Variability of the mesospheric nightglow during the 2002 Leonid storms

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Abstract

There was no significant increase in the intensities of three prominent components of the terrestrial nightglow during the 2002 Leonid storm peaks. The atomic oxygen line at 557.7 nm, the sodium D lines at 589.0 and 589.6 nm, and the OH(6,2) band at 826–862 nm were monitored using an airborne spectrometer over the North Atlantic (40–50°N). The results indicate that the meteor storm produced a negligible change in both atomic sodium and oxygen compared to the background concentrations. The spectrometer resolved the sodium doublet, and showed that the ratio of the D2 and D1 lines is not 2.0, as had been thought hitherto, but is highly variable on distances of a few tens of kilometers. The mean value is about 1.8, with values ranging from 1.3 to 2.4.

Keywords: Leonid meteor storm; Sodium nightglow; Sodium D line ratio; Oxygen green line; Meinel bands

1. Introduction

Several prominent components in the terrestrial nightglow occur in the upper mesosphere and lower thermosphere (75–110 km), as shown in Fig. 1 from a modelling study (Plane, 2003). This is also the region of the atmosphere where meteoric ablation deposits a variety of metal vapours (Na, Fe, etc.); these atoms then undergo hyperthermal collisions with air molecules, leading to the production of atomic oxygen, ions and electrons (Plane, 2003). In this paper, we examine whether the 1998 and 2002 Leonid storm peaks had a discernable impact on three nightglow emissions: the atomic oxygen “green” line (hereafter referred to as OI), the sodium doublet lines (NaD), and the hydroxyl Meinel bands (OH*).

NaD radiation at 589 nm arises from the atomic transition Na(3P3/2,1/2→3S1/2). Sydney Chapman postulated the following sequence of reactions to account for the emission (Chapman, 1939):

\[
\text{Na} + \text{O}_3 \rightarrow \text{NaO} + \text{O}_2
\]  \hspace{0.5cm} (1)

\[
\text{NaO} + \text{O} \rightarrow \text{Na}^*(3P, S) + \text{O}_2
\]  \hspace{0.5cm} (2)

\[
\text{Na}^*(3P) \rightarrow \text{Na}^*(S) + h\nu \ (589 \text{ nm})
\]  \hspace{0.5cm} (3)

Although both reactions (1) and (2) are fast, reaction (1) is rate-determining because [O3] is much less than [O] in the upper mesosphere. Hence, the intensity of the emission is proportional to [Na] and [O3]. The source of atomic Na is the ablation of approximately 30 ton of interplanetary dust that enters the atmosphere each day, giving rise to a global Na layer that peaks around 90 km (Plane, 2003, and references therein). The NaD emission layer peaks slightly lower, around 89 km (Fig. 1), and has a width of ~7 km (Plane, 2003).

The upper electronic state of Na has two spin–orbit substates, so that the Na(3P3/2,1/2→3S1/2) transition actually consists of two closely-spaced lines, D2 and D1, at 589.0 and 589.6 nm, respectively. One focus of the present study is the D2/D1 ratio, hereafter termed \( R_D \). This ratio should be 2.0 if Na(3P3/2) and Na(3P1/2) are produced according to their spin–orbit statistical weights. Nearly three decades ago, \( R_D \) was measured to be 2.0 ± 0.1 using a Fabry-Perot
Meinel emission is around 87 km (Fig. 1), where O\textsuperscript{3} is the OH(6,2) emission around 830 nm. The peak of the RD observations of (Slanger et al., 2005). RD study, instrument (Sipler and Biondi, 1978). Up until the present nightglow emissions, predicted by a 1D model (Plane, 2003).

Fig. 1. Height profiles of the atomic O green line, Na\textsuperscript{D} line, and OH Meinel nightglow emissions, predicted by a 1D model (Plane, 2003).

instrument (Sipler and Biondi, 1978). Up until the present study, RD has been assumed to be 2.0. Note that the observations of RD reported here are part of a larger study (Slanger et al., 2005).

OH radiation at 557.7 nm arises from the transition O(2\textsuperscript{1}S\textsubscript{0} \rightarrow 2\textsuperscript{1}D\textsubscript{2}). The currently accepted mechanism involves three steps (Barth, 1964):

\begin{align}
O + O(+M) &\rightarrow O_2^*(\epsilon_1\Sigma_u^-(\nu > 2), \text{etc.}) \\
O + O_2^* &\rightarrow O(\text{\textsuperscript{1}S}) + O_2(\text{\textsuperscript{3}Σ_u^-}) \\
O(\text{\textsuperscript{1}S}) &\rightarrow O(\text{\textsuperscript{1}D}) + h\nu (557.7 \text{ nm})
\end{align}

where M is a “third” body (N\textsubscript{2} or O\textsubscript{2}). Note that this mechanism predicts that the intensity of the green line is proportional to [O]\textsuperscript{3}. The peak emission occurs around 96 km (Fig. 1).

