Near-infrared thermal emissivity from ground-based atmospheric dust measurements at ORM

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ABSTRACT

We present an analysis of the atmospheric content of aerosols measured at Observatorio del Roque de los Muchachos (ORM; Canary Islands). Using a laser diode particle counter located at the Telescopio Nazionale Galileo (TNG) we have detected particles of 0.3, 0.5, 1.0, 3.0, 5.0 and 10.0 μm size.

The seasonal behaviour of the dust content in the atmosphere is calculated. Spring has been found to be dustier than summer, but dusty conditions may also occur in winter.

A method to estimate the contribution of the aerosols’ emissivity to sky brightness in the near-infrared (NIR) is presented. The contribution of dust emission to the sky background in the NIR has been found to be negligible compared to the airglow, with a maximum contribution of about 8–10 per cent in the $K_S$ band in the dusty days.

Key words: methods: data analysis – methods: statistical – site testing.

1 INTRODUCTION

Superb observing conditions are crucial to obtaining the best scientific output from the next generation of ground-based telescopes, and this requires monitoring all relevant parameters that may affect observations. Due to their potentially detrimental impact on astronomical observations, atmospheric aerosols are among the most important parameters to be monitored in modern site-testing campaigns. The performance and the safety of telescopes depend on the presence of atmospheric dust, which may deposit on mirrors, increase atmospheric extinction and emit in the infrared (IR) bands thus increasing the sky brightness.

Several studies about the atmospheric radiative effects of mineral dust exist. Gelado et al. (2003) analysed the mean aerosols content at Gran Canaria (Canary Islands) in the periods 1997–1998 and 2002–2003. A mean grain size of 0.6–4.9 μm and a large annual variability in both density and size distribution have been found.

Cuevas & Baldasano (2009) provided information on the incidence of the dust-loaded African airmasses at Observatorio del Teide in Tenerife (Canary Islands) and at Observatorio del Roque de Los Muchachos (ORM) in La Palma (Canary Islands). The analysis has been made using the high-quality observations performed by the Izaña atmospheric observatory. The in situ measurements for the 2002–2008 period show that the air is only partially affected by some dust loaded by African airmass intrusion. A significant PM10 concentration has been found only above the 80 percentile (26 μg m$^{-3}$) at Izaña.

The first analyses of the optical properties of dust and their impact on astronomy were done by Murdin (1985), Stickland et al. (1987), Guerrero et al. (1998) and Jiménez, Gonzalez Jorge & Rabello-Soares (1998). More recently, Lombardi et al. (2008) (hereafter Paper I) analysed 5+ years of time series data spanning the period 2001 August to 2006 December obtained with the Telescopio Nazionale Galileo (TNG) dust counter, and showed that dust particles increase the extinction in the $B$, $V$ and $I$ bands at ORM.

In the present paper we extend the analysis of Paper I by adding almost 3 years of new data (2007 March to 2010 January) to cover a total period of almost 8 years. In the first part of the paper we calculate the seasonal trend of the atmospheric aerosol content on yearly and monthly basis. In the second part of the paper we present a method to estimate the thermal emissivity of the dust in the near-infrared (NIR).

2 DUST MONITORS

Since 2001 the TNG site-monitoring group has used two different particle counters made by Particle Measuring System to monitor

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the dust content of the atmosphere around the telescope. Abacus TM301 measured between 2001 August and 2006 December, and LasairII 310B is in operation since 2007 March.

The data from Abacus TM301 were extensively analysed and presented in Paper I. LasairII 310B provides a significant improvement over its predecessor, in fact it measures six different particle sizes (0.3, 0.5, 1.0, 3.0, 5.0 and 10.0 μm) instead of only four measured by Abacus TM301.

Table 1 summarizes the basic instrumental characteristics of these counters that use a laser scattering technique for environmental ambient air analysis. Both are compact and portable devices designed to measure the air purity of closed environments such as clean rooms (Porceddu et al. 2002; Ghedina et al. 2004; Paper I). The light scattered by the dust particles is converted to voltage pulses of amplitude proportional to particle size and frequency proportional to particle density. A long silicon pipe through the enclosure feeds the pump with external air at 13 m above the ground, which corresponds to the level of the TNG primary mirror.

