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Atmospheric extinction at Devasthal, Naini Tal

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Abstract. The atmospheric extinction coefficients in Johnson U, B, V, R and I photometric passbands are determined for the first time at Devasthal, Naini Tal during 1998 and 1999. A solid state stellar photometer mounted on a 52-cm reflector was used for the measurements. The minimum atmospheric extinction was observed on Jan 21, 1998 with the values of coefficients 0.38, 0.22, 0.12 and 0.06 mag in U, B, V and R respectively. However, mean values of the coefficients during the observations are 0.49±0.09, 0.32±0.06, 0.21±0.05, 0.13±0.04 and 0.08±0.04 mag in U, B, V, R and I respectively. A comparison of the atmospheric extinction observed at Devasthal with those observed at other optical astronomical sites in India as well as abroad indicates that Earth's atmosphere at Devasthal site is fairly transparent and is suitable for precise photometric observations. The observed extinction values also agree fairly well with those expected due to molecular absorption, Rayleigh and aerosol scatterings by molecules and dust particles present in the Earth's atmosphere at an altitude of ~ 2.45 km. Variation in aerosol content of the Earth's atmosphere seems to produce the observed night to night variation in extinction at Devasthal.

Key words : site testing - atmospheric extinction

1. Introduction

The light coming from stars and other astronomical objects reaches us after travelling through the Earth's atmosphere. In this process it is scattered and absorbed. This leads to attenuation of the light which is called the Earth's atmospheric extinction. It is measured by extinction coefficients, which depend on various factors such as atmospheric conditions, altitude of the site, and the wavelength of the incoming light. The atmospheric extinction coefficients vary from night to night, as meteorological conditions strongly affect them. In order to compare the observations taken at different sites effectively, a knowledge of atmospheric extinction of a site is essential. We have therefore carried out such measurements on some nights during 1998 and 1999 at Devasthal, Naini Tal and present the results here. By road, Devasthal (latitude = 29°22′

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N, longitude = 79°41′ E, altitude = 2450 m above mean sea level) is about 50 km east of Naini Tal in the Shivalik hills of the Central Himalayan range. It is the site proposed for installing a 3 - metre class modern optical telescope jointly by U. P. State Observatory (UPSO), Naini Tal and Tata Institute of Fundamental Research, Mumbai. The site has been selected after a time-extended meteorological survey carried out during 1980's. Sagar et al. (1999a, b) and Pant et al. (1999) provide details of the site characterization carried out so far.

The next section describes the components of the Earth's atmospheric extinction. In Sect. 3, there is a brief account of the instruments and observations. In Sect. 4, the data analysis and results are given. Last section discusses the results and summarises the conclusions.

2. Components of Earth's atmospheric extinction

The observed magnitude, $m(\lambda, z)$ of an astronomical source at the Earth is related to its magnitude, $m_0(\lambda)$, outside the Earth's atmosphere by the following well-known Bouguer's linear formula for atmospheric extinction

$$m(\lambda, z) = m_0(\lambda) + 1.086k(\lambda)M(z) \tag{1}$$

where $k(\lambda)$ is the extinction coefficient of the atmosphere at wavelength λ and $M(z)$ is the air mass at zenith distance z. The important sources of extinction in the Earth's atmosphere are Rayleigh scattering by air molecules, $k_r(\lambda)$, aerosol scattering, $k_a(\lambda)$ and molecular absorption $k_0(\lambda)$. Each of these has its own characteristic wavelength dependence, distribution with height, and variation with time. Following Hayes & Latham (1975) and Bessell (1990), one can write Rayleigh scattering by air molecules at an altitude h in km as

$$k_r(\lambda) = \frac{0.0095e^{-h/8}}{\lambda^4}\left(0.23465 + \frac{107.6}{146-\lambda^{-2}} + \frac{0.93161}{41-\lambda^{-2}}\right) \tag{2}$$

while aerosol scattering which is due to particulates, including mineral dust, salt particles, water droplets and man made pollutants is expressed as

$$k_a(\lambda) = \frac{0.087e^{-h/1.5}}{\lambda^{0.8}} . \tag{3}$$

Molecular absorption occurs in lines and bands. Between $\lambda = 0.3$ to 1 μm, essentially ozone contributes to the extinction. The ozone is concentrated at altitudes between 10 to 35 km, so its contribution to extinction does not depend on the altitude of the ground based optical observatory, as the altitude of the highest one is ~ 5 km. Its value depends on λ as

$$k_0(\lambda) = 839.4375e^{-131(\lambda-0.26)} + 0.0381562e^{-188(\lambda-0.59)^2} \tag{4}$$

Furthermore, the effect of ozone absorption is negligible in UBVRI pass bands except for a small contribution to V due to absorption band at 590 nm. The extinction. due to aerosol scattering is less in comparison to that due to Rayleigh scattering and is mainly responsible for night to night variation in extinction at a site.

