EARLY VISUAL MEDIA LAB

CICANT

David Galadí-Enríquez, doctor in astrophysics by the University of Barcelona (Spain), centres his research in observational astrophysics: photometry, astrometry and spectroscopy. He worked for almost twenty years at Calar Alto Observatory. He has a long experience in science outreach in Spain many formats: books, radio, television and digital media. ORCID: https://orcid.org/0000-0003-4946-5653

Carmen Pérez González holds a M.Sc. in Astrophysics (University of Barcelona) and a PhD in History of Art (Leiden University). Since 2014 she is teaching on the history of photography at the IZWT (Interdisciplinary Centre for Science and Technology Studies), University of Wuppertal. She edited the book Selene's Two Faces. From 17th Century Drawings to Spacecraft Imaging (Brill, 2018). She is the brainchild of the tablet App Golden Memories. ORCID: https://orcid.org/0009-0000-5902-7935

Corresponding Author

Carmen Pérez González

IZWT – Bergische Universität Wuppertal

Gauß Str. 20

42119 Wuppertal

Germany

perez@uni-wuppertal.de

Acknowledgments

Yolanda Fernández-Barredo Sevilla and Juan José Sánchez García (FBS Collection), Lee Fontanella, Denis Pellerin and Rebecca Sharpe (Brian May Archive).

ON THE TECHNICAL ASPECTS OF 19TH-CENTURY AND EARLY 20TH-CENTURY ASTRONOMICAL STEREOSCOPIC PHOTOGRAPHY

DAVID GALADÍ-ENRÍQUEZ
University of Cordova, Spain

CARMEN PÉREZ GONZÁLEZ
Bergische Universität Wuppertal, Germany

INTERNATIONAL JOURNAL ON STEREO & IMMERSIVE MEDIA, Vol. 8 No. 1
pp. 70-101
DOI: 10.60543/ijsim.v8i1.9498
ijsim.ulusofona.pt

Abstract

This article aims to clarify early astronomer-photographers' creative and intriguing techniques for capturing stereoscopic images of celestial bodies during the 19th and early 20th centuries. We will showcase these astronomical stereoscopic photos in chronological order, based on when the first images of each astronomical object were taken. Additionally, we will outline the fundamental processes involved in achieving the stereoscopic effect for each subject. The article introduces some very rare stereoscopic images of the Moon on glass positives kept at the FBS Foundation in Spain.[1]

Keywords: *Warren de La Rue; Stereoscopic astronomical photography; Moon; Mars; Jupiter; Sun; Earth's rotation*

1. The FBS Foundation is the short name for the FBS Foundation for the study of the historical imprint of stereoscopic photography as science and art. The acronym FBS stands for Fernández-Barredo Sánchez, the last names of the owners of the FBS Collection and the founders of the FBS Foundation.

Within one year, two inventions were announced whose combination enabled the birth of stereoscopic photography: the stereoscopic effect in 1838 (Wheatstone 1838) and photography, or more precisely, the two first photographic (technical) processes (1839, daguerreotype, and 1840, calotype) (Arago 1839, Arnold 1977). Many scientists involved in the discovery and dissemination of the first photographic processes were astronomers (Bigg 2018, 118-119). From the moment of its inception, for instance, the daguerreotype was seen as a significant scientific tool for recording monuments, as well as for making photographic maps of the Moon. This later purpose was remarked upon by Dominique François Jean Arago (1786 – 1853), director of the Paris Observatory, when he informed the French Chamber of Deputies of the remarkable invention by the French artist Louis-Jacques Mandé Daguerre (1787 – 1851):

> The preparation on which Mr. Daguerre operates is a reactive, much more liable to the effects of light than any that has hitherto been made use of. The rays of the moon, we do not say naturally but condensed in the focus of a lens of the largest size, never produced any physical effect. The sheets of plated metal prepared by Mr. Daguerre, on the contrary, become so white, when exposed to the same light and to the subsequent operations, that we may really hope to make a photographic map of our satellite. This is to say that in a few minutes, one of the longest, most minute and delicate labors of astronomy may be effected. (Newhall 1971, 26).

As noted by David Norman, before Arago's public announcement of Daguerre's process on the 19th of August 1839 (Arago 1839, 250), Daguerre had tried, at Arago's suggestion, to photograph the moon. Still, his daguerreotype plates were so lacking in sensitivity that even long exposure gave only a faint image, completely lacking in detail (Norman 1938, 560).

In astronomical photography, all the celestial bodies share the difficult conditions of distance (meaning small apparent size) and apparent motion, making capturing a successful photograph of any of them challenging. Also, astronomical objects cover a wide range of apparent brightness requiring different solutions: in the case of the Sun there is a strong excess of light, while for nebulae or planets the problem is the opposite, being the Moon the only astronomical object that can be registered with film sensitivities and integration times similar to those normally used for daytime photography. Next, we have to add the inherent limitations of the early photographic medium, such as long exposure times. Parallel to the improvement of the telescope (and the appearance of the tracking mechanism), it was the improvement of the camera and the development of photographic techniques adapted to imaging the Moon that marked the different periods in the history of early lunar photography.

As explained by John Lankford, the 1840s were a decade of *firsts* in the history of astronomical photography: the first successful daguerreotype of the Moon in March 1840 by the Anglo-American chemist John William Draper (1811 – 1882); the first daguerreotype of solar eclipse in 1842 by G.A. Majocchi (dates unknown); the first daguerreotype of the sun in 1844 by Jean Bernard Léon Foucault (1819 – 1868) (Bonifacio, Malaquias and Fernandes 2007, 102) and Armand Hippolyte Fizeau (1819 – 1896) (Lankford 1984, 16-39)

Similar to Lankford's description of the *firsts* in astronomical photography, we would like to introduce and explain the *firsts* in astronomical stereoscopic photography. We are going to introduce here the milestones of astronomical stereoscopic photography, including the physical phenomenon and/or the physical or spatial conditions which allowed astronomers to produce successful stereos of each celestial body, which are explained in the following sections.

The third dimension: lost in space

To get a stereoscopic photograph of any astronomical object, in addition to the two pictures for the stereoscopic pair, we need a method to simulate the stereoscopic likeness.

In the normal stereoscopic effect, for an average observer, the baseline is the interpupillary distance *L*, close to 6 cm. For an object at distance *d*, its visual parallax angle α (see Figure 1) is

$$\alpha = arctan\frac{L}{2d} \approx \frac{L}{2d} rad = \frac{90L}{\pi d}^{\circ} \approx \frac{30L}{d}^{\circ}$$

Eq. (1)

The first approximation in Eq. (1) rules for small angles, setting the angle in radians equal to its tangent. The second approximation in the conversion to degrees implies π ≈ 3, and it is justified because we are not interested in high precision. Distance, *d* is close to 20π = 63 cm if the object is held at arm's length. If we set *L* = 2π = 6.3 cm (inter-ocular distance), we get

$$\alpha_a = arctan\frac{2\pi}{40\pi} \approx \frac{1}{20} rad \approx 3^{\circ}$$

Eq. (2)

The human visual system yields reliable stereoscopic information for parallax angles much smaller than α_a, but stereoscopy usually benefits from simulating larger parallax angles. Binoculars and stereoscopic rangefinders improve stereoscopic perception by increasing L. Stereoscopic photography of the landscape acts similarly by using as large baselines as possible.

However, the third dimension is lost in the vastness of space. If we want to recover the parallax α_a, Eq. (1) implies that the two pictures would have to be taken with a baseline equal to 0.1 times *d*. For the Moon *d* = 380 000 km and we would need *L* = 38 000 km, three times the Earth's diameter. Astronomical stereography requires an alternative approach, and the solution may differ depending on which celestial body is the subject. A proper understanding of the historic specimens we will describe requires some insight into how the stereoscopic effect is obtained in each case.

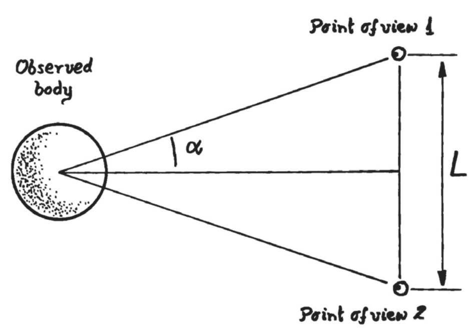


Fig.1 David Galadí-Enríquez, The definition of parallax angle, α, used in this article. L is the baseline, drawing, 2024

Libration: an exotic path to the third dimension for the Moon

The Moon is locked in synchronous rotation by the tidal forces of the Earth. This means that the rotation (around its axis) and revolution (around the Earth) periods are exactly the same and the Moon always shows the same face to us, which is what prevents using its rotation as a proxy for parallax.

One may think of using the true parallax caused by the rotation of the Earth. During half a day, the Earth's rotation moves the observatory a distance causing a change in the point of view. This is the astronomical effect of *diurnal parallax*, well known even to medieval astronomers. But the value of the diurnal parallax for the Moon (Figure 2) does not reach even one degree. Also, the Moon could be photographed from the same observatory with 12-hour difference, only close to the full phase. Finally, the shadow patterns of the Moon's landforms change in a matter of hours. All this makes it impractical to use diurnal parallax as a turnaround for lunar stereoscopy.

A celestial mechanics effect comes to our rescue. Its name is *libration*, split into two components: libration in longitude and latitude. The inertia of the solid body of the Moon imposes a strictly uniform rotation speed. But the orbit of the Moon around the Earth is slightly elliptical (Figure 3) and, according to Kepler's second law of planetary motion, the orbital angular speed is larger around the perigee and smaller around the apogee. So, rotation, which is uniform, is faster or slower than the orbital motion at different orbital positions. This translates into the effect of libration in longitude, a change of the point of view from the Earth, which amounts to an apparent angular shift of almost ±8° East and West, implying an apparent parallax angle of the same amount, which suffices for stereoscopic pairs (North 2007, 13-16).

