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The activity and mass distribution of the Geminid meteor shower of 1996-2007 from forward scatter radio observations

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Abstract. The activity and mass distribution of the Geminid meteor shower of 1996 - 2007 based on radio observations by a forward-scatter system operating along the Bologna - Modra baseline are analysed and presented. Activity curves corrected for an observability function derived for the system indicate a multiple-peak structure of the shower.The global activity curve for overdense echoes of durations $\geq 1s$ and $\geq 8s$ depicts two peaks at solar longitude 261.7°, 262.3° and 261.9°, 262.3°, respectively. Larger particles are concentrated more to the centre of the shower and slightly shifted towards the descending branch of the shower activity. The mean mass exponent of the Geminids is 1.73.

Key words: meteor showers – radio observations

1. Introduction

The Geminid meteor shower with visual zenithal hourly rates over one hundred meteors is one of the best known, relatively rich and most stable meteor displays of the year. The shower is active in December for about two weeks, having maximum on December 13-14 and with the radiant at $\alpha = 113°; \delta = 32°$ is for the northern hemisphere observers well observable for the whole night. It moves on a very short period orbit with a period of revolution of only 1.57 year. Since the discovery of Whipple (1983) that it is probably associated with asteroid 3200 Phaethon, the Geminids are one of the most intensively studied meteoroid streams. The existence of the shower was first recognized in England and the United States in 1862 (King, 1926) and the Earth will continue to cross it probably until about 2100 (Hunt et al., 1985).

The shower is observed by all available means and the longest series of radio observation covering 35 returns of the stream were performed by a back-scatter meteor radar at Ondřejov Observatory (Czech Republic) in 1957-1997 (Pecina and Šimek, 1999). The mean activity profiles showed a systematic change of the peak and width of activity depending on the distribution of echo duration across the stream. Further, that faint particles are more concentrated in the inner orbits, while larger particles dominate in the outer orbits. McIntosh (1974), analysing radar data, disclosed periodic variations which associated with a 3:5 commensurability of the average orbital periods of the Geminids and the Earth. This would mean that any observable structures in the stream cannot be stable for a long time. From a series of ten years (1988-1997) of visual observations Rendtel and Brown (1999) disclosed an indication of a double maximum on the activity curve of the shower. The first main peak at solar longitude $\lambda = 261.12^o$ is followed by a plateau until the descending branch begins at $\lambda = 262.36^o$. Later, Rendtel (2004), analysing a series of almost fifty years (1955-2002) of visual Geminid observations including also those from the previous analysis (Rendtel and Brown, 1999), has showed that a general activity profile of the shower seems to remain stable and there is observed a shift of the peak of about 0.008^o (approx. 0.2 hours) per year. Currently, the rate maximum occurs at solar longitude 262.16^o and a second peak appears at solar longitude 262.34^o.

In 1996 started regular radio observations of the shower also by a new forward-scatter system for meteor observation operating along two almost rectangular baselines Bologna-Lecce and Bologna-Modra. The transmitter is located at Budrio near Bologna (44.6°N; 11.5°E, Italy) and the receivers are at Lecce (40.3°N; 18.2°E, Italy) and Modra (48.4°N; 17.3°E, Slovakia). The first observations of the Geminids by the system (BLM forward-scatter) were performed already in 1992-1993, however over the baseline Bologna-Lecce only (Cevolani et al., 1995a). Results of a longer series of observations by the BLM system over a period of 1996-2003, presenting the activity curves for long-duration echoes ($t \geq 8s$), were published by Pupillo et al. (2004).

In the present contribution the activity and mass distribution of the Geminid meteor shower based on observations carried out by the Bologna-Lecce-Modra forward scatter radio equipment in 1996-2007 over the baseline Bologna-Modra, taking into account the observability function constructed for the system, are investigated and discussed.

2. Observations of the Geminids in 1996 - 2007

The BLM system (Cevolani et al., 1995b) was designed for a systematic monitoring of meteor activity in selected shower and sporadic periods. The equipment operates along both baselines each month for about two weeks, covering the periods of all major meteor showers. Standardly, a meteor shower activity is obtained by subtracting sporadic background echoes from all echo counts in corresponding time intervals. For sporadic background are normally taken the periods of two-three days prior to or after a shower activity, or by combination of both periods (prior to and after the shower activity).

