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Odin-OSIRIS detection of the Chelyabinsk meteor

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Abstract

On 15 February 2013 an 11 000 ton meteor entered Earth's atmosphere south east of Chelyabinsk creating a large fireball at 23 km altitude. The resulting stratospheric aerosol loading was detected by the Ozone Mapping and Profiler Suite (OMPS) in a high altitude polar belt. This work confirms the presence and lifetime of the stratospheric debris using the Optical Spectrograph and InfraRed Imaging System (OSIRIS) onboard the Odin satellite. Although OSIRIS coverage begins in mid-March, the measurements show a belt of enhanced scattering near 35 km altitude between 50° N and 70° N. Initially, enhancements show increased scattering of up to 15 % over the background conditions, decaying in intensity and dropping in altitude until they are indistinguishable from background conditions by mid-May.

1 Introduction

The Optical Spectrograph and InfraRed Imaging System (OSIRIS) is a limb scatter instrument launched in 2001 on the Odin satellite (Llewellyn et al., 2004). Odin was placed in a polar, sun-synchronous orbit at 600 km altitude with an inclination of 98°. OSIRIS views in the orbital plane providing measurements from 82° S to 82° N, provided the tangent point is sunlit. As Odin orbits the satellite nods to scan the instrument line of sight vertically through tangent heights ranging from 7 to 65 km during typical operation. The optical spectrograph measures wavelengths from 275 to 810 nm with approximately 1 nm resolution. Wavelengths in Hartley/Huggins and Chappius bands are used to retrieve ozone profiles, while the longer wavelengths are useful in the retrieval of stratospheric aerosols. Although not typically used to measure meteoric deposition in the stratosphere the Chelyabinsk meteor allows for a unique opportunity due to its size and high altitude explosion.

On 15 February 2013 the meteor entered the atmosphere at a shallow angle south-east of Chelyabinsk. Traveling at 18 km s^{-1} the meteor exploded at an altitude of

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23.3 km. With an approximate mass of 11 000 tons this was the most energetic impact event since the 1908 Tunguska event, also in Russia (Yeomans and Chodas, 2013). Due to solar illumination conditions OSIRIS begins measuring mid-to-high northern latitudes near the end of February; however, in 2013 engineering diagnostic modes on the instrument power supply prevented sustained measurements of higher latitudes until mid-March. While this precluded measurements of the initial impact subsequent measurements show the remnants of the explosion still present in the stratosphere for the months following the impact.

2 OSIRIS measurements

The long path lengths of OSIRIS limb measurements provide excellent sensitivity to extinction as low as $10^{-5}\,\mathrm{km}^{-1}$ under typical conditions in the stratosphere. This is particularly true at the longer optical spectrograph wavelengths where the relative contribution of aerosol scattering to Rayleigh scattering is higher. The ratio of total radiance to that expected from an aerosol-free atmosphere provides a good qualitative measure of the amount of aerosol present. This scattering ratio, SR, as a function of wavelength, λ, and altitude, j, is calculated as

$$\mathrm{SR}(\lambda, j) = \frac{I_{\mathrm{meas}}(\lambda, j)}{C(\lambda) \cdot I_{\mathrm{mod}}(\lambda, j)}, \quad (1)$$

where I_{meas} is the radiance as measured by OSIRIS, I_{mod} is the modelled radiance expected from a molecular atmosphere and C is an altitude normalization to help account for errors in the assumed air density and albedo. Radiances are modelled using SASKTRAN, a fully spherical, multiple scattering model using retrieved ozone profiles and neutral densities from ECMWF (Bourassa et al., 2008). Typically, these scattering ratios are inverted to produce aerosol extinction coefficients (Bourassa et al., 2007). However, this requires assumptions on the particle size and composition, and it is unlikely the typical sulphate aerosol with a lognormal distribution are representative of the

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meteoric particles investigated here. With an inaccurate particle size and composition, inversion provides little additional information and so for this study measurements are left as scattering ratios. This is sufficient to distinguish areas of enhanced scattering and monitor the removal of meteoric material.

An example of typical scattering ratios between 550 and 800 nm for two OSIRIS scans during the previous year with similar locations and illumination conditions are shown in in Fig. 1a and b. Here, the Junge layer is present below approximately 30 km with a strong peak just below 20 km. Above the Junge layer, little to no aerosol is present. Panels c–f show measurement vectors for four scans in 2013 following the meteor impact which show a second layer of aerosol above the Junge layer between 30 and 35 km. This is attributed to the Chelyabinsk meteor. Initially, the scattering due to aerosols at the high altitude peak is approximately 10–15 % of the total signal with a peak near 34 km altitude. By the end of April enhancements closer to 5 % are more typical with a peak that has dropped to 31 km.