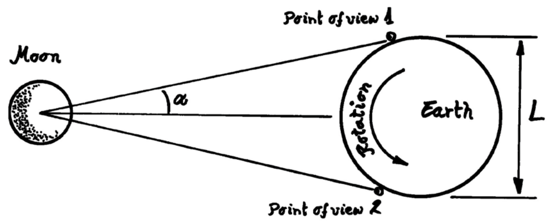


Fig. 2 David Galadí-Enríquez, The astronomical concept of diurnal parallax, α in the graph, is compatible with our definition of parallax if we take as baseline L the diameter of the Earth, drawing, 2024

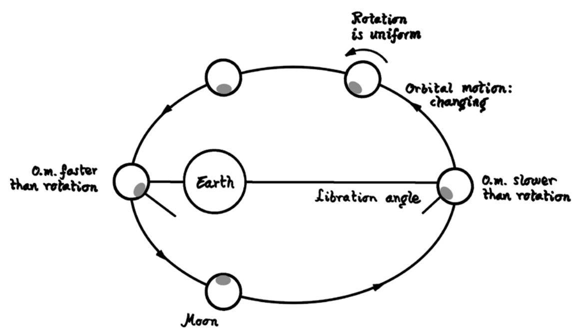


Fig. 3 David Galadí-Enríquez, Libration in longitude. The ellipticity of the Moon's orbit around the Earth is very greatly exaggerated in this figure, for the sake of clarity. For elliptical orbits, Kepler's second law of planetary motion imposes that orbital motion has to be non-uniform, accelerating at perigee and being slower at apogee. This, combined with the completely uniform nature of Moon's rotation, gives rise to the phenomenon of libration in longitude: from the Earth we are able to see an apparent East-West oscillation of the Moon every month, drawing, 2024.

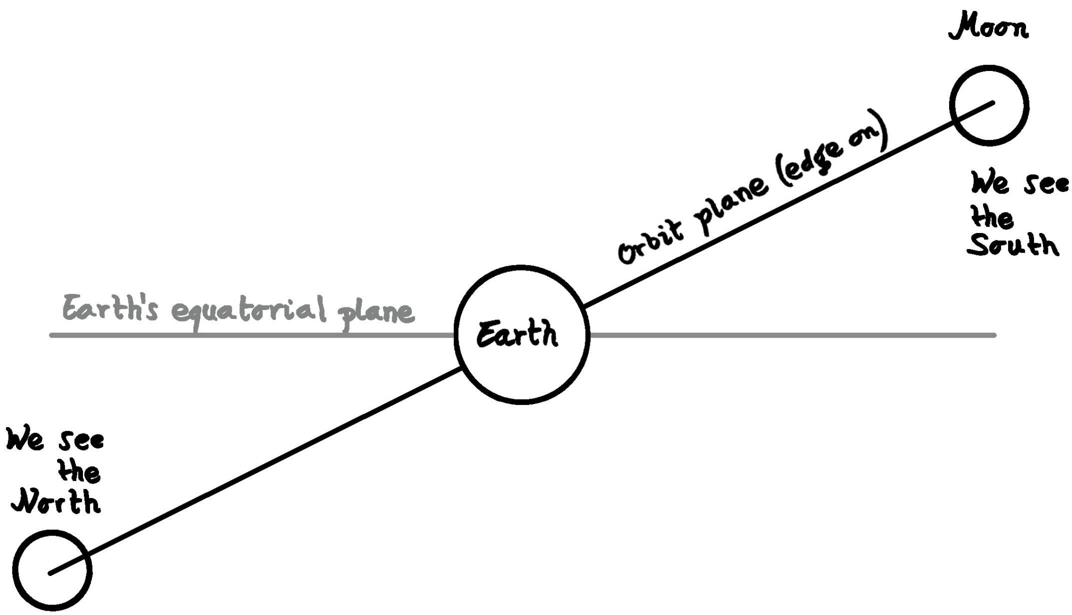


Fig. 4 David Galadí-Enríquez, Libration in latitude. The inclination of the Moon's orbit relative to the equator of the Earth allows us to see slightly further beyond the North and South poles of the satellite, depending on the orbital position, drawing, 2024.

Libration in latitude (Figure 4) is caused by the inclination of the lunar orbit with respect to the equator of the Earth, which makes us see, alternatively, a little distance beyond the North or the South poles of the Moon. This effect causes an apparent parallax smaller than 7°, and it is almost perpendicular to the libration in longitude (North 2007, 13-16). Both librations are always present in some amount and combine according to a complex pattern. Geometry proves that combining two rotations of different amounts around different axes can always be summarised as only one rotation of some intermediate value around an intermediate axis. This is guaranteed by the group properties of the space of three-dimensional rotation matrices SO (see Lema 13.2. and Proposition 13.3 in Apura 2017, 61). This implies that, given any pair of images of the Moon, it is always possible to rotate them so that the difference of libration conditions is reproduced as a left-right rotation around a vertical axis, and this is what we need to build stereoscopic pairs.

To use libration as a parallax proxy we have to combine photographs taken under libration conditions as different as possible, which normally implies large time spans. Also, the images paired have to be rotated to align their libration axis in the proper way, which explains that lunar stereo pairs are seldom printed with the North up or down, but at intermediate, apparently arbitrary positions.

The illumination conditions should be similar, to provide consistent images to both eyes. The main difficulty for this is the need to match the illumination conditions in the frontier between light and shadow, a line known as the *terminator*. The irregularities of the Moon's relief make the terminator seem not a line but a rugged and complex band that offers a wider apparent size when it crosses the central parts of the Moon's disk. As a result, slight differences in illumination conditions translate into an evident aspect change in the terminator area when it is close to the centre of the disk. In contrast, the terminator area is shrunk down to a very small apparent size width when it lies close to near the Moon's limb, which happens close to the full Moon phase. We conclude that images of the Moon close to full phase are easier to pair because the differences in illumination at the terminator area are not very outstanding.

If we want to produce a Moon stereo pair in phases far from full, then it is absolutely necessary to select photographs taken under similar illumination conditions, because the wider apparent size of the terminator area makes small differences very outstanding. The need to catch the Moon at largely different libration angles but under the same illumination for pairs far from full phase restricts the options so much that the time span between the two images in each pair is usually very long, sometimes even years long, depending on the combination of the Moon's cycles for a given observatory, and on weather conditions.

The illumination conditions are usually specified by the *lunar age* or *age of the Moon*. The age of the Moon is the time that has elapsed since the last new moon phase. So, in each stereo pair, we would combine Moon photographs taken on very different dates but with the same Moon age, but under libration angles as different as possible.

When lunar eclipses happen, they are always in full Moon, but the libration is different from one to another. Combining images from different Moon eclipses may lead to a good stereoscopic effect, but for this to be convincing, the Earth's shadow should cover areas of the Moon disk as similar as possible in the two shots.

The Moon, 1857 – 1862

Charles Wheatstone (1802 – 1875), who wrote the first paper on stereoscopic effect in 1838, was the first scientist to suggest that the libration of the Moon could be used to obtain the necessary baseline (Greenslade 1972, 536-40).

The great amateur astronomer Warren de la Rue (1815-1889) began experimenting with lunar photography using a telescope (without a clockwork mechanism) designed by himself and wet-collodion on glass negatives (Le Conte 2001, 14-35). His first experiments were done with the help of an assistant to carefully move his telescope in sync with the Moon's trajectory through the nightly sky:

> It is difficult to follow the moon's motion in any telescope without the aid of a clockwork driver; nevertheless, by means of a sliding plate holder in the place of the ordinary eye-piece, he was able to do so by viewing the image through the collodion film. […]. Mr. De La Rue soon relinquished the pursuit of lunar

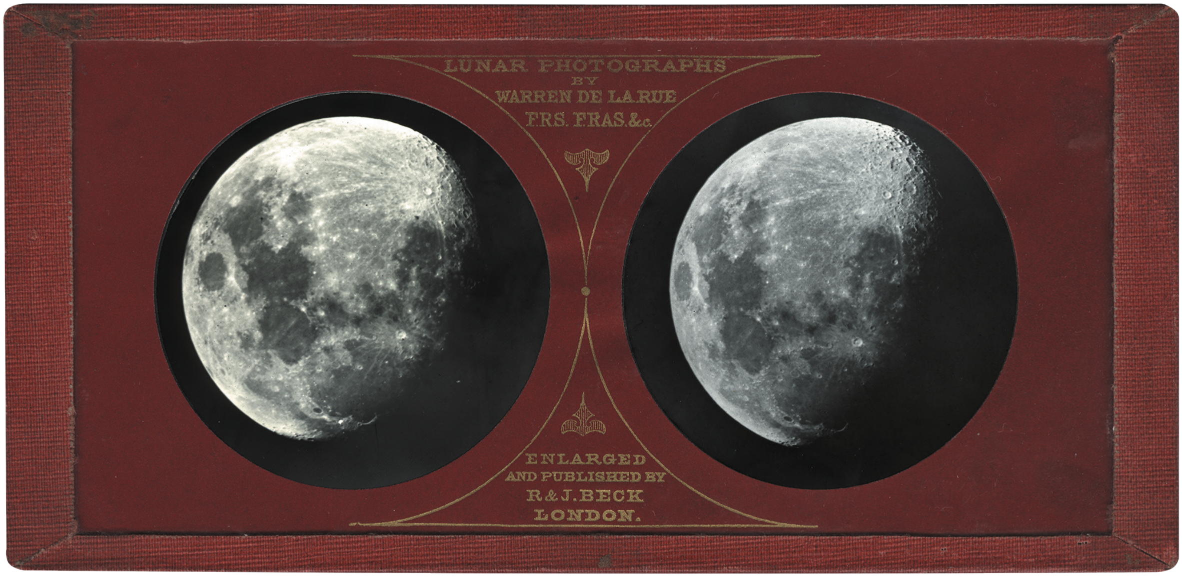


Fig. 5 Lunar Photographs by Warren de la Rue. FRS. FRAS. & Co. Enlarged and published by R. & J. Beck, London. Glass positive, mounted on one red mount, 1858 – 1862, 8 x 17 cm, FBS Collection