3. Instrumental set up and observations

For determining atmospheric extinction in Johnson U, B, V, R and I broadband filters, bright stars (V < 4 mag) were observed during 1998 and 1999 on 12 nights. A solid-state stellar photometer (model SSP-3) supplied by Optec Inc, USA mounted at the f/13 folded Cassegrain focus of the 52-cm reflector (Cox Hargreaves and Thomson, UK) installed at Devashtal was used for observations. The photometer uses a silicon PN-photodiode as detector which allows detection of light from UV to the near infrared (λ = 0.3 –1.1 μm) and at the same time has linearity over a 10^6 to 1 count range. The image of a star falls on the detector plane (size 1.3 mm square) which has < 1 % response variation over the surface. Typical integration time was 10 sec in each filter. An aperture size of 1 mm which correspond to 31″ on the sky at the focus of the telescope was used for observations. All the filters are made from a combination of Schott coloured glass. The glass type and thickness for each filter has been optimized for the best fit with the Johnson (1963) photometric standards.

In order to study the atmospheric extinction properties at Devasthal, as knowledge of mean wavelength (λ_0) as well as bandwidth (μ) of the passbands used here are required. They have been evaluated using following expressions :

$$\lambda_0 = \frac{\int \lambda S(\lambda)d\lambda}{\int S(\lambda)d\lambda} \qquad \mu^2 \; \frac{\int (\lambda-\lambda_0)^2 S(\lambda)d\lambda}{\int S(\lambda)d\lambda} \tag{5}$$

The values of $S(\lambda)$ given in the manual of the photometer were used in determining λ_0 and μ. The values obtained in this way are listed in Table 1. A comparison of these values indicates fairly good agreement between present and the standard Johnson system.

Table 1. A comparison of the mean wavelength (λ_0) and half-width (μ) of the present U, B, V, R and I passbands with those of the standard Johnson system.

Pass band	λ_0 in nm		μ in nm	
	Present	Johnson	Present	Johnson
U	374.4	360.0	18.9	21.2
B	435.4	440.0	36.6	35.4
V	550.9	550.0	33.5	38.9
R	703.1	700.0	78.6	75.4
I	887.5	880.0	75.9	85.4

4. Data analysis and Results

The apparent instrumental magnitudes (m_i) are determined using following relations

$$m_i = -2.5\log(S_i) + \text{const.} \tag{6}$$

where S_i is the star count corrected for sky in i passband. For determining atmospheric extinctions in U, B, V, R and I passbands, bright stars (V < 4 mag) were observed at varying air-mass in each filter. The linear equation (1) is used for the determination of extinction coefficients. The slope of the line was determined using least square regression to the data points and the values thus obtained are given in Table 2. The extinction coefficient in a passband can vary with sky transparency and night to night variations can be large particularly in U, B and V. The values of observed atmospheric extinction in U, B, V, R and I filters range between 0.38–0.61, 0.22–0.42, 0.12–0.30, 0.06–0.20 and 0.05–0.15 respectively. The corresponding mean values are 0.49, 0.32, 0.21, 0.13 and 0.08 respectively. The minimum and maximum values were observed on January 21, 1998 and March 16, 1999 respectively. Night to night variation observed in extinction coefficients of colours (U – B), (B – V), (V – R) and (V – I) are 0.12 – 0.26, 0.05 – 0.15, 0.06 – 0.10 and 0.09 – 0.16 mag respectively. Thus, variations in colour extinction coefficients are relatively smaller than those in a passband.

4.1. The extinction law at Devasthal

In order to derive the astmospheric extinction coefficient at λ_0 from that determined using broadband filters, account has to be taken of the effects of the colour of the observed star as well as the finiteness of the passband of the filters using following relation given by Golay (1976)

$$\frac{k}{1.086} = k(\lambda_0)\ (1-(\frac{\mu}{\lambda_0})^2\ (\frac{n}{\lambda_0}\ (\frac{14385}{T} - 5\lambda_0) - \frac{n(n+1)}{2}\ )) \qquad (7)$$

Table 2. Atmospheric extinction coefficients in mag per unit air-mass in standard Johnson U, B, V, R and I passbands at Devasthal. Errors in the extinction coefficients are derived from the least square linear regression to the data points. Spectral type and V magnitude of the stars used for this purpose are also given. In deriving the mean and standard deviation (σ) listed in the last row, all the extinction values in a passband have been given equal weightage.

