Review Article

345 years of the Master Degree of Edmond Halley and the trajectories of five comets after the passage of the Halley comet in 1986: a didactical and historical approach

ABSTRACT

This paper presents a historical approach of Edmond Halley and the discovery of the comet that will known as*comet Halley*. It will be presented a development of a geometrical method, based upon the second Kepler's Law, to calculate the trajectories of five comets: Halley, Hale-Bopp, McNaught, Neowise, Leonard. This method it was used in high schools classrooms. Furthermore, it will be presented all the photographic register of these five comets along 37 years of observation.

Comment [cmu1]: Line is not clear, grammar

Comment [cmu2]: Line is not clear, grammar.

Comment [cmu3]: Grammar is not clear

Comment [cmu4]: Line is not clear

Keywords: Edmond Halley, comets trajectories, Hale-Bopp McNaught, Leonard, Neowise, Science education.

1. INTRODUCTION

The aim of this paper is to commemorate the 345th anniversary of the Master Degree obtained by Edmond Halley (figure 1), the great friend of Isaac Newton, and the responsible to find the periodicity of the comet that will be recognized with his name: HALLEY COMET.

Comment [cmu5]: Line is not clear

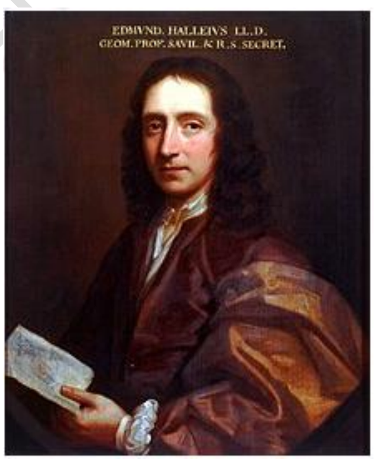

Figure 1. Edmond Halley (SAGAN; DRUYAN, 2011)

In our contemporaneity, Halley comet was observed around the world in 1986 (figure 2). Unfortunately its passage occured in a moment which its perigee was located when its coma was almost in frontline perspective of the Earth and the observational photographic registers were very bad if we compare with its passage in 1910 (figure 3), when its tail engulfed our planet, arriving to be having nearly 100 degrees of angular dimension in the skies.

Comment [cmu6]: Not clear, whose passage?

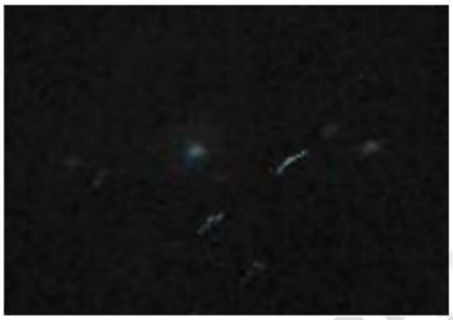

Figure 2. comet Halley observed in 1986.
(Source: one of the author of this paper)

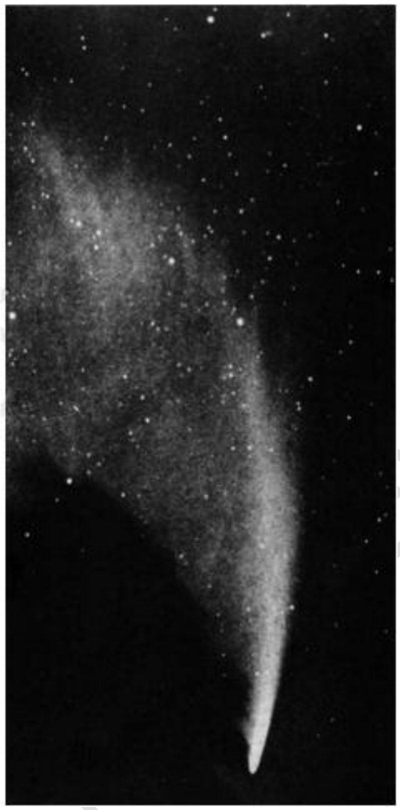

Figure 3. Comet Halley observed in 1910.
(SAGAN; DRUYAN, 2011)

In 1986 it was developed a geometrical method to calculate the orbit of the Halley comet to be used in courses to high school students (NEVES & ARGUELLO, 1986; NEVES & ARGUELLO, 1999). It will be not presented here the details of this geometrical method, but only a synthetic explanation to the trajectory of Halley's comet but extensive to another four comets: Hale-Bopp, McNaught, Leonard and Neowise. All these five comets were observed by different audiences of students of brazilian high schools in two different States of the Union, but nearly in the latitude 23.5^{o} S and longitude 52^{o} W.

Comment [cmu7]: Statement not clear

Comment [cmu8]: This line is not clear

2.HISTORICAL APPROACH

Edmund Halley was a famous astronomer that was born in 1656. He studied at St. Paul's School in England, and he was very interested in physics, mathematics and astronomy. When he changed school, Queen College (Oxford), his father gave to him a telescope of twenty four foot long. When he completed 19 years old he wrote do the Real astronomer John Flamsteed to informe that the tables of the calculations of the positions of Jupiter and Saturn, as well as the star positions as registered by Tycho Brahe, were wrong. An year after, Flamsteed encouraged Halley to publish a paper entilted *A direct and geometrical* *method to find aphelia, eccentricities and proportion of primary planets* in the prestigious *Philosophical Transactions of the Royal Society.* During 1676-1678 Edmund Halley change his residence to the Saint Helen island and constructed an Observatory with a great telescopic sextant publishing after a catalog of the stars of the meridional skies with the aid of King Charles II.

