THE ATMOSPHERIC EXTINCTION AT THE COMPLEJO ASTRONÓMICO EL LEONCITO AND THE BOSQUE ALEGRE STATION

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Abstract. The first- and second-order extinction coefficients in the *UBVRI* and DDO systems are derived for the first time at CASLEO. They define an extinction curve which is discussed in the framework of atmospheric absorption theory. From this curve the first-order extinction coefficients for the Washington and Strömgren systems are inferred. From a photometric point of view, CASLEO occupies a preferred place among the observatories of the world. A comparison of the *UBV* extinction coefficients obtained at Bosque Alegre with previous determinations supports the conclusion that the sky transparency at this station has deteriorated in the ultraviolet in the last years.

1. Introduction

Even on the clearest nights, the stars are dimmed significantly by absorption and scattering of their light by the Earth's atmosphere. The amount of light lost depends on the star's altitude, the wavelength of observation, and the current atmospheric conditions. The phenomenon known as 'atmospheric extinction' is essentially due to three processes: (1) scattering by molecules, (2) molecular absorption, and (3) scattering due to dust and atmospheric aerosols (atmospheric obscuration).

Experience has shown that the scattering by molecules obeys Rayleigh's law – i.e., it is proportional to λ^{-4} and depends on the air pressure and, therefore, on the altitude of the observatory. This effect produces an apparent selective absorption of the radiation, which is noticeable in the ultraviolet region and practically negligible in the red. In fact, if we observe a star at the zenith from the sea level, the fraction of radiation lost by molecular scattering does not reach 1.0% for wavelengths of about 10 000 Å.

On the contrary, the selective absorption that some molecules produce on the radiation is a real absorption, in the sense that the disappeared irradiated energy is used to disassociate molecules, to ionize them, or other physical phenomena. In the visible region as well as in the near-infrared, there are weak absorbing bands of water and molecule oxygen. However, ozone is the molecule absorbing most of the energy between 2200 and 3100 Å. This molecule is concentrated in the stratosphere between 10 and 35 km, although it exists very weakly near the Earth's surface.

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Atmospheric obscuration or aerosol scattering is due to the presence of solid particles and liquid droplets of any size in suspension which scatter radiation in a non-selective way. Normally, these particles are relatively large compared with the wavelength of visual radiation. In some cases, however, when the particles are of size comparable to the wavelength, atmospheric obscuration follows a rather complicated law which cannot be described by a simple theory.

To reduce the photometric observations it is fundamental to know the behaviour of the atmospheric extinction in the observing site. The accuracy of the photometric data depends on the accuracy of our knowledge of the extinction coefficients of a given system.

As a first step toward the study of the atmospheric absorption at observatories in Argentina, the extinction coefficients at the Complejo Astronómico El Leoncito, CASLEO (San Juan, Argentina), are determined for the first time. The spectral region selected for carrying out the measurements corresponds to the following effective wavelengths of the *UBVRI* and DDO photometric systems: λ3500, 4166, 4257, 4400, 4517, 4886, 5500, 6466, and 8290 Å. Also, after a period of more than 15 years, the *UBV* extinction coefficients are redetermined for Bosque Alegre Observatory, BAO (Córdoba, Argentina). The results obtained at CASLEO are discussed and compared with those of various observatories of the world. The observations are also analyzed on the basis of the atmospheric absorption theory.

2. Observations

The measurements at CASLEO were done with the 2.15 m telescope and the photopolarimeter VATPOL (Magalhães *et al.*, 1984), used as a photoelectric photometer. The VATPOL has two Ga–As RCA 31034 phototubes refrigerated with dry ice. The observations were carried out during a total of four nights in September and October 1987. Generally, the nights were of good quality with a typical seeing of about 2″. Most of the observations were made by use of a circular diaphragm of 8″ aperture.

Several procedures of determining the extinction coefficients are available, such as the Bouguer method (Clariá, 1974), the $\Delta\Delta$-method described by Gutierrez-Moreno *et al.* (1966), the Nikonov method (Nikonov, 1976), the Hardy–Jerzykiewicz method (Jerzykiewicz, 1966) and others. Given its simplicity and well-known efficiency, we decided to use the Bouguer method in the usual form. The use of this procedure is justified when constant atmospheric transparency during the night, absence of azimuthal effects, and constant instrumental sensitivity (Neizvestnyi, 1963) are assumed.