### Table 1. Main characteristics of the dust monitors.

|                 | Abacus TM301 | LasairII 310B |
|-----------------|--------------|---------------|
| Input flow rate | 0.1 foot³ min⁻¹ | 1.0 foot³ min⁻¹ |
| Size channels   | 0.3, 0.5, 1.0, 5.0 μm | 0.3, 0.5, 1.0, 3.0, 5.0, 10.0 μm |
| Light source    | Laser diode (λ = 780 nm) | Laser diode (λ = 780 nm) |
| Sample rate     | 1 data per min | 1 data per 2 h |
| Output          | RS-232       | Ethernet      |
| Running time    | 2001 August to 2006 December | 2007 March to today (2010 January for this paper) |

3 SEASONAL DISTRIBUTION OF DUST IN BACKGROUND AND DUSTY CONDITIONS

The raw data from the counters have been analysed following the method of Paper I. Because we cannot distinguish between the particles for their types, but can distinguish between them for their size, we rejected data obtained when the measured relative humidity was greater than 85 per cent, which corresponds to the condensation point for water vapour particles. As we will see later, this may introduce biases in the most humid months. Dust counts having values of a few σ above the median value have been classified as dust storms. The background was evaluated using a κ - σ clipping procedure described above, so these results correspond to strictly background dust conditions. Fig. 1 shows that the dust background is always larger in summer than in winter except in 2002 when the largest particles (5.0 μm) were significantly more abundant in winter than in summer. Curiously, this anomaly is not present for the smaller particles. A further comparison with the TOMS (Total Ozone Mapping Spectrometer) data does not show the same result. It is important to mention that the TOMS aerosol index (AI) has as a major limitation the inability to detect dust occurring at or near the surface since the ground signal can overwhelm the dust signal (Herman et al. 1997; Gao & Washington 2010). The 2002 dust recorded by our ground-based dust sensor could be confined to the lowermost layers of the atmosphere, which might explain why it could not be seen by TOMS. Our guess is that the 2002 phenomenon corresponds to a local event not seen by the satellite (contamination from local recycled dust?).

Table 2 presents the dust background in counts per cubic metre (count m⁻³) in background dust conditions distinguishing between wintertime, summertime and an entire annual cycle, and also the dust content during dust storms in an entire annual cycle, for three different cases:

1. using the Abacus TM301 data base between 2001 August and 2006 December for particles of the size of 0.3, 0.5, 1.0, and 5.0 μm;
2. using the LasairII 310B data base between 2007 March and 2010 January for particles of the size of 0.3, 0.5, 1.0, 3.0, 5.0 and 10.0 μm;
3. using both Abacus TM301 and LasairII 310B data bases between 2001 August and 2010 January for particles of the size of 0.3, 0.5, 1.0 and 5.0 μm, and the LasairII 310B data base for particles of the size of 3.0 and 10.0 μm.

Fig. 1 and Table 2 show that the prevailing aerosol conditions at ORM have not changed significantly during the 8 years of monitoring, with summertime being dustier than wintertime, with the exception of the 10.0-μm particles that show the opposite behaviour.

We now consider the monthly median counts without excluding the dust storms. In Paper I we found that between 2001 and 2006 the monthly distribution of aerosols is characterized by a significant increase in the count during February–April and July–August of each year. Fig. 2 shows the median monthly distribution of particles from the LasairII 310B data, which confirms the trends found in Paper I, with the exception of 2007 November which was clearly a very dusty month. June, September, October and December–January appear to be the cleanest months, but we remark that December and January are also the most humid months, so these results may be
The aerosols thermal emissivity in the NIR

Figure 1. Seasonal dust background distribution at TNG during background dust conditions, in counts per cubic metre ($N$ m$^{-3}$).

Table 2. Dust content in count m$^{-3}$ at ORM in wintertime, summertime and in the entire annual cycle for cases (1), (2) and (3) (see text in Section 3).