The present day data obtained by the BLM cover a series of observations of the Geminids from 1996 till 2007. Over the twelve years, the Geminids were almost regularly monitored in the period December 8-19 in which occasionally some short-term interruptions appeared due to various causes. Only data from 2001 and 2003, due to a malfunction of the transmitter, are missing completely.

A similar analysis of the Geminid shower monitored by the BLM in 1996-2003 made by Pupillo et al. (2004) was based on a standard procedure utilizing besides subtraction of the sporadic background from all echo counts also a correction for the zenithal distance of the shower radiant. The procedure did not take into account also directional sensibility and corresponding contours at the meteor zone of the transmitting and receiving antennas. These may to a rather large extent influence final results concerning the activity and flux of the meteor shower reduced from the observations. Therefore, for the present analysis a correction for the observability function of the BLM system was developed (Zigo, 2008) and applied to the observations obtained over the baseline Bologna-Modra.

The derivation of the function was based on the ellipsoidal theory presented by Hines (1958). The observability of a meteor shower is strongly dependent on the geometry of the forward-scatter baseline and the shower radiant position. The values of the function range from 0 when the shower radiant is below the horizon up to 1 under the optimal condition for detection of the shower members. The daily course of the observability function for the Geminids was calculated for the mean shower radiant at $\alpha = 113°; \delta = 32°$, its mean daily motion of $\Delta\alpha = 1°; \Delta\delta = -0,1°$, and the solar longitude of the shower maximum at $\lambda_{max} = 262°$.

The best observability $\sim 100\%$ appears for radiant zenithal distances $45° - 50°$ and azimuths perpendicular to the forward-scatter baseline. For the Bologna - Modra setup and Geminid radiant positions, the best value of the observability function is $\sim 83\%$. The course of the function corresponding to the Geminids is plotted (dashed curves) in Figs. 3 and 4.

To avoid large unrealistic corrections of the observed echoes at not optimal observing conditions corresponding to low values of the observability function (OF), an acceptable limiting value of the function has to be set. For a limiting value of the function of 20% corrections of the observed numbers of echoes are still realistic and acceptable. As for the BLM system the Geminid radiant is above the horizon for about 18 hrs, it itself reduces "visibility" of the radiant by the system to three-quarters ($\sim 75\%$) of a day. Applying to the data a limiting value of $OF = 30\%$, then daily activity of the shower available to analysis will be reduced to only $\sim 42\%$ and for $OF = 20\%$ it is $\sim 50\%$.

3. Activity and mass distribution of the Geminid shower

3.1. Activity profiles

The Geminid shower activity profiles for two overdense echo duration groups, $t \geq 1s$ and $t \geq 8s$, were derived by subtracting sporadic background echoes from all echo counts in corresponding one hour intervals. In a preliminary analysis, aimed at global activity of the Geminids 1996-2007 observed by the BLM system along the Bologna-Modra baseline (Zigo et al., 2008), a limiting OF was taken as 30% which might have caused that in some years the shower peak could be missed. Therefore, for the present analysis a lower limiting value of 20% was accepted and applied.

Figs. 1 and 2 show the observed activity profiles of the Geminids in individual years (1996-2007) obtained from observations on the Bologna-Modra baseline. The activity curves around the shower maximum (solar longitude $260° - 264°$) for two overdense echo groups of duration $t \geq 1s$ (crosses) and $t \geq 8s$ (points) are depicted by the shower echo counts in one hour intervals. The intervals when the radiant was above the horizon are marked by light grey areas. The shower radiant for the central area between the transmitter and receiver culminates at 01:25 UT and is above the horizon for 18 hours.

The observed hourly echo counts of echo duration $t \geq 8s$ corrected for the observability function up to the limiting value of 20% are plotted in Figs. 3 and 4 (points connected by a full line). The observability function normalized to (100%) is depicted by a dashed line. The light grey areas delineate intervals where the $OF > 20\%$.

An inspection of the corrected activity curves in Figs. 3 and 4 reveals a multiple-peak apperance and at least two peaks in each year can be disclosed. A similar double-peak activity is presented by Rendtel and Brown (1999) from a series of visual observations in 1988-1997. They analysed data obtained from an observational campaign organized by the International Meteor Organization in which 500 observers recorded over 110.000 Geminids.