To carry out the measurements, groups of three stars each easily observable at CASLEO were selected. Each group included an early, an intermediate, and a late-type star. They were selected in such a way that their right ascensions differ by about 5 hours and their declinations are nearly similar to the CASLEO latitude. To define correctly the Bouguer lines, the largest possible number of measurements were done at air masses from 1.0 to 2.5. Whenever possible, groups of stars located east and west of the meridian were measured to examine possible systematic differences.

In order to determine the extinction coefficients in the UBVRI system, stars taken from the list of Graham (1982) were selected, whereas for the DDO system the lists published by McClure (1976) and Dean (1981) were used.

To determine the DDO extinction coefficients pairs of stars instead of triplets were observed since the second-order coefficients are negligible in this system (Golay, 1974).

The measurements at BAO were performed with the 1.54-m telescope equipped with a photoelectric photometer of conventional design. A 1P21 photomultiplier refrigerated with dry ice and *UBV* standard filters were used.

The observations were carried out during two moonless nights of different quality in June 1987. In every case, the extinction stars, selected from the lists of Cousins (1973, 1974), were measured between air masses from 1.0 to about 2.5. The same as at CASLEO, the Bouguer method was also employed in this case, since the accuracy that can be obtained with it is enough for our aims.

3. Results

3.1. CASLEO

Tables I and II show the *UBVRI* and DDO extinction coefficients in mag/airmass determined at CASLEO for each of the observing nights. The number N in each table indicates the number of observations of each star.

Bouguer's straight lines are in general well-defined by an appreciable number of points (10 to 14), except for the night of 27 September of 1987 which includes only 5 points. All the coefficients were always determined using the least-squares method. Only a few measurements carried out in hour angles larger than 5 hours had to be rejected.

The extinction coefficients shown in Tables I and II were weighted taking into account

TABLE I

UBVRI extinction coefficients measured at CASLEO

Date	N	Mag/colour	First order	Second order
27 Sept., 1987	5	$U-B$	0.165	–
	5	$B-V$	0.102	–
	5	V	0.184	0.00
1 Oct., 1987	12	$U-B$	0.198	−0.01
	12	$B-V$	0.090	−0.03
	12	V	0.150	0.00
4 Oct., 1987	14	$U-B$	0.212	0.00
	14	$B-V$	0.114	−0.02
	14	V	0.160	0.00
5 Oct., 1987	12	$U-B$	0.203	0.01
	12	$B-V$	0.132	−0.05
	12	$V-R$	0.045	0.00
	12	$R-I$	0.036	0.00
	12	V	0.164	0.00

TABLE II

DDO extinction coefficients measured at CASLEO

Date	*N*	Mag/colour	First order
27 Sept., 1987	5	48	0.223
	5	41–42	0.036
	5	42–45	0.043
	5	45–48	0.018
1 Oct., 1987	10	48	0.187
	10	41–42	0.025
	10	42–45	0.042
	10	45–48	0.059
4 Oct., 1987	14	48	0.182
	14	41–42	0.025
	14	42–45	0.092
	14	45–48	0.038

the quality of the different nights. The values finally adopted for the CASLEO, together with their estimated errors, are given in Table III. These prelminary coefficients were published by Clariá *et al.* (1987).

TABLE III

UBVRI and DDO extinction coefficients adopted for CASLEO

System	Mag/colour	First order	Second order
UBVRI	$U - B$	0.20 ± 0.02	0.01 ± 0.01
	$B - V$	0.11 ± 0.01	-0.02 ± 0.01
	$V - R$	0.05	0.00
	$R - I$	0.04	0.00
	V	0.165 ± 0.011	0.00 ± 0.01
DDO	41–42	0.02 ± 0.01	
	42–45	0.05 ± 0.02	
	45–48	0.04 ± 0.01	
	48	0.21 ± 0.01	

3.2. Bosque Alegre

The *UBV* extinction coefficients obtained during two nights at BAO are shown in Table IV. The first night was of excellent quality whereas the second one, although completely clear, showed a remarkably inferior quality. The Bouguer lines obtained during both nights came out very well defined between air masses from 1.0 to about 2.5.

