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COLOR AND SPECTRAL CHARACTERISTICS OF LONG-LIVED METEOR TRAIL FORMED BY THE TUNKA BOLIDE

A.V. Mikhalev
Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, mikhalev@iszf.irk.ru

Abstract. The paper addresses color characteristics and possible spectral composition of emission of a long-lived (~40 min) meteor trail of uncommon geometry, which was formed due to the bolide passage in the Tunka Valley on November 17, 2017. Analysis of dynamics of RGB channels of the meteor trail colored image shows that during the first ~8 minutes the meteor trail emission might have been contributed by the ionization trail. The ionization trail was formed by particles of the meteoric matter neutral and ionized components that were heated to high temperatures on the surface of the main meteoroid and separated from it. We also examine the discussed mechanism of heterogeneous chemical reactions occuring on the surface of meteoric dust (FeS, FeO, etc.) with participation of atoms and molecules of atmospheric gases. The yellowish color of the Tunka bolide meteor trail was assumed to be determined, first of all, by the emission of molecular nitrogen N_2 band within the 570–750 nm spectral range (the first positive system) and/or enhancement of NO^*_2 continuum in heterogeneous chemical reactions. The meteor trail emission spectrum should also include relatively bright atomic lines and molecular bands of the meteoric matter and atmospheric gases FeI, MgI, CaI, SiI, NaI, FeO and SO_2, OI, OH, etc.

Keywords: bolide, long-lived meteor trail, meteor trail color, meteor spectra.

INTRODUCTION

Spectral observations of meteors and meteor trails are usually used to study dusty plasma phenomena and effects resulting from the passage of meteoroids through Earth's atmosphere, the chemical composition of cometary and asteroid meteoroids, the mechanisms of disruption of meteoroids, as well as to develop a theory about meteor emission [Baggaley, 1976; Bronsten, 1981; Zinn, Drummond, 2007; Vojáček et al., 2015; Koukal et al., 2016; Silber et al., 2018].

This paper deals with color characteristics and possible spectral composition of the emission of a long-lived meteor trail of unusual geometry, which was formed by the passage of a bolide in the Tunka Valley (Eastern Siberia, the Republic of Buryatia) on November 17, 2017 [Mikhalev et al., 2019]. The main purpose of the study is to determine the spectral composition of the emission and the possible mechanism of the long-lived meteor trail. Ivanov et al. [2019] used the IRAF software package to carry out an analysis that provided the absolute magnitude of this meteor of ~ -7.3^m. This allowed the authors [Ivanov et al., 2019] to consider the meteor under study as a bolide.

OBSERVATIONAL RESULTS AND DISCUSSION

The passage of the Tunka bolide has been recorded by three specialized optical cameras located in two observatories of the Institute of Solar-Terrestrial Physics (ISTP) SB RAS. A CCD color camera Kodak KAI-340 was located at the Sayan Solar Observatory (SSO) near the village of Mondy (51.6° N, 100.9° E). The bolide flash was recorded by this camera near zenith. Two other black-and-white wide-angle cameras with interference light filters at the wavelengths of [OI] 557.7 and 630.0 nm atomic oxygen emission were installed at the Geophysical Observatory (GPhO) (51.8° N, 103.1° E). The passage of the bolide was observed near the western horizon; its trail was recorded by these cameras.

Figure 1 presents color images from [Mikhalev et al., 2019; Mikhalev, 2021] of the passage of the Tunka bolide and its long-lived trail, which show the bolide flash itself and individual frames of the spatio-temporal dynamics of the trail. In the meteor trail, in contrast to the bolide flash, there is a predominant yellowish color that allowed the authors of [Ivanov et al., 2019; Vasilyev et al., 2021] to suggest the presence of Na 589.0–589.6 nm sodium doublet in the meteor trail. The meteor trail was observed for ~40 min and propagated mainly horizontally.

Meteor trails of two types are usually discussed in the literature — dust and gas (or ionization). Dust trails are formed only by bright bolides as a result of condensation of meteoric matter vapors in the head and trail of the bolide. Dust long-lived meteor trails formed due to scattering of dusk light usually have a smoky-whitish or silver color, depending on their illumination by the Sun or Moon. Such dust meteor trails are formed at 60–40 km and below [Astapovich, 1958; Babadzhanov, 1987; Shustov, Rykhlova, 2010]. Ionization meteor trails arise from the formation of emitting meteor plasma [Bronsten, 1981; Smirnov, 1994]. It is difficult to attribute the analyzed meteor trail to dust meteor trails given its yellowish color, inferred from

Figure 1. Color images of the passage of the Tunka bolide and its long-lived trail [Mikhalev et al., 2019; Mikhalev, 2021]

optical observations, the occurrence of the ionization meteor trail, and the meteor glow heights (~85–105 km) [Ivanov et al., 2019; Mikhalev et al., 2019; Vasilyev et al., 2021]. Of special note are some reports on long-lived meteor trails with a predominance of orange, yellow-red, and near-infrared shades of glow, which are not associated by the authors with scattering of external emission as dust trails [Murade, 2001].

