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THE FIRST ASTRONOMICAL HYPOTHESIS BASED ON CINEMATOGRAPHICAL OBSERVATIONS: COSTA LOBO'S 1912 EVIDENCE FOR POLAR FLATTENING OF THE MOON

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Abstract: Acceptance by the scientific community of results obtained with new technology can be a complex process. A particularly good example is provided by the unexpected hypothesis raised by Francisco Miranda da Costa Lobo upon examination of the cinematographic film obtained during the solar eclipse of 17 April 1912. Contrary to contemporary practice this eclipse was eagerly awaited in view of its astrometrical rather than astrophysical scientific interest. The observation of this hybrid eclipse provided, in theory, a good opportunity to improve several astrometric parameters, and in particular the Moon's apparent diameter. Observations were performed from Portugal to Russia and, for the first time, movie cameras were widely deployed to register astronomical phenomena. Upon analysing the film obtained at Ovar (Portugal), Costa Lobo realised that during totality Baily's Beads were not symmetrically distributed around the Moon. As an explanation and opposing current belief he proposed a lunar flattening in the range 1/1156 to 1/380. Initially other eclipse observers supported Costa Lobo's claim. In particular, Father Willaert obtained a flattening value of 1/2050 from his cinematographic film taken at Namur (Belgium). However, these results were quickly disregarded by the international astronomical community which favoured an explanation based upon the irregularities of the lunar profile.

In this paper we recall the characteristics of the 17 April 1912 eclipse and the cinematographic observations, and review the results obtained. We conclude that the lack of attention paid by the astronomical community to the new cinematographical results and Camille Flammarion's superficial analysis of the data were instrumental in the rejection of Costa Lobo's hypothesis.

Keywords: Astronomical cinematography, lunar flattening, shape of the Moon, 17 April 1912 solar eclipse, Francisco Miranda da Costa Lobo

1 A 'RARE' ECLIPSE

From the 1840's onwards solar studies were a 'hot' research topic. Observation of the 8 July 1842 eclipse, the discovery of the sunspot cycle and its correlation with the Earth's magnetic field, and Kirchoff's spectral laws all contributed to an increasing interest in the Sun (Bonifácio et al., 2007; Meadows, 1970). Following observations of the corona and prominences in 1842 (see Becker, 2010: 115), solar eclipse expeditions were sent to the far 'corners' of the Earth in order to study these features. Better transport systems and local logistics provided by host countries or colonial entities helped to make the nineteenth-century eclipse expedition a standard astronomical endeavour (Hingley, 2001; Pang, 2002; Ruiz-Castell, 2008). While solar eclipses had previously been used mainly to confirm solar and/or lunar ephemerides or—assuming these to be correct—as a tool to determine the longitude of the observing station, these applications declined during the nineteenth century. New techniques (i.e. electric telegraphy) were available for longitude determinations and the precision of astrometric predictions improved to the point where it was well above the data one could obtain from the majority of solar eclipses. So from the 1860s onwards what we refer to today as solar physics became the main scientific rationale behind solar eclipse expeditions. There was, nevertheless, one exception: eclipses of very short duration could in principle still be employed to better define several astrometric parameters, but particularly the Moon's position and its apparent diameter.

According to the eclipse predictions of Fred Espenak (2010), between 1800 and 1912 only five annular and four hybrid solar eclipses had maximum durations of ≤7 seconds (see Table 1). The 7 seconds cut-off

Table 1: Nineteenth-century hybrid (H) and annular (A) solar eclipses with durations of less than or equal to 7 seconds

Date	Type	Maximum duration (seconds)	Geographic location (*)
11 February 1804	H	0	Algerian desert
21 February 1822	A	2	USA and Canada
4 March 1840	A	3	India, China & Russia
27 June 1843	H	7	Pacific Ocean
30 October 1845	H	2	Antarctica
15 March1858	A	2	UK, Sweden, Finland & Russia
25 March 1876	A	1	Canada & Greenland
6 June 1891	A	6	Russia
6 April 1894	H	1	China

* Note that the last column is only a crude indication of the geographical location of the eclipse path. For instance, if the totality could be observed from Russia this only means in some part of that country.

Table 2: Elements for the 17 April 1912 solar eclipse according to different publications: NA = *Nautical Almanac*; EC = *Efemérides de Coimbra*; CT = *Connaissance des Temps*; AE = *American Ephemeris*; SF = *Almanaque Nautico de San Fernando*; M = Madrid Observatory paper. The last column lists the difference between the maximum and minimum values.

Body	Element	NA & EC			CT	AE	SF	M	Difference
		h	m	s	s	s	s	s	s
Conjunction in R.A. civil GMT time		2	3	45.2	35	27.1	45.2	45.18	18.1
Sun and Moon R.A.		1	40	36.54	36.53	36.5	36.55	36.53	0.05
		°	′	″	″	″	″	″	″
Sun	Hourly Motion in R.A.	0	2	19.1	19.1	19.05	19.1	19.1	0.05
	Declination	10	26	51.2	51.0	51.2	51.2	51.209	0.209
	Hourly Motion in Declination			52.8	52.8	52.8	52.8	52.8	0.00
	Equatorial horizontal parallax			8.76	8.8	8.8	8.77	8.76	0.04
	True Semidiameter		15	55.51	55.5	55.5	55.51	55.51	0.01
Moon	Hourly Motion in R.A.	0	30	51.5	51.4	51.45	51.4	51.5	0.1
	Declination	11	0	52.4	49.7	47.9	52.4	52.30	4.5
	Hourly Motion in Declination		15	0.7	0.8	0.8	0.8	0.7	0.1
	Equatorial horizontal parallax		57	40.98	41.0	41.4	40.98	40.98	0.42
	True Semidiameter		15	42.24	43.3	42.3	42.05	43.39	1.34
Moon eclipse semidiameter			15	31.65	32.71	31.88	31.89	32.83	1.18
			15		31.53			31.53	