Comment [cmu9]: grammar

In 1678 he returned to England but Oxford did not allow to continue the Master's studies, but he appealed to the King Charles II, and, finally Oxford conceeded to him the Master Degree. A detail: some days before the refuse of the Oxford to accept his Master, Halley had been elected, with 22 years old, as a fellor of the Royal Society. One year after he published a great *Catalogus Stellarum Australium.*

Edmond Halley and the prediction of the trajectory of the comet named in his honor since it "left us" for the last time, in 1986, has been moving away from Earth, but in September 2023 it will have reached its aphelion and thus, will start its trajectory back to its closest point to the Sun, sothat humanity will be able to see it shine in the sky again in 2061. Comets have always fascinated mankind and, for this reason, they have been the subject of many speculations over time.Galileo Galilei (1564-1642), for example, considered them as mere atmospheric phenomena, without carrying out any kind of observation of these bodies with the aid of devices (SILVA, 2006, p. 20), although it is well known that he hadused telescopes built by himself to visualize lunar craters and sunspots, among other observations.

However, a few decades before the mistake made by the Italian thinker, Tycho Brahe (1546-1601) had already established that these bright objects in the sky belonged to the supralunar region (in the Aristotelian sense of the term), even without the help of telescopes that had not yet been invented. Brahe had been built naked eye's instruments performing calculations from very precise measurements of stellar parallax.It is necessary remembering that the eminent Danish astronomer had at his disposal the Uraninburg Observatory, equipped with the best astronomical naked eye instruments known until then, such as astrolabes, quadrants and sextants. Until the end of the 17th century, natural philosophers did not imagine that comets could move in closed orbits around the Sun, like the planets.It was believed that comets only passed through our solar system once.However, understanding of the motion of these celestial objects evolved rapidly over the last two decades of the 17th century. In a letter to Isaac Newton (1642-1727), dated October 21, 1695, the English astronomer Edmond Halley (1656-1742) wrote to his fellow countryman:

> I have almost finished the Comet of 1682 and ye next you shall know whether that of 1607 were not the same, which I see more and more reason to suspect. I am now become so ready at the finding a Comets orb by Calculation [...]. And I intend as far as I can to limit the Orbs of all the Comets that have been hitherto observed, of all which I shall duly give you an account. (MacPIKE, 1937, p. 96)

Comment [cmu10]: Meaning of this line

The difficulty in determining the trajectory of comets was because they could only be observed for a time interval of just a few days, which, as a result, made it possible to fit several curves to the collected data, including a straight line.However, from the publication of Newton's Principia in 1687, it became generally accepted that the path traced by these celestial objects must be an ellipse, a parabola or a hyperbola. Halley's studies of comets were presented in his work *A Synopsis of the Astronomy of Comets*, published in 1705, in the scientific journal *Philosophical Transactions of the Royal Society of London*.This work brings a table containing data from 24 comets in parabolic orbits, covering a period from 1337 to 1698. (HALLEY, 1705, p. 7; HUGHES, 1985, p. 585-586).

By using the laws of planetary motion by Johannes Kepler (1571-1632) and the theory of universal gravitation recently proposed by Isaac Newton (1642-1727) to prepare the afore mentioned table, Halley noticed remarkable similarities in the data of the orbits of comets from 1531, 1607 and 1682 and, even considering only parabolic orbits, said that these three comets were perhaps the same celestial object, which would be describing an elliptical trajectory with an orbital period of about 75 or 76 years.(CROWE, 1994, p. 20).Thus, in his work of 1705, he states:

> Hitherto I have considered the Orbits of Comets as exactly *Parabolick*, upon which Supposition it wou'd follow, that Comets being impell'd towards the Sun by a Centripetal Force, descend as from Spaces infinitely distant, and by their Falls acquire such a velocity, as that they may again run off into the remotest Parts of the Universe, moving upwards with such a perpetual Tendency, as never to return again to the Sun. [...] The principal use therefore of this Table of the Elements of their Motions, and that which induced me to construct it, is, That whenever a new Comet shall appear, we may be able to know, by comparing together the Elements, whether it be any of those which has appear'd before, and consequently to determine its period, and the *axis* of its orbit, and to foretell its return. And, indeed, there are many Things which make me believe that the Comet which *Apian* observ'd in the year 1531. was the same with that which *Kepler* and *Longomontanus* took notice of and described in the year 1607 and which I my self have seen return, and observed in the year 1682. [...] Hence I dare venture to foretell, That it will return again in the year 1758. (HALLEY, 1705, p. 20-22).

The comet was actually observed on December 25, 1758, appearing a few days later than predicted by Halley's calculations, but in the same region of the sky that he had indicated.This was the first prediction made for the return of a comet, and therefore, from that year onwards, this celestial object was called Halley's comet, in his honor.Now there was no more doubt.Comets could be periodic and were subject to the same laws that planets were subject to as they made their paths around the Sun.

Halley's Comet takes an average of 76 years to complete one orbit around the Sun, but in practice, the intervals between successive returns can be a few years longer or shorter than that, due to the gravitational attraction between it and the planets., which sometimes speed it up and sometimes slow it down, causing its speed to increase or decrease, respectively, depending on the configuration they are in in space.Measuring the period from perihelion to perihelion, Halley's longest return was after 79.25 years, from June 451 to September 530, while the shortest interval was 74.4 years, from November 1835 toApril 1910. Halley devoted much of his life to astronomical observations.

