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The 1998 outburst and history of the June Boötid meteor shower

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ABSTRACT
The June Boötid meteor shower (sometimes referred to as Draconids) surprised a number of regular and casual observers by an outburst with maximum ZHRs near 100 on 1998 June 27 after a quiescent period of several decades. A total of 1217 June Boötid meteors were recorded during regular visual meteor observations throughout this outburst. An average population index of $r = 2.2 \pm 0.10$ was derived from 1054 shower magnitude estimates. The broad activity profile with ZHR > 40 lasting more than 12 hours and the large spread of apparent radiants in 1998 resemble the 1916 and 1927 outbursts. The peak time is found to be at about $\lambda_\odot = 95.^\circ7$ (2000.0); peak ZHRs are of the order of 200, whereas reliable averages only reach 81 ± 7. The period of high ZHRs covered by a single observer implies a full width at half maximum of 3–4 hours. The resulting maximum flux of particles causing meteors brighter than +6.5 mag is between 0.04 and 0.06 $\mathrm{km}^{-2}\,\mathrm{h}^{-1}$. The average radiant from photographic, radar and visual records is $\alpha = 224.^\circ12$, $\delta = +47.^\circ77$. The observed activity outbursts in 1916, 1927 and 1998 are not related to the orbital period or the perihelion passages of the parent comet 7P/Pons-Winnecke. These are probably a consequence of the effects of the 2:1 resonance with Jupiter.

Key words: meteors, meteoroids; techniques: radar astronomy; history and philosophy of astronomy

1 INTRODUCTION

Observations of unexpected meteor shower outbursts often comprise meagre data sets compared with annually occurring showers. The global collection of visual meteor observations and the standardization of observing methods within the International Meteor Organization (IMO) over the past decade, however, have allowed a quantitative analysis of the activity of such outbursts on a number of occasions.

Considerable activity of the June Boötids was observed on three occasions: 1916, 1927 and 1998. Some sources also list the year 1921, but the activity reported from this return is rather low (see Table 2). We go into the details of the historical record in Sect. 2; a detailed collection of historical records and their evaluation can be found in Arlt (1999). Additionally, there are some reports of possible activity before and after these returns, but the association to the June Boötids is not certain. The final catalogue of meteor radiants by Hoffmeister (1948) did not contain the shower because of insufficient observations, although he considered the shower 'real' and listed it as the 'June Draconids'. The shower was rejected from the current IMO working list (Arlt, 1995), because its regular activity had been below the detection limits for many years. However, June is a period of the year which is poorly covered by visual meteor observations generally, particularly by observations in the northern hemisphere.

In 1998, regular observers and casual witnesses noted high meteor activity visually and by radio means on June 27-28 as first reported by Sato et al. (1998). Extensive observations in the northern hemisphere are handicapped by the short duration of nights at this time of the year. Southern-hemisphere observers see the radiant of the June Boötids at extremely low altitudes. In total, we summarize observations or notes from 54 observers from 13 countries in what follows.

The parent object of the June Boötid meteoroid stream is comet 7P/Pons-Winnecke (Denning 1916c, Olivier 1916). It belongs to the Jupiter family of comets, and hence its orbit is subject to major gravitational perturbations. For example, its perihelion distance has increased continuously since discovery in 1819, and at the same time the inclination has also increased significantly (Table 1). The comet's

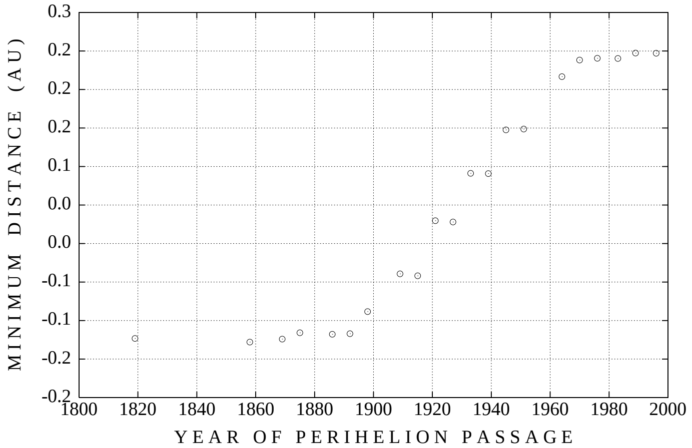

Figure 1. Evolution of the minimum distance of the orbit of comet 7P/Pons-Winnecke from the Earth's orbit. The distances were computed with help of the radiant prediction program introduced by Neslušan et al. (1998).