|       | Wintertime | Summertime | Annual | Dusty | Statistics |
|-------|------------|------------|--------|-------|------------|
| CASE (1) |            |            |        |       | running time |
| 0.3 $\mu$m | $1.3 \times 10^6$ | $4.4 \times 10^6$ | $3.0 \times 10^6$ | $1.8 \times 10^7$ | 2001 August to 2006 December |
| 0.5 $\mu$m | $1.2 \times 10^5$ | $3.8 \times 10^5$ | $2.5 \times 10^5$ | $6.1 \times 10^6$ | " |
| 1.0 $\mu$m | $0.5 \times 10^5$ | $1.5 \times 10^5$ | $1.0 \times 10^5$ | $4.1 \times 10^6$ | " |
| 5.0 $\mu$m | $0.7 \times 10^3$ | $1.5 \times 10^3$ | $1.1 \times 10^3$ | $1.6 \times 10^5$ | " |
| CASE (2) |            |            |        |       |            |
| 0.3 $\mu$m | $1.1 \times 10^6$ | $3.7 \times 10^6$ | $2.3 \times 10^6$ | $3.0 \times 10^7$ | 2007 March to 2010 January |
| 0.5 $\mu$m | $1.2 \times 10^5$ | $3.7 \times 10^5$ | $2.5 \times 10^5$ | $4.1 \times 10^6$ | " |
| 1.0 $\mu$m | $0.5 \times 10^5$ | $1.0 \times 10^5$ | $0.5 \times 10^5$ | $2.6 \times 10^6$ | " |
| 3.0 $\mu$m | $2.7 \times 10^3$ | $5.2 \times 10^3$ | $3.9 \times 10^3$ | $5.1 \times 10^5$ | " |
| 5.0 $\mu$m | $1.2 \times 10^3$ | $1.6 \times 10^3$ | $1.5 \times 10^3$ | $1.6 \times 10^5$ | " |
| 10.0 $\mu$m | $1.2 \times 10^2$ | $0.7 \times 10^2$ | $1.0 \times 10^2$ | $1.1 \times 10^4$ | " |
| CASE (3) |            |            |        |       |            |
| 0.3 $\mu$m | $1.0 \times 10^6$ | $3.7 \times 10^6$ | $2.3 \times 10^6$ | $2.8 \times 10^7$ | 2001 August to 2010 January |
| 0.5 $\mu$m | $1.2 \times 10^5$ | $3.7 \times 10^5$ | $2.4 \times 10^5$ | $4.6 \times 10^6$ | " |
| 1.0 $\mu$m | $0.4 \times 10^5$ | $1.1 \times 10^5$ | $0.6 \times 10^5$ | $2.6 \times 10^6$ | " |
| 3.0 $\mu$m | $2.7 \times 10^3$ | $5.2 \times 10^3$ | $3.9 \times 10^3$ | $5.1 \times 10^5$ | 2007 March to 2010 January |
| 5.0 $\mu$m | $1.0 \times 10^3$ | $1.5 \times 10^3$ | $1.3 \times 10^3$ | $1.6 \times 10^5$ | 2001 August to 2010 January |
| 10.0 $\mu$m | $1.2 \times 10^2$ | $0.7 \times 10^2$ | $1.0 \times 10^2$ | $1.1 \times 10^4$ | 2007 March to 2010 January |

biased because the dust counters are not reliable (relative humidity greater than 85 per cent).

Fig. 3 shows the monthly distribution of the overall dust density $M_D$ (in $\mu$g m$^{-3}$) computed by adding together all the particle sizes for Case (2) and assuming that all the particles have the same density of 2.5 g cm$^{-3}$, which is typical of silicates and quartz aggregates (Suh 1999) which are the main components of Saharan dust (Murdin 1985). In this plot July emerges as the dustiest month, while
somewhat surprisingly June is the cleanest. As we have already discussed, spring is dustier than summer and dusty conditions are also frequent in winter.

4 THERMAL BACKGROUND IN THE NIR

A dust particle of radius $a$ is heated by an ambient gas of molecules at a temperature $T_m$ at a rate that depends on the number density of the molecules and the fraction of energy $E$ that is deposited in the dust grain by the impinging particles (Dwek 1986). The dust particle radiates in the infrared the energy it has acquired in the collision at a rate that depends on the grain temperature $T_d$:

$$E_\nu = 4\pi a^2 \int_{\Delta \lambda} \pi B_\nu(T_d) Q_\lambda(a) d\lambda,$$

where $B_\nu(T_d)$ is the Planck function for temperature $T_d$ and $Q_\lambda(a)$ is the grain emissivity at wavelength $\lambda$ which is usually calculated using the Mie theory (Dwek 1986). In this section we estimate the thermal background emission of atmospheric dust in the NIR spectral bands, for which we will use the 2MASS photometric system reproduced in Table 3.

We can use our measured dust densities to calculate the total dust optical depth $\tau_\nu$ as the sum of the contribution of the optical depth of each particle size:

$$\tau_\nu = \sum_a \tau_\nu(a) = \sum_a N(a) \sigma_\nu(a),$$

Table 3. Absolute calibration of the 2MASS photometric system taken from Cohen, Wheaton & Megeath (2003).

| Filter | $\lambda_{\text{eff}}$ ($\mu$m) | $\Delta \lambda$ ($\mu$m) | $F_{\nu,\lambda}$ (W m$^{-2}$ $\mu$m$^{-1}$) |
|--------|-----------------|-----------------|-----------------|
| $J$    | 1.235           | 0.162           | $3.129 \times 10^{-9}$ |
| $H$    | 1.662           | 0.251           | $1.133 \times 10^{-9}$ |
| $K_S$  | 2.159           | 0.262           | $4.283 \times 10^{-10}$ |
where \(N(a)\) is the column density of particles of radius \(a\), and \(\sigma_\lambda(a)\) is the wavelength-dependent absorption cross-section from the Mie theory for particles of radius \(a\).

Satellite measurements indicate that the dust density over the Canary Islands is approximately constant at altitudes between 2500 and 5000 m above sea level, and drops to virtually zero above 5000 m (Hsu et al. 1999; Smirnov et al. 2002; Alpert et al. 2004; Paper I). Thus, the column densities are simply the volume densities multiplied by 2500 m. The resulting optical depths are calculated using the dust content in the background and dusty conditions obtained for an entire annual cycle and shown in Case (3) of Table 2. Results are given in Table 4 and are in a very good agreement with those in the visible in Smirnov et al. (2002) calculated for an altitude 2356 m above sea level in Tenerife Canarian Island (see table 2 in the mentioned paper). The extrapolation to NIR wavelengths still remains in a good agreement with our results.