As can be seen in Table IV the visual extinction of the second night (20 June) is higher than that of the first night (19 June), as expected. It was not possible to obtain trustworthy values for the $(U - B)$ coefficients during the second night. For comparison, the last column of Table IV lists the values measured by Milone (1973) about 15 years before.

TABLE IV

UBV extinction coefficients measured at Bosque Alegre Observatory.

Date Coeff.	19 June, 1987 Group 1	19 June, 1987 Group s	19 June, 1987 Group 3	19 June, 1987 Group 4	Previous value (Milone, 1973)
Kv	0.12	0.15	0.17	0.19	0.20
Kv	0.00	- 0.02	0.07	0.00	0.00
Kbv	0.14	0.12	0.14	0.12	0.11
Kbv	- 0.04	- 0.03	0.01	- 0.05	- 0.03
Kub	0.31	0.34	0.35	–	0.27
Kub	0.00	- 0.02	- 0.02	–	0.02

The mean values obtained at BAO in the present study are:

$$K_{V_1} = 0.16 \pm 0.03\,, \qquad K_{V_2} = 0.01 \pm 0.04\,,$$

$$K_{BV_1} = 0.13 \pm 0.01\,, \qquad K_{BV_2} = -0.03 \pm 0.03\,,$$

$$K_{UB_1} = 0.33 \pm 0.02\,, \qquad K_{UB_2} = -0.01 \pm 0.01\,.$$

4. Analysis and Discussion of the Results

4.1. CASLEO

The first-order extinction coefficients determined at CASLEO for the *UBVRI* and DDO systems give rise to a well-defined extinction curve represented by dark circles in Figure 1. The results obtained at CASLEO for both systems are absolutely consistent.

For comparison, extinction curves obtained at La Silla Observatory and BAO are also shown in Figure 1. The first of these curves has been obtained by Tüg (1977) using a photoelectric rapid spectrum scanner. The extinction coefficients were calculated in steps of 50 Å using the Bouguer method, hence, the continuous shape of the curve. This extinction curve can be considered as representative of the typical observing conditions at the observatories located in the north of Chile. On the other hand, the light circles in Figure 1 represent the values obtained at BAO by Milone (1973) and Clariá *et al.* (1987). These last authors have determined mean extinction values at BAO in 1986 for the spectral region ranging from 3650 to 5140 Å. The measurements were carried out using the narrow-band filters of the International Halley Watch.

It is quite clear that the atmospheric extinction at CASLEO is somewhat higher than that of the Chilean observatories. It is also evident that the sky transparency at CASLEO, at least in the region between 3500 and 4500 Å, is considerably larger than at BAO. In particular, in the ultraviolet region, the observing conditions at CASLEO do not seem different from those of the northern Chile.

The well-defined extinction curve obtained at CASLEO allows us to derived the first-order coefficients for other photometric systems. For the Strömgren and