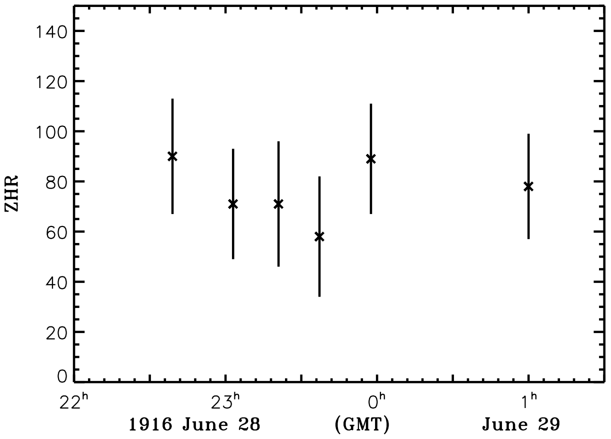

Figure 2. Estimates of the Zenithal Hourly Rate of Denning's observation on 1916 June 28-29 (Denning 1916b).

orbit has been completely outside Earth's orbit since 1921, and currently the minimum distance between the two orbits exceeds 0.24 AU.

The June Boötid meteor shower is often referred to by different names. Because of its link to comet 7P/Pons-Winnecke, historical records list the shower as 'Pons-Winneckids'. In his review of meteor shower outbursts, Jenniskens (1995) calls the shower 'ι-Draconids' according to the bright star closest to the 1916 position derived by Denning. Furthermore, designations like 'June Draconids' and 'Boötid-Draconids' can be found throughout the literature.

The geocentric velocity of the June Boötid meteoroid stream is generally given as $v_{\rm g} = 14$ km s^{-1} resulting in a pre-atmospheric velocity of $v_\infty = 18$ km s^{-1}. The velocity of the stream is significantly changed by the gravity of the Earth as is the position of the apparent radiant of the meteor shower depending on the local altitude of the radiant. In 1998, for example, Australian observers recorded the average radiant as shifted toward the zenith by about 20°.

Activity outbursts of meteor showers have been classified by Jenniskens (1995), and a few records of June Boötid activity were mentioned by him. In his work, the June Boötids did not show a clear distinction between the peak and background components at any of the last three significant returns; the similarity to the October Draconids which are also lacking a background component, according to his work, may be noted. Indeed, June Boötid activity may be associated with a class of outbursts which are controlled by Jovian perturbations and whose relation to near-comet type outbursts needs to be evaluated. The behaviour of the June Boötids remains peculiar, and the stream will be an instructive example for simulations of the evolution of meteoroid streams.

2 HISTORICAL RECORDS

2.1 The 1916 June Boötids

The first reliable June Boötid outburst occurred in 1916 when regular and casual observers recorded significant activity (earliest note in Denning 1916a). The shower was quickly associated with comet 7P/Pons-Winnecke (Denning 1916c and, independently, Olivier 1916). In his first detailed report concerning the outburst, Denning (1916b) gave a table with a breakdown of his observing period at 15 to 30 minute intervals. He did not give an estimate of the sky quality in terms of a stellar limiting magnitude, but he did mention the activity of eight other nights from June 23 to July 8 in terms of an uncorrected hourly rate of 2.25. Scaling this rate to a typical sporadic rate of 10 at that time of the year with a sporadic population index of 3.0, we expect Denning's limiting magnitude no higher than +5.5 mag.

His limiting magnitude should therefore not have been higher than +5.5 mag. A detailed meteor list in Denning (1916c) allowed the determination of the population index of the 1916 event and the radiant using modern methods (see Sect. 3).