Date	Extinction (mag per unit airmass)					Star
	U	B	V	R	I	(V, Sp. type)
20 Jan 98	0.42±0.01					η Tau (2.86, B7III)
21 Jan 98	0.38±0.01	0.22±0.01	0.12±0.01	0.06±0.01		ζ Leo (3.44, F0III)
19 Nov 98		0.42±0.01	0.30±0.01	0.20±0.02		α Ari (2.00, K2III)
20 Nov 98		0.35±0.05	0.18±0.07	0.08±0.04		β Tau (1.66, B7III)
16 Dec 98 (E)		0.29±0.02	0.17±0.02	0.12±0.02	0.08±0.03	β Tau (1.66, B7III)
16 Dec 98 (W)		0.35±0.01	0.20±0.01	0.11±0.01	0.05±0.01	β Tau (1.66, B7III)
18 Dec 98	0.47±0.03	0.33±0.01	0.21±0.01	0.12±0.01	0.07±0.03	β Tau (1.66, B7III)
14 Mar 99	0.41±0.08	0.29±0.01	0.24±0.03	0.16±0.03	0.15±0.02	β Leo (2.14, A3V)
15 Mar 99	0.56±0.04	0.30±0.01	0.18±0.04	0.10±0.03	0.04±0.01	β Leo (2.14, A3V)
16 Mar 99	0.61±0.01	0.40±0.01	0.29±0.01	0.19±0.02	0.13±0.03	β Leo (2.14, A3V)
17 Mar 99	0.49±0.02	0.29±0.02	0.19±0.01	0.12±0.02	0.07±0.02	β Leo (2.14, A3V)
18 Mar 99	0.61±0.02	0.39±0.01	0.26±0.01	0.18±0.01	0.11±0.02	β Gem (1.14, K0III)
19 Mar 99	0.47±0.04	0.30±0.02	0.17±0.02	0.12±0.03	0.06±0.02	β Leo (2.14, A3V)
Mean±σ	0.49±0.09	0.32±0.06	0.21±0.05	0.13±0.04	0.08±0.04	