3 The Chelyabinsk meteor

To help distinguish the meteor from the background conditions a measurement is considered to contain meteoric aerosol if it meets two conditions:

1. The highest peak in the 750 nm scattering ratio must occur at least 18 km above the 380 K tropopause.

2. The magnitude of this peak must be at least 1.02.

These criteria help to eliminate scans which have high aerosol loading at high altitudes due to isentropic transport from the tropics and ensure the peak is above the noise threshold of the measurements. The locations of scans which meet these criteria are plotted in Fig. 2 in two week intervals. Once OSIRIS is turned on in mid-March a strong belt of meteoric material is detected between 50° N and 70° N. This coincides

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well with the analysis performed by Gorkavyi et al. (2013), who showed the meteor circumnavigating the globe in a high-latitude belt within a week of the impact using OMPS (Rault and Loughman, 2013) measurements and trajectory analysis.

The altitude distribution of the material is also clear in zonal averages. Figure 3 shows zonal averages for the same time periods as Fig. 2. These averages include all scans from the time periods. At the end of March a clear enhancement is visible from 30 to 35 km altitude and between 50° N and 70° N. By early April the enhancement is noticeably weaker and has begun to spread to lower latitudes. Throughout April the plume continues to decay and merge with the background aerosol, with essentially no enhancements visible by early to mid-May.

4 Conclusions

The timing and location of meteoric detections by OSIRIS agree well with the analysis performed by Gorkavyi et al. (2013). The stratospheric influence of the Chelyabinsk meteor is visible using limb scatter techniques for approximately three months following the impact. OSIRIS measurements taken after 15 March show a band of meteoric material circling the globe between 50° N and 70° N at 35 km which decays into the background over the following two months.

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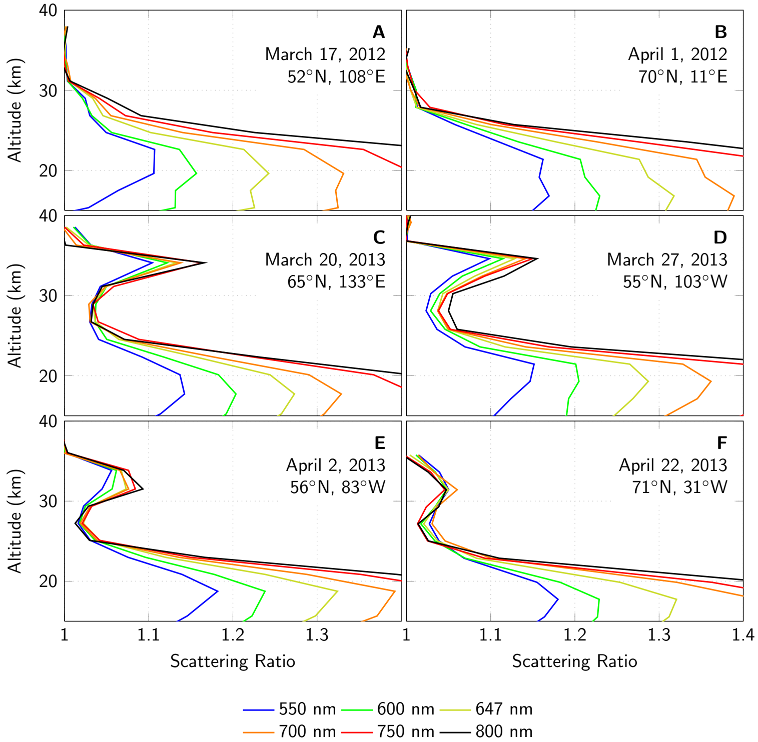

Fig. 1. Scattering ratios from six OSIRIS scans. Panels **(A)** and **(B)** are scans from 2012 and show typical background conditions. Panels **(C–F)** show scans with enhanced scattering at high altitudes. The enhancements near 30 to 35 km are attributed to the meteor, while the lower peak near 20 km is the Junge layer. Scattering ratios are shown at 6 wavelengths in approximately 50 nm intervals from 550 to 800 nm.