The estimated Zenithal Hourly Rates (ZHR) are shown in Fig. 2, based on a population index of 2.2 and a limiting magnitude of +5.2 mag. The graph indicates a plateau in activity lasting at least 3 hours which is unlike any other outburst of a cometary meteor shower, such as the Lyrids, Perseids, Aurigids, October Draconids or Leonids.

The reports of casual observers in Europe in 1916 underline this general impression of the activity and do not contradict an estimated ZHR of roughly 100. Reports by Northern American observers cover periods starting at $1^{\rm h}30^{\rm m}$ UT on June 28 noting meteor numbers suggesting that the ZHR was below 10 by then (Denning 1917; Olivier 1916). We conclude that the *maximum 1916 June Boötid activity was* ZHR ~ 100.

2.2 The 1921 June Boötids

Because of the linkage of the 1916 June Boötids to a periodic comet, expectations for 1921, one orbital period later, were high (Denning 1921a). The observational details are given in Table 2. All reports indicate low June Boötid activity, except for a questionable report from Japan (Yamamoto 1922). An unusually good perception is suggested in that source, where the visual observer Nakamura claims to see 20 stars in the Pleiades. The details given in Yamamoto & Nakamura

Table 1. Orbital elements of parent comet 7P/Pons-Winnecke for selected perihelion passages, taken from Marsden (1995).

T YYYY MM DD	q [AU]	e	Ω [°]	ω [°]	i [°]
1819 07 19.681	0.77188	0.75417	161.991	115.483	10.746
1858 05 02.5396	0.768939	0.754845	162.2032	115.4344	10.7939
1869 06 30.4417	0.781519	0.751932	162.4537	115.2969	10.7972
1875 03 12.5993	0.829004	0.740997	165.2101	113.1645	11.2766
1886 09 04.8864	0.885499	0.726178	172.0920	105.6074	14.5220
1892 07 01.4040	0.886555	0.725983	172.1650	105.5593	14.5202
1898 03 20.8686	0.923817	0.714814	173.4072	102.2358	16.9910
1909 10 09.7947	0.973066	0.701765	172.3173	100.5725	18.2846
1915 09 02.7901	0.970605	0.702320	172.4150	100.5177	18.3043
1921 06 13.4125	1.040893	0.685482	170.2992	99.1973	18.9243
1927 06 21.0654	1.039235	0.685685	170.3974	99.1422	18.9397
1933 05 18.7891	1.101784	0.669589	169.2709	97.5332	20.1145
1939 06 22.7150	1.101471	0.669678	169.3667	97.4818	20.1218
1945 07 10.5895	1.159202	0.654860	170.1315	95.1355	21.6928
1951 09 08.6129	1.160469	0.654566	170.2205	95.0850	21.6891
1964 03 24.5498	1.230129	0.639386	172.0462	93.6610	22.3252
1970 07 21.0309	1.247364	0.636004	172.2625	93.4682	22.3218
1976 11 28.7428	1.254207	0.634704	172.3779	93.4272	22.2933
1983 04 07.5070	1.253989	0.634714	172.3358	93.4311	22.3071
1989 08 19.8967	1.260964	0.633511	172.3375	93.4319	22.7222

(1922) reveal an unusually large number of meteors with $m \geq 5.0$ mag – 68% of the total number of June Boötids. These reports contrast with a note by Kanda (1922) from Japan, where total numbers and June Boötid numbers are given. Approximated hourly June Boötid rates of 5–6 can be estimated assuming that the non-June Boötids fulfill a sporadic rate of 10. We may conclude that *the June Boötid activity was* ZHR ≤ 10 *in the visual range in 1921* although the parent comet had passed its perihelion on June 13.4 in the same year.

2.3 The 1927 June Boötids

The next enhanced June Boötid activity after the 1916 event occurred in 1927 for which we find two main records: an observers group in Tashkent (summary in Sytinsky 1928; details are given in Sytinskaja 1928) and an observation by Dole in the USA (reported by King 1928). Although very large meteor numbers were reported, both reports do not necessarily indicate a June Boötid outburst similar to the 1916 event occurred.