Table 1 lists the shower maxima (for equinox 2000.0) derived from the present forward-scatter observations analysis of echoes of duration $t \geq 8s$, together with the results of Puppilo et al. (2004) and visual observations. The peaks listed in brackets are rather uncertain as are result of either a relatively high correction by the observability function or their further trend in activity cannot be reliable followed and is cut by an unfavorable orientation of the shower radiant with respect to the FS baseline causing that the shower cannot be observed by the system.

Visual data in Table 1 are taken from published analyses and IMO pages. In a global analysis of the Geminids 1996 Rendtel and Arlt (1997) found a single maximum at 262.15^{o}. Bone (1997) from observations of the British Astronomical Association observers besides the first peak found another one in the interval of 262.4^{o}-262.5^{o}. In 1999 (*http://www.meteorobs.org/maillist/msg16809.html*), two higher activity periods between 261.6°-261.9° and 262.1°-262.3° were observed. The second one was the main, however as evident from the observability function in Fig. 3, this peak could not be observed by the Bologna-Modra FS system. The observations in 2000 presented on IMO page *http://www.imo.net.node/177* are not complete and indicate the shower maximum between 262.1°-262.4°. The 2004 Geminids analysis based on global visual observations (Arlt and Rendtel, 2006) exhibits two close peaks at 262.16° and 262.23°. Visual observations of the Geminids in 2006 (*http://www.imo.net/live/geminids2006/*) indicate also existence of two peaks at 261.7°-261.8° and about 262.2°, as well as observations of Geminids 2007 from *http://www.imo.net/live/geminids2007/*.

Table 1. Solar longitudes of the Geminid meteor shower maxima derived from forward-scatter observations on the Bologna-Modra baseline and their comparison with other analyses (equinox 2000.0).

	This analysis		Pupillo et al. (2004)	Visual	
Year	Max. 1. (°)	Max. 2. (°)	(°)	Max.1 (°)	Max.2 (°)
1996	262.15	262.50	262.63	262.15	262.4-262.5
1997	262.05	262.42	262.41	-	-
1998	261.98	262.17	262.1	-	-
1999	261.55	(262.5)	(261.83)	261.6-261.9	262.1-262.3
2000	261.22	262.28	262.62	-	262.1-262.4
2002	(261.75)	(261.95)	262.1	-	-
2004	261.48	262.18	-	262.16	262.23
2005	(261.98)	262.20	-	-	-
2006	261.75	(261.95)	-	261.7-261.8	262.2
2007	261.65	(262.48)	-	261.6-261.7	262.1-262.2

3.2. Global activity

Combining the data from all years a global activity curve of the Geminids from the period 1996-2007 was derived. Fig. 5 shows the activity curves for two overdense echo duration groups, $t \geq 1s$ and $t \geq 8s$, derived as the average values from the rates in the bins of a length of 0.2°. The activity curves of both echo duration groups display maximum consisting of two peaks: for echo duration of $t \geq 1s$ at solar longitude 261.7° and 262.3°; for echo duration $t \geq 8s$ at solar longitude 261.9° and 262.3°. Both activity curves show an evident slower increase up to the maximum followed by a steeper decrease after it. The double peak maximum on the activity curve of the Geminids is known also from visual observations with the main peak at solar longitude 262.16° and a second peak at solar longitude 262.34° (Rendtel, 2004).

