BRIGHTNESS OF THE TOTAL LUNAR ECLIPSE OF MAY 15-16, 2003

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ABSTRACT

This work presents and analyzes brightness data and images obtained during the lunar eclipse on May 15-16 UT, 2003. A total of 12 magnitude and 15 Danjon estimates in addition to dozens of electronic images made by 23 experienced observers, most of them members of the Brazilian Network for Astronomical Observations (REA), have been gathered and reduced in order to provide a clear understanding on the illumination patterns exhibited by the totally eclipsed Moon.

The magnitude and Danjon Number estimates at mid-totality were respectively -2.1 and 2.3, indicating that the eclipse displayed an intermediate brightness only about half a magnitude darker than predicted. Also briefly discussed are the possible influence of volcanic aerosols and the likely dynamics of the phenomena that led to the major observed characteristics of the event.

I – INTRODUCTION

On May 15-16, 2003 just half a day after perigee, the Moon crossed the northern half of Earth´s umbral shadow and remained totally inside it for 52.7 minutes. During the total phase of the event, grazing sunlight scattered by our atmosphere was bent and cast into the umbral cone to dimly illuminate the eclipsed Moon positioned in Libra. An uneven illumination ensued from the Moon`s non-central path across the umbra as its southern half probed much deeper and consequently darker umbral regions than its northern half. At 3:40 UT (greatest eclipse) the umbral magnitude peaked at 1.134 as the Moon lay near the zenith for observers in southern Brazil. At that moment, while its southern limb passed only 8.6 arc-minutes north of the shadow´s axis, its much brighter northern limb was located 25.3 arc-minutes away from the center of the umbra and only 4.5 arc-minutes from its northern edge.

The eclipse began with the first penumbral contact at 01:05 UT. Almost an hour later, the partial eclipse started with the first umbral contact at 02:03 UT. From 03:14.7 UT until 04:06.4 UT the Moon remained totally inside the umbra. The second partial phase ended at 05:17 UT and finally the Moon left the penumbral shadow at 06:15 UT. The Moon's path through Earth's shadows as well as a map illustrating the worldwide visibility of the event is shown in Figure 1[1].

In order to investigate the time-dependent brightness distribution across the umbra, which cannot be predicted accurately, several Brazilian observers carefully monitored the eclipse and submitted electronic reports[2] to the author for reduction as part of a coordinated effort[3] to investigate the major characteristics of the umbra such as its dimensions[4] and illumination.

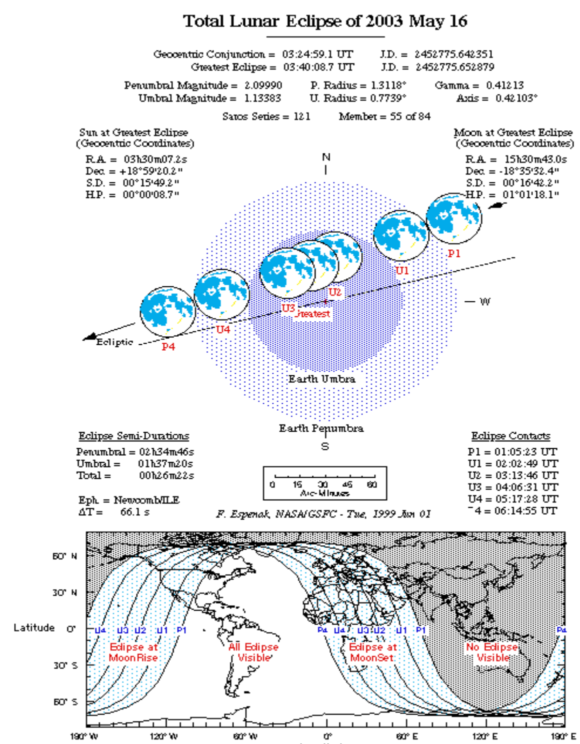


Figure 1: Worldwide eclipse predictions (courtesy of Fred Espenak - NASA/GSFC)

II – OBSERVATIONS

Table 1 lists the 23 observers` names and the types of observational data they have provided. The author wishes to thank and congratulate them all for the high quality of their observations that have made this work possible.

