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Sky transparency over Naini Tal : A retrospective study

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Abstract. We present an analysis of the atmospheric extinction coefficients measured during 1964 to 1999 in broad-band photometric passbands at U.P. State Observatory, Naini Tal. The extinction properties are also studied from the monochromatic extinction measurements carried out during 1970 to 1978. It is observed that except the yearly variation, no noticeable long term variation in extinction has been found over last 35 years. The extinctions in the ultraviolet region were found low at Naini Tal in comparison to other sites in the world. The extinctions due to aerosols are observed to be the minimum.

Key Words : atmospheric extinction, observatory site, aerosols

1. Introduction

For ground based photometric study of a celestial source, especially in the optical window of the electromagnetic spectrum, loss of light due to the Earth's atmosphere has to be accounted. The Earth's atmospheric extinction occurs mainly due to the scattering by air molecules and aerosols, and the absorption by ozone and water vapour. The mean physical state of these air constituents are modelled accurately enough by studying the global meteorological properties of the atmosphere (Allen 1976). The atmospheric aerosols above an observatory site are the most sensitive contributors of the commonly observed variation in the atmospheric extinction behaviour over the years at a site. In literature the behaviour of extinction properties in general and of the aerosols in particular have been studied at several observatory sites across the globe. For example, Gutiérrez-Moreno (1982) studied the extinction behaviour at Cerro Tololo Inter-American Observatory (CTIO), Chile and Rufener (1986) and Burki (1996) characterised the extinction properties at La Silla, Chile in view of the volcanic eruptions. Such studies help in knowing the behaviour and evolution of air constituents near the observatory site in particular and around the globe in general.

At U.P. State Observatory (UPSO), Naini Tal (latitude = 29°22′ N, longitude = 79°27′ E, altitude = 1951 m above mean sea level), the photoelectric photometric observational programmes using Johnson U, B and V passbands were continuously carried out since November 1964

(Srivastava 1983, Srivastava 1976). The monochromatic scanner observations were also made to study the absolute energy distribution of stars for few years in early seventies (Rautela 1981). The CCD photometric measurements in Johnson U, B, V and Cousins R, I passbands have begun since 1990 (Mohan et al. 1991). As a part of these observational programmes atmospheric extinction coefficients are determined. These measurements provide the desired set of data to study the temporal behaviour of atmospheric extinction as well as the aerosol extinction law at the UPSO, Naini Tal. The results are compared with the measurements carried out at Devasthal (latitude = $29^{0}22'$ N, longitude = $79^{0}41'$ E, altitude = 2450 m above mean sea level), which is located towards east from the present UPSO site at an aerial distance of around 20 km. Extensive site characterisation programmes were carried out during 1997-1999 at the Devasthal site (Mohan et al. 1999, Pant et al. 1999, Sagar et al. 2000a, b), where a 3-meter class modern optical telescope is planned to be set up jointly by the UPSO and the Tata Institute of Fundamental Research, Mumbai.

2. Extinction from model atmospheres

The observed flux, E (λ, z), of a star at zenith distance, z, suffers extinction due to the earth atmosphere. It's relation to the flux, E(λ), above the atmosphere is expressed as follows.

$$E\ (\lambda,\ z) = E(\lambda)e^{-k_{\lambda}M(z)} \tag{1}$$

where k_{λ} is the extinction coefficient at wavelength λ and $M(z)$ is the airmass at zenith distance, z. The extinction coefficient for the spectral region, 0.3μm to 1.0μm, can be estimated theoretically by assuming model atmospheres (Hayes & Latham 1975, Bessell 1990). The atmospheric extinction results either due to scattering by air molecules and aerosols or due to the molecular absorption by ozone and water vapour. Scattering alone is responsible for about seventy to ninety percent of the total extinction while the selective extinction by absorption in molecular bands contributes to the remaining. The components of the extinction are :

(i) The Rayleigh scattering by air molecules contributes from about 50% in the infrared regions to about 80% in the near ultraviolet regions. The extinction estimation due to the Rayleigh scattering at a wavelength λ in microns and at an altitude, h (km), is given by the following formula (Hayes & Latham 1975).

$$k_{Ray}(\lambda,\ h) = 0.0095B^{2}e^{-h\ /\ 7.996}\lambda^{-4} \tag{2}$$

where

$$B = 0.23465 + 107.6/(146-\lambda^{-2}) + 0.93161/(41-\lambda^{-2})$$

which is valid only for normal atmospheric pressure and temperature.