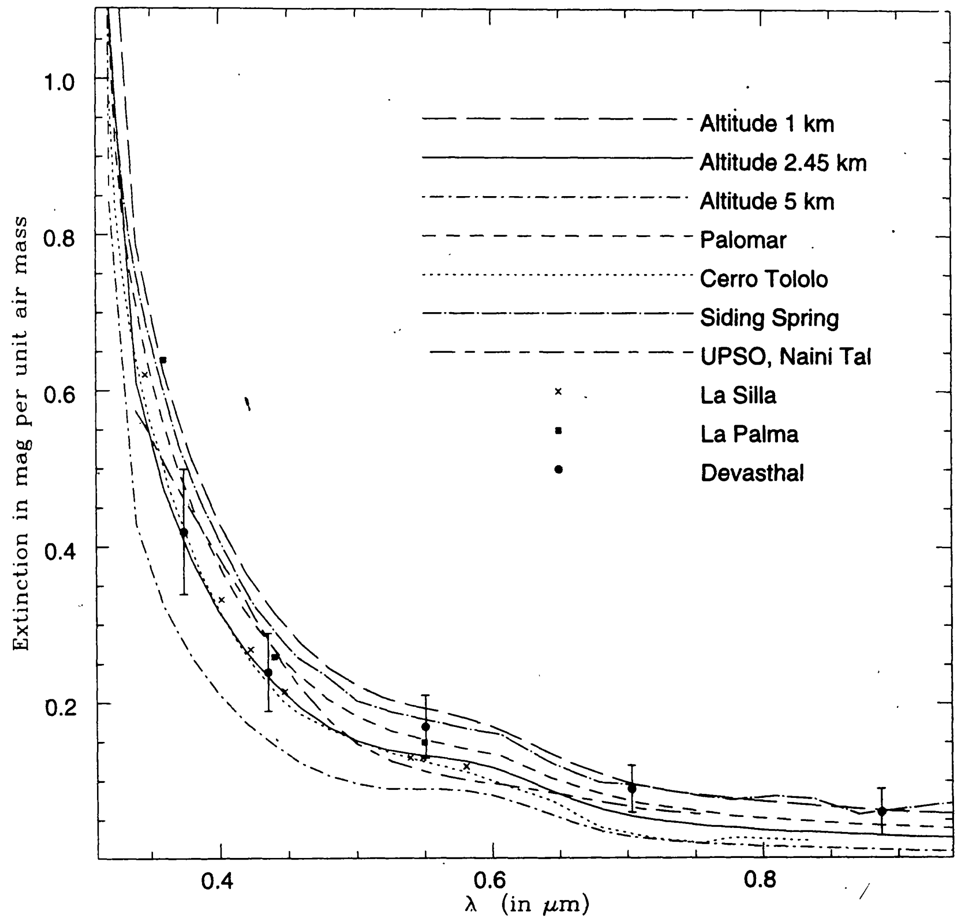

Figure 1. A comparison of the Devasthal's average atmospheric extinction law with those at Siding Spring in Australia, La Silla and Cerro Tololo in Chile, La Palma in Spain, Palomar in USA and UPSO, Naini Tal in India. Total extinction expected due to molecular absorption, Rayleigh and aerosol scatterings by molecules and particles present in the Earth's atmosphere for sites located at altitude of 1, 2.45 and 5 km are also shown.

where k is the observed extinction value; n is the power dependence of the atmospheric extinction on λ due to Rayleigh scattering and is taken as 4. The value of T is the colour temperature determined from the spectral type of the star assuming that energy distribution in optical region can be given by Wien's approximation. The values of μ and λ_0 are taken from Table 1.

The wavelength dependence of the mean atmospheric extinction at Devasthal is derived using equation (7) and is shown in Fig. 1 where error bar indicates the σ in observed extinction values. For comparison, we also plot the average atmospheric extinction curve of Siding Spring in Australia (Bessell 1995), La Silla (Burki et al. 1995) and Cerro Tololo (Gutierrez-Moreno et al. 1982) in Chile, La Palma (Murdin 1985) in Spain, Palomar (Hayes & Latham 1975) in USA and UPSO, Naini Tal (Rautela 1999) in India. This clearly indicates that the atmospheric extinction values at Devasthal and UPSO, Naini Tal appear as good as any other international observatories at similar altitude. From this, one may infer that the Earth's atmosphere in Shivalik hills of the Central Himalayan range has good transparency.

4.2 Comparison with theoretical estimates

In order to compare the observed extinction values with theoretical ones, we evaluated wavelength dependence of extinction due to $k_r(\lambda, h)$, $k_a(\lambda, h)$ and $k_0(\lambda)$ for h = 1, 2.45 (altitude of Devasthal) and 5 km (as altitude of the heighest ground based optical observatory is < 5 km) using equations (2), (3) and (4) respectively. Table 3 lists the extinction values expected for the altitude of Devasthal at the λ_0 and in the entire pass bands of the present U, B, V, R and I system. As expected, major contribution to extinction at a given altitude is due to $k_r(\lambda)$. The values of $k_0(\lambda)$ are small in comparison to the values of $k_r(\lambda)$ and $k_a(\lambda)$ for $\lambda \geq 0.35$ µm. The total extinction at the λ_0 derived in this way are plotted in Fig. 1. An inspection of this figure reveals that most of the observed extinction values around the globe including those at Devasthal agree very well with the theoretical ones. One may note that the lowest extinction values observed on 1998, Jan 21 at Devasthal (Table 2) are marginally better than the theoretically predicted values (Table 3). At any given site, such nights are the best ones and there could be some additional aerosols and very thin haze on other nights which will increase the atmospheric absorption. Photometric observations can be carried out even when the extinction is higher than this as long as it does not vary during the night. The low values of standard errors in the extinction determination (Table 2) indicate presence of several such nights at Devasthal site. It can easily be seen that on any given night extinction in addition to the minimal or theoretical value is due to aerosol scattering as it follows the $\lambda^{-0.8}$ law. The excess absorption due to aerosols over the entire period of observations has a median or mean value of ~ 0.07 mag in the V passband. On 4 out of 12 nights, the excess aerosol contribution in V is more than 0.10 mag. Such statistics is fairly acceptable and indicates suitability of Devasthal site for carrying out precise photometric observations.

Table 3. The total extinction expected at the mean wavelength λ_0, k_t and in the entire passband, k_p of the present U, B, V, R and I system due to different contributors (k_0, k_r and k_a) of Earth's atmosphere at the altitude of Devasthal.

