Planetary and Space Science (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Spectra and physical properties of Taurid meteoroids

Pavol Matlovič[a,*], Juraj Tóth[a], Regina Rudawska[b], Leonard Kornoš[a]

[a] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
[b] ESA European Space Research and Technology Centre, Noordwijk, The Netherlands

ARTICLE INFO

Keywords:
Meteor shower
Meteoroid stream
Comet
Asteroid
Taurids
2P/Encke

ABSTRACT

Taurids are an extensive stream of particles produced by comet 2P/Encke, which can be observed mainly in October and November as a series of meteor showers rich in bright fireballs. Several near-Earth asteroids have also been linked with the meteoroid complex, and recently the orbits of two carbonaceous meteorites were proposed to be related to the stream, raising interesting questions about the origin of the complex and the composition of 2P/Encke. Our aim is to investigate the nature and diversity of Taurid meteoroids by studying their spectral, orbital, and physical properties determined from video meteor observations. Here we analyze 33 Taurid meteor spectra captured during the predicted outburst in November 2015 by stations in Slovakia and Chile, including 14 multi-station observations for which the orbital elements, material strength parameters, dynamic pressures, and mineralogical densities were determined. It was found that while orbits of the 2015 Taurids show similarities with several associated asteroids, the obtained spectral and physical characteristics point towards cometary origin with highly heterogeneous content. Observed spectra exhibited large dispersion of iron content and significant Na intensity in all cases. The determined material strengths are typically cometary in the K_B classification, while P_E criterion is on average close to values characteristic for carbonaceous bodies. The studied meteoroids were found to break up under low dynamic pressures of 0.02–0.10 MPa, and were characterized by low mineralogical densities of 1.3–2.5 g cm^{-3}. The widest spectral classification of Taurid meteors to date is presented.

1. Introduction

The Taurid complex is an extensive population of bodies associated with comet 2P/Encke and certainly one of the most interesting structures in the Solar System. It is the widest known meteoroid stream in the Solar System, and has been linked with several catastrophic incidents including the Palaeolithic extinctions (Napier, 2010) and the Tunguska event of 1908 (Kresák, 1978). The low inclination of the orbit of the stream causes gravitational perturbations of inner solar system planets (Levison et al., 2006), resulting in the diffuse structure of the Taurid complex. The Earth encounters different parts of the stream annually from September to December, giving rise to several meteor showers, most significantly the Northern and the Southern Taurids peaking in late October and early November. Owing to the wide spread of the Taurid stream, the zenithal hourly rates of the resulting meteor showers usually do not exceed 5. However, the observed activity of the shower is known to be rich in bright fireballs, which induced discussions about the potential of Taurids in producing meteorites (Brown et al., 2013, 2016; Madiedo et al., 2014). While the orbits of most meteoroids are quite dispersed, it is still likely that the Taurid stream has a narrow and dense core consisting of particles concentrated near the orbit of the stream's parent object. It is often inferred that strong bombardment episodes have resulted at epochs when the material of the stream's core reached Earth intersection.

Although comet 2P/Encke is generally considered as the parent object of the Taurids (Whipple, 1940), various small near-Earth objects (NEOs) and recently even two instrumentally observed carbonaceous meteorite falls have been linked with the orbit of the stream (Haack et al., 2011, 2012). 2P/Encke is a short-period comet moving on an orbit dynamically decoupled from Jupiter with an orbital period of 3.3 years. The peculiar orbit of the 2P/Encke raises interesting questions relating its origin and the origin of the Taurid complex. Today, the most supported hypothesis claims that comet 2P/Encke and several other bodies including large number of meteoroids were formed by a fragmentation of an earlier giant comet. The theory was first suggested by Whipple (1940), and later elaborated by Asher et al. (1993) who argued that the Taurid meteoroid streams, 2P/Encke, and the associated Apollo asteroids were all formed by major comet fragmentation 20–30 ky ago. Napier (2010) suggested that the debris of this fragmentation event could have caused the Palaeolithic extinctions

* Corresponding author.
E-mail address: matlovic@fmph.uniba.sk (P. Matlovič).

http://dx.doi.org/10.1016/j.pss.2017.02.007
Received 14 September 2016; Received in revised form 8 February 2017; Accepted 10 February 2017

followed by the return to ice age conditions.

The broad structure of the Taurid complex was studied by several authors with over 100 of NEO candidates associated with the Taurid complex. Porubčan et al. (2006) identified 15 different sub-streams of the complex and by applying stricter criteria for generic relations found associations with 9 NEOs. The presence of these bodies in the Taurid complex implies the possibility that part of the Taurid meteoroid population might be produced as the decay or impact products of the associated asteroids. The connection to carbonaceous chondrites represented by Maribo and Sutter's Mill meteorites also needs to be further investigated. We expect significantly different spectral and structural properties of such bodies in comparison to fragile cometary meteoroids originating in 2P/Encke. So far, the efforts in finding traces of the common origin of the largest Taurid complex bodies gave rather sceptical results. Popescu et al. (2014) studied the spectral properties of the largest asteroids associated with the Taurid complex, but found no evidence supporting mutual relation. Similarly, the spectroscopic and photometric measurements of Tubiana et al. (2015) found no apparent link between comet 2P/Encke, the Taurid complex NEOs, and the Maribo and Sutter's Mill meteorites.

The Taurid meteor shower occasionally exhibits enhanced activity due to a swarm of meteoroids being ejected by the 7:2 resonance with Jupiter (Asher, 1991). The outburst of meteors observed in 2015 was anticipated by the model of Asher and Izumi (1998), which previously predicted enhanced activities of Taurids in 1998, 2005 and 2008. Some features of the Taurid meteor shower activity suggest that the Taurid swarm exist only in the southern branch (Southern Taurids) and not in the northern branch (Shiba, 2016).