(ii) The scattering due to the aerosols is highly variable and contributes from about 0% to 30% of the total extinction. The following power law determines its approximate contribution (Hayes & Latham 1975).

$$k_{aer}(\lambda,\ h) = Ae^{-h/H}\lambda^{-\alpha} \tag{3}$$

where the parameters A, α, and H vary greatly and depend on the content, size and scale height of aerosols respectively.

Table 1. The theoretical atmospheric extinction at Nainital.

λ (Å)	k_{Ray}	k_{oz}	k_{aer}	k_{sum}	$k_{Ray} + k_{oz}$
3390	0.618	0.027	0.056	0.701	0.645
3448	0.575	0.013	0.056	0.643	0.588
3509	0.534	0.006	0.055	0.597	0.540
3636	0.460	0.001	0.053	0.515	0.461
3704	0.426	0.000	0.052	0.479	0.426
4036	0.298	0.000	0.049	0.347	0.298
4167	0.261	0.000	0.048	0.300	0.261
4255	0.239	0.000	0.047	0.287	0.240
4464	0.196	0.001	0.045	0.242	0.197
4566	0.179	0.001	0.044	0.225	0.180
4785	0.148	0.004	0.043	0.194	0.151
5000	0.123	0.008	0.041	0.173	0.132
5263	0.100	0.018	0.040	0.157	0.118
5556	0.080	0.031	0.038	0.149	0.111
5840	0.065	0.038	0.036	0.140	0.103
6055	0.056	0.037	0.035	0.128	0.093
6435	0.044	0.022	0.034	0.100	0.066
6790	0.035	0.009	0.032	0.076	0.044
7100	0.029	0.003	0.031	0.063	0.032
7550	0.023	0.000	0.030	0.053	0.023

(iii) The extinction due to molecular absorption (ranges between about 5% to 30%) by ozone and water vapour is contributed in bands selectively between 0.3μm to 1.0μm. The water vapour attenuates weakly at 5436Å, 5744Å and at few bands beyond 7000Å while the ozone absorption mainly contributes in the Huggins band (3200Å - 3400Å) as well as in the Chappuis bands centered at 5750Å (Gutiérrez-Moreno et al. 1982). The following formula gives an approximate determination of the extinction only due to ozone assuming 0.232 atm-cm ozone content for the observatory site (Allen 1976).

$$k_{oz}(\lambda) = 0.2575\ C_{oz}(\lambda) \tag{4}$$

where $C_{oz}(\lambda)$ is the ozone absorption coefficient and is given by Bessell (1990) as under :

$$C_{oz}(\lambda) = 3025\ exp(-131(\lambda - 0.26)) + 0.1375\ exp(-188(\lambda - 0.59)^2$$

The theoretical values for the Rayleigh and ozone component, computed from these formulae at different wavelengths for our observatory location are given in table 1.

3. Extinction in passbands

The extinction coefficient $k(\lambda_0, \mu)$ in a passband with λ_0 as its mean wavelength and μ as the bandwidth, depends on the colour of the star, bandwidth μ as well as the condition of the continuity of the star's energy distribution $E(\lambda)$ around λ_0. If we neglect the second order airmass term then $k(\lambda_0, \mu)$ is given as under (Golay 1974):

$$k(\lambda_0, \mu) = 1.086k(\lambda_0)\left[1 + \left(\frac{\mu}{\lambda_0}\right)^2 \frac{n(n+1)}{2} - \left(\frac{\mu}{\lambda_0}\right)^2 \frac{n}{\lambda_0}(\phi\lambda_0 - 5\lambda_0)\right] \quad (5)$$

where

(i) ϕ_{λ_0} is the absolute gradient of stars radiation at λ_0 which when approximated by Planck's black body - is expressed as :

$$\phi_{\lambda_0} = \frac{hc}{k_B T}\left(1 - e^{-\frac{hc}{\lambda_0 k_B T}}\right)^{-1}$$

where h, c and k_B are Planck's constant, the speed of light and the Boltzmann constant respectively. T is the effective temperature, which can be determined from spectral type of the star (Schmidt-Kaler 1982).

(ii) $k(\lambda_0)$ is a monochromatic atmospheric extinction at λ_0 and n is a power dependence of atmospheric extinction law on λ due to scattering by air molecules and aerosols. The extinction from the sources of scattering have the form :

$$k(\lambda) = \beta/\lambda^n$$

where n lies between 1 and 4 and for scattering by air molecules, $n = 4$.