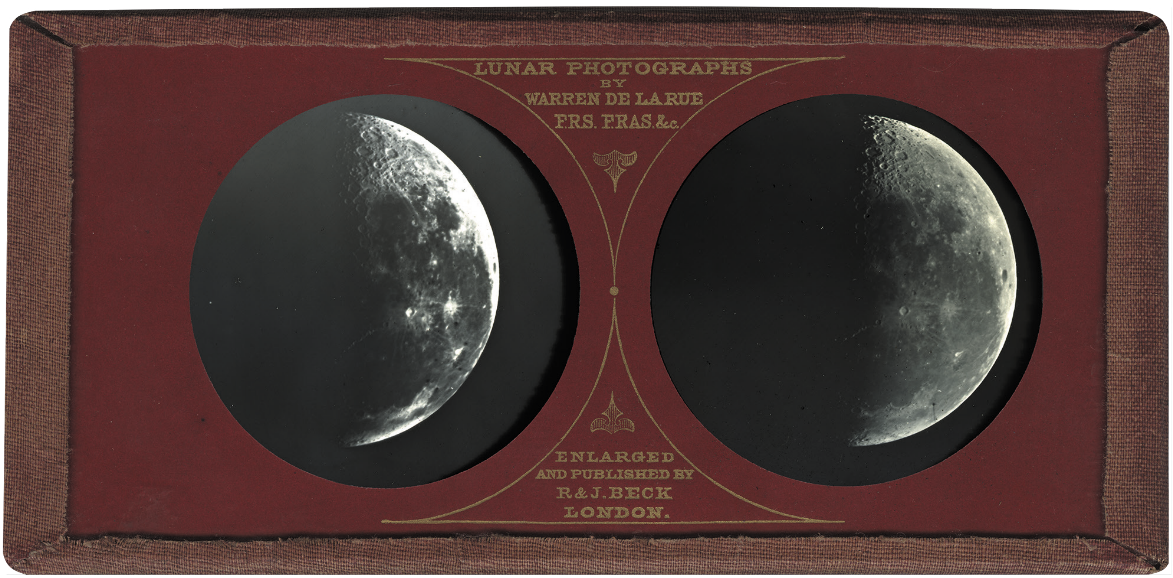


Fig. 6 Lunar Photographs by Warren de la Rue. FRS. FRAS. & Co. Enlarged and published by R. & J. Beck, London. Glass positive, mounted on one red mount, 1858 – 1862, 8 x 17 cm, FBS Collection

Fig. 7 Lunar Photographs by Warren de la Rue. FRS. FRAS. & Co. Enlarged and published by R. & J. Beck, London. Glass positive, mounted on one red mount, 1858 – 1862, 8 x 17 cm, FBS Collection

Fig. 8 Lunar Photographs by Warren de la Rue. FRS. FRAS. & Co. Enlarged and published by R. & J. Beck, London. Glass positive, mounted on one red mount, 1858 – 1862, 8 x 17 cm, FBS Collection

> photography, because it required two enthusiasts, one to uncover the mouth of the telescope, and one to follow the moon's apparent motion; and it was not easy to find a friend always disposed to wait up for hours, night after night, probably without obtaining any result. (MNRAS 1857, 16).

He then decided to discontinue his photographic experiments had until he applied a clock motion to his telescope. By 1857, he had refined his instruments and could begin to produce prints with unprecedented quality. This enabled him to use lunar photographs to produce extraordinary stereoscopic pictures by grouping pairs of photographs taken at different stages of lunar libration at the Cranford Observatory, which were presented to the Royal Astronomical Society in 1858 (MNRAS 1857 and 1858). He explained his method in detail in his article "The Present State of Celestial Photography in England" published in 1859 in The Report of the 29th Meeting of the British Association for the Advancement of Science, (Pérez González 2017, 45; De la Rue 1859, 130).

Smith, Beck & Beck published de la Rue lunar stereoscopic plates and photographs. The FBS Collection holds seven plates on glass positives. Five stereo pairs depict a different phase of the Moon (Figures 5 – 9), and two, very rare, are

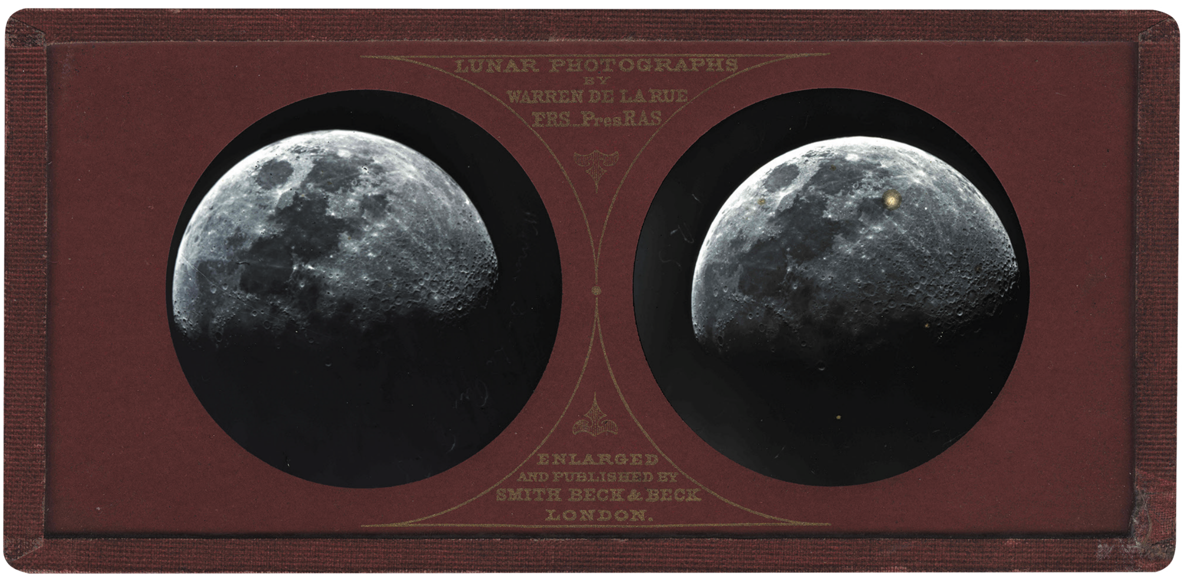


Fig. 9 Lunar Photographs by Warren de la Rue. FRS. FRAS. & Co. Enlarged and published by R. & J. Beck, London. Glass positive, mounted on one red mount, 1858 – 1862, 8 x 17 cm, FBS Collection

Fig. 10 and Fig. 11 Stereoscopic view of the phenomena of lunar eclipses formed by combining photographs of the eclipses of Febr. 1858 & Oct. 1865. Lunar Photographs by Warren de la Rue. FRS. FRAS. & Co. Enlarged and published by R. & J. Beck, London. Glass positive, mounted on one red mount, 1858 and 1865, 8 x 17 cm, FBS Collection

Fig. 12a and 12b Warren de la Rue, Moon Stereoscopic Series – I, Warren de la Rue, Smith, Beck & Beck Publishers, stereocard, 1858 and 1859, 8,5 x 17 cm, Brian May Collection photographic plates of a partial lunar eclipse (**Figures 10 and 11**).

Different stereoscopic photographs were printed next to these on glass positives, and on verso appeared detailed technical and observational information of the two photographs used in each pair. **Figures 12a and 12b** are the first stereoscopic photograph of a series of six. See **Table 1**, which shows six stereoscopic pairs of the 'Moon Stereoscopic Series' published by Smith, Beck & Beck and where we can see that pairs are taken at similar Moon ages.

Moon Stereoscopic Series	Right-Hand Picture	Left-Hand Picture
Nº I	19th February 1858 5.9 days old Libration in longitude: -3º 14' Libration in latitude-5º 13'	9th May 1859 6.9 days old Libration in longitude:+2º 6' Libration in latitude: +0º 11'
Nº II	22nd of February 1858 9 days old Libration in longitude:+0º 17' Libration in latitude: -6º 14'	12th of May 1859 10 days old Libration in longitude: +4º 24' Libration in latitude: +4º 42'
Nº III	5th of December 1859 11.3 days old Libration in longitude:-5º 48' Libration in latitude: -5º 29'	27th of August 1860 11 days old Libration in longitude: +5º 14' Libration in latitude: +1º 24'
Nº IV	11th of September 1859 14.8 days old Libration in longitude:-2º 48' Libration in latitude:-2º 40'	27th of February 1858 14.2 days old Libration in longitude:+4º 54' Libration in latitude:-0º 5'
Nº V	3rd of October 1860 18.8 days old Libration in longitude: -4º 58' Libration in latitude: -5º 19'	12th of August 1862 17.1 days old Libration in longitude: +6º 12' Libration in latitude: -5º 43'
Nº VI	15th of September 1862 21.5 days old Libration in longitude: -0º 25' Libration in latitude: +0º 45'	7th of December 1857 21.8 days old Libration in longitude: +8º 22' Libration in latitude: -0º 29'

Table 1 Texts written on the backs of six stereoscopic cards of the Moon with photographs taken by Warren de la Rue and printed as the Moon Stereoscopic Series by Smith, Beck & Beck.

Sir John Herschel (1792 – 1871), among many other astronomers, expressed his wonder and admiration at their effect:

> It is a step in nature but beyond human nature as if a giant with eyes some thousands of miles apart looked at the Moon through binoculars. What surprises me most is the extraordinary difference in the two pictures as seen by either of the eyes separately not only in form but in shadow & light & the way in which they blend into one is something quite astonishing (Herschel 1858).

Astronomers went on producing stereos of the Moon, which kept circulating among them and which provided detailed scientific information about under which circumstances and when the two photographs of the pair were produced. A beautiful example is a stereoscopic photograph (Figure 13), which was assembled by Carl Pulfrich (1858 – 1927) from Carl Zeiss (Jena). The two photographs of the pair were taken on the 20th of April 1896 and on the 7 February 1900 (almost 4 years after the first one). They were taken, as we can read off on the card, with the *grand équatorial coudé de l'Observatoire de Paris*. The two photographs of the pair were two among 10 000 photographs of the Moon taken with this legendary telescope at the Paris Observatory between 1896 and 1910, and which were published in the *Atlas photographique de la Lune*.(Loevy and Puiseaux 1896-1910).Maurice Loewy (1833 – 1907), the director of the Paris Observatory (since 1896), and Pierre Puixeus (1855 – 1928) were the astronomer-photographers who took the photographs.