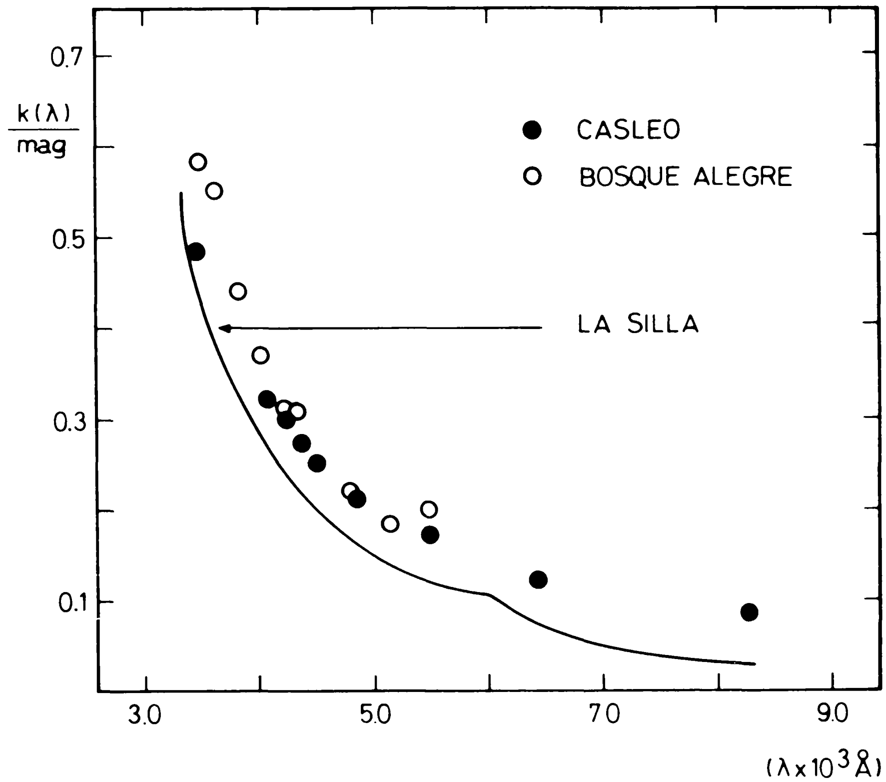

Fig. 1. Extinction curve obtained at CASLEO (dark circles) from photometric measurements carried out in 9 spectral bands between 3500 and 8300 Å. For comparison, the extinction curves of La Silla and Bosque Alegre Observatories are also shown.

Washington systems, for example, we can establish quite reliably the following values:

$$K_u = 0.48\,,\quad K_v = 0.32\,,\quad K_b = 0.23\,,\quad K_y = 0.17\,,$$
$$K_{by} = 0.06\,,\quad K_{c_1} = 0.07\,,\quad K_{m_1} = 0.02\,,$$
$$K_C = 0.40\,,\quad K_{M_1} = 0.19\,,\quad K_{T_1} = 0.13\,,\quad K_{T_2} = 0.09\,,$$
$$K_{CM} = 0.21\,,\quad K_{MT_1} = 0.06\,,\quad K_{T_1T_2} = 0.04\,,$$

According to Papoušek and Vetešník (1984), the total atmospheric extinction during a clear night can be described in a good approximation by the formula

$$K(\lambda) = K_R(\lambda)P/P_0 + K_0(\lambda)X/X_0 + K_P(\lambda)Y/Y_0\,,$$

where $K_R(\lambda)$ is the Rayleigh-scattering extinction coefficient for the standard atmosphere with standard atmosphere pressure P_0; $K_0(\lambda)$ is the extinction coefficient for the standard ozone content X_0, and $K_P(\lambda)$ is the extinction corresponding to the absorption by airborne atmospheric particles at standard content Y_0.

Figure 2 shows schematically the contribution of the three components (Allen, 1973). The amount of Rayleigh scattering depends on the atmospheric pressure – i.e., on the height above the sea-level. On the contrary, the ozone absorption is independent of height but usually has seasonal variations. The third scattering term is usually expressed