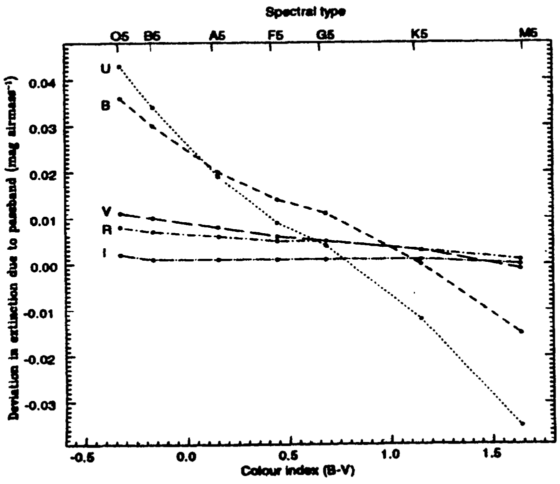

Figure 1. Variation of atmospheric extinction with spectral type in Johnson U, B, V and Cousins R, I passbands.

To study the effect of passbands, we have considered a normal atmosphere containing meteorological aerosol and, in such a case, the major source of extinction is due to the Rayleigh scattering by air molecules which is given by equation 2. The values of $k(\lambda_0, \mu)$ are calculated for Johnson U, B, V and Cousins R, I passband for stars of mid spectral type from O to M. The deviation with respect to the monochromatic extinction at the mean wavelength of these filters are plotted in figure 1. The deviation in extinction due to passband decreases with the temperature of the star. As can be seen, the colour of a star can introduce a maximum deviation of ~ 0.08 and ~ 0.05 mag airmass^{-1} in U and B passbands respectively. For U and B these deviations are positive for hot stars where λ_{max} (given by Wein's displacement law) is less than λ_0 and negative for cool stars where λ_{max} is greater than λ_0 while in V, R and I the effect is positive except for the coolest stars as λ_{max} is always less than λ_0 and gets added to the value at the mean wavelength. The deviation for V, R and I ranges between ~ 0.002 to ~ 0.01 mag airmass^{-1} and the mean deviation is the minimum for I. Thus, the extinction in V passband being less colour dependant and having reasonable extinction value may be used as the best representation of the sky transparency (Walker 1986).

4. The data

4.1 Photoelectric measurements

The heterochromatic extinction coefficients in Johnson U, B and V passbands were obtained from photoelectric observations at 38-cm, 52-cm and 104-cm Sampurnanand reflector telescopes at Naini Tal, UPSO during November 1964 to November 1988 under various observing programmes. This provides data for a total of 624 nights. Table 2 lists the yearly distribution of these nights. It can be seen that ~ 90% of the extinction measurements are obtained during 1964-1978 and only ~ 10% of the measurements, during 1978-1988. As we are interested primarily in behavioural and statistical study, no information was secured on the spectral type of stars while the stability of the photometric passbands characteristics were assumed appropriate during these years for the study undertaken. The uncertainty in extinction coefficients of a passbands may lie between 0.01 to 0.03 mag airmass^{-1} being the maximum in U and the minimum in V.

Table 2. The atmospheric extenction determined using photoelectric observations.

Year	No. of nights	Year	No. of nights	Year	No. of nights	Year	No. of nights
1964	11	1971	42	1978	23	1985	02
1965	45	1972	32	1979	06	1986	02
1966	49	1973	19	1980	08	1987	08
1967	27	1974	34	1981	11	1988	02
1968	55	1975	41	1982	03		
1969	48	1976	30	1983	25		
1970	70	1977	24	1984	07		

4.2 CCD measurements

For seventeen nights between Oct 1990 and Nov 1999 the extinction measurements were carried out in Johnson U, B, V and Cousins R, I passbands with CCD at 104-cm Sampurnanand telescope. Most of these measurements were made during observations of the stars in clusters. The uncertainty in the extinction coefficients determined in this way is around 0.02 mag airmass^{-1}.