Dole gave two active radiants, the Coronids at $\alpha = 235°$, $\delta = +30°$ with which he associated 130 meteors, and the Ursa Majorids at $\alpha = 215°$, $\delta = +57°$, with which he associated 145 meteors. The maximum was found on June 29 and June 30 with 35 Coronids, 65 Ursa Majorids and 48 Coronids, 37 Ursa Majorids respectively. The same note by King gives Dole's Orionid rates: 499 Orionids in total, at maximum 97 Orionids were seen on October 23. On the one hand, the Orionids usually furnish a maximum ZHR of about 25 implying that the possible June Boötid rates were as high as that at best. On the other hand, we should bear in mind that northern June nights are shorter than October nights, i.e. the meteors were probably seen in a shorter period of time. We can, nevertheless, conclude that the 1927 activity was not as high as in 1916 and did not exceed a value of about 30.

The second report (Sytinskaja 1928) gives enormous meteor numbers for the end of June. The nights of early June and early July with mainly sporadic activity free of major showers indicate that the observations were carried out under extremely good sky conditions, stellar limiting magnitudes are assumed to be between +7.0 mag and +7.5 mag. Fig. 3 shows the uncorrected hourly rates (including sporadics) for the most active observers of the Tashkent group, and it becomes obvious that the actual activity did not exceed sporadic activity by more than a factor of two.

A limiting magnitude of +7.5 mag results in reasonable sporadic rates before and after the event. With this assumption we can calculate the hourly rate, corrected for the limiting magnitude and radiant elevation, from the meteors actually associated with the June Boötids. It turns out that the ZHR did not exceed 10 indicating that the observers applied a very stringent shower association. Taking the total-rate graph and the ZHR as well as the results from Dole's observations into account, we can conclude that *the ZHR did not exceed a value of about 30 in 1927.*

2.4 Other records

A search for earlier recordings in the literature of the last century reveals that it is very difficult to link shower radiants given in diverse lists with the activity of the June Boötids. Radiants were usually derived without consideration of path length and angular velocity. In some cases general remarks like 'swift' or 'slow' were added. For example, the radiant list of Denning (1890) mentions two radiants at $\alpha = 213°$, $\delta = +53°$ and $\alpha = 238°$, $\delta = +47°$ for June 26. However, the meteors are described as being 'swift' and 'slow' respectively, although the second radiant is closer to the apex of the Earth's motion, and the geocentric velocity of a meteoroid stream cannot exceed 18 km s^{-1} for the first position, which is far from producing 'swift' meteors. An analysis of Italian meteor observations in 1872 (Denning

Table 2. Historical records of the June Boötid activity during the 1916, 1921 and 1927 returns of the shower. Rates do not refer to the term ZHR which is in modern use, but give only numbers per hour independent of the observing conditions. Other papers just give numbers of shower meteors noted by the observer. In several cases, the number of June Boötids was derived by the present authors from meteor coordinates given in the respective publication.