The OH\textsuperscript{*} bands are the only example of emission from a vibrationally excited ground state, and are the strongest contribution to the nightglow. The Meinel bands are predominantly formed from the following sequence of reactions (Meriwether, 1989):

\begin{align}
O + O_2(+M) &\rightarrow O_3 \\
H + O_3 &\rightarrow OH(\nu'' \leq 9) + O_2 \\
OH(\nu'') &\rightarrow OH(\nu'' - \Delta\nu'') + h\nu
\end{align}

Reaction (8) is exothermic by 320 kJ mol\textsuperscript{-1}, so the product OH is formed vibrationally excited up to the thermodynamic limit (\nu'' \leq 9). Most of the subsequent emission is due to \Delta\nu'' = 1 transitions in the infrared. However, overtone transitions up to \Delta\nu'' = 6 produce weaker emission in the visible at \lambda > 580 nm. Quenching by air molecules both reduces the emission intensity and redistributes the \nu'' population to lower levels. In this study we observed the OH(6,2) emission around 830 nm. The peak of the Meinel emission is around 87 km (Fig. 1), where O\textsubscript{3} is essentially in steady state between production by reaction (7) and loss by reaction (8). The intensity of the Meinel bands is proportional to the rate of reaction (7), and hence to [O].

An ablating meteoroid is a source of atomic sodium, atomic O both from mineral oxides and dissociation of atmospheric O\textsubscript{2}, and atomic H if the particle contains significant quantities of hydrates. Therefore, an intense meteor shower could potentially increase all three of these airglow emission intensities. Broadband photometric measurements during the 1966 Leonid storm did not reveal an increase in the night sky brightness (Gadsen, 1980), but spectroscopic measurements of individual airglow features are a more sensitive test. During the 1998 Leonid MAC mission (Jenniskens and Butow, 1999), we deployed a small telescope and spectrometer onboard the NCAR Electra aircraft. As shown in Fig. 2, both the Na\textsuperscript{D} and OH intensities increased during the 1998 Leonid shower, apparently in proportion to the meteor count rate. Note that the large increase in Na\textsuperscript{D} at solar longitudes >235.3\textdegree is caused by solar resonance fluorescence of Na during twilight. The apparent correlation between OH intensity and meteor count rate is particularly striking. However, because of the dependence of the OH intensity on [O]\textsuperscript{3}, an increase of [O] by a factor of only 1.7 (which can result from dynamical perturbations such as tides and gravity waves) would lead to the observed fivefold increase in OH. Furthermore, if meteors were responsible for the change in [O], then the OH intensity should vary as the meteor count rate cubed, rather than the linear relationship observed.

During the 1999 Leonid meteor storm, when meteor rates increased to a Zenith Hourly Rate (ZHR) of
3700 h⁻¹ for a period of time, a 30% increase of OH* band emission at near-IR wavelengths was detected by Kristl et al. (2000) that was perhaps correlated with the meteor activity. However, the change in airglow intensity was only apparent for OH emission. Also, no changes were observed in the NaD intensity measured by Brosch and Shemmer (2000) at Wise Observatory in Israel.

During the 2002 Leonid MAC mission, we set out to measure NaD, R⁡D, OI, and OH* during the 2002 Leonid storms, using a new spectrometer.

2. Instrument

The instrument consisted of a 0.14° field-of-view telescope pointed at an elevation angle of 23° (for convenient viewing out of the modified aircraft window), and coupled via a 1 mm fibre-optic bundle to a 0.5 m Czerny-Turner spectrometer (1200 groove mm⁻¹ grating). Dispersed spectra were recorded using a cooled CCD detector (1024 × 256 pixel array, maintained at −70 °C). This combination provided a resolution of 0.2 nm, sufficient to resolve the D lines (Fig. 3). Laboratory calibration tests, using a low-pressure Na hollow cathode lamp, showed that R⁡D could be measured with ±5% precision. Spectra in the 542–578 nm (OI), 572–612 nm (NaD) and 826–862 nm (OH*(6,2)) regions were recorded with 60 s exposure times on a continuous cycle. A co-aligned intensified camera with a field of view of 5° provided an image of the background star field and any meteor persistent trains in the field of view. This permitted us to occasionally point at persistent trains and reset the pointing direction to the previous setting by aiming at the same star field.

The mission deployed out of Torrejon AFB near Madrid, Spain, and followed a westward trajectory at an altitude of 26,000–37,000 ft over the Atlantic ocean and southern Canada to Omaha, Nebraska (Jenniskens, 2002). Near-continuous measurements of nightglow spectra were made from shortly after takeoff until just prior to the second storm peak, when the system was used to chase Leonid meteor trains.

Fig. 4 shows measurements of NaD and R⁡D on 19 November 2002, as well as the zenith hourly meteor count rate. Fig. 5 compares NaD, OI and OH* during the same night. There is no evidence for an increase in any of these airglow features when the rate of bright (visible) meteors increased from a normal ZHR ~ 15 h⁻¹ to 2500 h⁻¹.