At just 20 years old, as we mentioned, he traveled to the island of Saint Helen, off the west coast of Africa, and there he mapped the southern celestial hemisphere with about 340 stars, in addition to discovering a cluster of stars in the constellation of Centaurus.In his 1717 work, *Considerations on the Change of the Latitudes of Some of the Principal Fixt Stars,* he announced that at least some of the so-called "fixed stars" were notactually fixed in position relative to each other.(HALLEY, 1717). Halley was also concerned with the question of the size of the universe and the number of stars it contained, publishing his studies on this subject in 1720, in two works entitled *Of the Infinity of the Sphere of Fixed Stars*) and *Of the Number, Order, and Light of the Fixed Stars*(HALLEY, 1720a; 1720b).This problem was much discussed at that time, including by Newton, who stated that the universe must be infinite, otherwise gravity would attract all matter to its center.

The famous correspondence between the Newtonian disciple Samuel Clarke (1675-1729) and Gottfried Wilhelm Leibniz (1646-1716) attests to the intense discussion that took place around this theme (LEIBNIZ, 1983, p. 167-232). Halley's approach to this question, however, was purely observational, and in 1720 he concluded that it seemed acceptable to consider the universe to be really infinite, since each increase in telescopic power showed the existence of hitherto unobservable stars (RONAN, 1981, p. 70). It is also worth mentioning that Halley had a decisive diplomatic role as a mediator of some important scientific events, among them, his active role as Newton's main encourager for him to publish the Philosophiae Naturalis Principia Mathematica (*Mathematical Principles of Natural Philosophy*), or simply, Principia , having even financed all the costs and expenses for its printing (WESTFALL, 1995, chap. 8, p. 158-189). Another important event was the dispute that took place between Newton and Leibniz about the priority in the creation of Calculus (WESTFALL, 1995, p. 282).

GRAVITATION AND THE CALCUTATION OF THE ORBITS OF FIVE COMETS SINCE THE LAST PASSAGE OF THE HALLEY

Gravitation is one of the four fundamental forces of Nature, together with the electromagnetic force, the weak force and the strong force and is the area of Physics responsible for explaining the interaction between celestial bodies in the Universe, allowing us to understand how gravitational attraction influences the falling objects, the orbits of planets, asteroids and comets, and the dynamics of galaxies interactions and galaxies clusters. Gavity is an abstract concept, which can be challenging and is often considered an area of Physics which is based on complex mathematical formulas. This can make de learning of the gravitation a challenge for many students, do it is important in many other phenomena, such as the study of tides, satellite orbits, orbits of celestial objects in the solar system and much more. Although the gravity is a force that acts on cosmic scales, its principles also apply to the our daily lives. It is gavity that keep us firmly planted in the surface of the Earth, which allow objects to fall when released and influences to the way liquids flow. These simple examples illustrat how the understanding gravitation is relevant to everyday life.

Teaching gravitation provides students with the opportunity to understand and apply the fundamental principles of the law of universal gravitation formulated by Sir Isaac Newton, in addition to understanding the relationship between the mass of object, the distance that spearates them and the gravitational force that acts between them, allowing that explore the fundamental forces that govern the behavior of celestial bodies and apply these concepts in a variety of pratical contexts.

On the phenomena occurring outside the planet Earth, comets and their orbits have good potential to be used in the teaching of gravitation. The study of their orbits not only allow us to better undestand the formation of the solar system, but can also serve as a catalyst to awaken the scientific curiosity in students

Comets are made up of ice, rocks and dust, which is why they are considered primitive objects and their composition offers valuable clues about the materials that existed during the formation of the solar system. Their orbits are intriguing and offer a unique opportunity for studentes to explore the principles of celestial mechanics, such as gravity. They usually follow ellipitcal (periodic comets) orbits around the sum, with variable lengths and inclinations and these complex orbital patterns can be analyzed to understand the dynamics of the solar system, gravitational interactions and the forces that influence the movement of these celestial bodies.

This allows the students visualize and understand the practical application of the law of universal gravitation by Isaac Newton. Stidents can explore mathematical concepts, such as the geometry of ellipsis (or parabolic or hyperbolic trajectories) and investigate the influence of gravity on comet orbits. In addition, furthermore, comests have practical implications in areas sucj as exploration of space and the consequent detection of objects close to Earth, makin the teaching of these topics particularly relevant to fields suchs as Astronautic and Astronomy.

The occasional naked-eye visibility of comets provides an opportunity unique way to engage students in astronomical observations and awaken their interests in Science. Direct observation of a comet in the night sky can inspire curiosity about how the Universe works and stimulate exploration of topics related to Physics and Astronomy.

We developed a geometrical method based on the kepler's law, especially the second law, or law of the areas (NEVES & ARGUELLO, 1986; 2011). Considering figure 4, the geometrical method consists of a reproduction of triangles of the same area along an elliptical orbit (like a comet). We will named this method as MRTE: method of the reproduction of the triangles in ellipsis.