Date/Time (UT)	Activity	Observer and remarks	Source
1860, 1861 Jun 30	'many'	Lowe	Denning (1916c)
1916 Jun 28 2225–0010	55 meteors	Denning, Bristol	Denning (1916c)
1916 Jun 28 2300–0000	nearly 100 meteors	observer at Birmingham	Denning (1916d)
1916 Jun 28 2300–0130	~ 60/h	Raisin, Bournemouth	Denning (1916d, 1916e)
1916 Jun 29 0045–0115	14 meteors	Denning, Bristol; partly cloudy	Denning (1916c)
1916 Jun 29 0135–?	low	Barnard, Yerkes, USA	Denning (1917)
1916 Jun 29 ~0400	5.5/h	Brooks, Washington DC, USA	Olivier (1916)
1921 Jun 24	2.9/h	summary	Hoffmeister (1922)
1921 Jun 25	2.5/h	summary	Hoffmeister (1922)
1921 Jun 26	0.6/h	summary	Hoffmeister (1922)
1921 Jun 28 2349–0134	3 June Boötids	Denning, Bristol	Denning (1921b)
1921 Jun 28	1.7/h	summary	Hoffmeister (1922)
1921 Jun 28 2140–2250	3 June Boötids	Littmann, Löwenstein, Mrazek in Prague; hazy	Prey (1921)
1921 Jun 28 2150–2400	4 June Boötids	Svoboda, Ondřejov	Svoboda (1923)
1921 Jun 28 2150–2400	5.5/h	Štepanek, Ondřejov	Svoboda (1923)
1921 Jun 28 2308–0106	4 June Boötids	Jadot, Statte-Huy	Jadot (1921)
1921 Jun 29	6/h	Inouye, Hokkaido	Kanda (1922)
1921 Jun 29.17	7 June Boötids	Dole, USA	Kronk (1988)
1921 Jun 29	1.1/h	summary	Hoffmeister (1922)
1921 Jun 29 2135–2310	2 June Boötids	Mrazek, Prey in Prague; very hazy	Prey (1921)
1921 Jun 29 2140–0000	2 June Boötids	Svoboda, Ondřejov	Svoboda (1923)
1921 Jun 29 2140–0000	3.0/h	Štepanek, Ondřejov	Svoboda (1923)
1921 Jun 29 2116–0145	1 June Boötid	Jadot, Statte-Huy	Jadot (1921)
1921 Jun 30	5/h	observers at Chôsen, Japan	Kanda (1922)
1921 Jun 30.10	8 June Boötids	Dole, USA	Kronk (1988)
1921 Jul 01	0.4/h	Kanda, Hokkaido	Kanda (1922)
1921 Jul 01 2200–2300	3 June Boötids	Heybrock, Frankfurt; hazy, clouds	Heybrock (1921)
1921 Jul 03	135 met. in 35 min.	Nakamura, Kyoto	Yamamoto (1922)
1921 Jul 05	91 met. in 41 min.	Nakamura, Kyoto	Yamamoto (1922), questioned by Denning (1922)
1927 Jun 24 1723–2055	43/h	3 observers of Tashkent group	Sytinskaja (1928)
1927 Jun 25 1654–2023	32/h	3 observers of Tashkent group	Sytinskaja (1928)
1927 Jun 26 1700–2033	58/h	4 observers of Tashkent group	Sytinskaja (1928)
1927 Jun 27 ~0500	7.2/h	Olivier, Virginia, USA	Olivier (1927)
1927 Jun 27 ~0600	0 June Boötids	Brown, Minnesota, USA	Olivier (1927)
1927 Jun 27 ~0600	normal	Bunch, Monning, Texas, USA	Olivier (1927)
1927 Jun 27 1703–2030	61/h	4 observers of Tashkent group	Sytinskaja (1928)
1927 Jun 28 ~0500	5.1/h	Olivier, Virginia, USA	Olivier (1927)
1927 Jun 28 1909–2023	51/h	2 observer of Tashkent group	Sytinskaja (1928)
1927 Jun 29 1703–1923	46/h	2 observer of Tashkent group	Sytinskaja (1928)
1927 Jun 30 ~0500	100 June Boötids	Dole, Michigan, USA	King (1928)
1927 Jun 30 1720–1845	37/h	1 observer of Tashkent group	Sytinskaja (1928)
1927 Jul 01 ~0500	85 June Boötids	Dole, Michigan, USA	King (1928)
1927 Jul 02 1710–1855	29/h	1 observer of Tashkent group	Sytinskaja (1928)

1878) shows a radiant at $\alpha = 216°$, $\delta = +47°$ based on 10 meteors and a few more convergence points at positions east of that. Other radiants based on even more meteors can be found in the same period as well as radiants at similar positions in the neighbouring periods. The positions close to the June Boötids are, therefore, no indication for distinct activity from that particular stream.

The comprehensive radiant compilation of Denning (1899) repeats this information and does not give any more substantive details concerning June Boötid activity. These facts indicate that nothing significant was observed from a June Boötid radiant connected with a real meteoroid stream before 1916. The oldest indication for enhanced June Boötid activity is mentioned in Denning (1916c) citing the observations of Mr. Lowe who saw 'many meteors' on June 30 in 1860 and 1861. A reference to the original publication by Lowe was not given in Denning's note.