Table 1 – Individual Contributions to Eclipse Brightness Data

Observer	Initials	Observations
Alexandre Amorim	AA	*Mag, L, LD*
Antonio Coelho	AC	*L, LD*
Antonio Padilla Filho	APF	*L*
Antonio Rosa Campos	ARC	*Mag, L, LD*
Carlos Alberto Colesanti	CAC	*L,CCD*
Diego Moicano Gonçalves	DMG	*Mag, ,L, LD*
Edvaldo José Trevisan	EJT	*L, LD*
Fábio Plocos Carvalho	FPC	*Mag,, L, LD*
Frederico Luiz Funari	FLF	*L*
Frederico Paiva Quintão	FPQ	*L*
Giancarlo U. Nappi	GUN	*P, A*
Helio de Carvalho Vital	HCV	*Mag, L, LD*
José Carlos Diniz	JCD	*P, A*
Marilena Mollaco	MM	*L*
N. T. Frota	NTF	*L*
Nelson Falsarella	NF	*L*
Newton Ferreira Funari	NFF	*L*
Paulo Roberto Moser	PRM	*P*
Raquel Yumi Shida	RYS	*P, L*
Rogério Marcon	RM	*E*
Rosely Gregio	RG	*L, LD*
Tasso Augusto Napoleão	TAN	*L, CCD*
Willian Carlos de Souza	WCS	*Mag,L,P,A*

Where: ***Mag*** – Visual Magnitude and ***L*** - Danjon Number Estimates; ***P*** - Photos; ***LD*** – Danjon or Color Distribution; ***E*** – Eclipsed Moon Spectrum and ***A*** – Graphic Animation.

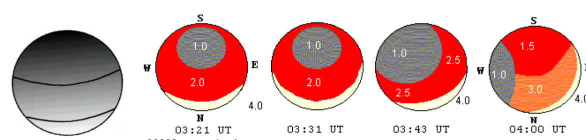
Visual Magnitude and Danjon Number Estimates. Table 2 lists 15 mid-totality Danjon Number estimates and 12 selected magnitude estimates of the Moon.

Table 2 – Danjon Number and Visual Magnitude Estimates

Observer´s Initials	Danjon Numb. (L)	Visual Magnitude at 03h : (mm) UT
AA	3.0	-2.5 (46); -3.0 (60)
AC	1.7	-
APF	2.0	-
ARC	2.7	-1.9 (32)
CAC e TAN	1.7	-
DMG e FPC	2.5	-2.2 (33);-3.9 (62)
EJT	1.6	-
FLF e NFF	2.5	-
FPQ	2.5	-
HCV	2.3	-3.3 (16); -3.0 (21); -2.1 (29); -2.1 (32); -3.3 (56); -3.3 (60)
MM e NF	1.5	-
NTF	3.0	-
RYS	3.0	-
RG	2.7	-
WCS	1.5	-2.1 (38)

**Observers` Experience, Instruments and Methods.** Observers` experience in lunar eclipse monitoring ranged from advanced (mostly) to intermediate. Newtonian reflectors with apertures ranging from 12 to 18 cm and magnifications around 40x were most often used to monitor crater contacts. In addition, visual magnitude and limb contacts were estimated using 7x50 binoculars. The reversed binoculars technique was unanimously adopted to estimate the overall visual magnitude of the totally eclipsed Moon. It consists in using one eye to watch the Moon through inverted binoculars while simultaneously comparing its brightness to that of a reference star of known magnitude observed with the other eye, which is kept unaided. The magnitude of the Moon is then found by accounting for the empirical brightness loss through the reversed binoculars that was consistently found to be equal to 5 magnitudes.

Drawings of Danjon and Color Distributions. Nine observers submitted either drawings or descriptions of the appearance of the Moon during totality detailing brightness and color patterns observed across the lunar disk. The strong asymmetry during totality is clearly seen in Fig. 2a. As expected, the northernmost part of the disk (about 15% of its area) remained brighter than the rest of the disk throughout totality. Its prevailing bright creamy color just after the beginning of the total phase turned into a bluish or greenish hue some minutes later and then to a paler reddish tint near middle eclipse. The sequence then repeated itself backwards as the Moon gradually recovered its normal brightness. Next to it prevailed a reddish region described by most observers that covered about 40% of the disk (center and south). The remaining 45% southernmost part of the disk, being closer to the center of the umbra, exhibited a dark gray appearance. Figure 2b, made by observer AA, depicts his view of the time-dependent Danjon and color distributions as the Moon sampled different parts of the umbra.