chosen was arbitrary but relates to the maximum duration predicted for the 17 April 1912 eclipse. Note that Herald (1983) believes that the eclipses listed in Table 1 cannot be categorized as either Type A or H since Baily's Beads were still visible at the maximum phase of each eclipse owing to irregularities of the lunar limb profile. As far as we can ascertain, only the 15 March 1858 eclipse was observed inside the Moon's shadow, an expected outcome due to the unfavourable geographical locations intersected by the Moon's shadow in the case of the other Table 1 eclipses.

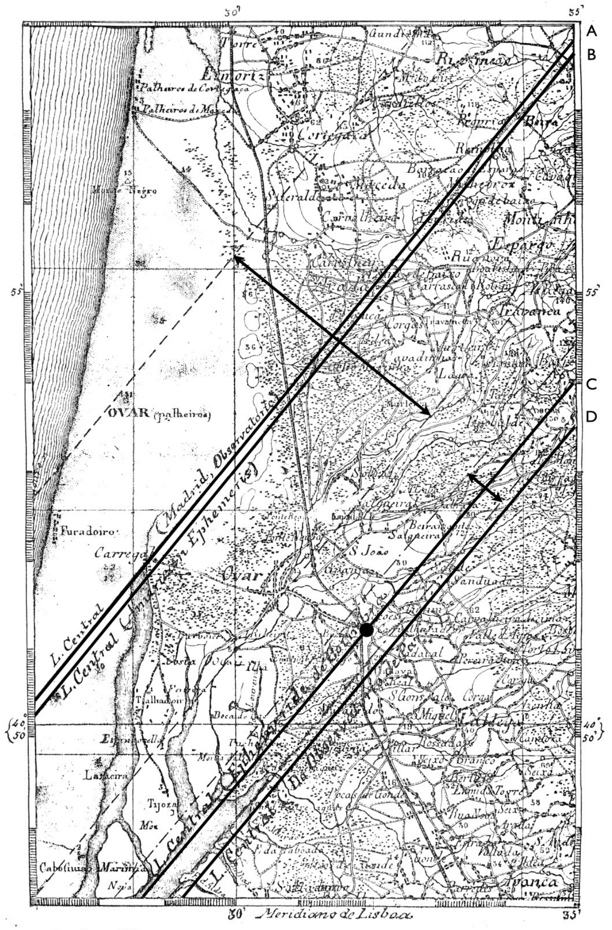

Figure 1: Central eclipse trajectories in the vicinity of Ovar are indicated by straight lines. The upper line (A) was calculated by the Madrid Observatory. Costa Lobo's calculated lines obtained using the eclipse elements from the *American Ephemeris* (B), *Efemérides de Coimbra* (C) and Paris Observatory (D) follow from top to bottom. Shadow band widths according to the Madrid Observatory and the *Efemérides de Coimbra* are indicated by the double arrows. The circle marks the approximate location of Costa Lobo's main eclipse observing station (after Costa Lobo 1912a:190).

The first twentieth-century solar eclipse with a duration of ≤7 seconds occurred on 17 April 1912, and this particular eclipse generated considerable interest for the following reasons:

1) The rareness of the eclipse was known at the time (Bigourdan, 1912b). To put it in context one should realise that during the five millennia from 2000 BC to AD 3000 analysed by Espenak and Meeus there were only 195 annular, total or hybrid eclipses with durations of ≤7 seconds. These represent just 2.5% of all solar eclipses that occurring during this interval.
2) The eclipse shadow path crossed several European countries (Costa Lobo, 1912a).
3) Prediction uncertainties allowed for the occurrence of either a hybrid or an annular eclipse.
4) The observed circumstances of this particular eclipse would provide a test for several astrometric parameters.

In the beginning of the twentieth century the major ephemerides were calculated with slightly different parameters. Table 2 summarises the parameters used in predicting the 17 April 1912 solar eclipse. The ephemerides mainly differed in their listing of the Moon's declination and semidiameter (Oom, 1912).

2 THE OVAR LOCATION

Different lunar eclipse elements implied an uncertainty in the location and width of the lunar shadow cone at the Earth's surface. The effect of the different eclipse parameters may be better appreciated by looking at the different predictions in the vicinity of Ovar, a town located on the west coast of Portugal close to the point where the Moon's shadow cone would first intersect the European continent.

It is obvious from Figure 1 that the eclipse shadow bands calculated using elements from the Madrid Observatory and the *Efemérides de Coimbra* do not overlap, the shadow path half-widths being smaller than the 4900m separation between the two predicted central line trajectories (Costa Lobo, 1912a). This meant that an observer located at the central line as defined by the Madrid Observatory would only see a partial eclipse according to the *Efemérides de Coimbra*, and *vice versa*.