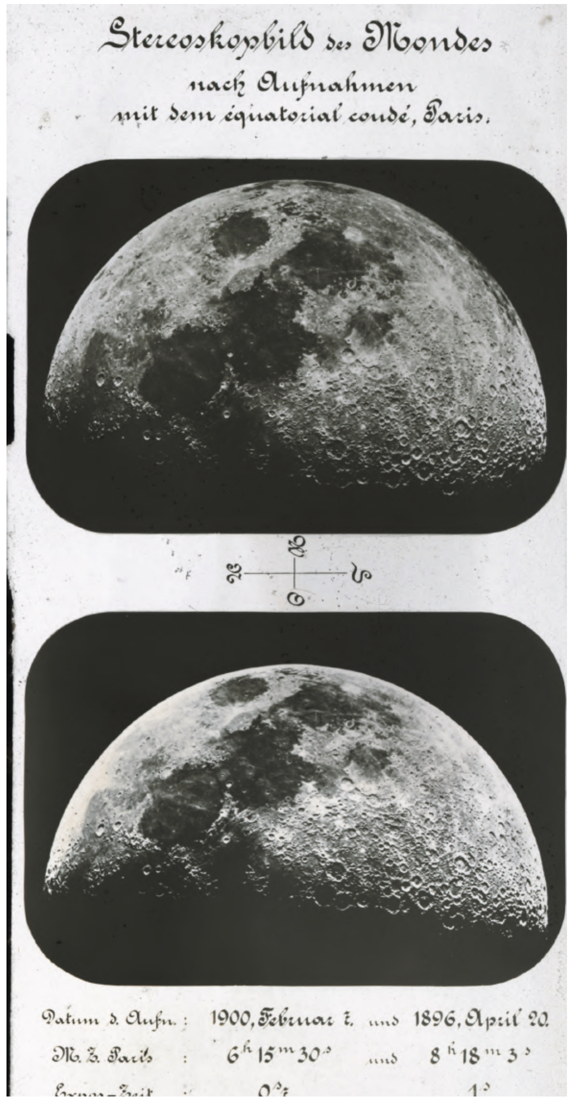


Fig. 13 Maurice Loewy and Pierre Puixeus, Paris Observatory, mounted by Carl Pulfrich, The Moon, stereocard, 1896 and 1900, 8,5 x 17 cm, FBS Collection

There were other pioneers who took extraordinary stereoscopic photographs of the Moon, such as Samuel Fry (1835 – 1890) and Ferdinand Quénisset (1872 – 1951). The FBS Foundation holds a stereo card of the Moon (Figure 14) taken by the French astronomer and pioneer astrophotographer Ferdinand Quénisset, who worked as an astronomer at the Jusivy Observatory from 1906 to 1947. Regretfully, we do not have any technical information about when the two photographs of the pair were produced and under what circumstances, but we are researching this further.

Lunar eclipses

We have not been able to locate the paper copies by Warren de la Rue of the partial moon eclipse presented above.

On the cover of each one of the two on glass positives, we can read on the left-hand side: „Stereoscopic View of the Phenomena of Lunar Eclipses, formed by combining Photographs of the Eclipses of Febr. 1858 & Oct. 1865". By searching through NASA's website devoted to the history of lunar eclipses, we can easily find the exact dates of the two lunar

Fig. 14 Ferdinand Quénisset, Jusivy Observatory, The Moon (*Photographie de la Pleine Lune*), stereoscopic photograph, c. 1930, 6 x 13 cm, FBS Collection

eclipses eclipses: the first on the 27th of February 1858, and the second on the 4th of October 1865.[1]

On the night of the 4th of October 1865, Warren de la Rue made several photographic experiments before, during and after the umbra and penumbra of the eclipse, as he thought that taking photographs of the Moon with the penumbra would render more details about the surface than if he took them directly under sunlight:

> As the penumbra gradually encroached on the disk, it was remarked that the various details of the lunar surface came out much more distinctly than when seen under the full and direct illumination of the sun (De la Rue 1865, 276).

De la Rue further writes that with the help of his assistant, Mr. Reynolds, he took seventeen photographs:

> …between 7h and 11h 5m, this interval commencing nearly an hour and half previous to the first contact of the penumbra and concluding 15 minutes after the greatest phase (De la Rue 1865, 276).

And, especially interesting for the topic of this article are his comments on the way he made the stereoscopic photographs of the lunar eclipse by pairing photographs taken at very different times: 1858 for one and 1865 for the other:

> The photographs of Febr. 1858 stand in the stereoscopic relation to those of Oct. 1865, - i.e. they combine in the stereoscope and produce good stereoscopic pictures of the lunar eclipse (De la Rue 1865, 277).

In its early days, photography caused a great social and cultural impact because of its ability to capture moments in a realistic manner, an effect that was accentuated in early stereoscopic images by their three-dimensional effect. Stereoscopic photographs of people or landscapes consisted of snapshots captured simultaneously and from the same place. But, as we show in this article, the construction of astronomical stereoscopic images often involves combining individual photographs taken at separate points in time, sometimes even years apart. In this type of images, the character of the stereoscopic image as an illusion-creating technique is revealed in all its intensity: the realistic, almost material, perception of depth in a celestial landscape is induced with resources that are largely fictitious and that involve constructing a unique "current" fiction or illusion (the vision of a celestial body in relief) from pieces that correspond to locations in space and time that are far apart from each other. Astronomical stereoscopy is not *false* in the strict sense of the word, but neither is it possible to affirm, literally, that it is *real*.

Rotation: Jupiter, Mars, and the Sun

Rotation offers a straightforward solution to produce stereoscopic pairs of certain celestial bodies. If an object rotates

1. https://eclipse.gsfc.nasa.gov/LEcat5/LE1801-1900.html

with period T, the angular speed is 2π/T. The rotation angle in time t is 2πt/T rad, corresponding to a simulated parallax,

$$\alpha_r = \frac{\pi t}{T} rad = \frac{180t}{T} \circ$$

Eq. (3)

αr, half this value. If we obtain images separated by a time interval t, we get the rotational parallax:

Let us see what should be the lapse between shots to get a reference parallax α_a = 3°:

$$t_{3^\circ} = \frac{T}{60}$$

Eq. (4)

This leads to the approximation that if the rotation period is T hours, then two shots to build a stereoscopic pair would be separated by a minimum of T minutes. Bigger time intervals would also work, as long as we do not induce unrealistically large parallax angles, not acceptable by the perceptual system. Setting that limit around 15°, the upper boundary for the time lapse is t_{15° = *T*/12, and some no-nonsense value for stereography may be around the average of t_{15° and t_{3°, t_r = *T*/20. This would lead to a rotational parallax equal to the average of 9 degrees.

Table 2 shows the rotational data for three celestial bodies that have been traditionally the subject of stereographic photographs using the rotation method to simulate the stereoscopic effect: Jupiter, Mars and the Sun. The rotational periods have been rounded because high precision is not necessary for stereo photography.

Object	*T* (h)	*T* (d)	t_{3°	t_r	t_{15°
Jupiter	10	0.42	10 min	30 min	50 min
Mars	25	1.04	25 min	1.25 hours	2 hours
Sun	655	27.27	11 hours	33 hours	55 hours

Table 2 Table 2 Some rotational parameters relevant for stereography of Jupiter, Mars and the Sun. The synodic rotation period in hours, T (the apparent rotation period of the object for an observer on the Earth) is given in hours in the second column, and in days in the second. Column four displays the time needed to get the minimum useable rotational parallax of 3 degrees, while column six provides the time that leads to the maximum reasonable value of 15 degrees. The fifth column gives an intermediate value. See the text for more details.

The Sun and Jupiter display differential rotation, which means that the rotation period changes with latitude. The Sun rotation period provided in the table corresponds to sunspots observed at the Sun's Equator and it is a synodic value (it reflects the time needed for the Sun to perform one complete rotation as seen from the moving Earth).

Jupiter rotates so fast that viable stereoscopic pairs can be produced with time intervals below one hour. The atmospheric details of Jupiter evolve in times of the same order, making it inconvenient to enlarge the time span further. This was less important in ancient times, when Jupiter photographs did not capture much detail, but is more relevant for high quality, contemporary images. Also, Jupiter, as the Sun, displays differential rotation, what means that the rotation period changes with latitude, yielding different apparent parallaxes at each distance from the equator for long intervals. The period of 10 hours stated in Table 2 is a rounded value, and the true ones vary from 9 hours and 55 minutes close to the poles to 9 hours and 50 minutes at the Equator (Kaufmann 1994, 229). The rotation of Jupiter is direct, which means that, if we look to the planet with its North Pole upwards, the disc rotation runs from left to right. Thus, later images have to be fed to the left eye if North is up, or to the right eye if North is down, in order to get a stereoscopic effect in relief.

Observations during one night may provide stereoscopic pairs of Mars. Again, the rotation is direct and later images are to be shown to the left eye if North is up, or to the right eye if North is down. The details on Mars do not evolve as fast as on Jupiter. Also, its phase angle (the conditions of illumination) does not change rapidly. All this allows combining images obtained in different (preferably consecutive) nights. In 24 hours, Mars completes 0.96 rotations, which leaves an apparent parallax of 7 degrees, suitable for stereoscopy. But the second day, at the same hour, the planet has not yet reached the rotation position that it had reached the previous night, and now the image from the second day should serve as the right-eye element of the stereoscopic pair, if the North Pole of the planet is placed up.

The Sun poses challenges due to its slow rotation and the fluid and changing nature of its visible surface, or photosphere. Photographs taken with a few hours difference may induce a slight stereoscopic effect, but Table 2 shows that it is better to enlarge the time span. An interval on the order of half day is not practical, because it implies taking one image with the Sun low at the Eastern part of the sky and the second one in symmetric conditions, so both of them through large air masses, which degrades the quality. It is better to split the pair between consecutive days, around noon, benefitting from the best atmospheric conditions in each case, near noon. In 24 hours, the Sun rotates close to 14°, yielding a parallax of 7°, sufficient for stereoscopy. It makes sense to separate the shots by up to two days to increase the stereoscopic effect. However, attention has to be paid to the evolution of sunspots, which change in time scales on the order of one day. As does Jupiter, the Sun displays differential rotation, rotating faster in the areas closer to the equator, what may result in weird effects if the photographs are taken close to a period of maximum activity of the Sun, when there may be sunspots at different latitudes. The rotation of the Sun is also direct (later images are for the left eye if North is up).