4.3 Scanner measurements

The observations of standard stars were made at different zenith distances using photoelectric spectrum scanner during 1970 to 1978 for 14 nights in total, using either 52-cm or 104-cm Sampurnanand telescope. The instrumental set-up is described in detail by Rautela (1981). The standard stars used to determine extinction coefficients are α Lyr, α Leo η Uma, γ Gem and ξ^2 Cet. They are bright (V < 4.3 mag) and have spectral types between B3 to A0. The measurements were taken at line free wavelengths (Oke 1965) in the wavelength range 3390Å to 7550Å with a bandwidth of 50Å. The passband effect is negligible as the maximum deviation due to bandwidth is found to be around 0.005 mag airmass^{-1} at 3390Å. And hence the observations are considered monochromatic. Accuracy of the measurements lies between 0.01 and 0.02 mag airmass^{-1} being the maximum shortward of 4167Å.

5. Analysis and Discussion

5.1 Heterochromatic extinction

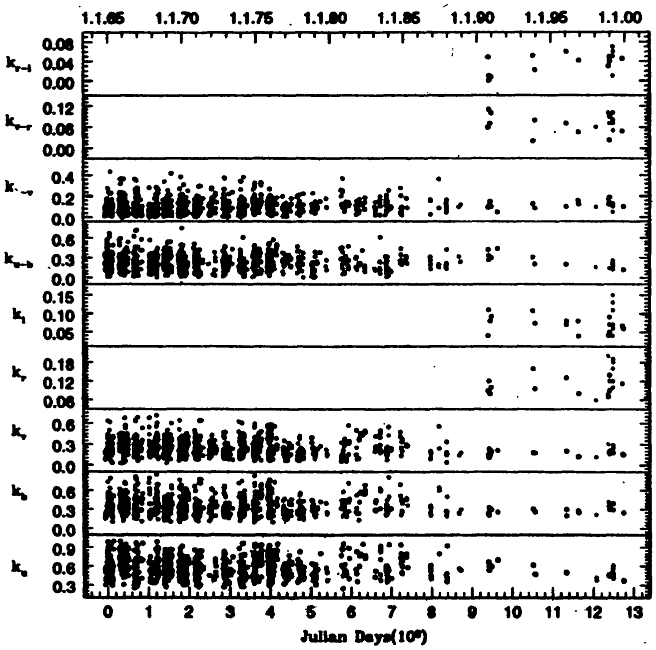

Figure 2. Time variation of extinction and colour extinction coefficients in mag airmass^{-1} for Johnson U, B, V and Cousins R, I passbands are shown. Filled and open circles represent the photoelectric and CCD data respectively at Naini Tal. Asterisks represent Devasthal data.

Figure 2 shows the plot of extinction coefficients and colour extinction coefficients with time in days taking JD2438762.0 as a reference for the combined photoelectric and CCD data. The vertical gap appearing periodically in the plots are due to the unavailability of data during rainy season (July to September) at Naini Tal. No long term variation is noticed between 1968 to 1999. The dispersion in the colour coefficients is low, as expected. The yearly plot of these coefficients in figure 3 shows an increase from March to mid June. The solid line across the data points connects the monthly means. The variation in the U, B and V passbands are in the range of ~ 0.12 - 0.13, ~ 0.12 - 0.14 and ~ 0.08 - 0.09 mag airmass^{-1} respectively with respect to the dust free winter observing season. In the Cousins R and I the statistics of yearly variation is not clear mainly due to less number of data points as well as less extinction value in comparison to U, B and V. The yearly variation is due to the enhanced dust and haze in summer. In figure 4 we have tried to see the correlation among the extinction coefficients. A very strong correlation is seen in both k_u versus k_b and k_b verus k_v for the photoelectric data. Their relations and mean values are given below.

$$k_b = (0.60 \pm 0.02)\, k_u - (0.01 \pm 0.01), \; k_v = (0.75 \pm 0.01)\, k_b - (0.02 \pm 0.01)$$

$$\overline{k_u} = 0.57 \pm 0.02, \; \overline{k_b} = 0.34 \pm 0.02, \; \overline{k_v} = 0.24 \pm 0.01.$$

