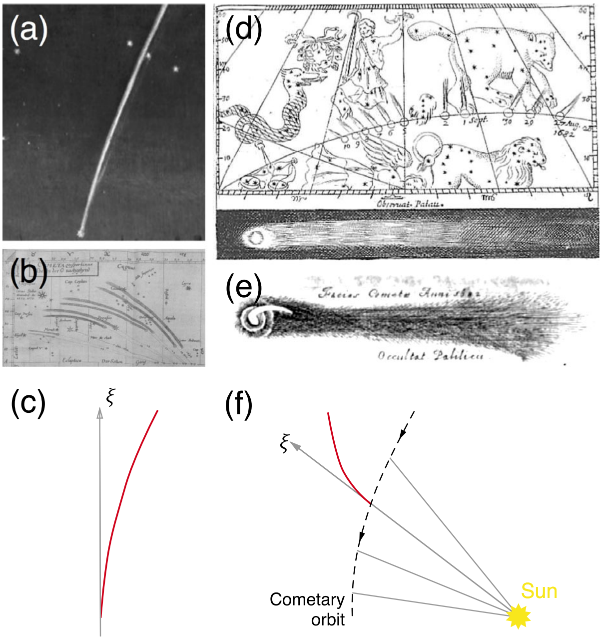

Figure 5 Fragments of (**a**) the painting by Lieve Verschuier, (**b**) drawing by Voigt (1681) of the great comet C/1680 V1. (**c**) Deviation of the cometary tail from the prolonged radius-vector $\boldsymbol{\xi}$ sketched from Bredikhin (1880). Fragments of a drawing of comet 1P/1682 (**d**) by Montanari (1682) and (**e**) by Hevelius (1685). (**f**) Deviation of the cometary tail from the prolonged radius-vector sketched from Bredikhin (1880).

before ("Cauda rarior quam antehac & brevior…"). On 13 January 1681, the tail was very weak, but sufficiently wide ("Cauda valde debilis satis tamen lata fuit").

The comet had small a perihelion distance ($q = 0.006$ AU) and was observed throughout Europe. There are numerous engravings of this comet with a straight (Mayern, 1681; Cassini, 1681) or a curved (Merian, 1691; Voigt, 1681, Figure 5) tail.

Figure 5a shows a fragment of the painting by Lieve Verschuier "The Great Comet of 1680 over Rotterdam". To the right of the bright tail, another dim tail is depicted. Plasma tails are well known to be always located on the leading edge of dust tails. One can hypothesise that a bright tail is a syndyne, and a dim tail is a synchrone. A syndyne is the locus of the dust particles for a given radiation pressure, and a synchrone is the locus of particles emitted at the same time.

For the bright tail, Bredikhin (1880, 1886) defined $R = 1$ and ϵ varied from 1° to 20° (generally $\epsilon > 10°$, dust tail). Figure 5c shows the hyperbola–asymptote (red curve) of the cometary tail and the prolonged radius-vector $\boldsymbol{\xi}$. The figure is sketched following Bredikhin (1880).

3.14. Halley's Comet 1P/1682 Q1

The comet (Figure 6) was observed by Hevelius (1685), Honold (1682), Kirch (1682), Montanari (1682), and others. Hevelius (Figure 5e) drew a bright, short, and curving jet emanating from the nucleus: on 8 September, in the evening, the comet's head was visible in the optical tube. The nucleus not only kept its oval shape. A bright curving jet (or ray) was prolonged from the nucleus to the tail (Hevelius, 1685: "Die 8 Sept. vesp... Caput Cometae hâc die per Tubum Opticum merebatur videri; non solùm quòd constanter clarissimum nucleum figuræ ovalis conservaret, sed simul incurvatum splendidissimum radium, ad ipso nucleo in Caudam usque, sese extendentem exhiberet").