This point is reinforced by Fig. 6, which shows observations of the same nightglow emissions during the night of 17th November, 2002 when the DC-8 flew eastwards from Nebraska to Torrejon AFB. This shows typical variability in the emission intensities, as a result of tides and gravity waves. Note that the large increase in NaD after 07:30 GMT is caused by resonance fluorescence in the dawn twilight.

More interesting than the nightglow intensities is the variation in the NaD-line ratio. Figs. 4 and 6 both show that R⁡D is extremely variable – certainly not the constant value of 2.0 that has been assumed for the last three decades (Sipler and Biondi, 1978). In Fig. 4, a total of 100 measurements of R⁡D yielded an average R⁡D of 1.8 (range: 1.5–2.0). In Fig. 6, 86 measurements of R⁡D yielded a similar average R⁡D of 1.8, with an even greater range (1.4–2.4). On the flight leg from Nebraska to Edwards AFB in California on the night of 20th November, 2002 a further 67 measurements yielded an average R⁡D of 1.8 (range: 1.3–2.4). Note that R⁡D appears to vary over horizontal distances of 50–100 km (corresponding to flight times of 3–6 min), which are typical of the horizontal wavelengths of short-period gravity waves (Hecht, 2004), although longer-term fluctuations consistent with tides appear to be absent. Although there is sometimes evidence of correlation between R⁡D and the NaD intensity (e.g. in the early segment of the flight in Fig. 4), this was not consistently observed.

The rotational lines in the OH(6,2) band were also used to obtain the local kinetic temperature to ±5 K, by fitting a synthetic spectrum (Fig. 7a). Fig. 7b shows that there is no significant correlation between R⁡D and temperature, although it should be noted that the Meinel emission is centered in a layer about 3 km below the Na nightglow layer (Fig. 1).

3. Discussion

The lack of a significant change of the NaD airglow is unsurprising. The total mass influx of meteoric matter during the 0.52 h storm peak amounted to the equivalent of only about 0.36 h of normal sporadic meteoroid influx. That is because most of the sporadic mass influx is from much smaller grains than observed visually, ~200 μm in size (Love and Brownlee, 1993; Jenniskens et al., 1998). Integrated over the 2-h storm profile, 3.2 × 10⁻¹² kg m⁻² of Leonid matter was deposited, compared with 1.8 × 10⁻¹¹ kg m⁻² of sporadic matter. Given that the residence time of Na atoms in the layer centered at 90 km is several days (Plane, 2004), the addition of Na
from the storm was insignificant. Furthermore, these meteors have an entry velocity of 71 km s\(^{-1}\) and therefore the Na ablates between 113 and 98 km, where there is little ozone to generate Na\(D\) emission (Plane, 2003, 2004).

The production rate of O atoms by Leonids during the storm can be estimated by assuming that essentially all O\(_2\) is dissociated in the initial train, whose radius can be estimated as a function of meteoroid size (Jones, 1995). For the observed meteor distribution, and assuming that the brightest meteor is of magnitude \(m_v = -14\), we find that the fraction of atmospheric surface area impacted by the meteors directly, and hence the upper limit to the fraction of O\(_2\) dissociated, is only about \(1.1 \times 10^{-8}\) during the 1.8 h of the storm peak. Since the fraction of O\(_2\) that is dissociated by the daytime absorption of UV radiation in the Schumann–Runge bands and continuum is about 0.05 at 90 km and 0.3 at 100 km (Plane, 2003), the additional dissociation by Leonid meteors was negligible. Thus, no meteor-related change in either the OI or OH\(^*\) intensity would be expected, in accord with our observations.
4. Conclusion

The increased Na\(D\) and OI emission intensities during the 1998 meteor storm were not observed during the two storm peaks in 2002. It therefore appears that the correlation observed in the 1998 data set (Fig. 2) was most likely a coincidence. The important result from the present study is the discovery that \(R_D\) is highly variable on quite short horizontal distances (or perhaps time periods). The average value was around 1.8, but values from 1.3 to 2.4 were observed. Since the observations were all made with the same telescope elevation angle and hence optical depth through the sodium layer, self-absorption is not an explanation. We also observe no correlation with upper mesospheric temperature. The most likely explanation for the variability of \(R_D\) is that reaction (1) generates NaO in its first excited NaO(A\(^2\Sigma\)) state, which is then slowly quenched to the ground NaO(X\(^2\Pi\)) state. Reaction (2) thus involves reaction of O with either NaO(A) or NaO(X), which may generate Na\(^2\P_3/2\) and Na\(^2\P_1/2\) with different propensities (Slanger et al., 2005). \(R_D\) would then depend on the distribution of the Na layer with height, since quenching of NaO(A) to NaO(X) will depend on the atmospheric pressure and mixing ratio of O, and hence on any significant wave perturbations present at that time.

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