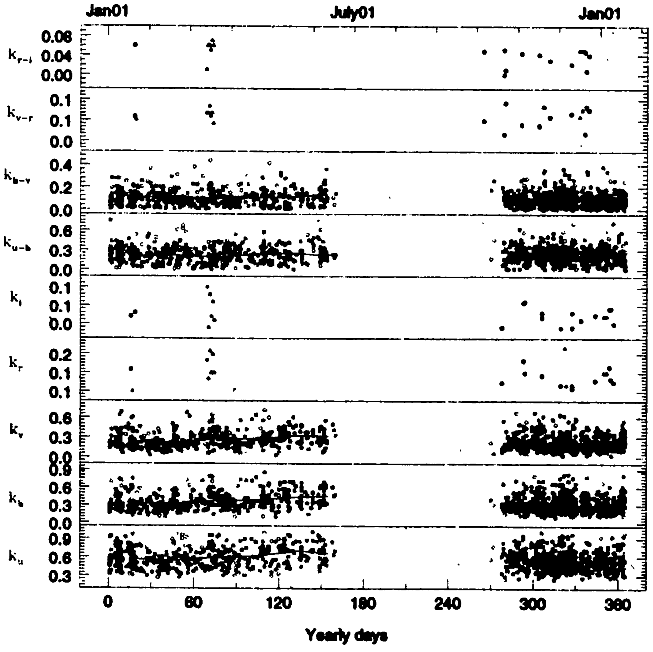

Figure 3. Yearly variation of extinction and the colour extinction coefficients in mag airmass^{-1} for Johnson U, B, V and Cousins R, I passbands are shown. Open and filled circles represents the photoelectric and CCD data respectively at Naini Tal while filled triangles represent the Devasthal data.

Figure 4 also contains similar plots for the CCD data at Naini Tal (present paper) and Devasthal (Mohan et al. 1999). The solid state stellar photometer on 52-cm reflector was used for measurements at Devasthal, and the determined characteristics of the photometric passbands are close to the standard Johnson UBVRI system (Mohan et al. 1999). Due to statistically insignificant number of data points the correlations are poor, however there is a match for Naini Tal and Devasthal data except the plot between k_u versus k_b. In the topmost panel of figure 4, no colour - colour dependence of extinction is seen and it is so because of the power dependence of extinction on the wavelength. The mean extinction values for Naini Tal and Devasthal are $\overline{k}_u = 0.57 \pm 0.09$, $\overline{k}_b = 0.28 \pm 0.04$, $\overline{k}_v = 0.17 \pm 0.03$, $\overline{k}_r = 0.11 \pm 0.02$, $\overline{k}_i = 0.07 \pm 0.02$ and $\overline{k}_u = 0.49 \pm 0.09$, $\overline{k}_b = 0.32 \pm 0.06$, $\overline{k}_v = 0.21 \pm 0.05$, $\overline{k}_r = 0.13 \pm 0.04$, $\overline{k}_i = 0.08 \pm 0.04$ respectively. In figure 5 we have compared the observed mean extinction coefficients at Naini Tal and Devasthal with other Indian sites (Mayya 1991, Singh et al. 1998, Kulkarni & Abhyankar 1978, Das et al. 1999, Barthakur & Duorah 1996, HIROT team 1996, Singh et al. 1988., Singh et al. 1989., Singh et al. 1990). It is clear that as we go beyond an altitude of two kilometer the decrease in atmospheric extinction is very little.

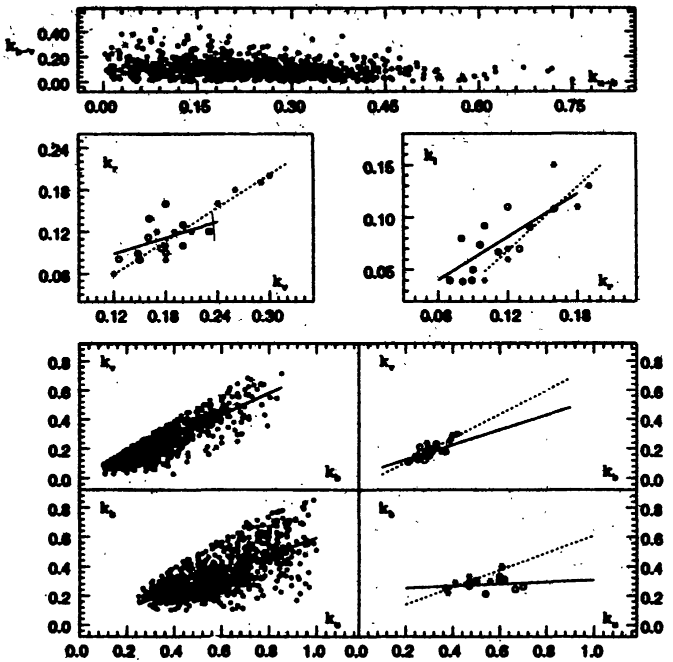

Figure 4. Correlations are shown for extinction coefficients and their color differences. Open and filled circles represent the photoelectric and CCD data respectively at Naini Tal. Asterisk represent the Devasthal data.