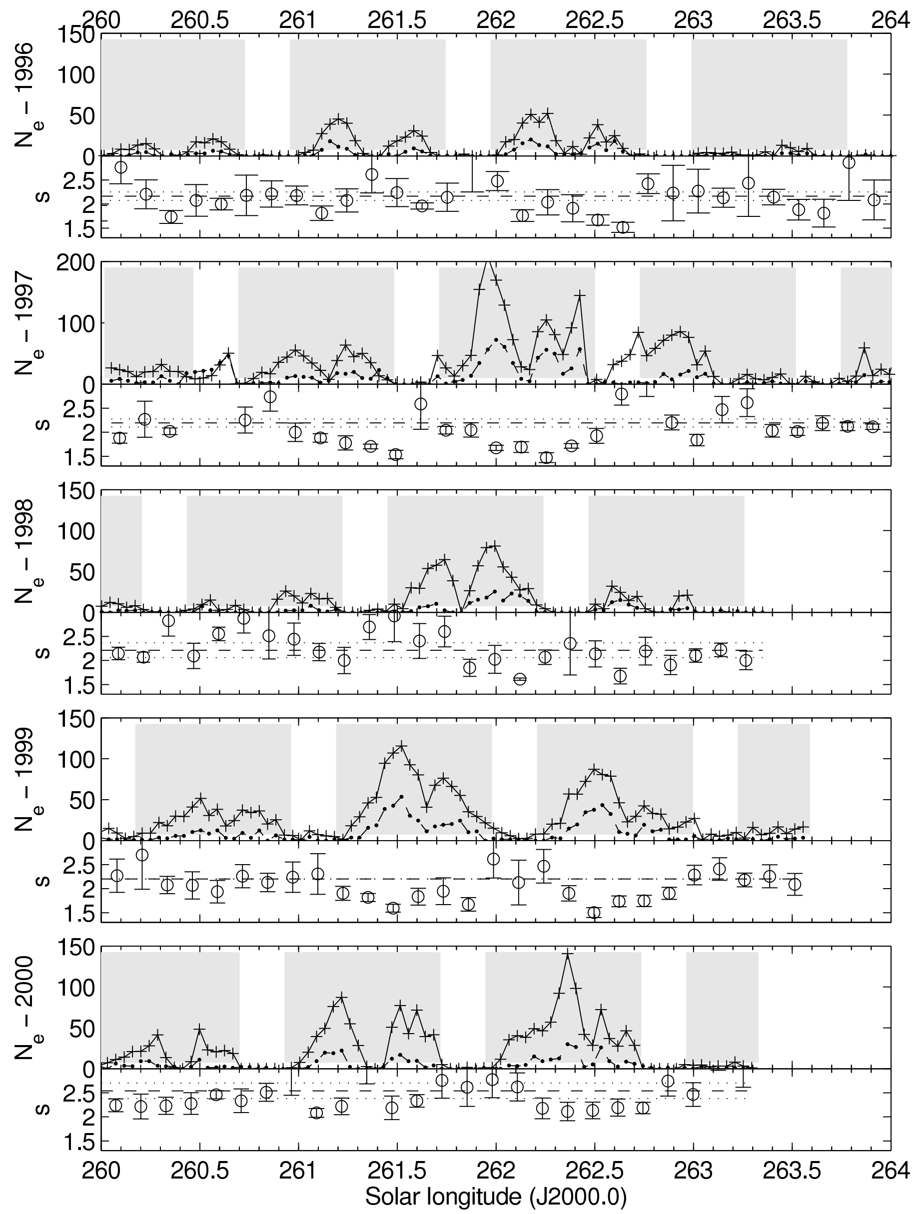

Figure 1. The observed hourly echo counts of the Geminid overdense echoes of duration $\geq 1s$ (full line) and $\geq 8s$ (dashed line) and the mass distribution exponent s (lower plots) observed by the BLM forward scatter on the Bologna-Modra baseline in 1996-2000. Light grey areas are intervals with the Geminid radiant above the horizon.