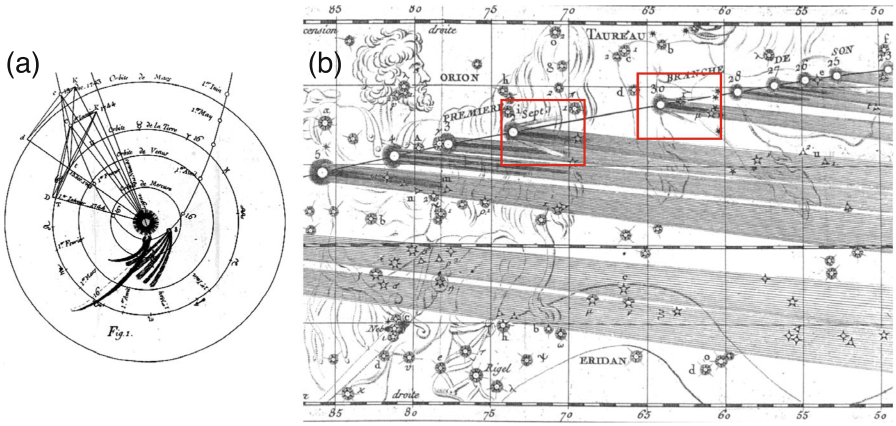

Figure 6 Drawing of the great comet C/1743 X1 by Cheseaux (1744) (**a**). Fragment of the drawing of the great comet C/1769 P1 by Messier (1778) (**b**). *Red blocks* mark the nights when the cometary tail had a complex structure.

According to Bredikhin (1880), the orientation of the tail of Halley's comet 1P/1682 Q1 corresponds to type I with $R = 12$ and $\epsilon = 23°$ (Figure 5f). Black arrows mark the comet path, $\boldsymbol{\xi}$ is the prolonged radius-vector, and the red curve is the asymptote of the tail. The value of ϵ indicates the dust nature of the tail of Halley's comet.

3.15. Comets C/1739 K1 and C/1742 C1

Comet C/1739 K1 was drawn by Zanotti (1739), and comet C/1742 C1 was plotted by Zanotti (1742) and Wiedeburg (1742). The tails of both comets are too short to define their nature.

3.16. Great Comet C/1743 X1

The comet had quite a complex structure. A few days after perihelion, numerous observers (Cheseaux, 1744; Euler, 1744; Heinsius, 1744; Zanotti, 1744) reported multiple tails. Figure 6a shows that the cometary tail is curved and significantly delayed relative to the prolonged radius-vector, which is typical for dust tails.

Bredikhin (1880, 1886) quantified $R = 1$; 2.4; 12; and 17; he concluded that the multiple tail belongs to type I and II.

3.17. Great Comet C/1769 P1

According to Pingre, on 4 September 1769, he clearly saw ripples in the tail similar to what can be seen in the aurora borealis. The tail was curved, its convex side faced toward the north. Sometimes the tail formed in its extremity a smaller arc, the convexity of which faced to the south, as translated by us from Pingré (1784, "des ondulations dans la queue, analogues à celles que l'on apercoit dans les aurores boréales... La queue ètoit fenfibiement arquèe, sa partie convexe tournèe vers le nord; quelquefois même elle formoit vers fon extrèmitè un second arc plus petit, dont la convexitè regardoit le sud..."). Pingré also referred to the observations by La Nux, who reported a 97° length of the tail on 11 September. A curving cometary tail was also reported by de Thury (1770).

According to Messier, on the night from 4 to 5 September, the sky was serene. Between the first and second hours of the morning, the comet was clearly visible. The tail was 43° long, located below the third Orion star. The distant half of the tail shone with a very weak light. The tail was also curved, with a bulge to the north. Up to 8° from the nucleus, the tail was intermittent along its length with luminous and dim parts. The nucleus had the same colour as the day before, it was white with a slightly reddish or orange tint (Messier, 1778: "La nuit du 4 au 5 de Septembre, le ciel serein; entre une heure & deux heures du matin, on apercevoit très-distictement la Comète à la vue simple, avec une queue très-longue, qui passoit au-dessous de la troisième étoile d'Orion... ayant quarante-trois degrés; plus de la moitié de la queue vers sa fin étoit d'une lumière très-foible; ele se courboit sensiblement, & la convexité étoit tournée vers le Nord. La queue depuis le noyau jusqu'à huit degrés de distance environ, ètoit partagée suivant sa longueur par des parties lumineuses, & par d'autres qui étoient obscures; ces traces lumineuses & obscures étoient dans des directions parallèles. Le noyau de la Comète étoit de la même couleur que la nuit précédente, d'une lumière blanchâtre, tirant un peu sur le rouge ou l'orangé…").

Figure 6b shows the fragment of the drawing in a concave cylindrical projection by Messier (1778). Contrary to the text description, the comet was depicted with a straight tail. On 30 August and 2 September 1769, the cometary tail had a complex structure. On the right and left of the main tail, Messier painted two short tails less than 5° in length (red blocks in Figure 6b).