Figure 2 shows the temporal dynamics of the glow of the meteor trail head in RGB channels of the color camera (*a*) and the typical spectral sensitivity of the Kodak KAI-340 camera (*b*) [www.kodak.com/go/imagers]. Intensities in the RG channels are seen to be close with some predominance of intensity in the R channel. The whole time interval for reducing the brightness of the meteor trail in RGB channels is quite clearly divided into two intervals with different brightness reduction rates (marked with a vertical dashed line).

Here, the horizontal line with arrows marks the period of observation of the ionization trail recorded by a chirp ionosonde of vertical and oblique sounding [Mikhalev et al., 2019]. Considering the spectral sensitivity of RG channels of the matrix near the Na (589.0–589.6 nm) sodium doublet emission length as ~0.06 and ~0.18 respectively (Figure 2, *b*), we can assume that the contribution of sodium emission to the formation of the yellowish shade of the meteor trail is unlikely to be decisive.

In this case, it is necessary to search for an additional source of the emission in the spectral sensitivity region of the camera's R-channel. Kelley et al. [2000] and Clemesha et al. [2001] addressed a similar problem of interpreting the intense image of a long-lived meteor trail in the near-infrared spectral region and in channels of recording of the [OI] 557.7 and 630.0 nm atomic oxygen emissions. The authors suggested that the significant emission in the red region may be associated with the emission of OH hydroxyl molecules. The P branch of the OH (7-1) band could provide a signal in the channel with a 557.7 nm emission filter; and the P branch of the OH (9-3) band, in the channel with a 630.0 nm emission filter. Vasilyev et al. [2021] have used this interpretation to analyze the possible emission spectrum of the long-lived trail of the Tunka bolide under study.

Clemesha et al. [2001] have noted that emission excitation in a meteor trail may well differ from the excitation mechanism associated with natural airglow. It was not ruled out that there might be an unknown mechanism

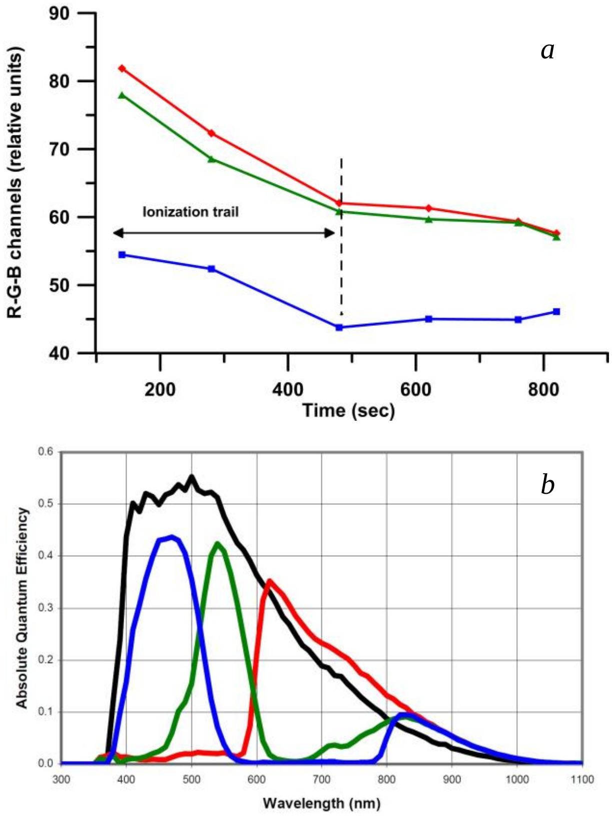

Figure 2. Temporal dynamics of the glow of the meteor trail head in RGB channels (*a*) and typical spectral sensitivity of the Kodak KAI-340 camera (*b*)

(for example, vibrational distribution in the O_2 atmospheric band) completely different from those recorded in airglow and auroras. A specific mechanism of the glow of the meteor trail analyzed can be proposed based on the concept of disruption of large meteoroids of some types, developed by academician S.S. Grigoryan [Grigoryan, 1979].