Apart from the annual variation of extinction mainly due to the seasonal variation of meteorological aerosols described above - one may also notice the variation triggered due to volcanic eruptions occurred during 1963 to 1988. Mt. Agung (lat : 8^0 S) erupted on 17 March 1963 and its effect was noticed at CTIO, Chile during 1964 to 1966 (Moreno & Stock 1964 and Gutiérrez-Moreno et al. 1982). Another comparatively strong explosion erupted on 23 March and 04 April 1982 at El Chichón (lat: 17^0N in Mexico and the effect was extensively studied at La Silla, Chile (Rufener 1986; Burki et al. 1995). The effect of El Chichón erupted aerosols on extinction were reported 0.070, 0.055 and 0.048 mag airmass^{-1} at 3456Å, 4245Å and 5500Å (the mean wavelength of Geneva U, B and V photometric passbands respectively). The influences of the above erruptions were not noticed at Naini Tal (lat:29^0 N). This may be

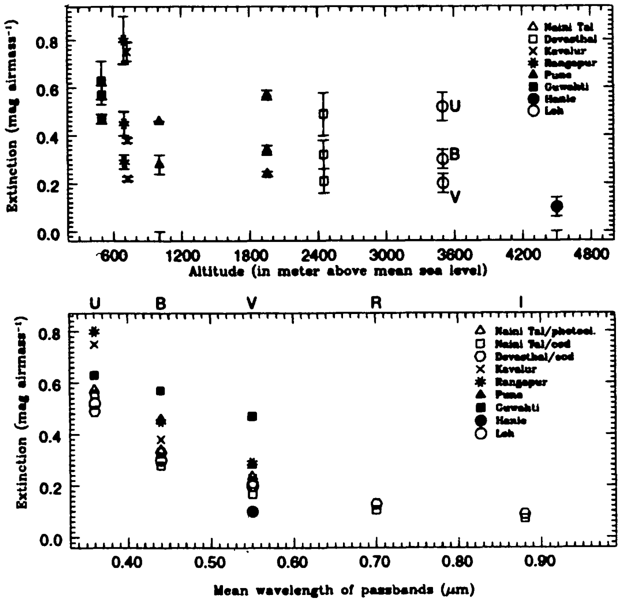

Figure 5. In lower panel, the mean extinction coefficients at Naini Tal and Devasthal are plotted with other Indian sites. The upper panel shows the variation of mean extinction coefficients for the passband with altitudes.

due to the combined effect of the large latitude and longitude separations between eruptions and the site, and the passband and colour effect on extinction which is of the order of the effect reported due to eruptions.

In June 1991 the Pinatubo (lat: 15^0 N) in Philippines erupted and was observed to have two to three times stronger effect on extinction attenuation (Burki et al. 1995). At Naini Tal we did not have enough data to study the effect.

5.2 Monochromatic extinction

5.2.1 Low extinction obtained in the ultraviolet region

To study the aerosol properties and its effect on the extinction at Naini Tal, we subtracted the Rayleigh and ozone contributions from the total extinction obtained during scanner observations. The water vapour contribution at wavelengths of our observation were considered to be negligible. The residuals obtained in this way gave negative values in some part of the ultraviolet region (3390Å - 4785Å) for winter nights from October to March. Quantitatively the mean extinction in this range is 0.0 to 0.2 mag airmass^{-1} lower than that expected from the model atmosphere given by Hayes and Latham (1975). However, such behaviour of the extinction was not observed for the nights of April and May. On these summer nights the extinction was well above the predicted over the complete span of the wavelength. The lower panel of figure 6 shows the observed extinction points during 1970-1978 and the dotted line is what is expected due to Rayleigh scattering by air molecules only. The bluer part contains more number of points well below the dotted line. Moreover, the region 3390Å to 4785Å is almost ozone free as can be seen from table 1. The behaviour longward of 4785Å is normal and well above the dotted line. However, it is important to note that our extinctions refer to only night time measurements.