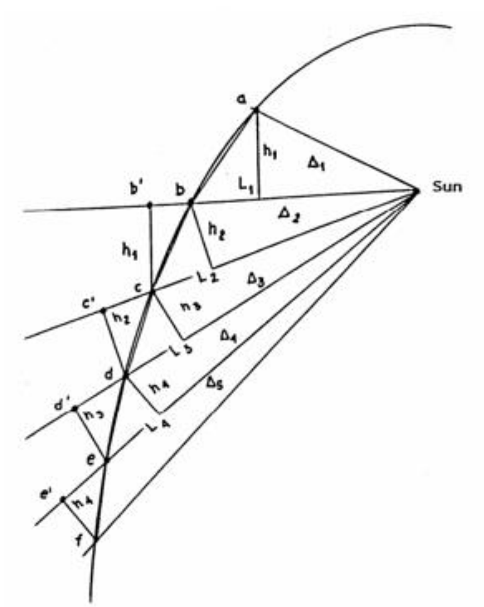

Figure4. Source: Method of the reproduction of the triangles in ellipsis MRTE.

Figure 5 shows the complete reproduction of the triangles of equal areas in a complete ellipsis. In this way, figure 2 exemplifies the geometrical method of reproduction of triangles on a curve (NEVES & ARGUELLO, 1999) that allows the possibility of triangles of the same area. The method consists of the following stages: from the principal focus (occupied by the sun) we construct the first triangle $\Delta 1$. When the height h1 of the triangle is found, we will extend it to keep a right angle, perpendicular to cathetus of the first triangle. With two setsquares we will find a point in the ellipsis which will give us the same height h1. When this point is found, we will pass a straight line through it till we find the sun, the principal focus of the ellipsis. Thus, we have a second triangle $\Delta 2$ with the same area as the first $\Delta 1$ using as a

Comment [cmu11]: Correction on this figure common base one side (cathetus) of the previous triangle. Figure 3 shows the MRTE applied in its totality on an ellipsis with a great eccentricity.

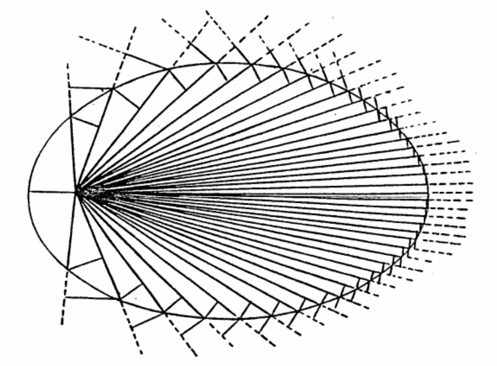

Figure 5. MRTE used in a complete ellipsis.

Using this method to the orbit of Halley comet, we arrive as a result of the figure 6 (NEVES & ARGUELLO, 1986).

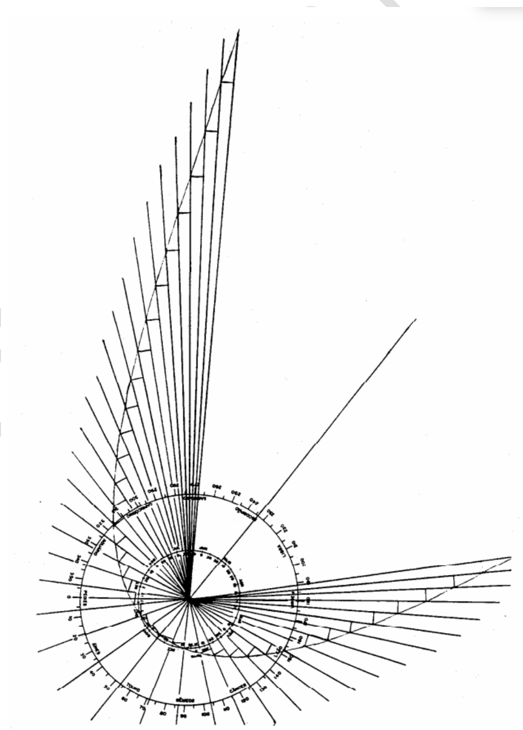

Figure 6. MRTE applied to the orbit of the Halley comet (NEVES & ARGUELLO, 1986).

Figures 7 shows the orbital elements of Halley's comet. To apply MRTE we should, first construct the characteristic ellipsis of a comet orbit. Figure 4 demonstrates the elements of the ellipsis. Below, formula (1) agrees with the equation of ellipsis in its polar form:

$$r = [a\ (1 - \varepsilon^2)] / (1 - \varepsilon \cos\theta) \qquad (1)$$

Comment [cmu12]: Scientifically write the equation, atleast use equation editor

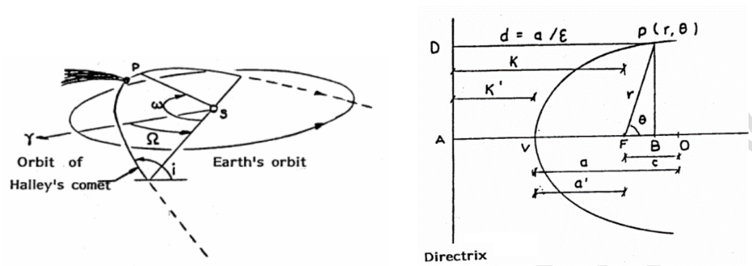

Figure 7. orbital elements of Halley comet. (NEVES & ARGUELLO, 1986)

We see that the only variable present in the equation (1) is the angle θ. Thus, if we alter the latter (on the condition that we have previously chosen a scale for the astronomical unit, A.U.) we get the angular variation of r, giving us the possibility of constructing the ellipsis. For the construction of the first triangle we have a fundamental *datum*: the date of the perihelion passage of the comet (the passage of time referring to previous appearances in 1759, 1835-36 and 1909-11). If we want to monitor the comet's orbit every ten days, for instance, we have to know the area travelled by the comet during this interval of time. We know that the area of an ellipsis is given as $S_T = \pi\ a\ b$. So, finding the partial area S_P in an interval of ten days is an easy matter, using only the simple rule of proportion. Having the value of the perihelion distance a' (Figure 7) and the partial area S_P, we can find the height of triangle ∆1 in an approximative method:

$$h1 = (2\ S_P) / a' \qquad (2)$$

When the first triangle is found, we will reproduce it along the ellipsis (due to its extreme eccentricity of the comet's orbit it will not be reproduced along all the ellipsis) using MRTE.
Figure 8 shows the orbit of the comet deduced by MRTE using the values of ecliptical longitude λ for the points present in the Figure and obtained by the method of decentered circumferences (NEVES & ARGÜELLO, 1986; NEVES, 1988).