Jupiter, 1886

In a very short article published by W. J. H. in 1891, in the scientific journal *Nature*, we read about the first stereoscopic photographs of Jupiter (Figure 15):

> In Admiral Mouchez's "Photographie Astronomique" (1887) – a small book, and cheap – are eight photographs of Jupiter, by the M.M. Henry, taken in April 21, 1886. Several are at intervals of only three minutes in time. What with the large red spots, the irregularities of the two belts, and white spots on the upper belt, there are quite details enough to enable the eye to perceive the solidity of the planet, in a stereoscope, if the earlier picture is submitted to the right, and the later to the left eye. Reversing the order of the pictures gives a

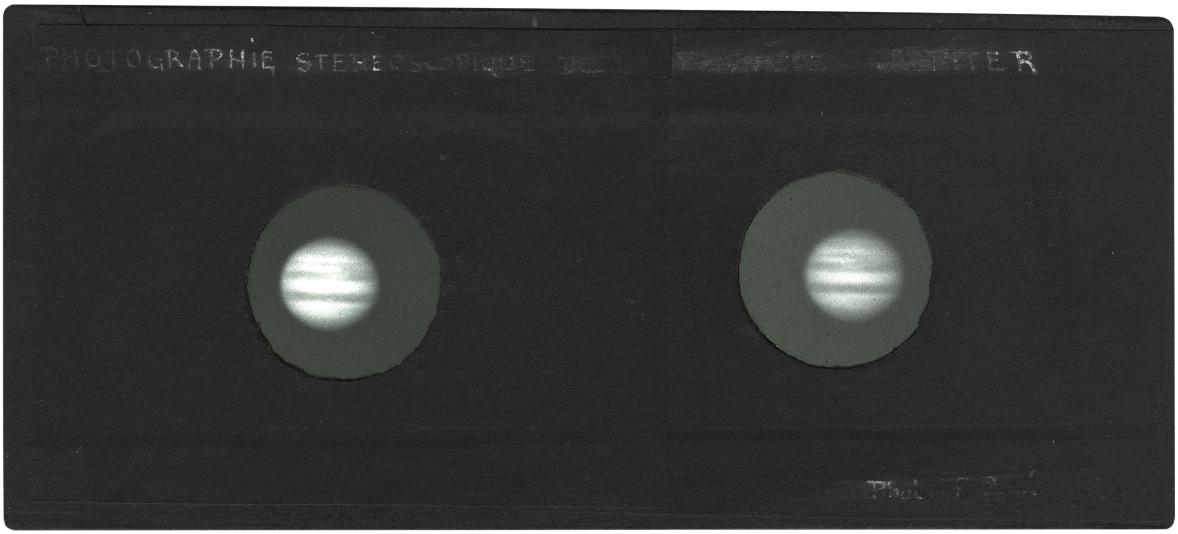


Fig. 15 M. M. Henry, Jupiter (*Photographie stéréoscopique de la Planète JUPITER*), stereoscopic photograph, 1886, 6,2 x 15,2 cm, FBS Collection

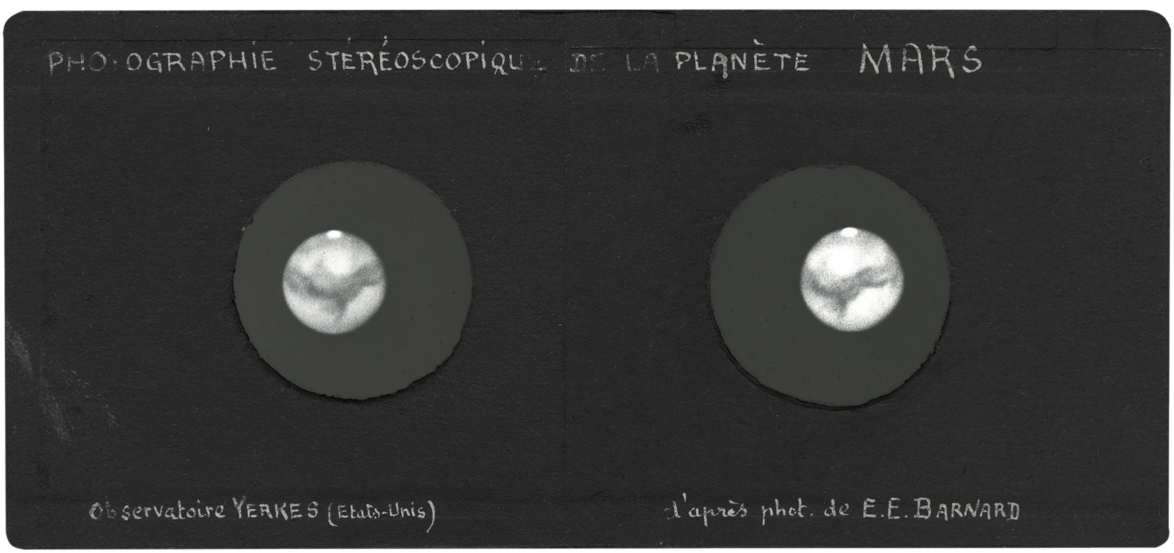
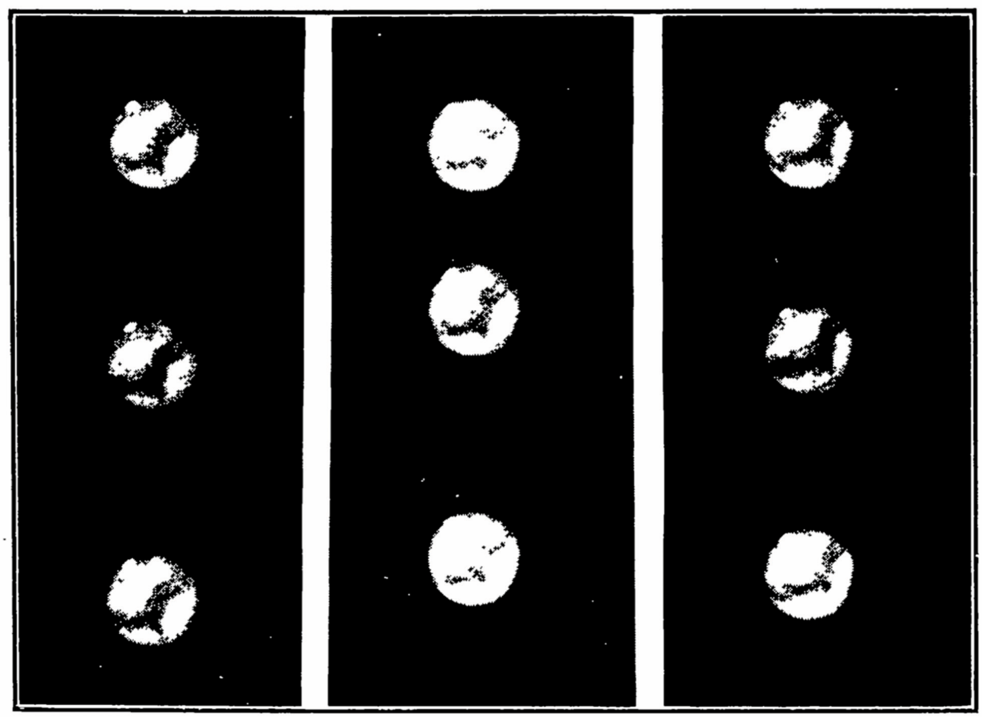


Fig. 16 E. E. Barnard, Yerkes Observatory, stereoscopic photograph of Mars (*Photographie stéréoscopique de la Planète MARS*), stereoscopic photograph, 1909, 7,2 x 15,2 cm, FBS Collection

PLATE XIV



Mars, September 28, 1909. Region of the Syrtis Major, showing change due to rotation. 40-inch Telescope, Yerkes Observatory

—*E. E. Barnard*

Fig. 17 PLATE XIV, Mars, September 28, 1909. change due to rotation. Region of the Syrtis Major, showing 40 inch Telescope, Yerkes Observatory, published in E.E.Barnard (1923).

> puzzling effect, which, with a little practice, is seen to be hollowness instead of solidity. But the mind resents this true result, and so gets puzzled (W.J.H. 1891, 269).

Mars, 1909

In his article "Photographing the Sky" (1923), Barnard describes the nine photographs that he took of Mars (Yerkes Observatory, through a 40-inch telescope), and printed in his article, two of which were used for the stereoscopic photograph (Figure 16), which was also later used in the stereograph published in the Keystone Series 600 SET (Pérez González 2017):

> Here are some photographs of the planet Mars taken with the great telescope at Yerkes Observatory (see Plate XIV, Figure 17). The white spot at the upper part of the disc is the south polar cap – presumably of snow and ice. There is a similar one at the North Pole. These white spots, during the winter of the planet, become very large and extend to middle latitudes; while in the Martian summer they melt away almost entirely. They perhaps consist of a comparatively thin sheeting of snow (Barnard 1923, 189).

He then goes on to provide further information that hints about how he managed to produce the stereoscopic effect by combining two of the images that he took that night:

> You will see that these photographs show the turning of the planet on its axis, from west to east. This great dark spot here, called the Syrtis Major, is to the right of the center, and here you see it three hours later to the left of the center, thus showing the rotation of the planet on its axis, producing day and night (Barnard 1923, 189).