The cooling times for dust particles of the sizes and temperatures typical of the Saharan dust above ORM are very short (Kaiser 1970; Draine 1981; Dwek 1986), so it is reasonable to assume that the dust is locally in thermal equilibrium with the surrounding air, while clearly the dust is optically thin even under the dustiest conditions. Thus, the thermal radiation emitted by the dust particles can be calculated as

\[
I_\lambda = \tau_\lambda B_\lambda(T_d) = \frac{2\pi^2 h}{\lambda^5} \frac{1 - e^{-\tau_h}}{\exp \left( \frac{hc}{\lambda kT_d} \right) - 1},
\]

where \(B_\lambda(T_d)\) from Tokunaga (2000) is expressed in W m\(^{-2}\) \(\mu\)m\(^{-1}\) sr\(^{-1}\), \(c\) is the light speed in vacuum, \(h\) is the Planck constant, and \(k\) is the Boltzmann constant.

We must calculate the Planck function considering that \(T_d\) decreases with altitude \(h\) from the median value at the ground (about 282 K, see Lombardi et al. 2006) with a wet vertical adiabatic lapse rate of \(-0.006\) K m\(^{-1}\) (Kittel & Kroemer 1980). Thus, the thermal spectrum of the dust is given by the expression

\[
F_\lambda = \sum_a \int_0^{2500} \tau_\lambda(a) B_\lambda(T_d(h)) dh,
\]

where the sum is over all particle sizes, \(a\). Using the absolute calibration of the 2MASS photometric system presented in Table 3, we obtain the aerosols sky brightness in the NIR in background and dusty days as

\[
m_\lambda = -2.5 \log \frac{F_\lambda}{F_{0,\lambda}}.
\]

The results are shown in Table 5, which clearly show that the sky brightness due to dust in the atmosphere is significant only during dusty conditions, and only in the \(K_s\) band. From the TNG data archive we know that the sky background in \(J\) is between 15.0 and 16.0 mag arcsec\(^{-2}\), in \(H\) it is between 13.4 and 14.7 mag arcsec\(^{-2}\), while in \(K_s\) it varies between 12.5 and 13.0 mag arcsec\(^{-2}\). We conclude that at ORM the contribution of the dust to the sky background in the NIR is mostly negligible in both background and dusty conditions, with a maximum contribution of about 8–10 per cent in the \(K_s\) band in the dusty days.

### 5 CONCLUSIONS

Using a laser diode particle counter near the TNG at ORM, we have measured the densities of airborne aerosols of the size of 0.3, 0.5, 1.0, 3.0, 5.0 and 10.0 \(\mu\)m. The seasonal trends of the particle content in the atmosphere have not changed significantly between 2001 and 2010. The monthly distribution of aerosols is characterized by an increase during February–April and July–August of each year: the spring is dustier than the summer, but dusty conditions may also occur in winter.

Using the Mie theory we have calculated the dust absorption cross-section and thus estimated the thermal emission in the 2MASS NIR spectral bands. Assuming that the dust particles are locally in thermal equilibrium with the surrounding air, and that the air temperature decreases with altitude with the wet vertical adiabatic lapse rate \(-0.006\) K m\(^{-1}\), we found that the contribution of dust emission to the total sky background in the NIR is negligible compared to the airglow component during both background and dusty conditions, with a maximum contribution of about 8–10 per cent in the \(K_s\) band in the dusty days.

### ACKNOWLEDGMENTS

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**Table 4. Aerosol optical depth calculated for the 2MASS filters.**

| Filter | Background | Dusty |
|--------|------------|-------|
| \(J\)  | 0.006      | 0.296 |
| \(H\)  | 0.005      | 0.280 |
| \(K_s\)| 0.004      | 0.270 |

**Table 5. Aerosols background NIR emissions in mag arcsec\(^{-2}\) in background and dusty days.**

| Filter | Background conditions | Dusty days |
|--------|-----------------------|------------|
| \(J\)  | 39.2                  | 35.2       |
| \(H\)  | 27.8                  | 23.6       |
| \(K_s\)| 20.3                  | 15.8       |

**Table 6. Aerosols optical depth and NIR emissions in mag arcsec\(^{-2}\) for the major events occurred between 2007 July 25 and 30.**

| Filter | \(\tau_\lambda\) | Emission |
|--------|------------------|----------|
| \(J\)  | 0.388            | 34.5     |
| \(H\)  | 0.372            | 23.0     |
| \(K_s\)| 0.356            | 15.2     |