The eclipse would start as annular in Venezuela and terminate as annular in Russia. If it was a hybrid then totality would start over the Atlantic Ocean and terminate either in the Gulf of Biscay, as predicted by the *American Ephemeris* (see Figure 2), or in Belgium, according to the *Connaissance des Temps* (Anonymous, 1912a; Moreux, 1912b). Modern calculations by Espenak (2010) confirm that the April 1912 eclipse was a hybrid, with a maximum totality duration of 2 seconds. The eclipse transitions from annular to total and back occurred over the Atlantic Ocean and in the Bay of Biscay (ibid.).

The best locality for a total eclipse observation was the Iberian peninsula, and expeditions from the Imperial Academy of Sciences of Saint Petersburg, Paris Observatory and the South Kensington Solar Physics Observatory were located in and around Ovar, even though the predicted duration of the eclipse was at best just a few seconds. Madrid Observatory predicted the longest duration, which was just 6.7 seconds (Costa Lobo, 1912a; 1912c).

Being aware of the eclipse characteristics, Francisco Miranda da Costa Lobo (Figure 3), Professor of Astronomy in the Faculty of Sciences at Coimbra University and an astronomer at the University Observatory, decided to establish several observing stations in a line perpendicular to the shadow path predicted by the Coimbra ephemeris in order to better define the true one. This technique had been tried before, for instance by Airy during the annular solar eclipses of 1847 and 1858 and in Algeria during the 30 August 1905 eclipse (Airy, 1896; Fouché, 1912). It was also applied elsewhere in 1912: for example, between Trappes and Neauphle students from the Paris Polytechnic School were located at observing sites 100m apart (Carvallo, 1912). In Ovar, eleven different observing stations approximately 500m apart were spread along a 6km line. Nine stations were maintained by Coimbra University, and one each by the French and Russian expeditions. Not surprisingly, the majority of the Coimbra University expedition equipment was located near the central line calculated by Costa Lobo (Figure 1). Besides the expected astronomical equipment, this station boasted a novel instrument: a 'modest' film camera (Costa Lobo, 1912c).

3 ASTRONOMICAL CINEMATOGRAPHY DURING THE 1912 ECLIPSE

The film camera featured a horizontally-placed 0.07m aperture and 1.14m focal length lens. A heliostat tracked the Sun and fed the solar radiation to the lens (Figure 4).

In the camera focus plane the solar image had a diameter of 10.6mm. A film of the partial and total phases was obtained (Anonymous, 1912b). During totality the camera recorded 560 images per minute, that is approximately 9.3 images per second (Costa Lobo, 1912b). The total length of the film is unknown. To our knowledge this was the first Portuguese scientific film ever made and one of the earliest astronomical films worldwide (see Matos-Cruz, 1989).

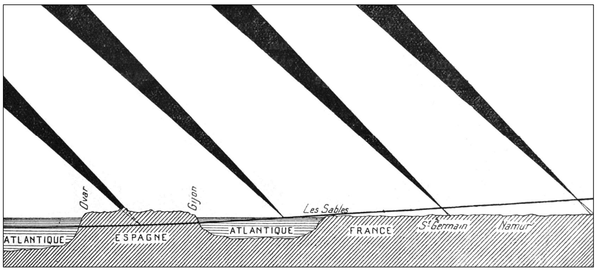

Figure 2: Path of the Moon's shadow cone vertice (after Moreux, 1912a).

The beginning of time lapse photography to capture astronomical events occurred when Janssen attempted to record the 1874 transit of Venus contacts with his 'photographic revolver', the first of all the cinema precursors (see Launay and Hingley, 2005). The film camera's adoption by astronomical observatories did not happen quickly, due—we believe—to the lack of

Figure 3: Francisco Miranda da Costa Lobo, 1864–1945 (after Amorim, 1955).

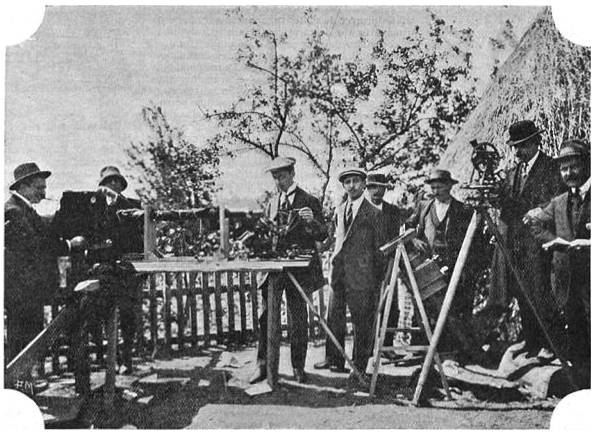

Figure 4: The main Portuguese eclipse station. The film camera can be seen on the left facing the heliostat approximately located at the figure center. Costa Lobo is behind the theodolite wearing a bowler hat (photograph by Ricardo Ribeiro, after Costa Lobo 1912c: 190).