The Sun, 1917

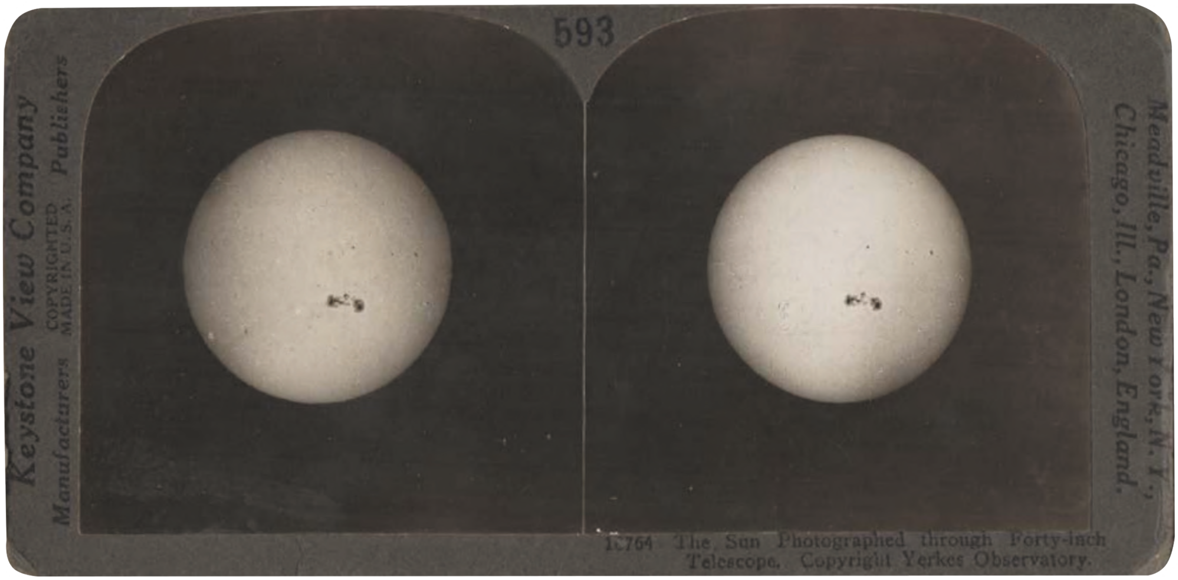
The two images of the Sun in the stereoscopic pair published in the Keystone Publishing Company must have been taken on the same day (Figures 18a and 18b). After consulting *An Illustrated Catalogue of Astronomical Photographs* (1923), it was confirmed that the photographer of the Sun for this stereograph was Miss Rhode Calvert (Frost 1927)the wife of Edward Emerson Barnard, who took the two photographs, on the 14th of February 1917 (An illustrated Catalogue 1923, 29)

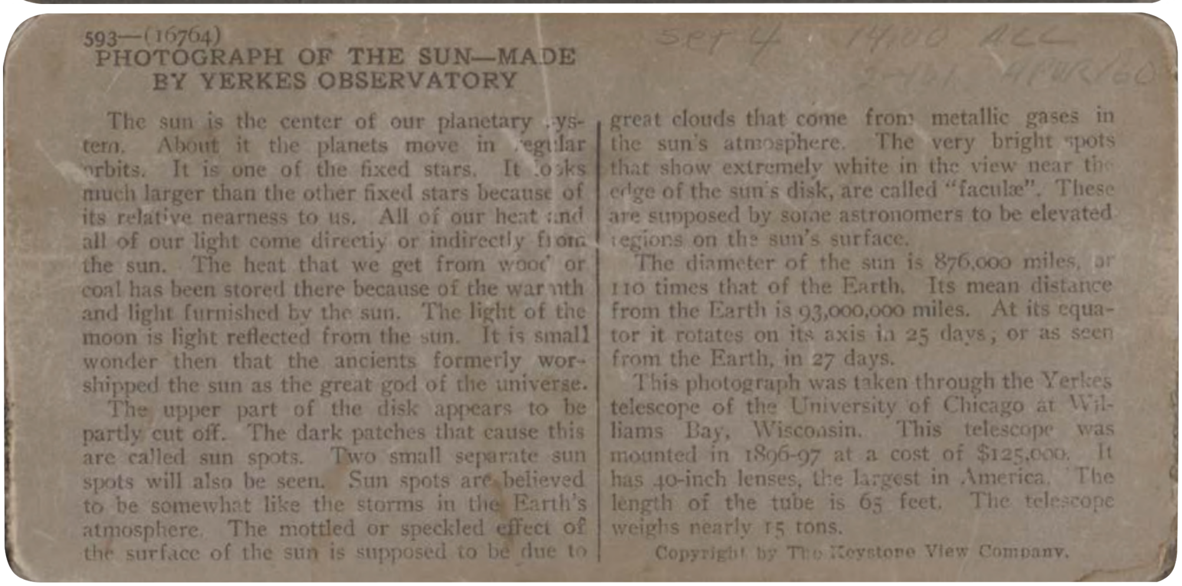
The text written on the back of The Sun photographed through the forty-inch telescope (Figure 23b) identifies the photograph as taken through the Yerkes telescope of the University of Chicago, at Williams Bay, Wisconsin. It further informs the reader that "the telescope was mounted in 1896-97 at a cost of $125,000. It has 40-inch lenses, the largest in America. The length of the tube is 65 feet. The telescope weighs nearly 15 tons".

But before this stereoscopic photograph of the sun, Ferdinand Quénisset managed to produce an excellent stereoscopic photograph of the solar eclipse on August 1914 (Figure 19). Here, the Moon's fast orbital motion yields the stereoscopic effect against an apparently flat Sun.

Star trails and the precession of the equinoxes

Some stereoscopic pairs have been produced using star trails as their subject. In this kind of photograph, the shutter is kept





593—(16764)
PHOTOGRAPH OF THE SUN—MADE BY YERKES OBSERVATORY

The sun is the center of our planetary system. About it the planets move in regular orbits. It is one of the fixed stars. It looks much larger than the other fixed stars because of its relative nearness to us. All of our heat and all of our light come directly or indirectly from the sun. The heat that we get from wood or coal has been stored there because of the warmth and light furnished by the sun. The light of the moon is light reflected from the sun. It is small wonder then that the ancients formerly worshipped the sun as the great god of the universe.

The upper part of the disk appears to be partly cut off. The dark patches that cause this are called sun spots. Two small separate sun spots will also be seen. Sun spots are believed to be somewhat like the storms in the Earth's atmosphere. The mottled or speckled effect of the surface of the sun is supposed to be due to great clouds that come from metallic gases in the sun's atmosphere. The very bright spots that show extremely white in the view near the edge of the sun's disk, are called "faculæ". These are supposed by some astronomers to be elevated regions on the sun's surface.

The diameter of the sun is 876,000 miles, or 110 times that of the Earth. Its mean distance from the Earth is 93,000,000 miles. At its equator it rotates on its axis in 25 days, or as seen from the Earth, in 27 days.

This photograph was taken through the Yerkes telescope of the University of Chicago at Williams Bay, Wisconsin. This telescope was mounted in 1896-97 at a cost of $125,000. It has 40-inch lenses, the largest in America. The length of the tube is 65 feet. The telescope weighs nearly 15 tons.

Copyright by The Keystone View Company.

Figs. 18a and 18b The Sun photographed through forty-ich telescope, Yerkes Observatory, Keystone Publishing Company (593 – 16764), stereocard, 1917, 8,5 x 15 cm, Carmen Pérez González Collection

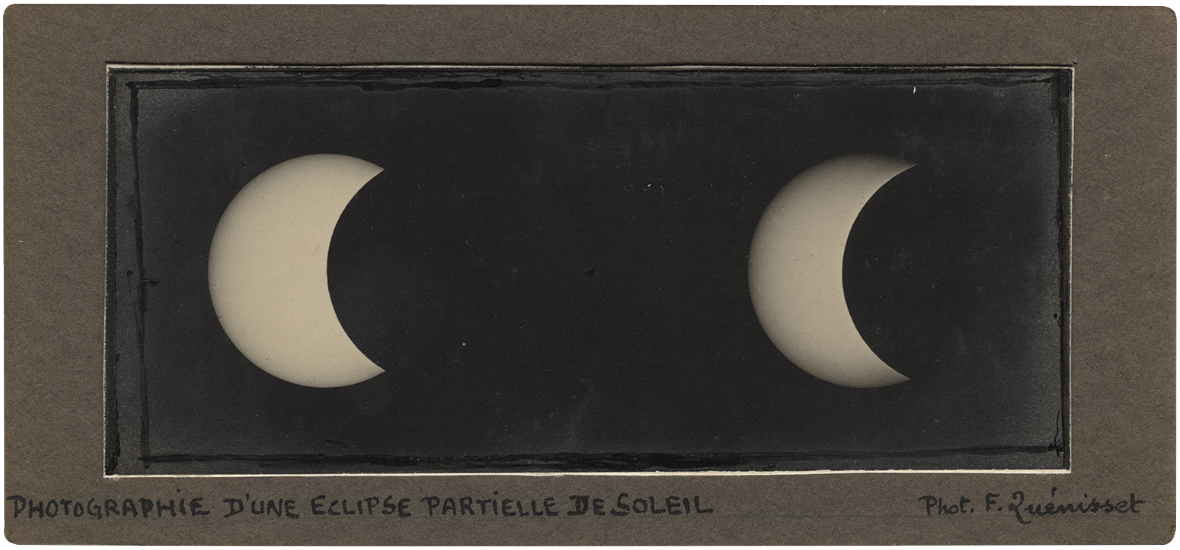


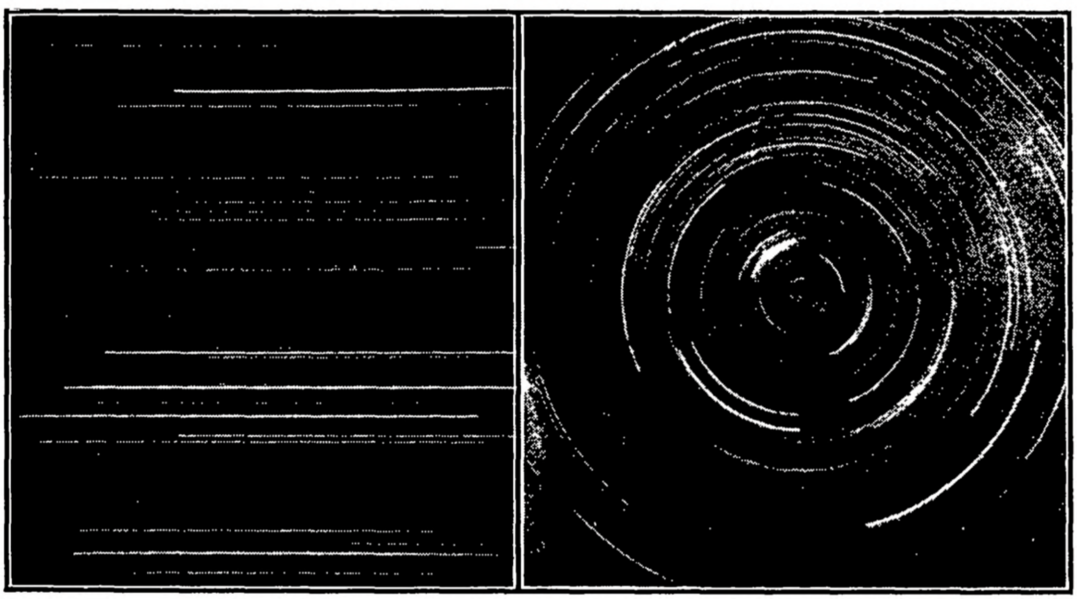
Fig. 19 Ferdinand Quénisset, Jusivy Observatory, Solar Eclipse (*Photographie d'une eclipse partielle de Soleil*), August 1914, stereoscopic photograph, c. 1930, 6,2 x 15,2 cm, FBS Collection

open for several hours, and the rotation of the Earth causes the stars to leave a trace on the detector. Those traces may show different levels of curvature, depending on the field of view and the angular distance to the celestial pole. The curvature is maximum for star trails very close to the pole, while they appear almost rectilinear for stars placed at the celestial equator. If the field of view is very large, then different curvatures will be present.