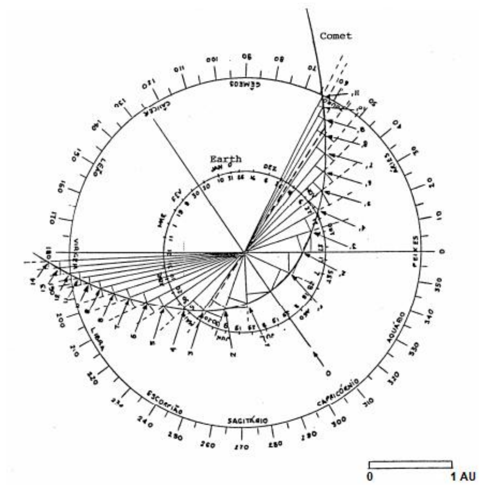

Figure 8. MRTE in part of the trajectory of the Halley comet (NEVES & ARGUELLO, 1986)

To delineate the apparent movement of the comet, we must know the various ecliptic latitudes β. To calculate this in a simple way (this method was presented for appreciation to high school students) we take Figure 8 and draw it once more. However, this time it will be inverted. From this figure we can still cut the part that corresponds to Halley's orbit in the strict sense and invert it too. We can thus construct a tridimensional model (Figure 9) which allows us to find latitude β with certain case.

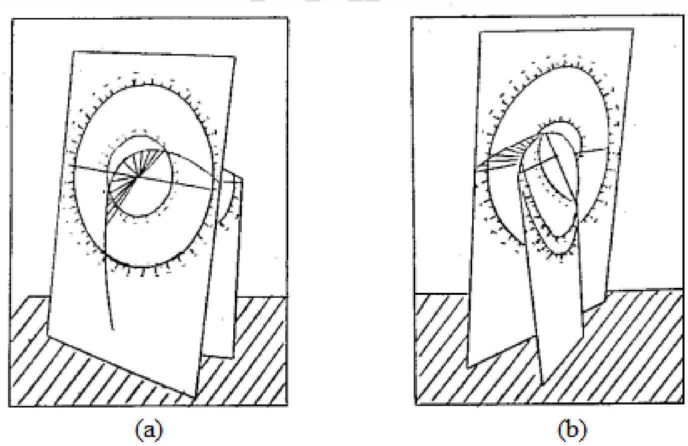

Figure 9. Display in 3-D to calculate more easily some variables of the trajectory of Halley comet (NEVES & ARGUELLO, 1986).

We deduce an elementary trigonometric relation from the tridimensional model so that we may find the ecliptic geocentric latitude (as seen from the Earth – see Figure 10). From this last figure we have: $\beta = \text{arc}\ [\tan (DCE / DTC)]$ (equation 3) where, DCE is the distance of the comet to the plane of the ecliptic. DTC is the distance of the Earth to the comet.

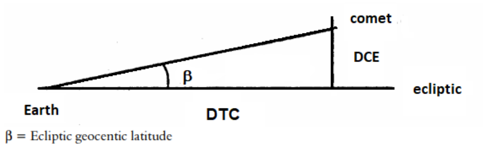

Figure 10. elements from the 3-D display.

All the calculations done, Figure 11 shows the apparent trajectory of Halley comet calculated by MRTE and Figure 12, the same trajectory, but given in the bibliography (NEVES & ARGUELLO, 1986).

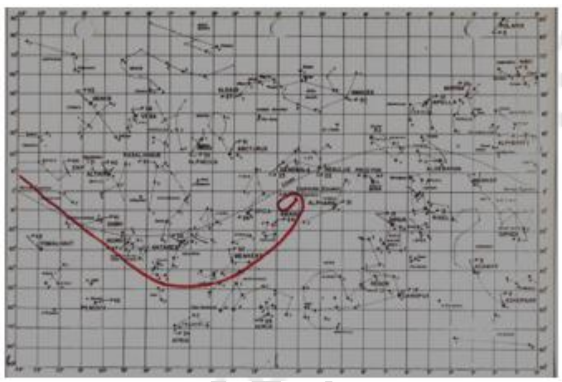

Figure 11. Halley: calculated trajectory by MRTE.