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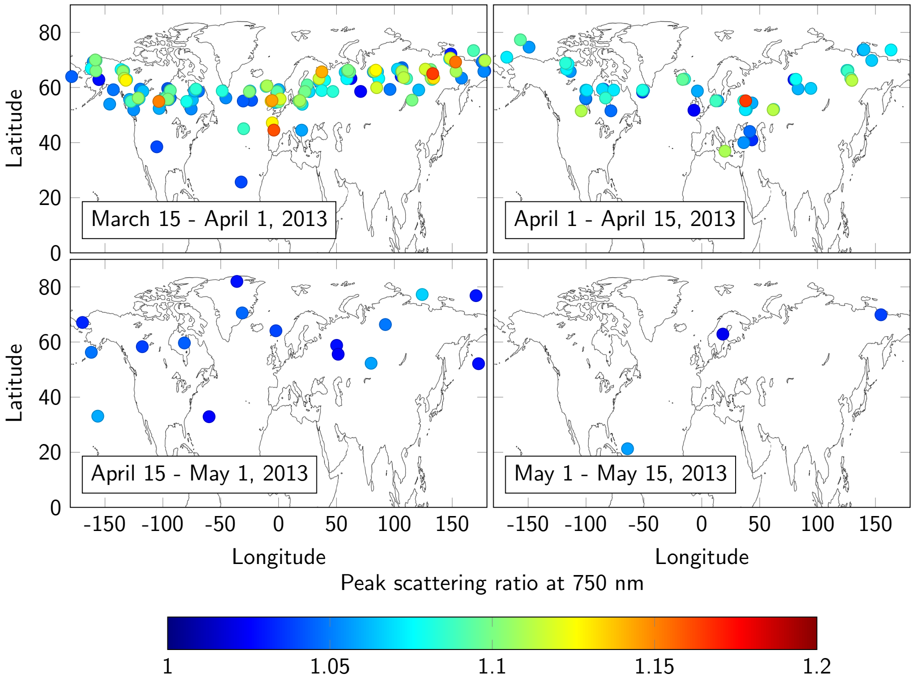

Fig. 2. Locations of scans which show meteoric enhancements. Color shows the 750 nm scattering ratio at the highest peak in the profile.

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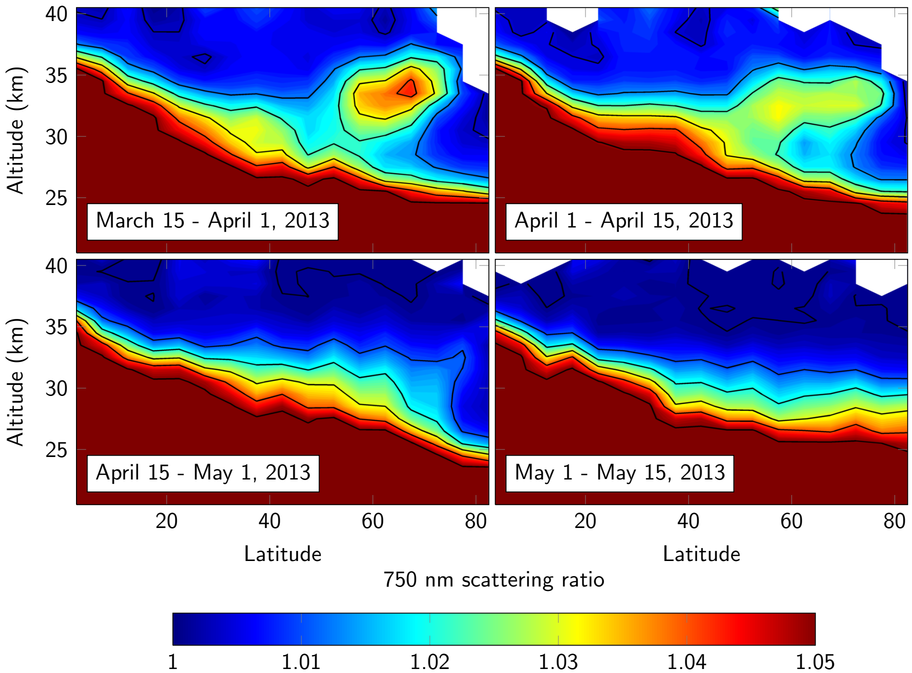

Fig. 3. Zonal average of 750 nm scattering ratios for four, two week time periods starting approximately one month after the meteor impact. Contours mark every 1 % increase over background scattering up to 5 %.