If the celestial pole is inside the frame, then the traces are circular arcs centred on the pole. The celestial pole is the projection of the Earth's rotation axis on the celestial sphere. But the Earth's axis is not fixed in space; rather, it moves very slowly, at a pace of less than one minute of arc per year, needing some 72 years to complete a full degree. This motion is known as the precession of the equinoxes. Thus, taking separate photographs of star trails close to the celestial pole within a time span of several years (depending on the field of view), the resulting trails will be centred at different points, which will yield an interesting but absolutely spurious perception of depth that is not related at all with the distance to the stars, rather with the pace of the precession and the apparent separation of the stars to the celestial pole.

Photographing the Earth's rotation and precession, 1903 - 1906

In his article published in 1923, Barnard wrote about the process needed to make a photograph of the Earth's rotation (Figure 20):



1. 2.

Photographs of the Rotation of the Earth;
Camera Stationary, Stars Trailing

1. Pointed to Equator of the Sky, Exposure 1 h.
2. Pointed to Pole of the Sky, Exposure 5 h.

—*E. E. Barnard*

Fig. 20 PLATE XIII, Photographs of the Rotation of the Earth; Camera Stationary, Stars Trailing. 1st photo: Pointed to Equator of the Sky, Exposure 1 h; 2nd photo: Pointed to Pole of the Sky, Exposure 5 hours, published in E.E.Barnard (1923).

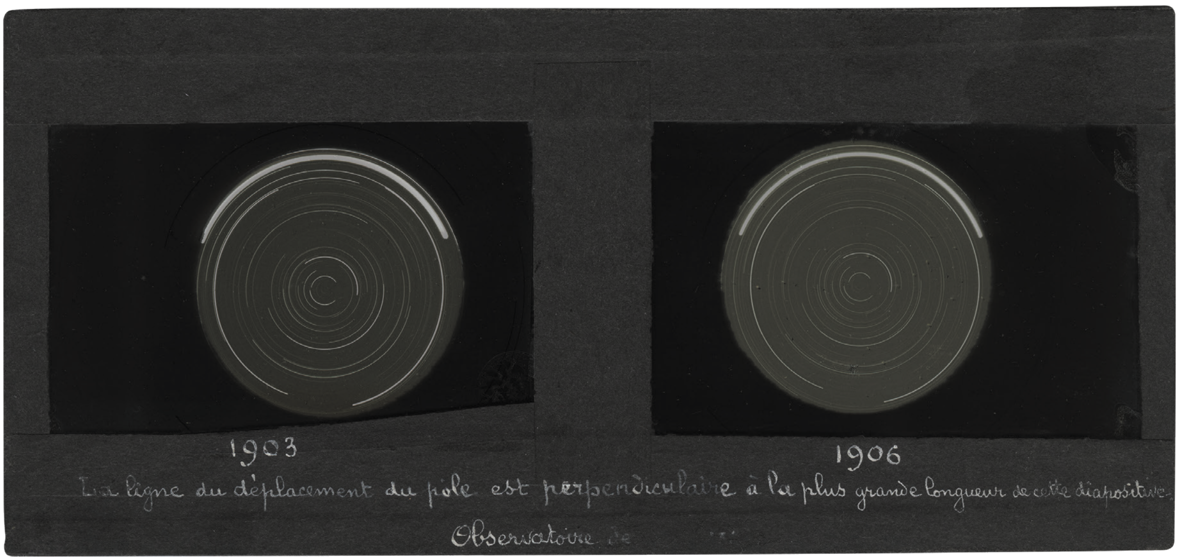


Fig. 21 Stereoscopic photograph of the Rotation of the Earth, stereoscopic photograph, 1903, 1906, 7 x 15 cm, FBS Collection

The telescope was stationary during the exposure of 1 hour, but the stars have not remained stationary on our plate and are not points of light. The plate is covered with straight bright and faint lines that stretch nearly across it. These are due to the drift of the sky westward to the equator of the sky – to the constellation of Orion. Here is another photograph made with the instrument stationary and pointed to the pole of the heavens. In this case, the stars trails are sections of circles. The exposure was 5 hours. Had it been possible to have made it twenty-four hours, they would have been complete circles. By this means, we do not get a picture of the sky, but simply a photograph of the rotation of the earth (Barnard 1923, 183).

In the FBS Collection, there is a stereoscopic photograph of the Earth's rotation (Figure 21), and the two photographs of the pair were taken with three years of difference, 1903 the first one and 1906 the second one, which results in an apparent shift of point of view due to the precession of the equinoxes during that time interval.

Celestial mechanics and stereography: the satellites of Jupiter

Orbital motion is described by the three laws discovered by Johannes Kepler (1571 – 1630) (Caspar 1993) in the 17th century from data obtained with the unaided eye. We have seen that rotation acts as a proxy for parallax useful in the case of several planets. In this section we will see that orbital motion can be used with the same aims, but the results will never be neither realistic nor accurate.

The main application of this approach is for the four larger satellites of Jupiter, the Galilean moons: Io, Europa, Ganymede and Callisto. Discovered by Galileo Galilei (1564 – 1642) with his first telescopes, they are very easily observed even with binoculars as four tiny stars, of similar brightness, beside the disc of Jupiter (Leutwyler 2003), around which they move completing revolutions with the periods indicated in Table 3. All four satellites share the same orbital plane, coincident with the planet's equator and with the direction towards the Earth, in such a way that we see the orbits edge-on, and these moons transit in front of Jupiter, and get eclipsed by it, once in every revolution. The orbits are at different distances from the centre of Jupiter (see, again, Table 3), and for our purposes, we can accept that they are circular. These moons follow their orbits in direct motion, i.e., in the same direction of the rotation of Jupiter: if North is up, then the satellites move from left to right when they are in front of the planet, and from right to left when they are beyond it.

Orbital motion induces an apparent parallax related to the displacement of the bright points of the satellites, which, in turn, is defined by celestial mechanics through Kepler's laws. We are now interested in Kepler's third law, which relates the sizes (radius, for circles) of the orbits to the periods of revolution. This law admits different formulations, but for our aims the simplest of them will suffice. If a is the radius of the circular orbit (distance of the satellite to the centre of the planet) and T the orbital period, then Kepler's third law states:

$$\frac{a^3}{T^2} = constant$$

Eq. (5)

The value of this constant is the same for all the satellites present in the system, but it depends on the units elected to measure both the orbital radius a and the period T. For the system of Jupiter, using as length unit the mean radius of the planet itself (R_J = 69 911 km) and measuring periods in days (d), we get the value 70.5 R_J^2/d^3 for the constant. The physical meaning of this law is that if the distance a to the planet grows, then the period T has to grow too, in order to keep the quotient constant. And the period has to grow much more than the distance, because the distance is shifted to the third power, while the period is only squared. As a result, satellites further from the planet run in their orbit at increasingly much slower speed: distant moons are stragglers.

This effect can be checked in Table 3.

Satellite	*a* (km)	*a* (R_J)	*T* (d)	*v* (km/s)	*v* (R_J/d)
Io	421 800	6.03	1.76	17.3	21.4
Europa	671 100	9.60	3.53	13.7	17.0
Ganymede	1 070 400	15.3	7.16	10.9	13.4
Callisto	1 882 700	26.9	16.69	8.20	10.2

Table 3 basic data of the Galilean satellites of Jupiter (adapted from NASA's Jet Propulsion Laboratory reference table at https://ssd.jpl.nasa.gov/sats/phys_par/ and references therein)

But this physical fact has implications for the stereoscopic photography of the satellites of Jupiter. Let us imagine all four Galilean moons passing between Jupiter and the Earth. Their velocities are perpendicular to the line of sight, and the

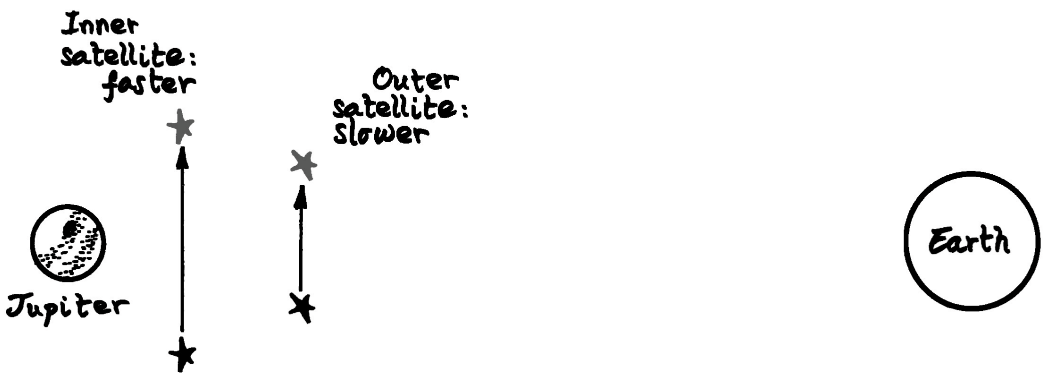


Fig. 22 David Galadí-Enríquez, The apparent motion of the satellites of Jupiter as seen from Earth. According to Kepler's third law of orbital motion, those satellites more distant from their central body move much slower thant those closer to the centre. This implies that the 3D stereoscopic effect, as seen from Earth, is reversed: objects closer to the observer seem placed further away. Drawing, 2024.

moons move towards the right if North is up. Callisto is the most distant to Jupiter, thus it is the closest to Earth. Io is the closest to Jupiter and, thus, the most distant from Earth. But, according to celestial mechanics, during the same time interval t, the motion of the satellite closest to us (Callisto) will be the slowest, while the moon more distant from us (Io) will be the fastest (Figure 22). It follows that, if we take two photographs separated by that time interval t, then Io will display the largest apparent parallax, and Callisto will show the weakest apparent parallax.