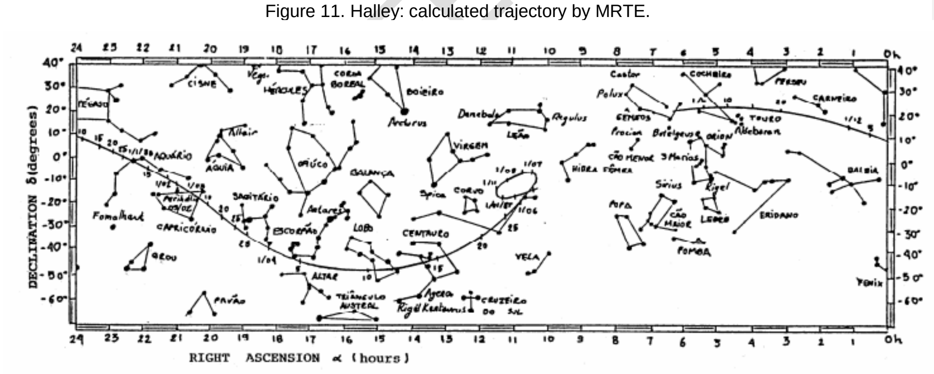

Figure 12. real trajectory of the comet (NEVES & ARGUELLO, 1999).

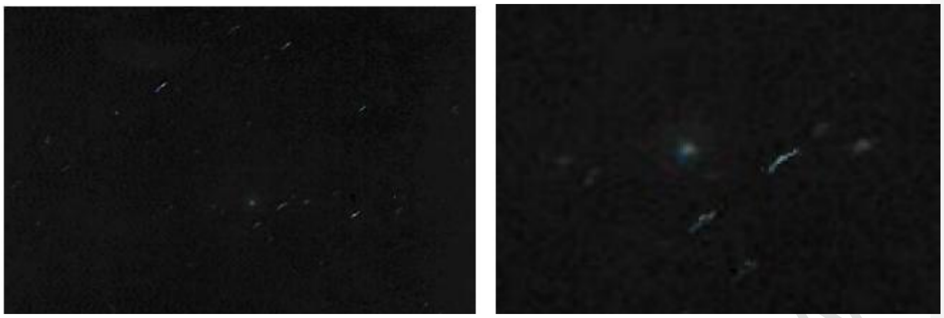

Figure 13. Two photographs of Halley comet in 1986. (Source: one of the authors)

3. RESULTS AND DISCUSSION

The present paper represents our didactical efforts to teach to high school students the themes like Copernican Revolution, Kepler's Law, Gravitation and the sensational history of the prediction of the next passage of a periodic comet by Edmond Halley. The paper represents, also, a history of observation (astrophotography and calculation the trajectories by MRTE) of other four comets (periodic or not – figure 14) observed and photographed along 37 years after the passage of Halley comet in 1986: Hale-Bopp (figures 15, 16, 17), McNaught (figures 18, 19, 20), Neowise (figures 21, 22, 23) and Leonard (figures 24, 25, 26).

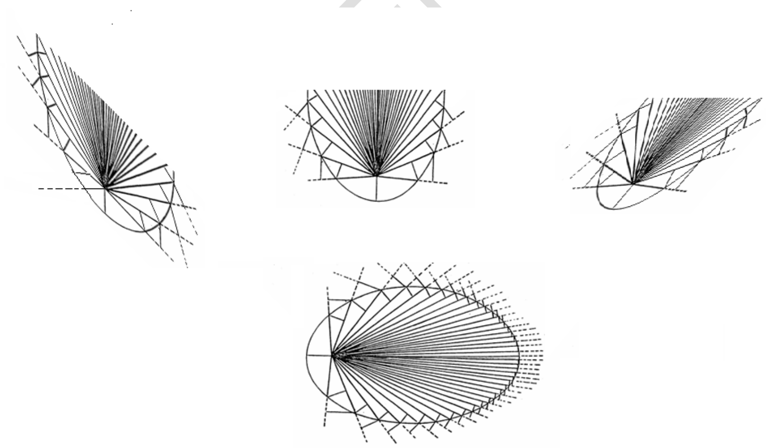

Figure 14: MRTE applied at different comets trajectories.

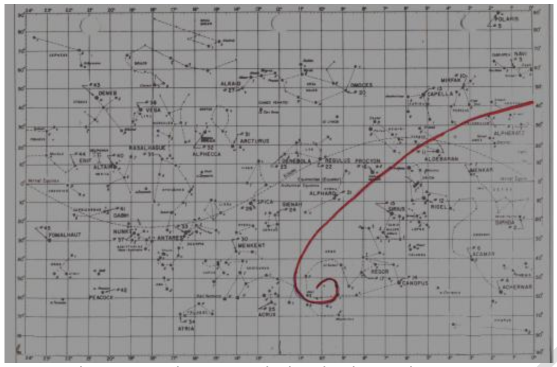
Figure 15. Hale-Bopp: calculated trajectory by MRTE.

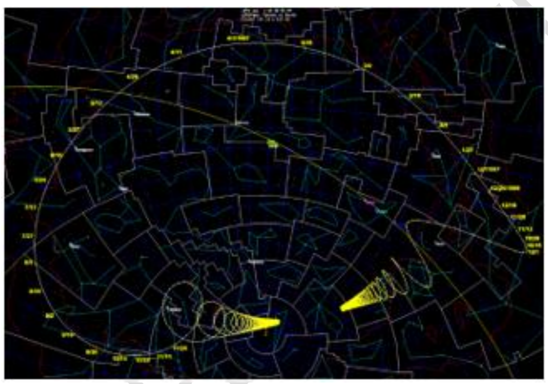
Figure 16. Hale-Bopp (C/1995 O1): real trajectory of the comet (WIKIPEDIA, 1997).


Figure 17. Photograph of Hale-Bopp comet in latitude 23,5°S, longitude 52°W.