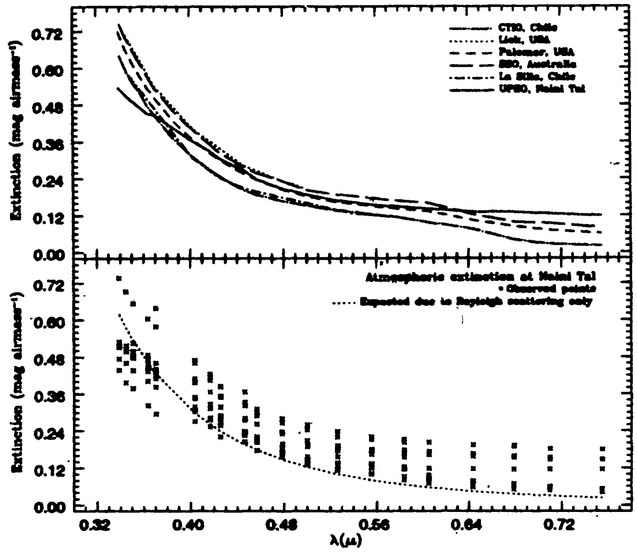

Figure 6. Observed and the theoretically predicted extinction at Naini Tal are shown in the lower panel while the upper panel shows the mass monochromatic extinction observed at other world sites.

The mean extinction obtained by averaging 14 night - time measurements during 1970-78 at Naini Tal is compared with the mean values at other world sites around the globe in the upper panel of figure 6. The mean extinctions at Cerro Tololo, Siding Spring, La Silla and Lick & Palomar are taken from Gutiérrez-Moreno et al. 1982, Bessell 1995, Burki et al. 1995 and Hayes & Latham 1975 respectively. A comparison shows that atmospheric air behaviour over an Himalayan site such as Naini Tal may be different from the sites which lie either in coastal or island regions.

5.2.2 Aerosol behaviour in the ultraviolet region

Table 3. Aerosol extinction parameters at Naini Tal.

Date	$a \pm \sigma_a$	$\alpha \pm \sigma_\alpha$
1970 May 31	0.010 ± 0.000	3.22 ± 0.22
1971 Jan 15	0.034 ± 0.016	1.50 ± 0.57
1973 Dec 19	0.005 ± 0.004	2.22 ± 1.04
1974 Oct 03	0.039 ± 0.018	0.92 ± 0.55
1974 Dec 13	0.004 ± 0.003	2.50 ± 1.04
1975 Nov 11	0.015 ± 0.005	2.83 ± 0.46
1977 May 22	0.006 ± 0.005	2.08 ± 1.72
1978 May 10	0.057 ± 0.013	1.06 ± 0.25

Keeping in view the low ultraviolet extinction scenario at Naini Tal, the following procedures were adopted to study the aerosol extinction properties. In the low extinction region (3390Å - 4785Å), the relative extinctions were obtained with respect to the lowest reported extinction on 11 Jan 1972. The relative extinction determined in this way is assumed only due to aerosol scattering as the observed region receives negligible molecular absorption. The customary power lay $a\lambda^{-\alpha}$ was fitted. The resulting aerosol parameters are listed in table 3. The amount of aerosol a was undetectable below the accuracy of our measurement which is 0.01 mag airmass^{-1}. In such cases it is not possible to determine the corresponding values of α. Therefore the parameters for these nights were not considered. Usually the observations indicate the α lies between 0.5 and 1.6 for the meteorological haze and aerosols in the absence of any pollution from man made pollutants or volcanic aerosols (Burki 1995). The lower limit is approached in case of larger volcanic particles and the upper limit witnesses the minimum pollution of the sky. Although, the upper limit is observable upto 2.6 at CTIO, Chile (Gutiérrez-Moreno et al. 1982). The α value obtained at our site lies between 0.92 and 3.22 with a mean of 2.04±0.73, which indicates that extinction contribution is mainly due to the areosols particle size of the order less than the wavelength. However as our aerosol parameters are determined from a single day's observations and the observed minimum extinction obtained on 11 Jan 1972 at Naini Tal is below the theoretical Rayleigh limit, this may push the α values little towards the lower limit. The mean α is observed to be 0.021 ± 0.008. Our values are comparable to the average value (~ 0.02) obtained at CTIO (Gutiérrez-Moreno et al. 1982) and at La Silla (Rufener 1986) suggesting normal aerosol behaviour during seventies at Naini Tal.

6. Conclusions

It is clear from the present analysis that the photometric quality of nights at Naini Tal are stable and there is no noticeable aerosol contamination of the sky. The mean extinction values are low at Devasthal compared to Naini Tal. The monochromatic extinction study underlines the fact that it is difficult to explain the meteorological conditions over the Himalayan site in comparison to the costal and island sites around the world.

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