(a) **(b)**

Figure 2: (a) Brightness distributions observed by HCV and (b) by AA (courtesy of Costeira1[5]) (south is up)

Pictures of Totality. Figure 3 includes photos[6] made by WCS (3a to 3e) and by JCD (3f) that clearly show the highly asymmetric brightness and color distributions across the totally eclipsed lunar disk. A reddish coloration prevails in picture (3c) taken only a few minutes before middle eclipse contrasting with the bluish hue in (3b), (3d) and (3e) and the distinct copper-like tint in photo (3f).

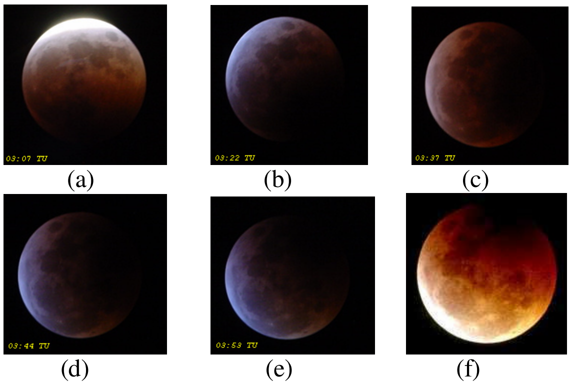


Figure 3: Selected photos of the totally eclipsed Moon (courtesy of WCS and JCD)

**Moon`s Spectra**. Figure 4 compares intensity and absorption line plots of the uneclipsed full Moon`s spectrum with those obtained during the total phase of the eclipse by RM[7]. Easily noticed are the relatively larger dips in the lower spectrum produced by the larger photon absorption in water and oxygen molecules for the case of the eclipsed Moon (orange line). The same effect is also responsible for the darkening of the corresponding spectral lines observed in the spectrum of the eclipsed Moon (bottom).

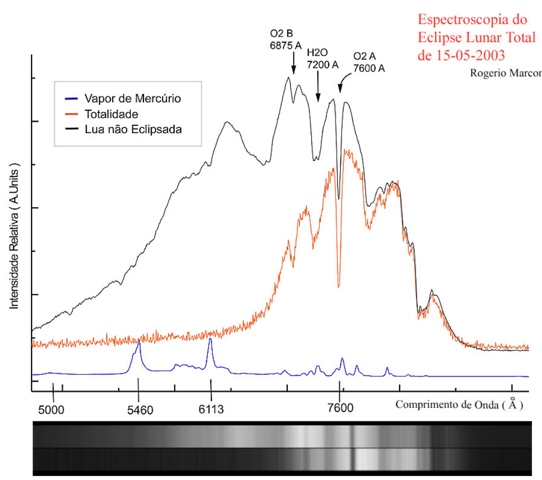


Figure 4: Full Moon`s uneclipsed (black) and eclipsed (orange) intensity and line spectra (courtesy of RM)

III – DATA ANALYSES

Danjon´s Brightness. Most observers found the event "somewhat darker than what they had expected" and some even called it "a dark eclipse". However the magnitude estimates consistently showed that the Moon remained several times brighter than the zero-magnitude star Alpha Centauri throughout totality**.** In order to investigate that apparent inconsistency Danjon estimates can be used. The Danjon Number (**L**) is a coarse indicator of eclipse brightness and ranges from 0 (for an extremely dark event with the Moon almost invisible) to 4 (a bright copper-orange Moon with a very bright bluish umbral rim). Thus in order to determine the brightness of the Moon at mid-totality 15 estimates of **L** ranging from 1.5 to 3.0 were gathered (Table 2) and averaged. The arithmetic average being $\mathbf{L}_1$ = 2.3 (with a ± 0.6 sample standard deviation) indicates an eclipse of intermediate brightness. A second way to calculate a mean value for **L** is to assign different Danjon Numbers to each of the three distinct areas illustrated in Fig. 2a accounting for the fraction of the disk it covers. Reasonable estimates (and corresponding fractions) are: 3.7 (0.15), 2.7 (0.40) and 1.5 (0.45). As a result, the corresponding average for **L** weighed over the area fractions also yields: $\mathbf{L}_2$ = 2.3. In addition a third way to calculate an average for **L** is to convert individual Danjon estimates (**L**) into magnitudes (**m**) by using a correlation determined from 23 past eclipses given in Eq. 1 (the standard sample error is ± 0.3). It yields results in good agreement with those from a similar correlation found by Westfall[8]:

$$\mathbf{m = 4.2 - 3\,L + (\,L/2\,)^2} \qquad \textbf{(Eq.1)}$$

The resulting magnitudes should then be added up in the form of light intensity ratios. The sum allows an average value for **m** to be calculated and then converted back into an average Danjon Number by applying the same correlation. The result is $\mathbf{L_3}$ = 2.5. Finally, an even more sophisticated way is to combine the second and third methods. The resulting sum of the converted magnitudes weighed over the corresponding area fractions should give $\mathbf{L}_4$ = 2.1. Therefore, regardless of the averaging method, the mean Danjon Number for the event has been found to lie between 2.1 and 2.5, thus most likely **L = 2.3 ± 0.2**, indicating an eclipse of intermediate brightness.