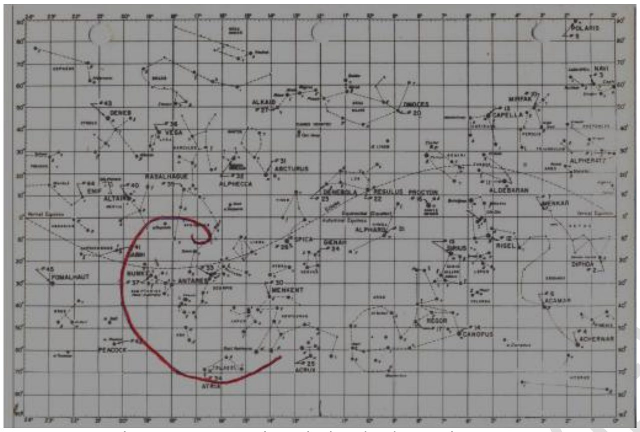
Figure 18. McNaught: calculated trajectory by MRTE.

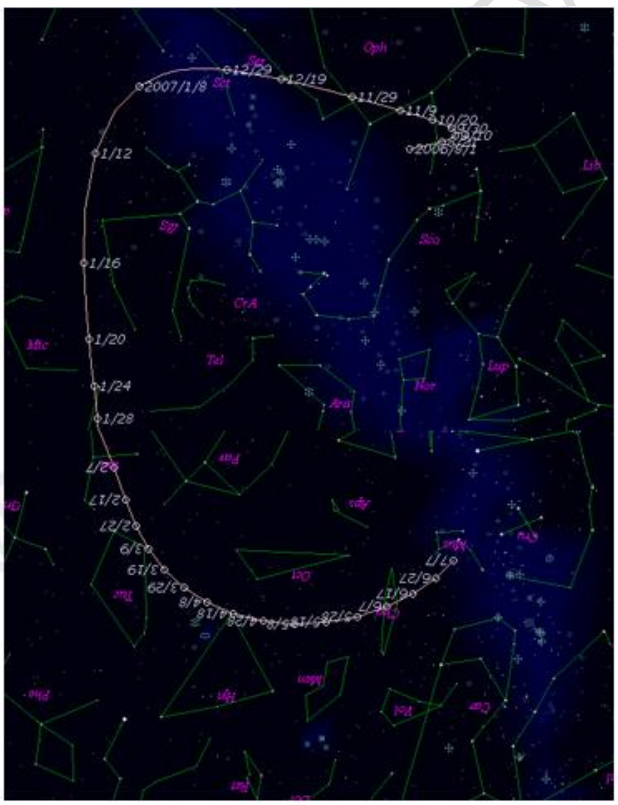
Figure 19. McNaught (C/2006 P1): real trajectory of comet (AERITH, 2006; STELLANAVIGATOR, 2023)

Figure 20. Photograph of McNaught comet in latitude 23,5°S, longitude 52°W.

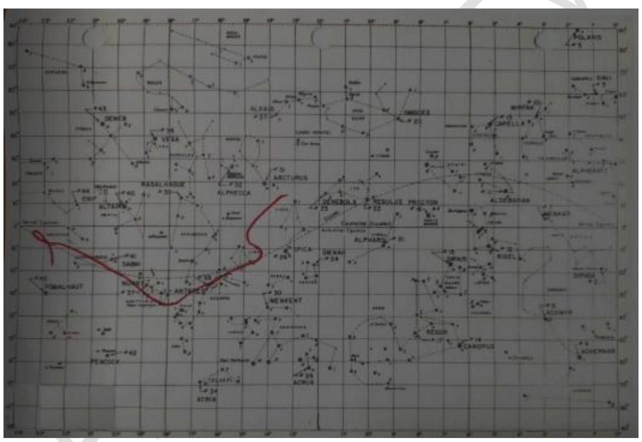

Figure 21.Neowise: calculated trajectory by MRTE.

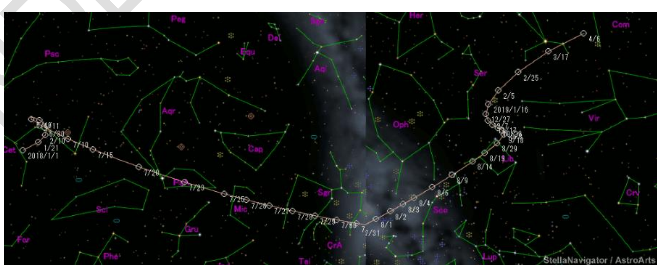

Figure 22.Neowise (C/2018 N1): real trajectory of comet (AERITH, 2018; STELLANAVIGATOR, 2023)

Figure 23. Photograph of Neowise comet in latitude 23,5°S, longitude 52°W.

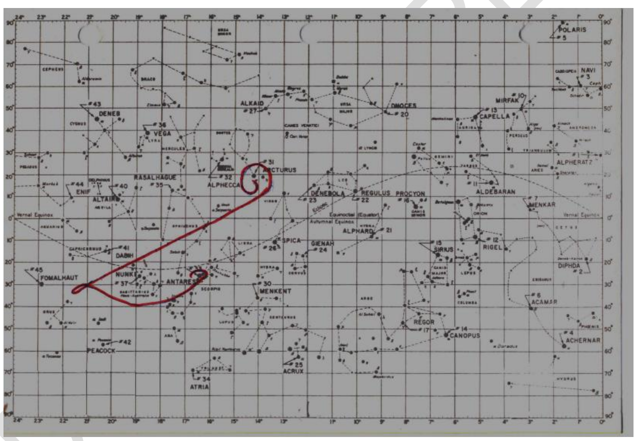

Figure 24. Leonard: calculated trajectory by MRTE.