Pass band	k_o	k_r	k_a	k_t	k_p
U	0.000	0.371	0.037	0.408	0.48
B	0.000	0.200	0.033	0.233	0.29
V	0.028	0.078	0.027	0.133	0.16
R	0.003	0.029	0.023	0.055	0.08
I	0.000	0.012	0.019	0.031	0.04

4.3. Comparison with other Indian astronomical sites

The photometric quality of the site is best ascertained by determining the values of atmospheric extinction coefficients as a function of λ. Larger the values at a wavelength, the less clear the air (Walker 1986). We have therefore compared the extinction values of various Indian sites in Table 4. The values at shorter wavelengths namely in U, B and V passbands are compared, as they are more sensitive to variations in atmospheric conditions. For UPSO, Naini Tal and Devasthal, the lowest observed extinction values are also given. The most extensive data is available for Leh site due to concentrated efforts by Singh et al. (1988, 1989, 1990). The advantages of sites above an altitude of ~ 2 km is apparent from Table 4 and Fig. 1 where the effect of enhanced aerosols and haze at lower altitude sites resulting in higher attenuation is clearly visible. There is no significant gain with still higher altitudes in the optical region, as there is a good agreement between the mean extinction at Leh and at Devasthal and Naini Tal. Also, the best values at Devasthal and Naini Tal are comparable to the values at Hanle (altitude 4.5 km).

Table 4. A comparison of the atmospheric extinction coefficients at Devasthal in U, B and V passbands with those of some other astronomical sites in India. The values are in magnitude as per unit airmass. For UPSO, Naini Tal and Devasthal, the least observed extinction values are also given.

Site	Latitude (North)	Longitude (East)	Altitude (metre)	Mean extinction in Pass band U	B	V	Year	Source
Kavalur	12° 34′	78° 49′	725		0.42±0.05	0.22±0.04	1991	Mayya (1991)
				0.75±0.04	0.34±0.01	0.23±0.01	1987	Singh et al. (1998)
Rangapur	17° 06′	78° 43′	695	0.7–0.9	0.4–0.5	0.26–0.32	1973–77	Kulkarni & Abhyankar (1978)
IUCAA site	19° 05′	73° 40′	1005		0.46	0.28±0.04		Das et al. (1999)
Guwahti	26° 06′	92° 32′	< 500	0.63±0.08	0.57±0.04	0.47±0.02	1994	Barthakur & Duorah (1996)
				0.63±0.08	0.57±0.04	0.47±0.02	1995	Barthakur & Duorah (1996)
Naini Tal	29° 22′	79° 27′	1951	0.55	0.26	0.15	1968	Sinvhal et al. (1972)
				0.45	0.20	0.10		Sinvhal et al. (1972)
Devasthal	29° 22′	79° 41′	2450	0.49±0.09	0.32±0.06	0.21±0.05	1998-99	Present
				0.38±0.01	0.22±0.01	0.12±0.01		Present
Hanle	32° 47′	78° 58′	4500			0.10±0.04	1996	HIROT team (1996)
Leh	34° 09′	77° 34′	3500	0.59±0.19	0.42±0.19	0.32±0.18	1985	Singh et al. (1988)
				0.46±0.05	0.22±0.05	0.15±0.05	1986	Singh et al. (1988)
				0.53±0.08	0.28±0.05	0.18±0.05	1987	Singh et al. (1989)
				0.50±0.05	0.28±0.04	0.17±0.03	1988	Singh et al. (1990)

5. Discussion and conclusions

As a part of astronomical characterisation of Devasthal site, the values of atmospheric extinction coefficients have been determined in Johnson U, B, V, R and I filters on 12 nights during 1998 and 1999. A SSP-3 solid state photometer mounted on a 52-cm reflector has been used for the observations. The extinction values range between 0.38 to 0.61 mag in U, 0.22 to 0.42 mag in B, 0.12 to 0.30 mag in V, 0.06 to 0.20 mag in R and 0.04 to 0.15 mag in I passband. The corresponding mean values are 0.49±0.09, 0.32±0.06, 0.21±0.05, 0.13±0.04 and 0.08±0.04 mag respectively. The wavelength dependence of Earth's atmosphere extinction coefficient at Devasthal site has also been studied. The mean extinction law is similar to other well known astronomical sites over the globe . A comparison of these values with those obtained at other optical astronomical sites in India as well as some abroad indicates that photometric quality of the Earth's atmosphere at Devasthal site is good globaly and excellent nationally (Walker 1986). A comparison of the expected extinction values at different altitudes indicates that star light will be less attenuated only by about 0.21, 0.10, 0.06, 0.04 and 0.025 mag in Johnson

U, B, V, R and I passbands respectively, if the ground based optical observatory is located at an altitude of 5 km instead of 2 km. The maximum advantage, as expected, is at shorter wavelengths specially in U passband. It is worth mentioning that most of the worlds well known ground based optical observatories are located at altitudes of about 2-3 kms. At higher altitudes costs of site development, operation and maintenance of the observing facilities are much more than the scientific gain specially at optical wavelengths.

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