**Moon`s Total Visual Magnitude.** Figure 5 shows how the Moon`s estimated visual magnitude varied during totality.

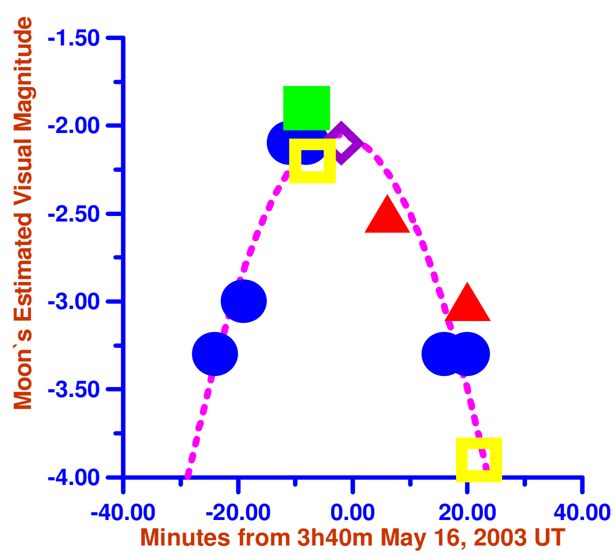


Figure 5: Visual magnitude estimates of the Moon

Different colored symbols have been used to represent data from 5 different observers. The dashed curve, described by Eq. 2 as a second-degree equation, closely fits the magnitude estimates (r^2=0.85) and the x-axis scale represents the time interval (ΔT) in minutes from the instant of middle eclipse (such that ΔT= t – 3h40m UT). The fitted curve has been determined by using the least-squares method and exhibits a slight asymmetric behavior around a minimum brightness at magnitude **-2.1 ± 0.2** reached about 2 minutes prior to the instant of mid-totality. Owing to the asymmetry, Eq. 2 predicts magnitudes -3.5 and -4.1 for the beginning and the end of totality, respectively.

$$\mathbf{m = -2.10 - 0.0113\,\Delta T - 0.00251\,\Delta T^2} \quad \textbf{(Eq.2)}$$

Equation 1 predicts **L**= 2.7 ± 0.3 for **m** = -2.1 ± 0.2 which is 4 tenths higher than the mean **L** from all estimates 2.3 ± 0.2 although both figures agree when experimental errors are accounted for. A possible explanation for that small discrepancy could be the fact that most observers were strongly influenced by the dark appearance of the central and southern parts of the lunar disk and failed to realize that its relatively small northernmost region remained very bright throughout totality. As a result, the observers had the impression that the eclipse was somewhat darker than it actually was and consequently assigned it a slightly underestimated Danjon Number. In addition to the severe asymmetry in illumination other possible factors that could have darkened the inner umbra and caused observers to judge the eclipse as "dark" are: the very high value of the lunar parallax (capable of reducing the magnitude of the Moon by a few tenths[9]) and the existence of an above-average number of extensive cirrus and stratus cloud formations or tropospheric aerosol concentrations along the limb of the Earth.

Brightness Distribution and Density of the Umbra. In order to investigate the brightness distribution across the umbra the photos shown in Fig. 3 were analyzed using an image processing software. The pictures were first converted into an 8-bit grayscale such that an extremely bright (white) picture element (pixel) was assigned a brightness (gray) value equal to 256 and a completely dark (black) pixel to 0. Then they were scanned to determine gray values along the line joining the edge of the umbra and its center by passing though the center of the lunar disk. The radial traverse yielded point-wise digitized brightness values that were then converted into magnitude differences relatively to that on the edge of the umbra. The magnitudes plotted in Fig. 6 as a function of increasing penetration into the umbra (from edge towards its center) and crossing the center of the Moon clearly exhibit an approximately linear trend. At the start of totality the Moon had lost about 9 magnitudes. That figure corresponds to a 4,000 times fading relatively to the full uneclipsed Moon. The additional brightness loss during totality reached 1.6 magnitudes rendering it a maximum 10.6 magnitude loss, equivalent to an overall $17\text{x}10^3$ times fading. Also the density[9] of the umbra (**D**), given by Eq.3, becomes:

$$\mathbf{D = \log_{10}(17{,}000) = 4.2} \qquad \textbf{(Eq.3)}$$

Those findings are in good agreement with Karkoschka`s predictions[10] using his most realistic simulation which accounts for the combined effects of both high tropospheric stratus and cirrus clouds. Other simulations based on his model, considering either a cloud-free atmosphere or cirrus clouds only, yield smaller total magnitude losses as well as curves that are roughly flat across the inner umbra. Many observers reported that most of the limb and several major lunar formations remained visible throughout totality supporting the previous conclusion that the optical density of the umbra was not significantly higher than predicted.

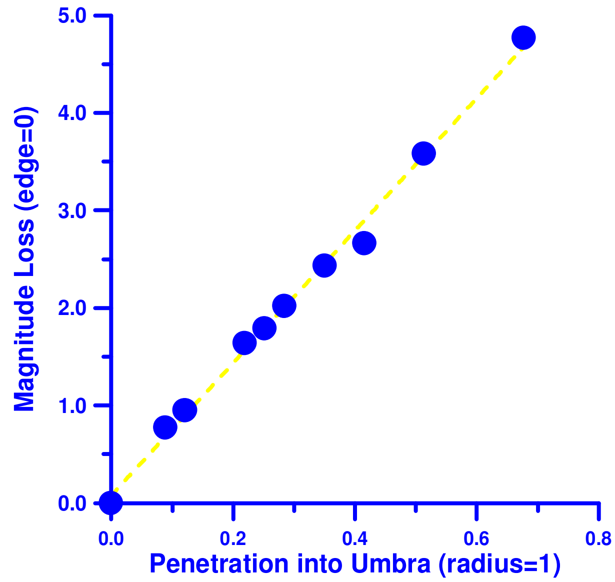


Figure 6: Magnitude loss with penetration into the umbra

Refraction Ring. The observed illumination patterns displayed by the Moon during totality can be better understood by recalling a simplified description of the event as it would have been seen from the Moon. As the Sun gradually disappeared behind the disk of the Earth its image had already become severely distorted due to the strong refraction by the atmosphere of the Earth. Two other competing mechanisms should also have been in action: (1) selective molecular scattering in the lower atmosphere (stronger towards shorter wavelengths according to Rayleigh`s λ^{-4} extinction law) and (2) stratospheric ozone absorption of red light. Since blue light is more strongly scattered out of the light path by air molecules and aerosols, the first mechanism caused most of the Sun´s disk (compressed by intense refraction into a segment of arc) to look dark red and was probably responsible for the reddish color observed during most of the total phase. In contrast, the second mechanism caused a very small part of the residual solar image to appear as a very bright bluish projection on top of the arc`s center. Thus it was responsible for the predominantly light blue coloration observed for a few minutes after the second contact and just before the third one. The average brightness of the Sun`s image at mid-totality may be estimated by recalling that the full Moon shines at magnitude -12.7 while being illuminated by the uneclipsed Sun (m=-26.7). Thus assuming the same 14-magnitude drop in brightness, it may be concluded that at middle eclipse a hypothetical observer on the surface of the eclipsed Moon would see the Sun`s residual image shine at an average magnitude equal to that of the Moon (estimated as -2) added to -14 which gives -16. If that same observer traveled from a region near the edge of the umbra towards south he would see the initially very bright blue part of the distorted Sun`s disk gradually flatten, change color and finally merge with the segment of arc just below it. As a result the overwhelming blue figure ($m \approx$ -17) seen at the Moon`s northernmost region would have turned into a dimmer ($m \approx$ -15) copper-like or bright red segment of arc. He would then be crossing the central regions of the Moon`s disk. Proceeding on his journey he would see the residual image of the Sun as a gradually thinner and darker ($m \approx$ -13) red segment of arc stretching along the Moon`s limb. He would then be crossing the darkest southernmost region of the totally eclipsed Moon.

