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Geminid Meteor shower activity 2003–2005 as observed by Gadanki radar

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Abstract

The distribution of meteor signals reflected from a backscatter radar is considered according to their duration. This duration time (T) is used to classify the meteor echoes and to calculate the mass index (S) of different meteoroids of shower plus sporadic background. Observational data on particle size distribution of the Geminid meteor shower are very scarce, particularly at low latitudes. In this paper the observational data from Gadanki radar (13.46°N, 79.18°E) have been used to determine the particle size distribution and the number density of meteoroids inside the stream of the Geminid meteor shower. The mean variation of meteor number density across the stream has been determined for three echo duration classes, $T<0.4$, $T=0.4$–1 and $T>1$ s. We are more interested in the appearance of echoes of various durations and therefore meteors of various masses in order to understand more on the filamentary structure of the stream. It is observed that the faint particle flux peaks earlier than the larger particles. We found a decreasing trend in the mass index values from the day of peak activity to the next observation days. The mass index profile was found to be U-shaped with a minimum value near the time of peak activity. The observed minimum s values are 1.64 ± 0.05 and 1.65 ± 0.04 in the years 2003 and 2005, respectively. The activity of the shower indicates the mass segregation of meteoroids inside the stream. Our results are best comparable with the "scissors" structure model of the meteoroid stream formation of Ryabova [2007. Mathematical modeling of the Geminid meteoroid stream. Mon. Not. R. Astron. Soc. 375, 1371–1380] by considering the asteroid 3200 Phaethon as an extinct comet.

Keywords: Meteors; Geminids; Activity; Mass index; Radar

1. Introduction

The Geminid meteor stream is one of the highest flux annual meteor showers currently visible from the earth. The regular appearance of its high activity near 13 December is its main feature. The current rate profile for the Geminid shower is very asymmetric, with the peak activity occurring only a day or so from the end of the display (Roggemans and Koschack, 1991; Williams and Wu, 1993). The generally accepted parent body of the shower is asteroid (3200) Phaethon. Orbit of the shower and its parent body is notable by the short period (~1.5 years) and small perihelion distance (0.14 AU). Orbital elements of the shower are extremely different from all other major showers intersected by the Earth (Rendtel et al., 1995). Observational data as well as theoretical modelling of the stream indicate that the appearance of the Geminid shower is a relatively recent phenomenon for Earth-based observations and the Earth will continue to intersect the Geminid meteoroid stream until about the year 2100 (Hunt et al., 1985). It is important to monitor the annual activity of meteor showers in order to know the structure and evolution of meteoroid streams. Interest in this particular shower is due to the fact that since the discovery of Phaethon in 1983, its true nature is still considered to be an unsolved issue. The question arises as to whether it is a regular asteroid or an extinct comet.

Metallic abundances of a 2004 Geminid meteor spectrum, especially Na/Mg depletion and excess Ni/Mg, show different features from other meteors of cometary origin (Kasuga et al., 2005a, b). Search for activity in 3200

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Phaethon by deep optical imaging has shown no sign of cometary behaviour (Hsieh and Jewitt, 2005). Research may suggest a lack of volatiles in Phaethon, which may be an asteroidal feature. But, spectroscopic analysis of Geminid meteors shows that the Mg/Fe ratio was 1.5–3 times larger than the chondritic value. Similar values were found earlier for cometary showers Leonids and Perseids (Borovička, 2004). The high Mg/Fe ratio suggests cometary origin of Geminid meteors (Borovička, 2006). Ryabova (2001) contemplates the requirement of observational data in order to support or reject the existence of the proposed model considering the asteroid 3200 Phaethon as an extinct comet, in order to explain the bimodal rate curve of Geminid meteor shower activity and ''scissors'' structure model of the meteoroid stream. In this point of view, the present observations are most important.