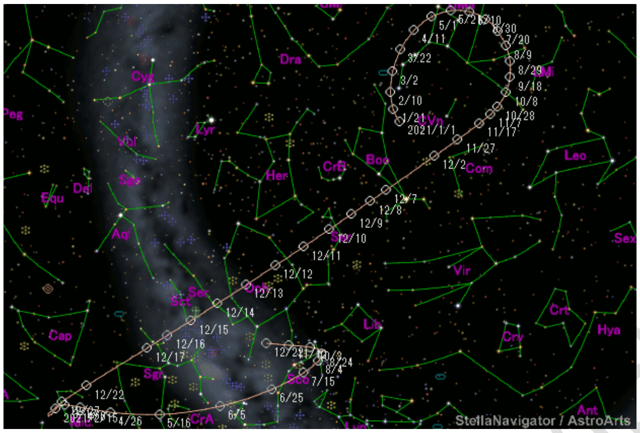

Figure 25. Leonard (C/2021 A1) real trajectory of comet (AERITH, 2021; STELLANAVIGATOR, 2023)

In nowadays we have a new comet in sky: Nishimura (figure 26). It is necessary to observe it, photograph it and finally trace its trajectory in classrooms with physics teachers and students of high schools and their enchantment of astronomical science and its heavenly extraordinary phenomena.

Figure 26. Comet Nishimura (NASA, 2023)

MEMORY

This paper is dedicated to the memory of the Prof. **CARLOS ALFREDO ARGUELLO**, physicist, astronomer, navigator, indigenist and freirian educator.

REFERENCES

AERITH - **McNaught**. In:http://www.aerith.net/comet/catalog/2006P1/2006P1.html

AERITH - **Neowise.** In:http://www.aerith.net/comet/catalog/2018N1/2018N1.html

AERITH – **Leonard.** In:http://www.aerith.net/comet/catalog/2021A1/2021A1.html

CROWE, M. J.**Modern theories of the universe from Herschel to Hubble**. New York:Dover, 1994.

HALE-BOPP. In: https://en.wikipedia.org/wiki/Comet_Hale%E2%80%93Bopp#/media/File:Comet_Hale-Bopp_starmap_1997.png

HALLEY, E. **A Synopsis of the Astronomy of Comets.** London: John Senex, 1705.

HALLEY, E. Considerations on the Change of the Latitudes of Some of the Principal Fixt Stars. **Philosophical Transactions of the Royal Society,** v. 30, p. 736-738, 1717.

HALLEY, E. Of the Infinity of the Sphere of Fix'd Stars. **Philosophical Transactions of the Royal Society of London**, v. 31, issue 364, p. 22-24, 30 April 1720a.

HALLEY, E. Of the Number, Order, and Light of the Fix'd Stars. **Philosophical Transactions of the Royal Society of London**, v. 31, issue 364, p. 24-26, 30 April 1720b.

HUGHES, D.W.; DRUMMOND, A. Edmond Halley's Observations of Halley's Comet. **Journal for** the **History of Astronomy,** v. 15, n. 3, p. 189–197, 1984.

HUGHES, D.W. The accuracy of Halley's cometary orbits.**Vistas in Astronomy**, v. 28, part 3, p. 585-593, 1985.

LEIBNIZ, G.W.**Correspondência com Clarke.** São Paulo: Abril Cultural, 1983. Coleção *Os Pensadores*, p. 167-232.

MacPIKE, E.F. (ed.). **Correspondence and papers of Edmond Halley.** London: Taylor and Francis, 1937.

NASA. **Introducing comet Nishimura.** In: https://science.nasa.gov/introducing-comet-nishimura .

NEVES, M.C.D.; ARGUELLO, C.A. **Astronomia de Régua e Compasso: de Kepler a Ptolomeu.** Campinas: Papirus, 1986.

NEVES, M.C.D. The Universe of Ptolemy revisited. **Acta Scientiarum**, 20(4), p. 473-476, 1998.

NEVES, M.C.D.; ARGUELLO, C.A. Approximate orbits of comets. **Acta Scientiarum,** 21(4), p. 809-816, 1999.

NEVES, M.C.D. **Astronomia e Cosmologia: fatos, conjecturas e refutações**. Maringá: EDUEM, 2011.

O'CONNOR, J.J.; ROBERTSON, E. F. **Petrus Apianus.** Disponível em: https://mathshistory.st-andrews.ac.uk/Biographies/Apianus/. Acesso em: 04/9/2023. Última atualização em abril de 2002.

RONAN, C.A. Edmond Halley. *In*: GILLISPIE, Charles Coulston (ed.). **Dictionary of Scientific Biography**, v. 6, p. 67-72. New York: Charles Scribner's Sons, 1981.

SAGAN, C.; DRUYAN, A. **Comet**. Ballantine Books, 2011.

SILVA, C.C. A natureza dos cometas e o escorregão de Galileu. **Scientific American História**, n. 6, p. 20-25, 2006.

STELLANAVIGATOR/ASTROARTS ステラナビゲータ12. In: https://sinfren.org.br/ecahezhjqt/fw-2029565.html , Acess: 09/05/2023.

THOREN, V. E. Christian Severin (Longomontanus). *In*: GILLISPIE, Charles Coulston (ed.). *Dictionary of Scientific Biography*, v. 12, p. 332. New York: Charles Scribner's Sons, 1981.

WESTFALL, R.S.**A Vida de Isaac Newton.** Rio de Janeiro: Nova Fronteira, 1995.