Table 3: A list of films obtained during the 17 April 1912 solar eclipse.[1]

Location	Observer	Nº	D_{Sun} (mm)	Frames /s
Ovar, Portugal	Francisco Costa Lobo	1	10.6	9.3
Barco de Valdeorras, Spain	José Comas Solá[2]	1	-	-
Cacabelos, Spain	Fred Vlès; Jacques Carvallo[3]	1	4.6	?
Between Trappes and Neauphle, France	Emmanuel Carvallo	?	?	?
Saint-Germain-en-Laye, France	Aymar Baume-Pluvinel	1	14	13-14
Grand-Croix, France	Léon Gaumont	1	?	?
Lyon Observatory, France[4]	Perrigot	1	?	10
Namur, Belgium	Father Willaert	1	8.5	14
Hagenow, Germany	Kasimir Graff; Lippert	1	5.4	7.5

Notes:

1. The following sources were used in assembling this table: André, 1912; Carvallo, 1912; Costa Lobo, 1912b; de la Baume Pluvinel, 1912; Flammarion, 1912a; 1912c; Schorr, 1912; and Vlès and Carvallo, 1912.
2. Solá used two prisms in front of the film camera and successfully recorded the variation of the solar spectra during the eclipse.
3. Vlès and Carvallo had two film cameras but one stopped working. Emmanuel Carvallo simply referred in passing to the use of a few film cameras.
4. At Lyon Observatory a partial eclipse was observed. The film camera recorded the eclipse projected onto a screen.

convenient observable subjects, celestial objects usually being rather faint. Solar eclipses offered a notable exception, where a permanent record of these short-duration event was desirable. Although film cameras had been deployed during solar eclipses prior to 1912, this year marks the first time that widespread use was made of this technology (Deslandres, 1900; Solá, 1905). Table 3 summarises the various attempts that were made to photograph the 1912 solar eclipse using film cameras.

Figure 5: Seven frames from Costa Lobo's film published in the *Comptes Rendus* (Lobo, 1912b: 1398). The non-uniform distribution of Baily's Beads is apparent.

The first reports of cinematographical observations were usually succinct. They referred to the use of film cameras, provided a short description of the apparatus used—but not always, as an inspection of Table 3 shows—and gave a brief account of the images obtained. Scientific results obtained from the film images were not discussed. For example, at the 22 April 1912 session of the *Académie des Sciences de Paris* the cinematographic results of the Paris Polytechnic School effort led by Emmanuel Carvallo were still unknown (Carvallo, 1912), and we could not find a later reference to this expedition. However, at the next session of the Academy, on 29 April, the cinematographical observations and apparatus used by Aymar Baume-Pluvinel in France and Fred Vlès and Jacques Carvallo in Spain were described. De la Baume Pluvinel (1912) used the apparent intensity of the three Baily's Beads to estimate the eclipse central phase (cf. Carvallo, 1912). On 12 May Richard Schorr wrote a paper that was later published in *Astronomische Nachrichten* where he described the observations made at Hagenow in Germany. According to Schorr (1912), the film confirmed the observers' visual impression that their station was located to the north of the central eclipse line. Several film strips were reproduced in Schorr's paper, but no comment about them was provided.

4 COSTA LOBO'S ECLIPSE FILM ANALYSIS

A substantially different approach was presented by Costa Lobo in a note read at the 20 May session of the Paris Academy and published in the 28 May issue of *Comptes Rendus de l'Académie des Sciences* (Costa Lobo, 1912b). In it he described the Ovar cinematographical apparatus, analysed the film obtained and proposed an unexpected hypothesis. The Ovar film recorded the eclipse totality at a rate of approximately 9.3 images per second (ibid.). The second and third contacts were registered, and 158 images showed Baily's Beads. Costa Lobo realised that the images revealed a non-uniform distribution of Baily's Beads around the lunar limb (see Figure 5).

In particular, forty-four images after the appearance of the first Baily's Beads they disappeared for 4.4 seconds (40 images), in the approximate direction of the Moon's movement while staying visible at the Moon's north and south limbs. The unavailability of Costa Lobo's complete totality film, which is presumably lost, prevents a confirmation of these times. Costa Lobo concluded that the eclipse was total in the direction of the Moon's movement and annular in the perpendicular direction. Further, assuming that the observed asymmetry arose from polar flattening (defined as equatorial radius — polar radius/equatorial radius) he proceeded to estimate it in two limiting situations. Firstly, Costa Lobo considered that the lunar valleys grazed the solar disk in the direction perpendicular to the Moon's movement. This implied a difference between the lunar equatorial and polar diameters equal to the space travelled by Moon during the 4.4 seconds when the Baily's Beads were invisible. This provided a lower limit for the lunar flattening parameter. Secondly, he assumed that the highest lunar mountain tops rose 8km above the lunar valley floor and, somewhat arbitrarily, that Baily's Beads became visible when the mountain was half inside the solar disk. The first and last Baily's Beads appeared approximately in the Moon's east and west directions, respectively. By assuming that the highest north and south lunar mountains were at most half inside the solar disk Costa Lobo obtained an upper limit to lunar flattening. In this situation, the difference between the equatorial and polar diameters was equal to twice the half height of a lunar mountain (4km) plus the space travelled by the Moon during the Baily's Beads' 4.4 seconds of invisibility. Taking the lunar radius and velocity relative to the Sun as equal to 1,736.66km and 1km/s respectively, he obtained the values shown in Table 4.

Table 4: Costa Lobo considered the Moon's radius and velocity relative to the Sun as equal to 1,736.66km and 1km/s, respectively.