This concept explores the possibility of instantaneous disruption of some meteoroids under the action of aerodynamic force and spreading of meteoric matter in a direction transverse to the main motion of the core. This mechanism might have determined the main features of the meteor trail of the Tunka bolide, consisting in its unusual shape, duration of glow, velocity and trajectory of horizontal expansion.

In particular, the velocity of this meteor trail in the plane quasi-horizontal to the Earth surface, according to various estimates, is ~80–300 m/s [Ivanov et al., 2019;

Vasilyev et al., 2021], which is much lower than the velocities of meteoroids at the initial stages of their entry into the atmosphere (about tens of kilometers per second) leading to the formation of meteor trails. This excludes the classical mechanism of glow of meteor bodies associated with ionization and recombination processes in the meteor plasma and neutral atmosphere due to intense heating of a meteoroid by incoming atmospheric flow from direct consideration [Bronsten, 1981]. In the case of the low kinetic energy of meteoric matter associated with its directed motion and the meteor trail velocity comparable to the thermal velocities of air molecules (~300–400 m/s) at heights ~90–100 km, the meteor trail emission energy should probably be provided by the internal property and/or state of the meteoric matter. For example, the meteor trail emission should probably be provided by relaxing meteor plasma after its separation from the meteoroid head and by physicochemical reactions involving atmospheric components and meteoric matter during thermal collisions.

In this case, for instance, the results obtained in [Murade, 2001] are of particular interest. The author examines heterogeneous chemical reactions involving atmospheric gases, which occur on the surface of meteoric dust of meteoric components FeS, FeO, etc., such as the recombination reactions of atomic oxygen and nitric oxide $O+NO+dust \rightarrow NO_2^*+dust$ [Murade, 2001]. According to the author, heterogeneous chemical reactions can ensure the existence of long-lived (tens of minutes or more) meteor trails. This scenario of their formation, according to [Murade, 2001], consists of two stages. The first, implemented at high velocities of meteoric matter (approximately 1–10 kilometers per second), includes traditional mechanisms of heating and ablation, evaporation of meteoric matter, chemiluminescent reactions with O and O_2 atmospheric components, and physicochemical reactions of formation of meteor plasma. After the meteoric matter decelerates to velocities close to thermal ones, heterogeneous chemical reactions become the dominant processes providing the possible meteor glow. Molecular and atomic emission sources are supposed to be SO_2, FeO, Fe, and NO_2 in low excited electronic states, whereas the expected spectra should consist of a continuum NO^*_2, FeO, and SO_2 bands, as well as numerous iron lines. The probable heights of ~100 km are indicated at which this mechanism for maintaining long-lived meteor trails can be realized.

Noteworthy here is one feature of the NO^*_2 continuum emission in the atmospheric component of undisturbed nightglow. Despite the relatively low intensity of the continuous spectrum (~20 R/nm), the total intensity in the spectral range of ~200 nm, comparable to the spectral ranges of RGB channels of a color camera, can average ~4000 R, which is by an order of magnitude greater than the mean intensity of the brightest discrete line of visible spectrum 557.7 nm [Fishkova, 1983; Mikhalev et al., 2016]. With sufficient enhancement of the NO^*_2 continuum in the above heterogeneous chemical reactions, this emission can make a major contribution to the exposure of RGB pixels of a color camera and form the color of long-lived meteor trails of one of the types with the yellowish shade [Murade, 2001].

Figure 3 illustrates the dynamics of heights of reference points of the meteor trail from the Tunka bolide according to [Vasilyev et al., 2021]. On the left is an image of the Tunka bolide, reduced to the heights of its observation [Ivanov et al., 2019; Vasilyev et al., 2021]; on the right is a meteor trail image indicating the points for which the heights of the meteor trail were calculated [Vasilyev et al., 2021].

The meteor trail can be seen to occur mainly at heights ~85–105 km. A similar range of heights for propagation of this meteor trail (~85–96 km) was observed in [Ivanov et al., 2019; Mikhalev et al., 2019].

The propagation velocities of this meteor trail were subsonic [Ivanov et al., 2019; Mikhalev et al., 2019; Vasilyev et al., 2021]. Such velocities cannot ensure the implementation of traditional mechanisms of heating, ablation, and meteor glow, usually considered when a meteoroid enters the atmosphere at velocities of several tens of kilometers per second. It is conceivable that the meteor trail might have been formed from a liquid film and/or by evaporation of the solid phase of the meteoric matter [Bronsten, 1981] at the stage of separation of neutral and ionized components of the meteoric matter already heated to high temperatures from the surface of the main meteoroid body.