The activity of meteor shower can be studied from various aspects. We confine ourselves here to the echo duration method to study the particle size distribution and the structure of stream as described in literature (Šimek, 1975; McIntosh and Šimek, 1980; Šimek and McIntosh, 1989; Pecina and Šimek, 1999). Comparison between the meteoroid lifetime and the mass distribution of the shower meteoroids gives an idea about the stream structure and age. The Geminid meteor shower activity has been observed regularly by radar since 1957 at Springhill Observatory near Ottawa, Canada and also at Ondřejov meteor radar of the Czech Republic since 1958 (McIntosh and Šimek, 1980; Šimek and McIntosh, 1989). Results of long-term radar meteor records from 35 Geminid campaigns in four echo duration categories carried out from 1958 to 1997 found the particle size dependence of the widths and the degree of skewness (Pecina and Šimek, 1999). The activity profile of the shower suggests an age of the meteoroid stream of several thousands years (Ryabova, 1999). Observational data on particle size distribution inside the stream and on duration of meteor echoes are very scarce, particularly at low latitudes. In this context, we investigate stream structure and particles size distribution inside the stream using observational data collected with the Gadanki radar (13.46°N, 79.18°E), which is at a lower latitude than most of the other meteor radars.

The Gadanki radar is monostatic coherent-pulsed Doppler radar operating at 53 MHz with a peak power aperture product of $3\times10^{10}\,\mathrm{W\,m^2}$. For meteor-related studies, the antenna beam will be tilted in five directions, i.e., North, South, East, West and Zenith. Observational specifications used in meteor mode of operation are given in detail by Phanikumar et al. (2006). The technical specifications and system description of this radar were given in Rao et al. (1995).

In this paper, first we outline how the atmospheric radar like Gadanki radar can be effectively used for observation of occurrence of meteor trails in the upper atmosphere. In the following section, the observational method of radar meteor echoes of different echo duration is discussed. Comparative results of the Geminid meteoroid stream for 3 different years are presented in the third section. In the last two sections, discussion and tentative conclusions are drawn from the observations presented here.

2. Meteor echo duration theory

Due to interaction with the atmosphere, a meteoroid's surface is heated up and vapourizes. The vapourized atoms collide with other atmospheric particles, and as a result of these inelastic collisions, an ionized column is created. This ionization trail makes the meteor detectable with radar techniques, because plasma reflects radio waves. The plasma inside the trail scatters the transmitted signal according to the number of electrons per unit length (line density) and the radar frequency. The radar signal received from a meteor trail is a measure of the power and phase of the total scattering from the trail within the radar beam, although there are biases that can attenuate the power received. The main factors that cause the attenuation in echo power are the ambipolar diffusion, the initial trail radius effect and the finite meteor velocity effect (Thayaparan, 2000).

Applying the classical radio echo theory for backscatter radar like Gadanki radar to explain the echoes from meteor trails, it is assumed that in the wake of the meteor a stationary column of free electrons is created with a diameter that is small in comparison to the radar wavelength. According to the electron density of the ionized trail, the meteors can be classified into two limiting cases: very high electron line density (overdense) and very low electron line density (underdense). An overdense trail is detected when the plasma frequency is greater than the radar frequency. Under this condition, overdense or secondary scattering becomes important and the trail can be modelled as a metallic cylinder. The transmitted pulse cannot penetrate through it and gets reflected at its surface. The ionized cylindrical trail volume expands radially by diffusion and, consequently, the trail radius increases. This reduces the number density of the electrons in the trail. The imaginary dielectric constant becomes less negative and the transmitted signal can penetrate through the trail, where every electron acts like an individual scatterer. For the overdense trail, it is assumed that the radius of the trail is far smaller than the incident wave length, the electron line density q_o is constant; the trail is perpendicular to the radar beam direction and the distribution of the electron concentration of the trail is Gaussian. If the initial radius of the trail is zero, the radar equation can be described as (Davies, 1965; Brown and Lovell, 1962; Millman and McKinley, 1963)

$$p_r = \frac{P_t G^2 \lambda^2 \sqrt{(4Dt\ln(R_e q_0 \lambda^2))/(4\pi^2 Dt)}}{(32\pi^2 r^3)}, \quad (1)$$

where P_r is the received echo power, P_t is the transmitted power, G is the antenna gain (the radar is assumed to be monostatic), r is the range, λ is the radar wavelength, R_e is the classical electron radius ($\sim 2.8\times10^{-15}$ m), D is the