The two main branches of the Taurid complex, the Northern and the Southern Taurids are well observed meteor showers with established orbital characteristics, which clearly trace them to comet 2P/Encke. The majority of Taurid shower analyses have been focused on orbital properties of the stream, with only several Taurid meteor spectra observed before the outburst of 2015 (e.g. Srirama Rao and Ramesh (1965), Madiedo et al. (2014)). Borovička et al. (2005) analyzed six Taurid emission spectra observed by low-resolution video spectrograph, identifying three Na-enhanced meteoroids, while another three Taurids have been classified as normal type. Using the same instrumentation, Vojáček et al. (2015) observed three more normal type Taurids including one meteoroid with lower iron content. The determined spectral characteristics of normal to enhanced sodium content and lower iron content would suggest cometary parent body. Asteroidal meteoroids are expected to be depleted in volatile sodium by the processes of space weathering (e.g. Borovička et al. (2005), Trigo-Rodríguez and Llorca (2007)). Determined spectral properties give us valuable input into the studies of the origin of meteoroids; however, for doubtless differentiation between cometary and asteroidal particles, precise orbital and ideally physical characteristics must be obtained.

Besides the two major Taurid meteor showers, there are several smaller meteor streams associated with the Taurid complex. Most notably, this includes the Piscids, Arietids, chi Orionids, and the daytime showers of beta Taurids and zeta Perseids, encountered by the Earth in June and July. The beta Taurids and zeta Perseids have been shown to be the daytime twin branches to the Southern and the Northern Taurids respectively. The possibility of Taurid sub-streams being produced by a different parent object was discussed by Babadzhanov (2001), who found shower associations to each of the Taurid complex asteroids and interpreted them as the evidence for the cometary origin of these asteroids. Recently, Olech et al. (2016) found very close resemblance between the orbits of two 2015 Southern Taurid fireballs and the orbits of 2005 UR and 2005 TF50 asteroids. Precise observations of Taurid fireballs observed during the 2015 outburst were examined by Spurný et al. (2017), who emphasized the orbital resemblance of the 2015 Taurids to the orbits of asteroids 2015 TX24 and 2005 UR. They argue that the outburst may have been caused by Taurid filaments associated with these asteroids.

All of the previous associations between different sub-streams of the Taurids and the Taurid complex asteroids were based on the orbital similarities. Certainly, studying the spectral and physical properties of the Taurid meteoroids could extend our understanding of the origin and evolution of the Taurid complex and its individual meteoroid streams.

2. Observations and data reduction

The outburst of Taurid meteors in 2015 was observed globally by numerous meteor networks. Here we present the detailed analysis of 33 Taurid meteor spectra captured by the spectral All-sky Meteor Orbits System (AMOS-Spec) (Rudawska et al., 2016). Particular focus will be placed on 16 of these spectra, which were observed in Modra Observatory, Slovakia. Multi-station observations for 14 of these meteors were provided by four AMOS stations comprising the Slovak Video Meteor Network, which carries out routine meteor observations on every clear night (Tóth et al., 2011, 2015), supplemented by individual observations provided by Pavel Spurný (European Fireball Network) and Jakub Koukal (Central European MEteor NeTwork).

Additional 17 single-station Taurid spectra were observed by AMOS system in Chile during the testing for two new, now already established, southern AMOS stations. The system made observations during the activity peak between November 5 and November 10 at San Pedro de Atacama in the Atacama Desert. The observational conditions here enable much higher efficiency in capturing meteor events. These single-station meteors were identified as members of the Taurid stream based on their estimated radiant position and geocentric velocity.

The AMOS-Spec is a semi-automatic remotely controlled video system for the detection of meteor spectra. The main display components consist of 30 mm f/3.5 fish-eye lens, image intensifier (Mullard XX1332), projection lens (Opticon 1.4/19 mm), and digital camera (Imaging Source DMK 51AU02). This setup yields a 100° circular field of view with a resolution of 1600×1200 pixels and frame rate of 12/s. The incoming light is diffracted by a holographic 1000 grooves/mm grating placed above the lens. The spectral resolution of the system varies due to the geometry of the all-sky lens with a mean value of 1.3 nm/px. A 500 grooves/mm grating was used for the observations in Chile, providing a mean spectral resolution of 2.5 nm/px. The system covers the whole visual spectrum range from app. 370–900 nm. The spectral response curve of the AMOS-Spec system (camera, image intensifier, and lens) is given in Fig. 1. It was determined by measuring the known spectrum of Jupiter and is normalized to unity at 480 nm. The typical limiting magnitude of the system for meteors is approx. +4 mag., while only meteors brighter than approx. 0 mag. can be captured along with its spectrum. More details about the properties and capabilities of the AMOS systems can be found in Tóth et al. (2015). The main disadvantage of the wide-field camera is the interference of the moonlight and bright Moon spectrum causing occasional difficulties in meteor detection. Fortunately, the Moon illumination percentage was descending from 45% to 10% during the activity peak of the 2015 Taurids (November 4–November 8) and caused no significant problems in spectra analysis.

2.1. Spectra reduction

The all-sky geometry of the lenses causes slight curvature of the meteor spectra captured near the edge of the FOV. For this reason, each spectrum was scanned manually on individual video frames using ImageJ[1] program. Before scanning the spectra, all of the analyzed spectral events were corrected for dark frame, flat-fielded, and had the star background image subtracted. We are particularly interested in the relative intensities of the Na I – 1, Mg I – 2, and Fe I – 15 multiplets, which form the basis of the spectral classification of meteors established

[1] 〈https://imagej.nih.gov/ij/〉.