Mikhalev et al. [2019] have estimated variations in the velocity of meteoric particles with sizes from 1 μm to 10 mm for heights ~70–120 km for horizontal particle motion. It was shown that the mode of the meteoric particle motion without deceleration on the characteristic time scale of ~10^3 s at heights 70–90 km can be realized only for sufficiently large particles of more than 100 μm (for a height of 120 km, more than 1 μm).

Considering the peculiarity of the behavior of the meteor trail glow in RGB channels, associated with a change in the rate of decrease in the intensity of the trail glow after ~480 s (Figure 2), we can assume that the glow of the meteor trail analyzed might have been formed by two different mechanisms. This could be the traditional mechanism of meteor glow due to emission of fine-dispersed meteoric matter particles, heated to high temperatures (~2000 K), and meteor plasma consisting of ionized and neutral meteoric matter components and atmospheric gases [Bronsten, 1981].

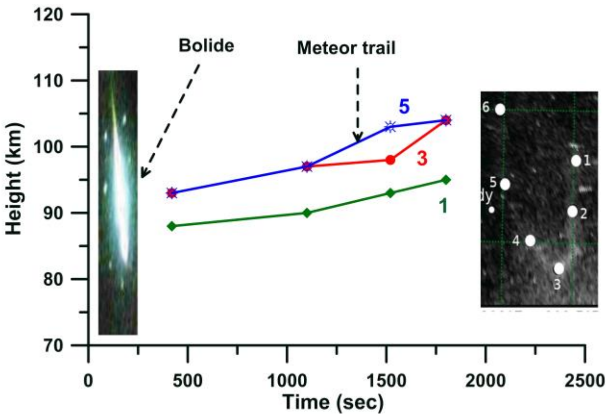

Figure 3. Dynamics of observation of meteor trail heights at reference points. Data is used on three reference points of the trail, indicated on the right in the image from [Vasilyev et al., 2021]

The meteor trail emission spectrum in this case could be close to the traditional spectra of meteors themselves. The second mechanism may involve heterogeneous chemical reactions [Murade, 2001], and it might have worked throughout the period of observation of the meteor trail.

In this case, the meteor trail at the interval of observation of the ionization trail could represent relaxing meteor plasma and cooling fine-dispersed meteoric matter particles, on the surface of which heterogeneous chemical reactions occurred over the entire period of observation of the meteor trail. The spectral composition of the trail emission could consist of the traditional spectra of meteor trails and the spectra of heterogeneous chemical reactions proposed in [Murade, 2001].

Meteor spectra are comprised of emission of atomic lines of FeI, MgI, CaI, SiI, NaI, etc., ion lines of the same elements, and atmospheric lines and bands OI, NI, N_2, OH and have some features for various meteors and meteor showers [Smirnov, 1994; Vojáček et al., 2015]. Ivanov et al. [2019], according to triangulation observations, assigned the Tunka bolide under study to the Leonids meteor shower. Figure 4 gives examples of typical meteor emission spectra from the Leonids meteor shower, taken from a large catalog of representative meteor spectra with low spectral resolution [Vojáček et al., 2015]. We can see that the emission of N_2 molecular nitrogen bands can make a significant contribution to the integral exposure of the RGB channels of the color camera in the meteor trail under study. Table lists general characteristics of atmospheric bands of N_2 molecular nitrogen [Vojáček et al., 2015]. Note that the presence of insignificant emission of the NaI (589.0–589.6 nm) sodium doublet in the given spectra probably could not provide the yellowish shade of the meteor trail discussed in its early studies [Ivanov et al., 2019; Vasilyev et al., 2021]. Since the color formation system used in the RGB matrix adopted sums up the total emission within the spectral sensitivity of the color channels, in this case the yellowish shade of the meteor trail could be provided, for example, by the corresponding ratio of the emission distribution of the N_2 molecular nitrogen to that of the OI (777.4 nm) atomic oxygen in the R and G channels of the color matrix, at least over the period of observations of the ionization trail.