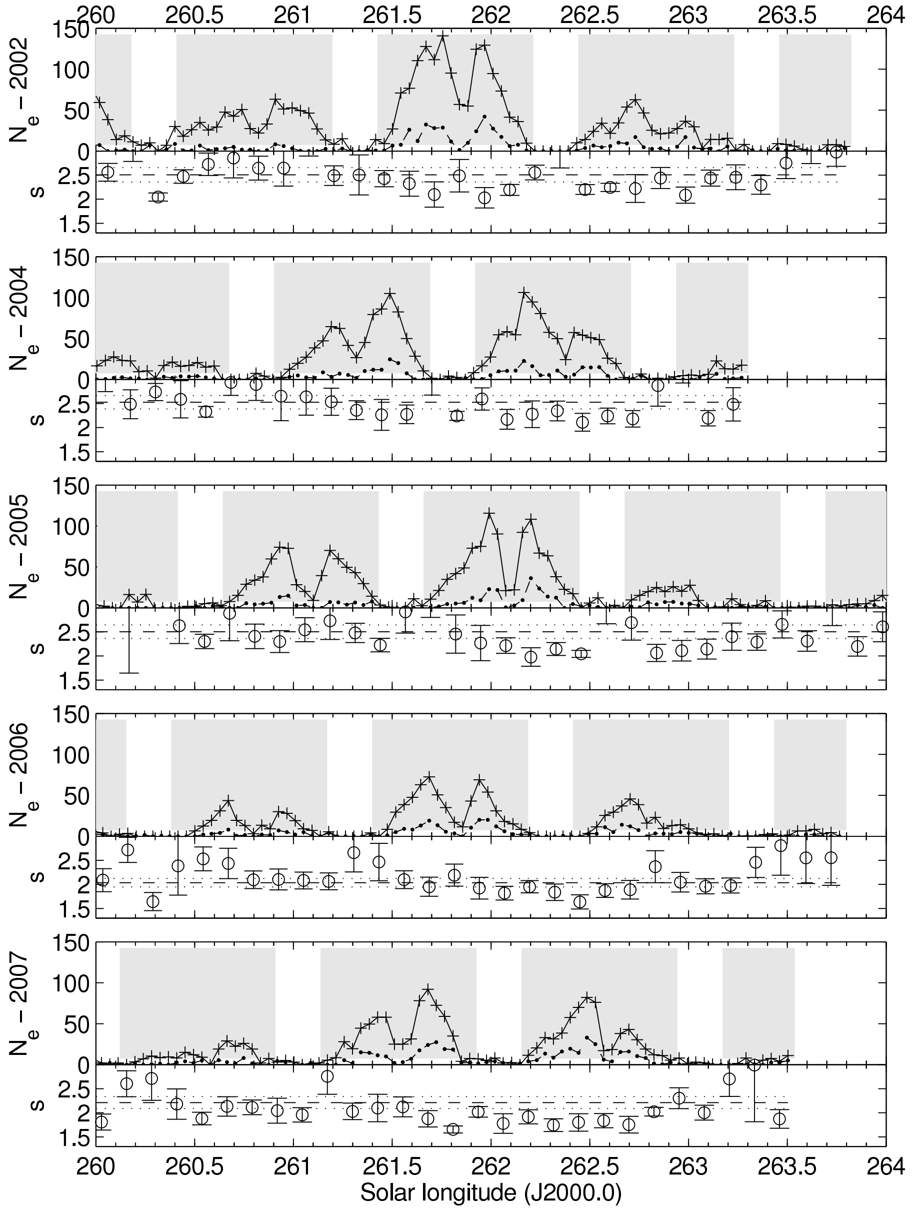

Figure 2. The observed hourly echo counts of the Geminid overdense echoes of duration $\geq 1s$ (full line) and $\geq 8s$ (dashed line) and the mass distribution exponent s (lower plots) observed by the BLM forward scatter on the Bologna-Modra baseline in 2002-2007. Light grey areas are intervals with the Geminid radiant above the horizon.