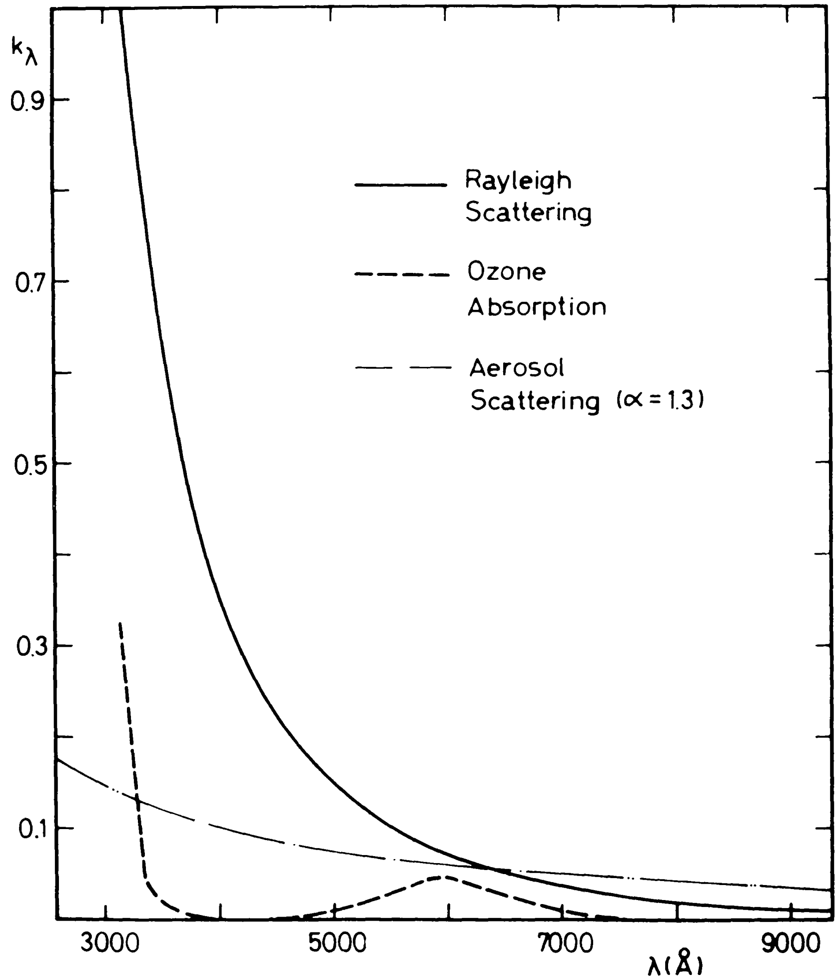

Fig. 2. Contribution to the atmospheric extinction of the Rayleigh scattering, absorption by the ozone layer, and aerosol scattering ($\alpha = 1.3$).

in the exponential form $K_P(\lambda) = K_1(\lambda)\lambda^{-\alpha}$, where $K_1(\lambda)$ characterizes the extinction at $\lambda = 1$ μm and α depends on the physical properties of the dust and aerosol particles contaminating the atmosphere. It is well known that the sizes of aerosol particles vary strongly with time and place (Hayes and Latham, 1975). The effect is reflected in the variations of the exponent α that can acquire values between zero (nonselective scattering) and 4 (molecular scattering). In Figure 2 the contribution corresponding to scattering by aerosols with $\alpha = 1.3$ (Allen, 1973) is shown.

The ozone absorption affects the measurements only in the *V*-band of the *UBVRI* system. Therefore, due to ozone absorption, the first-order extinction coefficient in the *V*-band should be slightly larger than that due to pure scattering Rayleigh. This effect, clearly evident in the extinction curve of the La Silla Observatory, is hardly perceptible in the values measured at CASLEO. In fact, the point corresponding to $\lambda = 5500$ Å in Figure 1 lies slightly above (~ 0.01–0.02 mag) the curve that best represents the measurements made at CASLEO.

With the observations on hand, nothing can be said with respect to the physical properties of the contaminating aerosols at CASLEO. With a larger number of observations carried out systematically in a larger number of spectral bands, the exponent α could be determined and, therefore, some type of physical information could be obtained about these particles, such as their type and size.

It is possible to establish a comparison between the *UBV* extinction coefficients of the CASLEO and those of other 18 observatories with comparable heights. Using part of the data compiled by Neizvestnyi (1983), the diagrams of Figure 3 were drawn. They show how the first-order extinction coefficients K_V, K_B, and K_U are distributed. The observatories of La Silla, Cerro Tololo, Las Campanas, and CASLEO, are represented with the letters *S*, *T*, *L*, and *C*, respectively.

A quick analysis of these data shows that the sky at CASLEO occupies a preferred place among the observatories of the world. In fact, in the sample in question, CASLEO is only surpassed in sky quality by the North Chilean observatories. The ultraviolet extinction at CASLEO is really low, whereas the blue and visual extinction appears to be acceptable.