Of course, for all this argumentation we are assuming that later images are fed into the left eye if North is up, as corresponds to a situation of direct motion.

We end up with the paradox, imposed by Kepler's third law, that the objects closest to us will seem the furthest in a stereoscopic photograph based on orbital motion as a proxy for parallax. Careful reasoning on the same principles shows that the situation is reversed if we consider the other half of the orbits. Any moon placed beyond the planet will display an apparent retrograde (opposed to direct) motion and the relief that it would have shown being between the planet and Earth will turn into depth. So, faster satellites will appear deeper, which again reverses the real situation.

The vision becomes even more contorted if we consider orbital positions different from those located exactly in front of the planet or beyond it, because the projected, apparent

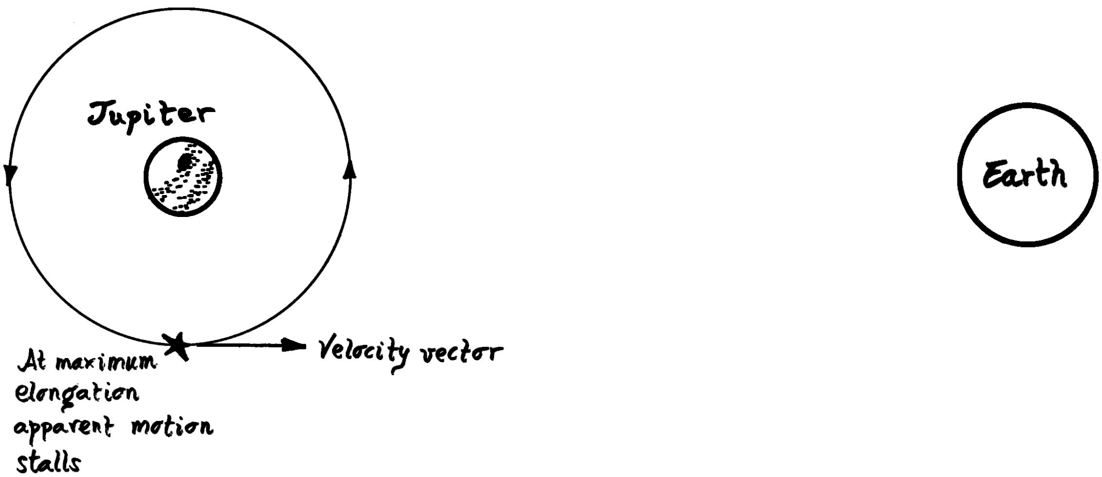


Fig. 23 David Galadí-Enríquez, One more complication of using orbital motion as a proxy for parallax in planetary satellites is that the projected, apparent angular motion of satellites depends on elongaton, i.e., on the apparent distance to the central planet. At maximum elongation, apparent motion stalls, and it gets intermediate values at other places of the orbit. The final result is non reallistic in what refers to the true distance of the satellites to the observer. Drawing, 2024.

Fig. 24 Ferdinand Quénisset, Jusivy Observatory, Jupiter's Satelites (*Photographie stéréoscopique des satellites de Júpiter*), c. 1930, 6,2 x 15,2, FBS Collection.

angular speed of the satellites depends on their elongation or apparent distance from the planet. When any Galilean satellite is close to maximum elongation, its apparent motion stalls, which temporarily freezes to zero its apparent parallax (Figure 23). This places it (correctly) at the same perceived distance from us as the planet, that also displays zero parallax. But at points intermediate between maximum elongation and conjunction with the planet, angular speeds vary in such a way that the apparent parallaxes rendered may result in a random distribution of perceived distances.

The conclusion is that orbital motion used as a proxy for parallax leads to unavoidable confusing results. For this reason, stereoscopic photographs of the satellites of Jupiter (or Saturn) show some perception of depth (Figure 24). Still, there is no chance for this sensation to be related to the real spatial configuration of the satellites, whose perceived distances will always be reversed and mixed. A more detailed discussion of the effects and results of this stereoscopic process would deserve further consideration and research.

Conclusion

Observational astronomers are scientists who are known for their enormous patience, and pioneer astrophotographers (and even more, pioneer stereo-astrophotographers!) were not only remarkably patient and rigorous scientists but also, in their own right, fascinatingly creative minds.

In this article, we have introduced some of these genial scientists and pioneer stereo-astrophotographers, and we have also provided an introduction to the physical processes that render the apparent stereoscopic effect in each case.

Studying the astronomical context of the stereoscopic images of different celestial bodies, we learn that a significant amount of creativity is needed to induce the stereoscopic effect for objects placed at such enormous distances from the observer. In some cases (Sun, Mars, Jupiter), the rotation of the objects provides a solution, although the time interval between the two elements of each stereo pair has to be selected for each body depending on its rotational properties. For the Moon the situation is unexpectedly complex and we see that getting realistic stereoscopic effects from true photographs of the Moon requires patience and a difficult interplay between Moon phase and the subtle effect of libration. Studying in detail the celestial mechanics involved in photographs of the Galilean satellites of Jupiter we learn that the stereoscopic effect that they convey is purely spurious, an interesting curiosity in which celestial mechanics directly forbid any realistic result in what refers to the perception of depth and the true relative positions of the satellites in their orbits.

Bibliography

An Illustrated Catalogue of Astronomical Photographs including Latern Slides, Transparencies, and Prints from Negatives Made at Yerkes Observatory (1923, 3rd edition). Chicago University Press.

Apura, D. (2017). *Notes on Algebra*. Department of Mathematics, Purdue University, accesible at: https://www.math.purdue.edu/~arapura/algebra/algebra.pdf

Arago, F. (1839). Le Daguerréotype. *Comptes rendus des séances de l'Academia des Sciences* (9), 250-267.

Arnold, H.J.P. (1977). *William Henry Fox Talbot: pioneer of photography and man of science*. Hutchinson Benham.

Barnard, E. E. (1909 May 3). On the Erroneous Results of a Stereoscopic Combination of Photographs of a Comet. *Monthly Notices of the Royal Astronomical Society* (69), 624- 627.

Bigg, Ch. (2018). Of Blurs, Maps and Portraits. Photography and the Moon. In Pérez González (Ed.), *Selene's Two Faces. From 17th Century Drawings to Spacecraft Imaging* (pp 116-146). Brill.

Bonifacio, V., Malaquias, I., & Fernandes, J. (2007). Solar photography in the nineteenth century: the case of the infante D. Luiz Observatory in Lisbon (1871-1880). *Journal of Astronomical History and Heritage*, 10 (2), 101-113.

Caspar, M. (1993). *Kepler*. Translated from German by C. Doris Hellman. Dover Publications.

Crookes, Sir W. & Wharton Simpson, G. (1860). Celestial Photography. *The Photographic News, a Weekly Record of the Progress of Photography*, 98 – 99.

De la Rue, W. (1865). Observations of the partial eclipse of the moon of October 4, 1865. *Monthly Notices of the Royal Astronomical Society*, 25, 276-77.

De la Rue, W. (1859). The Present State of Celestial Photography in England. *The Report of the 29th Meeting of the British Association for the Advancement of Science*, 130.

Frost, E. B. (1927). Edward Emerson Barnard, 1857-1923. *Memoirs of the National Academy of Sciences. Volume XXI, 14th Memoir*. Government Printing Office.

Greenslade Jr. T.B. (1972). The First Stereoscopic Pictures of the Moon. *Am. J. Phys*. (40), 536 – 40.

Herschel, J. (1858). Letter from Herschel to de la Rue, 10 October 1858 (Royal Society HS.6.D.143)

Judge, A. W. (1926). The educational value of the stereoscope. In Stereoscopic photography. Its application to science, industry and education. America Photographic Publishing Co.

Kaufmann, W.J. (1994, 4th edition). *Universe*, fourth edition. New York: W.H. Freeman and Company.

Lankford, J. (1984). The impact of photography on astronomy. In O. Gingerich (Ed.), *Astrophysics and twentieth-century astronomy to 1950, part A* (pp 16-39). Cambridge University Press. Cambridge.

Le Conte, D. (2011). Warren de la Rue – Pioneer astronomical photographer. *The Antiquarian Astronomer* (5), 14 -35.

Leutwyler, K. (2003). *The Moons of Jupiter*.W.W. Norton & Company.

Loevy, M. & P. Puiseux, P. (1896 -1910). *Atlas photographique de la Lune*. Imp. Nationale.

MNRAS 1857 (*Monthly Notices of the Royal Astronomical Society*) (18), 16 -17.

MNRAS 1858 (*Monthly Notices of the Royal Astronomical Society*) (19), 40.

NASA ECLIPSE WEBSITE. Five Millennium Catalog of Lunar Eclipses (1801 – 1900): https://eclipse.gsfc.nasa.gov/LEcat5/LE1801-1900.html

Newhall, B. (1971). *Daguerre - An historical and descriptive account of the various processes of the Daguerreotype and the Diorama, by Daguerre*. Winter House.

Norman, D. (1938). The Development of Astronomical Photography. *Osiris* (5), 560 – 594.

North, G. (2007). *Observing the Moon: The Modern Astronomers Guide*, second edition. Cambridge University Press.

Pérez González, C (2017). From the Observatory to the Classroom: Space Images in the Keystone "600 SET" and "1200 SET. *International Journal on Stereo & Immersive Media (1)*1, 41-62.

Wheatstone, Ch. (1838). XVIII - Contributions to the physiology of vision. – Part the first. On some remarcable, and hitherto unobserved, phenomena of binocular vision. *Philosophical Transations* (128), 371-394. https://doi.org/10.1098/rstl.1838.0019

W.J.H. (1891). Stereoscopic Astronomy. *Nature 1108* (43), 269.