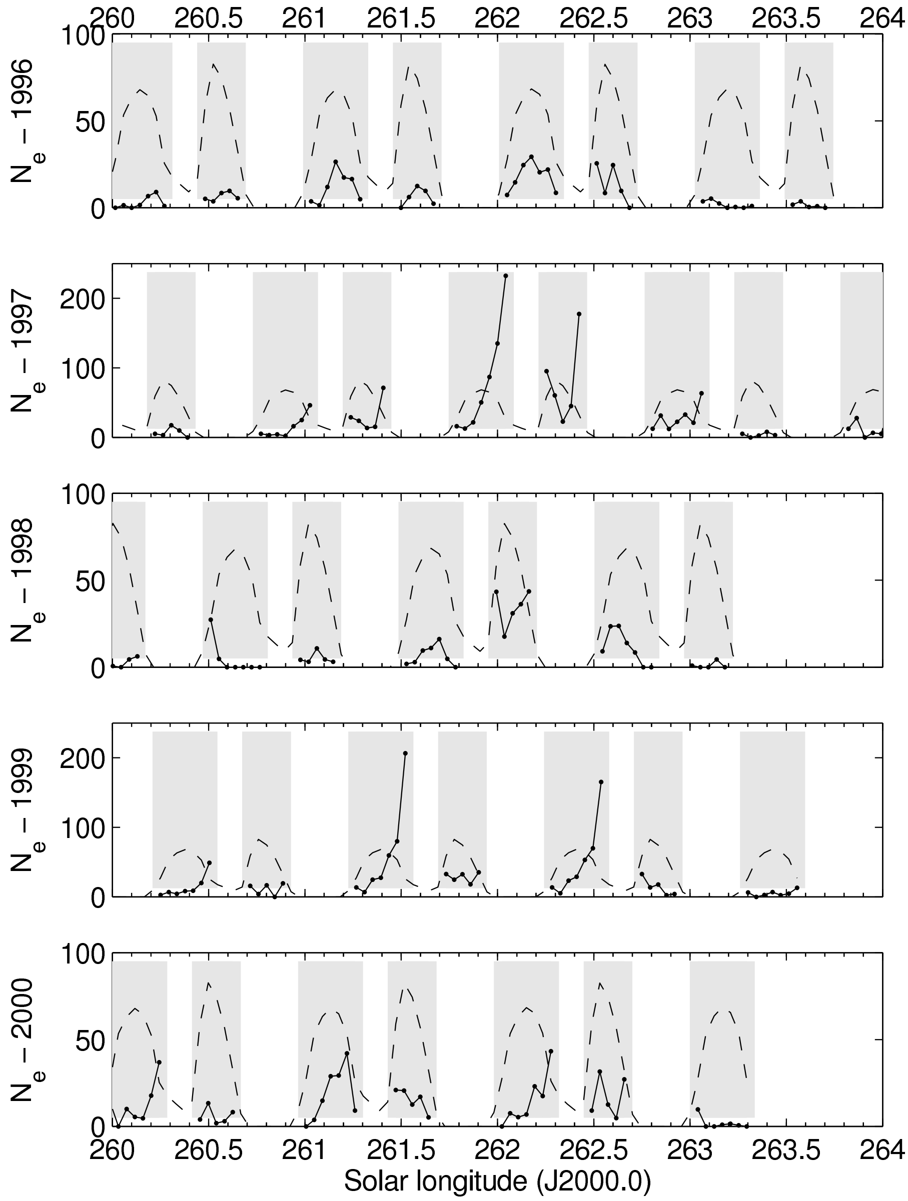

Figure 3. The hourly echo counts of the Geminids 1996-2000 for echo duration $\geq 8s$ corrected for the observability function in the intervals where the function is $\geq 20\%$ (full line). Dashed line: the observability function normalized to 100%. The light grey areas are intervals where the observability function is $> 20\%$.