For the bright and long main tail, Bredikhin (1880, 1886) defined $R = 12$ and ϵ varied from $-5°$ to 13° (on average $\epsilon \approx 4°$). He discussed the type of the tail (I or II). Approaching perihelion (8 October 1769), the nucleus became bright, but the tail became dim. Therefore, the calculations were made from 20 August to 12 September and from 25 October to 27 November 1769.

The low average value of ϵ signifies that observers might have seen a plasma tail whose ray structure indicates a non-stationary flow of the solar wind. The large scatter of ϵ might indicate either sudden changes in the solar wind speed or an uncertainty in observations and further calculations. To clarify this question, more sophisticated research is required.

Messier also reported more than ten comets in the second half of the eighteenth century. We analysed their descriptions and drawings. Unfortunately, the cometary tails were too short to define their nature.

3.18. Catalogues of Hevelius and Lubieniecki

The catalogues of Hevelius and Lubieniecki collect comets that have been observed from ancient times. Cometographia (Hevelius, 1668) is devoted to the analysis of the variety of cometary nuclei and tails in order to find regularities and explain them. He considered the structure of the sunspots observed by Scheiner (1630) to reveal the structural features and matter of which they consist that might be in common with those of comets. Hevelius (1668, Figure G therein) shows the author's poetic description of comets in the distant past. The first object in Figure G of Cometographia is the artistic imagination of a comet ("Cometan Solarem, seu Rosam") portrayed as a flame-coloured or red rose ("colore igneo seu rutilo"); the second object is a comet with bright flame rays. Comets were also compared to shields ("clypei", the forth object in Figure G), hair, or mane movements ("Crines", the seventh object), lamps or facula with straight rays ("adinstar Lampadis, seu faculæ ardentis", objects 11 – 13). Figure H and I depict comets with tails. All these drawings are the author's vision of the shape of comets, according to ancient observations since the fifth century. In particular, object 28 is the comet that was seen in 1099 and described as a scimitar or curved

Persian sword. The cometary nucleus is depicted like the hilt of a sword. Objects 37 and 38 in Figure K portrayed vibrating ("vibrantibus") tails. Hevelius also reported comets of the seventeenth century and his own observations. He discussed the parabolic, hyperbolic, and other forms of the asymptotes of cometary tails (Hevelius, 1668, Figure Q therein).

We also analysed Historia Cometarum (Lubieniecki, 1666) and Teatrum Comticum by Lubieniecki (1681). The author focused on the position of comets in the starry sky. Cometary tails are schematically shown as wide and straight. Here we would like to conclude that these catalogues are not fruitful material for a discussion of the plasma tails.

4. Conclusions

Plasma tails of comets are natural probes of interplanetary space. Their physical parameters may shed light on the solar wind speed in the most intriguing period, the Maunder minimum.

In this paper, we considered descriptions and drawings of comets in historical archives. To define whether plasma tails were reported in the distant past, we addressed the colour, shape, and orientation of cometary tails.

Reviewing the colour of comets in European, Chinese (in the translations of Williams and Kronk), and Russian observations, we identified a lack of convincing facts that naked-eye observers saw bluish plasma tails. This finding is trivial, because the bluish colour originates from the violet bands of ionised carbon monoxide and is poorly recognised by the human eye.

Another crucial attribute of plasma tails is their antisolar orientation. The angle ϵ between the observed tail and the prolonged radius-vector of a comet is typically limited to 6°. Here, we provided Bredikhin's estimates of ϵ. The average deviation of cometary tails from the antisolar vector exceeds 10°, which in turn suggests to us that observers reported dust tails.

Dust and plasma tails need to be distinguished by their shape, which should be performed taking the projection effects into account. When a comet passes near the ecliptic plane, the dust tail appears straight and thin. Short dust tails also seem almost straight.

One may conjecture that solar cycle minima represent conditions similar to those during the MM, whose activity level is hotly debated (Usoskin *et al.*, 2015; Zolotova and Ponyavin, 2016). The prolonged minimum of Cycles 23 – 24 was remarkably spotless, but the Sun was not entirely shrouded in a coronal hole, and the solar wind speed was suppressed but not crucially so. Moreover, Livingston *et al.* (2007) showed that the basal quiet atmosphere is unaffected by solar cycle. If so, we would like to hypothesise that comets in the distant past exhibited plasma tails, but they were not reported because they are hardly seen by the naked eye. By accumulating the light, telescopes might help somewhat to make out the dark bluish plasma tail in the night sky. However, early telescopes likely suffered from spherical and chromatic aberration (Svalgaard, 2017). Therefore, the first indication of a plasma tail was identified by us only for the great comet C/1769 P1.

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