Lunar	Lower limit	Upper limit
$D_{eq} - D_{pol}$ (km)	4	12
Flatness	1/1800	1/600

We were unable to reproduce Costa Lobo flattening results. Our calculation approximately doubles Costa Lobo's flattening values for both lower and upper limits. This points to a trivial mistake, which coupled with the crudely-approximated lunar velocity used in the calculations led us to believe the note presented at Académie des Sciences de Paris was hastily written.

Later that year Costa Lobo wrote a longer more detailed paper for the new Coimbra University journal *Revista da Universidade de Coimbra*. This paper also included two illustrations of 42 positive and 80 negative film frames (see Figure 6). According to Costa Lobo, the maximum eclipse phase was shown in both.

In this new paper Costa Lobo improved his film analysis. For the lunar flattening lower limit, he maintained the rationale presented in May but changed the Moon's relative velocity to 692.66m/s, which was its then-accepted value. He then proceeded to estimate a different upper limit based upon a new assumption. An interval of 13.2 seconds elapsed between the appearance of Baily's Beads before the second contact and their disappearance after the third contact. This implied a lunar travel distance of 9.143km. Assuming the worst case scenario, i.e. that the Beads appear firstly in the east-west direction and at most the top of the north and south mountains graze the solar disk, the distance travelled corresponds to the diameter difference between the two directions everything else being considered equal. The results obtained are presented in Table 5.

In this paper he also determined whether the libration of an ellipsoidal Moon, with the longest axis in the Moon-Earth direction as predicted by celestial mechanics models, could explain the observations. He concluded that the effect was far too small. Costa Lobo believed the Moon was slightly flattened, although he had reservations about the upper limit in the absence of more data, remarking that "It is evident that other observations are necessary so that definitive values may be established." (Costa Lobo, 1912c: 571; our translation).

We believe that Costa Lobo's second paper (1912a), despite being written in French, was not available to a wide audience. For instance, the journal *Revista da Universidade de Coimbra* does not appear in the library catalogues of either the Royal Astronomical Society or Paris Observatory, although an offprint exists in Paris. Unfortunately it was not possible to establish Costa Lobo's offprint distribution network. Importantly, for the discussion that will follow, we do not know if Camille Flammarion had access to this paper and its larger number of film images.

5 DISCUSSING THE ECLIPSE RESULTS

Costa Lobo's papers not only break with usual astronomical movie film analysis methodology but more importantly propose a totally unexpected hypothesis—evidence of lunar flattening. At the time it was known that fluid dynamics implied a non-spherical Moon. An ellipsoid with the longest axis directed towards the Earth was the model commonly employed. Some authors considered the lunar shape was better described as a spheroid (i.e. with equal polar and equatorial radii), while others claimed a small difference—less than 20m—between these two radii (Saunder, 1905; Puiseux, 1908).

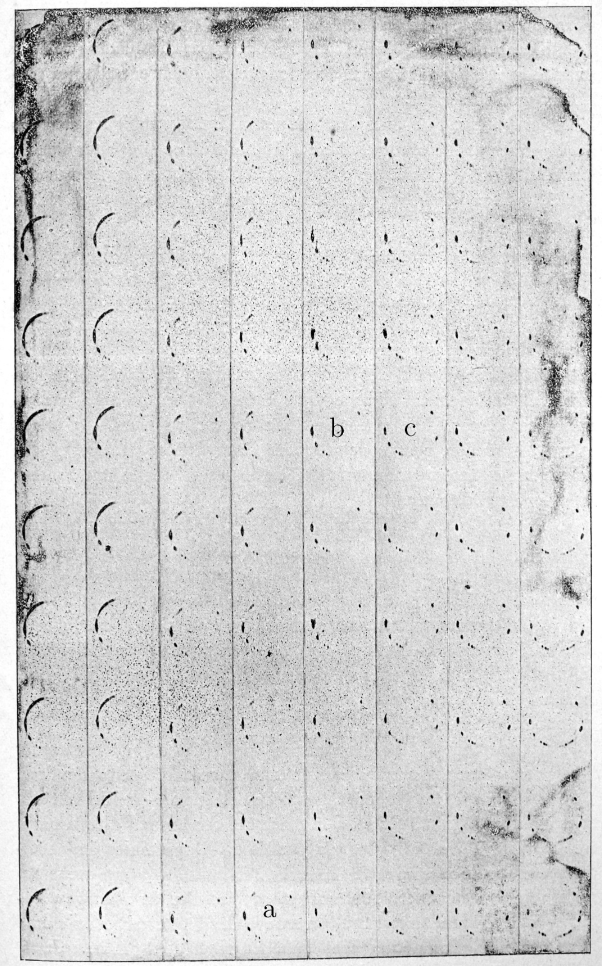

Figure 6: Eighty non-consecutive negative film frames including the maximum eclipse phase. The seven frames published in the *Comptes Rendues* note (Figure 4) are similar to that indicated by letter *c*. The images should be read vertically from the top left image to the bottom right one for correct eclipse evolution. After reaching the bottom of a column the reader should continue at the top of the following column to the right. The letters allude to frames that will be analysed later in Figures 6 and 8 (after Costa Lobo, 1912c: 583).