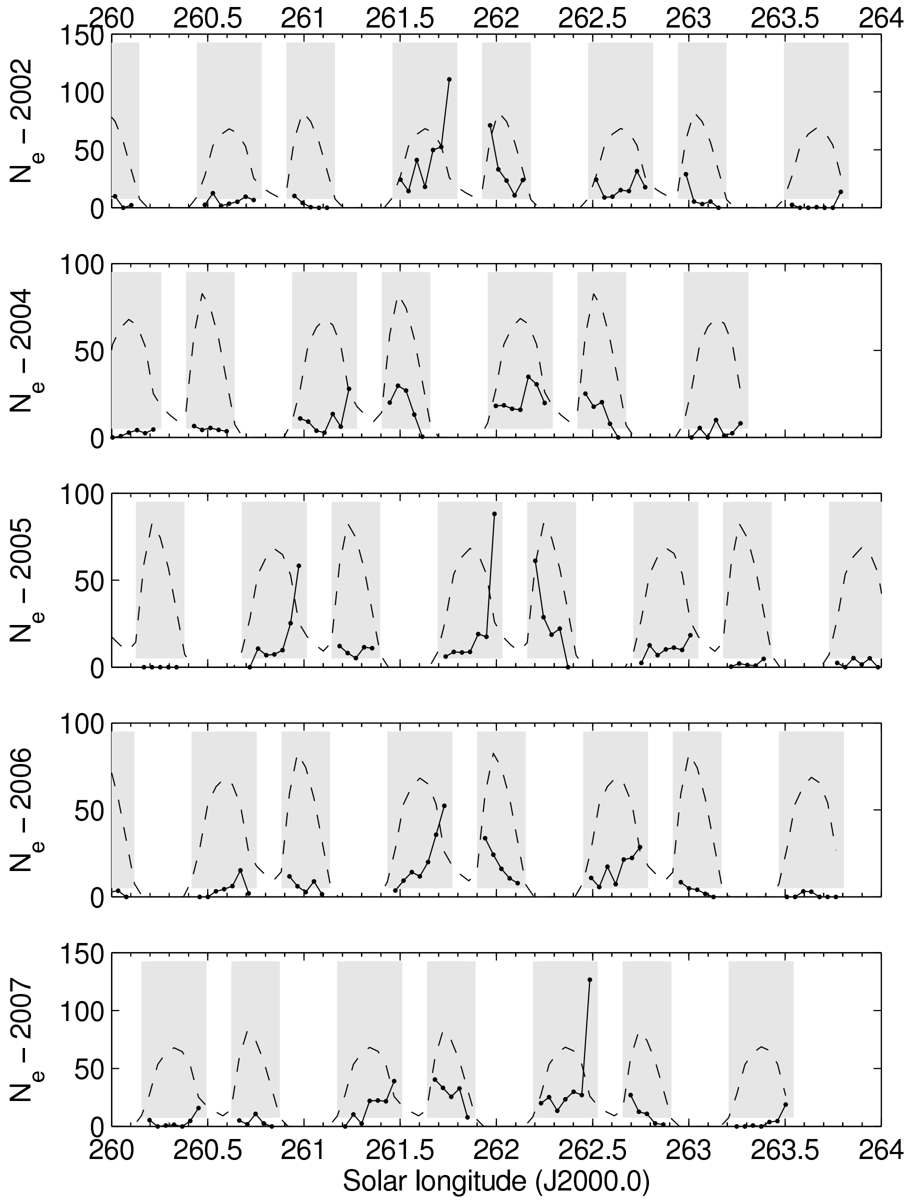

Figure 4. The hourly echo counts of the Geminids 2002-2007 for echo duration $\geq 8s$ corrected for the observability function in the intervals where the function is $\geq 20\%$ (full line). Dashed line: the observability function normalized to 100%. The light grey areas are intervals where the observability function is $> 20\%$.

The width of the shower, defined by a rate limit of the half-maximum activity, is 1.9° and 1.5° for the echo duration group of $t \geq 1s$ and $t \geq 8s$, respectively. This documents that larger particles ($t \geq 8s$) are less dispersed and are concentrated more towards the core of the stream. However, as evident, larger particles are slightly shifted towards the descending branch of activity.

A similar trend is observed also on a global activity curve of photographic Geminids compiled from the IAU Meteor Database catalogue consisting mostly of bolides and covering observations from 1939-1996, i.e. 47 years (Lindblad et al. 2003). Applying the Southworth-Hawkins D-criterion for separation of Geminids from the catalogue (Southworth and Hawkins, 1963), for a limiting value of $D = 0.20$, 385 Geminids were separated. The numbers of photographic Geminids in bins of 0.1° in solar longitude (lower plot in Fig. 5 - asterisks connected by dashed line) are the sums obtained from all years normalized to 10 year counts (dividing overall counts N in bins by 4.7) and represent a mean activity curve of photographic Geminids in 10 years. The error bars correspond to $1/\sqrt{(N)}$ values.

The curve also exhibits two peaks, at solar longitudes of 261.9° and 262.75°. Though for the first peak it is not so prominent, the curve confirms a mass segregation of meteoroids in the Geminid meteoroid stream with the largest particles concentrated more to the second peak, i.e. to the descending branch of activity.

3.3. Mass distribution

The mass exponent s, providing information on size distribution of particles in the stream, was found from the cumulative numbers of echo duration considering diffusion for a dominant process of an echo decay in the form published by Kaiser (1955). The cumulative numbers from intervals of 3 hours of echo duration $t \geq 1, 1.5, 2, 3, 4, 5, 7, 8, 10$ sec were taken into computation. The values of the mass exponent in individual years are plotted in Figs. 1 and 2 (plots bellow the activity curves) together with error bars corresponding to the 95% confidence intervals. Values of the mass exponent of the sporadic background are depicted by dashed lines. The dotted lines confines the 95% confidence intervals. The values of the mass exponents derived for the shower from periods about the maximum of activity and for the sporadic background in individual years, restricted to the 95% confidence intervals, are listed in Table 2.

The mass exponent indicates a tendency of variation over the observed period with an increase from 1996 up a maximum in 2002-2005 and followed by a decrease. However, the data from 2001 and 2003 are missing and the highest value of $s = 2.11$ in 2004 is based on a relatively high activity of the sporadic background in that year, therefore, the variation cannot be considered for conclusive. The mean mass exponent of the Geminids 1996-2007 is 1.73 ± 0.20 and without the data from 2004, 1.69 ± 0.17.