Possible Effects from Volcanic Aerosols. The Moon shines during totality because it is illuminated by sunlight attenuated and refracted by Earth`s atmosphere (primarily by the stratosphere) into the umbra. In addition, stratospheric aerosols (mostly from strong volcanic eruptions) play an important role in scattering sunlight and reducing its transmission into the umbra, for the effective path length of sunlight grazing through an stratospheric layer is known to be about 40 times the vertical thickness of the layer.[11-13] Thus the brightness of the eclipsed Moon is extremely sensitive to the amount of aerosols present in the stratosphere and can be used as an indicator of the hemispherical average optical depth of stratospheric aerosols of volcanic origin. Therefore, the aerosol optical thickness can be calculated for the date of an eclipse from the difference between the observed brightness of the eclipse and the expected one. The expected brightness can be computed in two ways: the first is based on data generated according to theoretical models computed for an aerosol-free (clean) standard atmosphere modified by assumed distributions of ozone and cloud; the second uses an empirical correlation between eclipse magnitude and eclipse brightness data obtained from past eclipses known not to have been significantly affected by aerosols. In this work the second method has been employed. Data for 24 eclipses from 1956 until 2001 have been used to get a correlation between eclipse magnitude ($\mathbf{U_{mag}}$) and eclipse brightness ($\mathbf{m}$) at middle eclipse. The events found to be definitely linked to major volcano explosions were then left out of the input data used to obtain a second similar correlation for aerosol-free events only. The resulting positive correlation (r^2=0.88) is expressed in Eq. 4 as:

$$\mathbf{m = -7.34 + 4.29\, U_{mag}} \qquad \textbf{(Eq.4)}$$

Substituting for $\mathbf{U_{mag}}$ (= 1.134) in Eq. 4 gives the predicted magnitude for the eclipse being studied: -2.5. Also, since the estimated magnitude was -2.1, the observed difference in magnitude is: $\mathbf{\Delta m = +0.4}$ and the corresponding average aerosol optical depth ($\boldsymbol{\tau}$) at the time of the eclipse is given by $\boldsymbol{\tau = \Delta m/40 = 0.010}$. Such small value for $\boldsymbol{\tau}$ coincides with the average error associated to Eq. 4 and is thus insufficient to allow conclusions to be drawn with confidence. However, the chance that it could have originated from the eruption[14] of Mount Reventador in Ecuador 6 months prior to the eclipse cannot be discarded either. Just for the sake of illustration: data from REA analyzed by using the same method provide the following aerosol optical depths: τ = +0.122 for the Dec. 09, 1992 and τ = +0.024 for the Nov. 29, 1993 total lunar eclipses which happened 18 and 29 months, respectively, after the explosive eruption of Mount Pinatubo in June 1991.

Attenuated and Reddened Eclipse Spectrum. The strong differences clearly illustrated in Fig. 4 between the uneclipsed and eclipsed lunar spectra result from the different paths traveled by sunlight through Earth`s atmosphere before reaching the observer. In the first case sunlight reflected by the Moon penetrated our atmosphere only once and almost vertically before reaching the detection system and producing the spectrum in black. In the second case however, sunlight first grazed Earth`s atmosphere tracing a very lengthy optical path tens of times longer than its effective vertical thickness. It was then reflected back by the Moon and reached the counting system after crossing our atmosphere a second time to produce the severely attenuated and reddened spectrum depicted in orange. The reddening occurs because air molecules and aerosols cause blue light photons to be scattered out of the main beam of light more efficiently than for the red ones.

IV – CONCLUSIONS

Observational data obtained during the May 15-16, 2003 lunar eclipse by Brazilian observers have been analyzed to provide a dynamical picture of the Moon`s illumination during totality. The reductions have consistently indicated that contrasting with the opinion of many observers, the eclipse was not dark. They have also provided curves describing how brightness parameters such as the Moon`s magntude and the Danjon Number varied with time. At mideclipse, the Moon`s total magnitude was estimated as -2.1 $\pm$ 0.2, corresponding to a decrease in brightness by a factor of 17 thousand times. Also the average Danjon Number was 2.3 $\pm$ 0.2 which indicates an event of intermediate brightness. The severe contrast in illumination between the northernmost (very bright) and the southern (dark) parts of the lunar disk together with the very high value of the Moon`s parallax and the high density of stratus and cirrus clouds along Earth`s limb may have contributed to make the eclipse look darker than it really was. Finally, the influence of stratospheric volcanic aerosols on the brightness of the Moon cannot be ascertained due to the small value found for the average aerosol optical depth (0.01 ± 0.01). However there is also some chance that the eruption of Mount Reventador 6 months prior to the eclipse could have produced the small aerosol concentration found provided it did not simply result from uncertainties in the data.

V – REFERENCES

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