The noted French astronomer, Camille Flammarion (Figure 7) reprinted Costa Lobo's "... especially interesting ...." 28 May *Comptes Rendus* note in the July 1912 issue of the *Bulletin de la Société Astronomique de France* (Flammarion, 1912c). In his communication, entitled "Lunar shape deduced from cinematographical observation" (our translation), Flammarion mentioned that Léon Gaumont's film obtained at Grand-Croix also showed a larger lunar axis in the direction of lunar movement than in the perpendicular one. The paper also briefly referred to another observer claiming a similar conclusion (Flammarion, 1912a). Nonetheless, the best support for Costa Lobo's hypothesis was provided by Fernand Willaert (1877–1953) in a paper he and D. Lucas published in the 20 July 1912 issue of the journal *Revue des Questions Scientifiques*. At Namur (in Belgium) the eclipse was

Table 5: The values assume a 1,736.66km Moon radius and a Moon-Sun relative velocity of 0.69266 km/s.

Lunar	Lower limit	Upper limit
$D_{eq} - D_{pol}$ (km)	3.004	9.143
Flatness	1/1156	1/380

Figure 7: Camille Flammarion, 1842–1925.

annular, and when the film was first inspected by Willaert he was

> … struck by the fact that not only the north-ernmost part of the ring was thicker than the southern part which indicated a station located to the north of central line, but that the ring's southern part was thicker than in the equatorial region. (Lucas and Willaert, 1912; or translation),

Analysing the Moon's movement registered on the film and assuming a circular Sun, Willaert obtained a difference between the two lunar radii that was smaller than Costa Lobo's and a corresponding lunar flattening of 1/2050, and he claimed that this result contradicted the previous finding by Bessel and Wichmann of no lunar flattening. From his paper, one realises that Willaert was aware of the other 1912 eclipse cinematographical attempts and, in particular, of Costa Lobo's *Comptes Rendus* note.

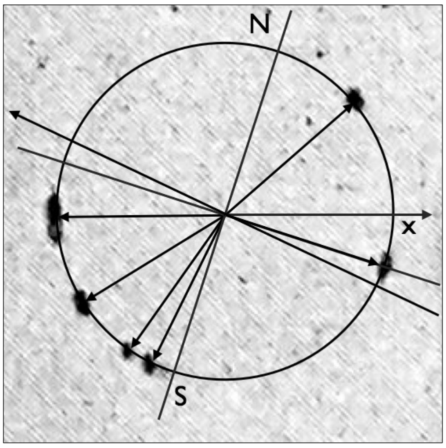

Figure 8: Eclipse frame from Ovar during the central phase. This is the frame signalled by letter *c* in Figure 5. Letters *N* and *S* indicate lunar north and south poles, respectively. The longest arrow defines the approximate direction of lunar motion. The arbitrarily-chosen x-axis (see the text) is also represented.

In a communication read on 16 September 1912 at the Paris Academy, Fred Vlès presented his Cacabelos film analysis and results. He measured the size of the chords joining the Moon tips and their direction as a function of the angle between the chord and the horizon. He then compared the results with those obtained by passing several geometrical figures (circles and ellipses) in front of each other. Several combinations were compatible with the film data although all implied the need for "… at least one of the celestial bodies to possess a non-circular shape." (Vlès, 1912.; our translation). More importantly, Vlès claimed that an ellipse with a major axis in the Moon's movement direction and a circular Sun, as proposed by Costa Lobo, did not agree with his film results. Any possible consequences of Vlès' location approximately 4km away from the eclipse centre line and outside the lunar shadow path were not discussed (ibid.; Vlès and Carvallo, 1912).

By November Flammarion had changed his mind. While still analysing more than 250 eclipse reports he received or that were sent to the Société Astronomique de France, he was already dismissing Costa Lobo's interpretation, remarking

> … that the Moon was not elongated as we believed in the east-west direction. The observed difference is due to the mountains. (Flammarion, 1912b; our translation).

At the time it was known that Baily's Beads were a consequence of the lunar profile irregularities. The specific conditions of the 1912 eclipse led to *a priori* predictions and to *a posteriori* determinations of the lunar profile (Graff, 1912a, 1912b; Hayn, 1912; Simonin, 1914). In particular, Graff (1912a, 1912c) determined a profile from micrometrical measurements performed upon an eclipse photograph obtained at Becklingen (Germany) that was published in *Astronomische Nachrichten* and later in the December issue of the *Bulletin de la Société Astronomique de France*.

In the *Annuaire Astronomique et Météorologique pour 1913*, Flammarion summarised all the relevant eclipse observations relating to possible lunar flattening, including his previously referred to analysis of Gaumont's film. He concluded (Flammarion, 1913; our translation) that Costa Lobo's "… explanation does not seem likely. Instead, we must attribute the [observed] irregularity …" to the Moon's limb profile. Flammarion (1912a) believed Graff's lunar profile showed a lunar movement direction almost parallel to the highest lunar mountains and perpendicular to the deepest valleys.

To test Flammarion's explanation we selected a frame from Costa Lobo's film strip (Figure 6) similar to those published in the Costa Lobo (1912b). This frame is shown in Figure 8, where six Baily's Beads are visible. We qualitatively estimated the Moon's centre by passing a circumference through all of the Bailey's Beads. Next we considered an arbitrary cartesian coordinate system with x- and y-axes parallel to the image sides. In this system we measured the angle between each Bailey's Bead direction (indicated by the arrow) and the x-axis. If the Bailey's Beads were located at the deepest lunar depressions by adding or subtracting a constant from our measured angles we would be able to match Graff's profile results. Despite position uncertainties resulting from the shape of the Baily's Beads and the Moon's center estimation there

Table 6: The deepest lunar valleys and the locations of Baily's Beads.