As for recording of the meteor trail from the Tunka bolide by wide-angle cameras with narrow-band interference filters (~2 nm) centered on the forbidden [OI] 557.7 and 630.0 nm atomic oxygen lines, several chemical elements can be pointed out whose emission could be observed in the emission of the meteor trail at 557.7 and 630.0 nm. This is the P branch of the OH (7-1) hydroxyl band, which might have provided a signal in a channel with a filter for the 557.7 nm emission, the P branch of the OH (9-3) hydroxyl band in a channel with a filter for the 630.0 nm emission [Clemesha et al., 2001], and the NO_2 emission continuum in the heterogeneous chemical reactions proposed by Murade [2001] for interpreting long-lived meteor trails. The meteor glow (at least during the period of observation of the ionization trail), for example, in the FeI 629.8 and 630.15 nm lines [Smirnov, 1994], should also not be excluded for the interference filter for the 630.0 nm emission.

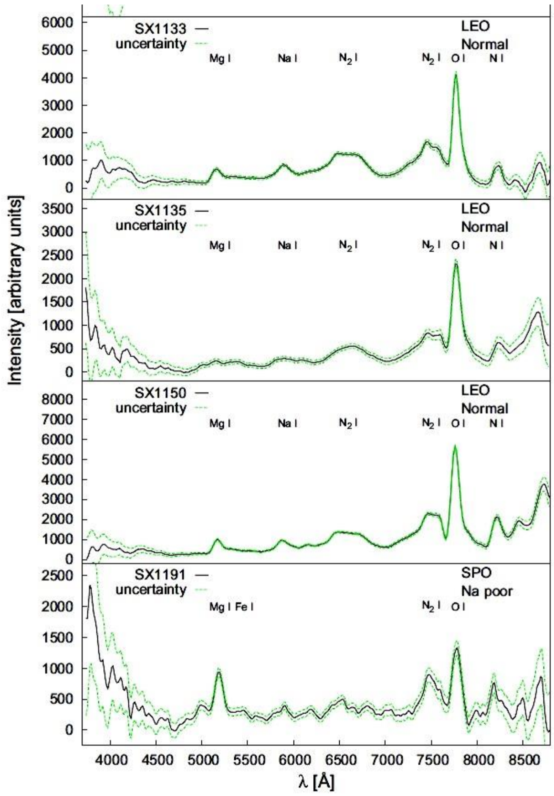

Figure 4. Examples of typical emission spectra of meteors from the Leonids meteor shower [Vojáček et al., 2015]

Atmospheric molecular bands

Wavelength, nm	Chemical element	Multiplet
570–600	N_2 (1st positive system)	Δν=4
620–680	N_2 (1st positive system)	Δν=3
700–750	N_2 (1st positive system)	Δν=2

CONCLUSIONS

The analysis of the dynamics of color characteristics of the long-lived meteor trail (RGB channels of a color image) during the passage of the Tunka bolide on November 17, 2017 and the consideration of the mechanisms of long-lived meteor trails discussed in the literature lead to the following preliminary conclusions.

1. The meteor trail was formed as a result of the emission of particles of neutral and ionized meteoric matter components initially heated to high temperatures on the surface of the main meteoroid and separated from it and the heterogeneous chemical reactions that occur on the surface of meteor dust particles (FeS, FeO, etc.), involving atoms and molecules of atmospheric gases. The former emission mechanism contributed to the meteor trail emission during the existence of the ionization trail (first ~480 s). The mechanism of heterogeneous chemical reactions is likely to contribute to the meteor trail emission over the entire period of its observation.

2. Taking into account the peculiarities of color formation in the RGB color space with wide spectral bands of RGB channels, the yellowish shade of the meteor trail of the Tunka bolide could, first of all, be deter-

mined by the emission of N_2 molecular nitrogen bands in the spectral ranges 570–600, 620–680, and 700–750 nm (1st positive system) and/or by the enhancement of the NO^*_2 continuum in heterogeneous chemical reactions involving meteoric dust and atmospheric gases.

3. The spectral composition of the meteor trail emission at various stages of its development, according to the above mentioned mechanisms of meteor and meteor trail emission, should also contain the following relatively bright atomic emission lines and molecular bands: atomic lines of meteoric matter elements FeI (in particular, 516.9, 520.5, 629.8, and 630.15 nm), MgI (457.1, 518.2 nm), CaI, SiI, sodium doublet NaI (589.0–589.6 nm), etc.; atmospheric oxygen lines [OI] (777.4, 557.7 nm); OH hydroxyl bands (in particular, the 7-1 and 9-3 bands); molecular bands FeO and SO_2, and numerous Fe lines in heterogeneous chemical reactions.

The findings call for further research into spectra of such meteor trails with high spectral resolution.

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