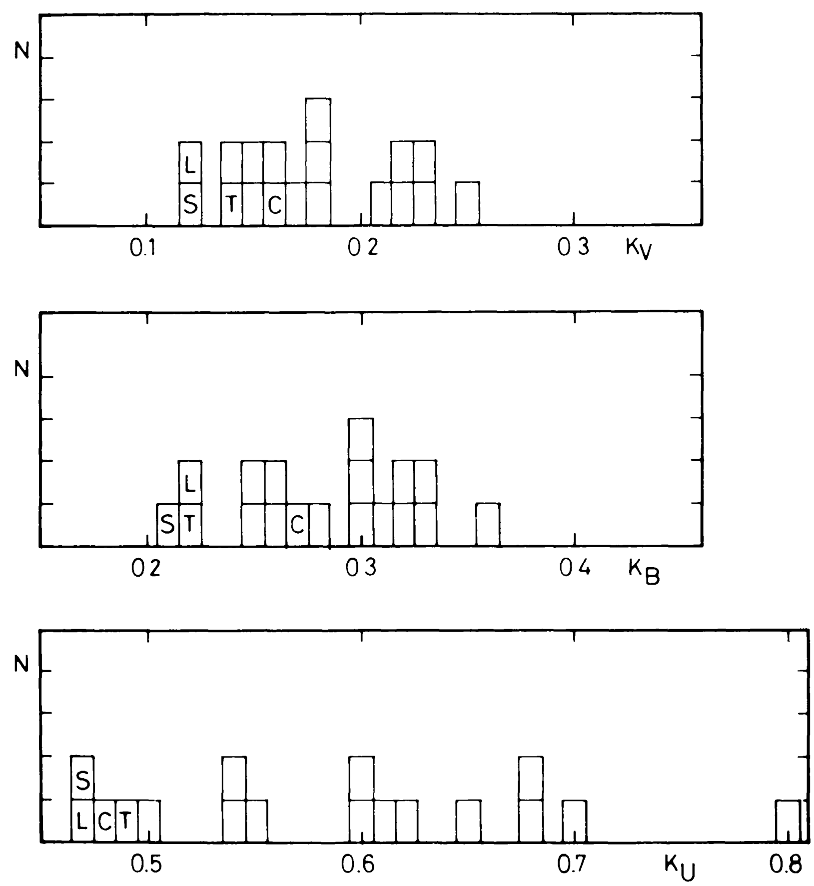

Fig. 3. Distribution of the first-order extinction coefficients K_V, K_B, and K_U for 18 observatories located at heights larger or equal to 1500 m above the sea level. The observatories of La Silla, Cerro Tololo, Las Campanas, and CASLEO are represented by letters *S*, *T*, *L*, and *C*, respectively.

4.2. Bosque Alegre

If we compare the extinction coefficients measured at BAO with those obtained by Milone (1973) 15 years ago, we note: (1) The extinction in the visual region is significantly lower during the nights of June 1987 than in 1973, which may be due to the exceptional character of one of the nights in 1987. (2) This relation is inverted if we consider the $(U - B)$ colour index. (3) In the $(B - V)$ index the agreement is acceptable.

Given that the $(U - B)$ extinction measured in 1987 comes exclusively from a night of exceptional quality, the values given in Table IV seem to indicate a slight deterioration of the sky transparency at BAO for the ultraviolet radiation. This deterioration of the observing conditions at BAO are probably due to contamination by aerosols of nearby factories situated at Malagueño as well as in the cities of Córdoba, Alta Gracia, and Carlos Paz. In any case, it would also be advisable to make a systematic study of the atmospheric extinction in this observatory.

5. Conclusions

The analysis of the extinction measurements carried out at CASLEO and BAO lead to the following conclusions:

(1) From the photometric point of view, CASLEO occupies a preferred place among the observatories of the world. The atmospheric extinction coefficients determined in this study (see Table III) are slightly higher than those of the observatories in the north of Chile. In the ultraviolet, however, the obtained values appear to be comparable.

(2) The errors involved in the determination of the first-order extinction coefficients are comparatively small, which shows that there are no appreciable variations in the amount of pollution of terrestrial origin. The altitude of CASLEO and its great distance from large urban centers can partially explain this result.

(3) The amount of data gathered at CASLEO does not enable us to do a detailed analysis of the influence of the different components which contribute to the atmospheric absorption, although it is possible to draw some preliminary conclusions. For instance, the influence of the ozone layer at the time of observation was rather weak, since the first-order extinction coefficient in the visual exceeds by scarcely 0.01–0.02 mag the extinction curve due to Rayleigh scattering.

(4) The extinction coefficients determined for the CASLEO are considered preliminary. Only a detailed and systematic study – involving a larger number of observations and spectral bands – of the behaviour of the atmospheric absorption at CASLEO will allow us obtain definitive results. Such study should include the analysis of possible seasonal, azimuthal, and night to night variations, using methods more refined than Bouguer's.

(5) The *UBV* extinction coefficients determined at BAO after 15 year's lapse seem to indicate a slight decrease in the sky transparency for the ultraviolet radiation.

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