PA (°)	10 x valley depth (arcsec)	Baily's Bead location (°)
108	–25	108
140	–15	139
162	–9	162
172	–15	171
266	–21	269
328	–17	328

Note: The first two columns show the position angles (PA) of the lunar valleys measured from the lunar north pole in a counter-clockwise direction and ten times their depth referred to a mean circular Moon as determined by Graff.

is a good qualitative agreement between the two data sets (Table 6). This also enabled us to approximately mark in Figure 8 the Moon's polar and equatorial directions (Graff, 1912a; Flammarion, 1912a).

However Flammarion's objection to Costa Lobo's hypothesis referred not to lunar positions but to diameters. Using Graff's data, we therefore proceeded to calculate the lunar diameters as a function of position angle (see Table 7). The polar and equatorial diameters correspond to angular positions of 0° and 90°, respectively.

Analysis of Figure 6 shows that following the disappearance of the upper left Baily's Bead, five Baily's Beads are still visible (Figure 9a), four in the lower left quadrant and one in the upper right one (Figure 9b), before a new Baily's Bead appears at the lunar equator (Figure 9c). This seems to contradict Graff's small lunar diameter in the east-west direction (Table 7) and to indicate—as was originally claimed by Costa Lobo —a larger lunar diameter in the direction of the Moon's movement than in the perpendicular direction. The problem is, however, more complex since Graff's published values do not include any uncertainties.

The Paris Observatory astronomer Martial Simonin reviewed all of the 1912 eclipse information that he could locate, and in his 1914 memoir he presented a mean lunar profile for the eclipse day calculated from micrometrical measurements of photographs obtained by Graff, Hayn, Senouque, Croze and Solomos (Simonin, 1914). In Figure 10 we have plotted Simonin's mean profile and corresponding sample standard deviations where available as a function of position angle.

Two conclusions are immediate. Firstly, the data have large uncertainties (Table 8). Secondly, four out of Graff's six lunar depressions correspond to the deepest and better-defined (higher signal-to-noise ratio) lunar valleys (see Tables 6 and 8), the other two valleys also being compatible with Simonin's data. Consequently, the good agreement previously mentioned between the observed Baily's Bead locations and lunar profile depressions is maintained, despite two poorly-defined (low signal-to-noise) valleys not showing Baily's Beads (Table 8). This result lends support to the suggestion that the irregular lunar profile is the origin of the appearance and evolution of the observed Baily's Beads.

Table 7: The six smallest lunar diameters according to Graff and the observed locations of Baily's Beads.

PA (°)	10 x diameter variation (arcsec)	Baily's Bead location (°)
56	–13	
90	–11	89
108	–30	108
140	–20	139
146	–16	148
172	–15	171

Note: The first two columns show the lunar diameter position angle (PA) measured from the polar direction in a counter-clockwise direction and ten times the corresponding variation from a mean circular Moon. The third column presents the Baily's Bead location as explained in the text.

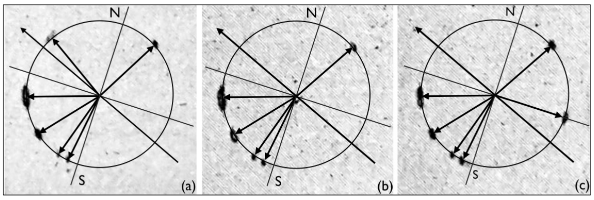

Figure 9: Three eclipse instants. Time increases from (a) to (c) (see corresponding letters in Figure 6). Arrows from the frame centers indicate Bailey's Bead directions. The Moon's polar, equatorial and approximate movement directions were superimposed on the film frames.

On the other hand, the lunar diameter variation from the mean value was poorly defined in the north-south and east-west directions. For example, from Simonin's data one obtains for position angles of 0.6 and 89.6 values of –0.40 ± 0.64 and 0.20 ± 1.2 arcsec respectively.

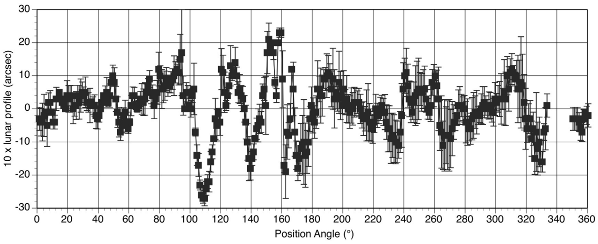

Figure 10: Plot of Simonin's lunar limb profile for 17 April 1912. Uncertainties are the sample standard deviation. Position angle (PA) is the angle measured from the lunar North Pole in a counter-clockwise direction. The Moon's west and east correspond to PA angles of 90° and 270°, respectively. The gap indicates a region for which only one set of measurements was available.

Due to all the uncertainties, we are not surprised by the cautious response provided by Paul Stroobant (1914; our translation), a future Director of the Royal Belgian Observatory:

> The agreement between Costa Lobo and Fr Willaert's film results is remarkable, especially since direct measurements have never shown this difference, which must be verified by other methods.

Table 8: The locations and depths (<1 arcsec) of the deepest lunar valleys according to Simonin (1914).