Sekanina (1976) associated four streams he found from radar data with the orbit of 7P/Pons-Winnecke. The most prominent is the 'July Draconid' shower (54 orbits) between June 2 and July 19 with an average radiant at $\alpha = 209\overset{\circ}{.}8$, $\delta = +70\overset{\circ}{.}7$. Much closer to our best radiant estimates for the June Boötids is the 'Boötid-Draconid' shower in Sekanina's list based on 12 meteors, with a nodal passage on 1969 July 2 and a radiant at $\alpha = 233\overset{\circ}{.}7 \pm 3\overset{\circ}{.}1$, $\delta = +52\overset{\circ}{.}2 \pm 1\overset{\circ}{.}8$. The geocentric velocity was found to be $v_{\rm g} = 14.7$ km s^{-1} which

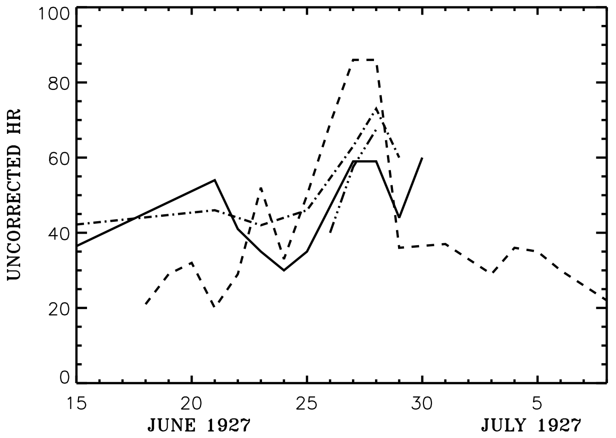

Figure 3. Uncorrected hourly rates given by observers of the Tashkent group in June 1927. Total rates increased by a factor of two during the June Boötid maximum compared with the sporadic background.

is accelerated by the Earth's gravity to a pre-atmospheric velocity of $v_\infty = 18.3$ km s^{-1}. A search in the Meteor Orbit Database of the IAU by Lindblad (personal communication 1998) did not reveal any records which could be associated with the June Boötids.

The visual activity in most recent years was very low and cannot be distinguished from mere chance alignments of sporadic meteors with the June Boötid radiant. The Visual Meteor Database of the IMO (started by Roggemans 1988) contains observations of 1985–1987, 1991–1995 and 1997 discriminating the June Bootids among the observed meteors, but the activity was at the detection limit caused by sporadic contamination in all these years.

3 ACTIVITY ANALYSIS FROM VISUAL RECORDS

3.1 Population index

The considerable number of 1054 magnitude estimates in the present records allows the determination of an average population index r for the June Boötids. The population index is defined as the factor by which the true meteor number increases from one magnitude class to the next fainter class:

$$r = \Phi(m+1)/\Phi(m), \tag{1}$$

where Φ is the true number of meteors visible in a certain field of the sky. These true numbers can be obtained from visual observations through knowledge of perception probabilities as a function of the difference of the meteor magnitude from the limiting magnitude, LM. The perception values have been determined by several authors, e.g. Kresáková (1966) based on 1351 individual magnitude estimates, and Koschack & Rendtel (1990) based on 6248 estimates. The set of perception probabilities of the latter source was used because of their superior amount of data, and since they refer to an individual observers' field of view instead of the whole sky. A complete profile of the population index is shown in Fig. 4.

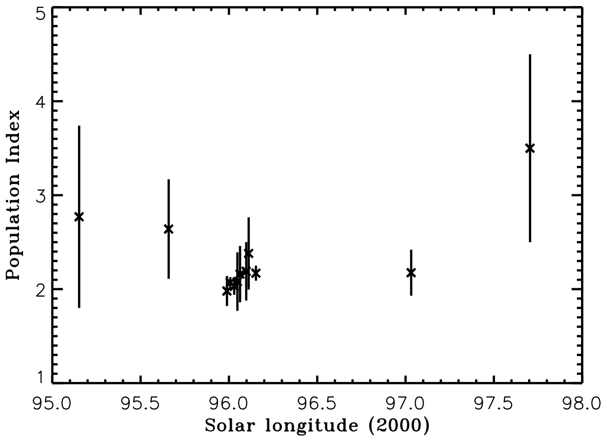

Figure 4. Population index profile of the 1998 June Boötids.