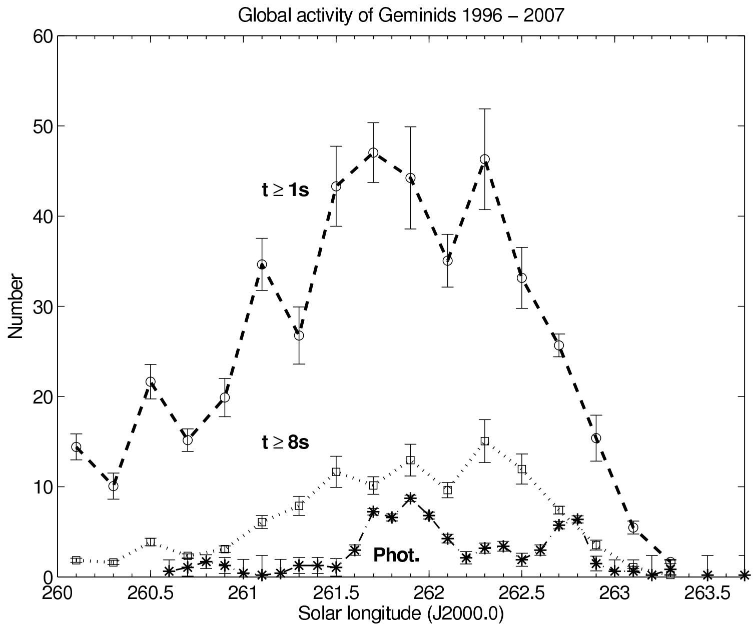

Figure 5. Global activity of the Geminids 1996-2007 for overdense echoes of $t \geq 1s$ (open circles), $t \geq 8s$ (squares) and the photographic activity curve (asterisks) normalized to 10-year counts.

4. Conclusions

Radio investigation of the activity of the Geminid meteor shower by the BLM forward-scatter system for meteor observation along the Bologna-Modra baseline in 1996-2007, has revealed a complicated structure of the stream. The shower activity was derived by subtracting the sporadic background echoes from all echo counts and by applying the observability function constructed for the system taking into account also directional sensibility and corresponding contours of the transmitting and receiving antennas at the meteor zone (Zigo, 2008).

From a multiple peak structure of the stream two dominant peaks can be recognized (Table 1). A global activity curve obtained from a twelve-year period (1996-2007) for the echo duration group of $t \geq 1s$ and $t \geq 8s$ (Fig. 1) confirms the existence of a double peak structure of the Geminid maximum. The result is consistent with extended visual observations of the shower in 1988-1997 (Rendtel, 2004), as well as with photographic observations of the Geminids collected from a period of almost 50 years (Fig. 5).

Positions of the two peaks at solar longitude 261.7^o, 262.3^o for echoes of $t \geq 1s$ and at 261.9^o, 262.3^o for echoes of $t \geq 8s$ are very close. The widths of

Table 2. The Mass exponent s of the Geminids 1996-2007 and sporadic background derived from forward scatter observations on the Bologna-Modra baseline.

Year	Geminids	Sporadics
1996	1.52 ± 0.11	2.11 ± 0.11
1997	1.47 ± 0.10	2.22 ± 0.13
1998	1.61 ± 0.02	2.21 ± 0.15
1999	1.50 ± 0.10	2.2 ± 0
2000	1.79 ± 0.21	2.41 ± 0.14
2002	1.86 ± 0.12	2.51 ± 0.15
2004	2.11 ± 0.19	2.53 ± 0.14
2005	1.98 ± 0.19	2.50 ± 0.14
2006	1.82 ± 0.14	2.04 ± 0.08
2007	1.65 ± 0.07	2.21 ± 0.12

activity in solar longitude corresponding to a half-strenght of the maximum of 1.9^{o} (echoes of $t \geq 1s$) and 1.5^{o} (echoes of $t \geq 8s$) differs by almost half a degree. This means that larger particles are less dispersed and concentrated more to the centre of the stream. At the same time, larger particles are approvingly with photographic Geminid meteors slightly shifted towards the descending branch of activity. The mean mass exponent s of the Geminids derived from the shower maxima is 1.73, and a possible variation of s over the ten years of observation indicating a non-uniform distribution of meteoroids according to masses along the orbit of the stream is observed.

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