PA (°)	10 x Valley depth (arcsec)	SNR	Baily's Bead locations
108.6	–26.7 ± 1.5	18	108
139.6	–18.2 ± 3.5	5.1	139
162.6	–19.3 ± 8.1	2.3	162
170.6	–17.8 ± 3.7	4.9	171
175.6	–14.3 ± 9.7	1.4	
236.6	–11.1 ± 3.9	2.8	
265.6	–10.7 ± 7.5	1.5	269
325.6	–14.5 ± 4.8	3.1	328
330.1	–15.6 ± 3.1	5.2	

Note: PA is the angle measured from the lunar North Pole in a counter-clockwise direction. Valley depth uncertainty is given by the sample standard deviation. SNR is the signal to noise ratio. PA angles 325.6 and 330.1 correspond to the two deepest points in a wide depression.

In reality, and despite the fact that no definitive conclusion could be obtained without more data (see Table 9), a 'consensus' was quickly established within the international astronomical community and Costa Lobo's and Willaert's observations were soon forgotten, as the following examples show.

In his report for the *Annuaire du Bureau des Longitudes pour 1913*, Bigourdan (1912a; our translation) remarked that

> It seems premature to conclude that there is Moon flattening since everyone agrees that the serrated edge of the Moon is more pronounced in the north and south than in the east and west.

Meanwhile, the "Council note on solar research in 1912" delivered at the annual meeting of the Royal Astronomical Society on 14 February 1913 merely mentioned that "Kinematograph records were obtained by some of the French observers." (Anonymous, 1913), and the Eclipse Commission report presented on 4 August 1913 at the Fifth International Union for Co-operation in Solar Research conference in Bonn did not even mention any 17 April 1912 eclipse films (Anonymous, 1914: 147).

Table 9: Costa Lobo's and Willaert's differences between the lunar equatorial (R_{eq}) and polar (R_{pol}) radii, and flattening. For comparison, this table also includes the median, mean and range of the data sample standard deviations calculated from Simonin's memoir.

Author	$R_{eq} - R_{pol}$ (arcsec)	$R_{eq} - R_{pol}$ (km)	Flattening
Lobo (1912b)	0.82	1.5	1/1156
Lucas & Willaert	0.47	0.83	1/2050
Profile uncertainties			
	Std dev'n (arcsec)	Std dev'n (km)	
Median	0.40	0.74	
Mean	0.44	0.81	
Range	< 1.4	< 2.6	

6 CONCLUSIONS

In contrast to late nineteenth and early twentieth century common practise, the main scientific rationale behind the 17 April 1912 eclipse observation was astrometric rather than astrophysical. This was also the first astronomical observation where movie cameras were widely used to record a solar eclipse. Films of this eclipse were obtained in Portugal, Spain, France, Belgium and Germany. Analysing the Ovar film, Portuguese astronomer Costa Lobo hypothesised a lunar flattening to explain the observed asymmetrical distribution of the Baily's Beads. Costa Lobo estimated a lunar flattening in the range of 1/1156 to 1/380. Father Fernand Willaert analysed a film recorded at Namur where the eclipse was annular and he also concluded that the Moon was slightly flattened, albeit with a lower value of 1/2050. Initial international support for this viewpoint soon waned due to a lack of supporting data, and the international community preferred to attribute the film observations to lunar limb profile irregularities. Soon Costa Lobo's lunar flattening hypothesis was disregarded and the cinematographical observations were forgotten. In our opinion, several facts contributed to this outcome:

1) Costa Lobo and Willaert were not well known within the international astronomical community. In particular, the 20 May note read at the *Académie des Sciences de Paris* was not only Costa Lobo's first international astronomical paper but we believe that it was also hastily written. A more thorough follow-up paper written by Costa Lobo in French was published in *Revista da Universidade de Coimbra*, but this new journal was not available to most astronomers.

2) Costa Lobo's results were obtained with a recent and still unproved technique, namely cinematography. We also need to point out that when compared with photographs, film images were small and difficult to disseminate.

3) Three different interpretations of the cinematographical data were put forward to explain the observations: lunar and/or solar flattening, or a lunar limb profile irregularity effect. This last-mentioned option not only maintained the accepted view of a mean circular Moon in the line of sight but was also supported by influential astronomers like Flammarion.

4) Finally, confirming the 1912 cinematographical results would require similar observations but unfortunately short duration eclipses of this type were rare. In fact, astronomers had to wait until 1927 for the occurrence of a suitable eclipse, so a speedy confirmation of the 1912 eclipse observation was not possible.

This paper reviews the first astronomical hypothesis based upon cinematographical observations and its impact. Costa Lobo's lunar flattening hypothesis caught the scientific community by surprise. Despite the fact that the available data were inconclusive—in particular, the lunar polar and equatorial radius differences estimated by Costa Lobo and Willaert were comparable with known lunar profile uncertainties—the scientific community quickly arrived at an agreed-upon interpretation. The observations could best be explained by irregularities of the lunar profile and the cinematographical results were quickly forgotten. Notwithstanding this decision, it is time, we believe, to highlight this important milestone in the history of astronomy.

Finally, we should note that Costa Lobo's proposed lunar flattening interval of 1/1156 to 1/380 accommodates the modern value of 1/581.899 which was obtained recently by the Kaguya (Selene) satellite mission (see Araki et al., 2009).

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