The magnitude distributions covering the period from June 27, $19^{\rm h}30^{\rm m}$ to June 28, $1^{\rm h}30^{\rm m}$ UT yield an average r-value of 2.19 ± 0.07. A breakdown of the population index from observations for which detailed meteor lists were available indicates an increase of the r-value during the declining part of activity (Fig. 5). The population index of Denning's meteor list (Denning 1916c) is about $r = 2.2$ if we assume a limiting magnitude of +5.2 mag; the r-value is fairly consistent with the particle distribution of the 1998 event. We applied the r-profile shown in Fig. 4 to correct the visual observations for their limiting magnitudes.

3.2 ZHR activity and flux

The standard quantity to measure the visual activity of a meteor shower is the Zenithal Hourly Rate (ZHR) which is computed by

$$\mathrm{ZHR} = \frac{n\, r^{(6.5-\mathrm{LM})} F}{T_{\rm eff}\, \sin^\gamma h_{\rm R}}, \tag{2}$$

where n is the number shower meteors, LM is the average stellar limiting magnitude during the observation period, F is a correction for clouds or other field-of-view obstructions and $h_{\rm R}$ is the radiant altitude. The exponent γ is sometimes used as an additional correction to the merely geometric consideration of the radiant height, and empirically accounts for the radiant height dependence of the meteor phenomenon (basically the maximum magnitude). Values larger than unity have been derived, though observations of Perseids and Leonids indicate no significant deviation from 1.0 (Bellot Rubio 1995, Koschack 1995, Arlt et al. 1996). The June Boötids are in fact a cometary shower, too, but there is little information for a stream of such a low geocentric velocity in connection with the γ value. Here we set $\gamma = 1.0$.

The details of the activity analysis of the regular meteor observations reported on the June Boötids are given in Table 3 and graphically shown in Fig. 6 with a magnification of the maximum in Fig. 7. The maximum is resolved with $0\overset{\circ}{.}030$ bins ($\sim$ 40 minutes), shifted by $0\overset{\circ}{.}015$ until $\lambda_\odot = 96\overset{\circ}{.}05$, and with $0\overset{\circ}{.}050$ bins ($\sim$ 70 minutes), shifted by $0\overset{\circ}{.}025$ from $96\overset{\circ}{.}05$ to $96\overset{\circ}{.}2$. Observations with a total correction larger than 5.0 were excluded, except for the average given for $\lambda_\odot = 95\overset{\circ}{.}629$.

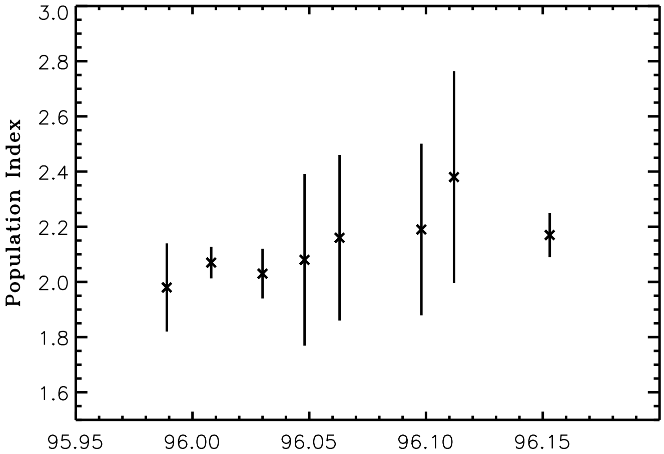

Figure 5. Population index profile of the 1998 June Boötids as derived from observations in the period June 27, $19^{\rm h}30^{\rm m}$ to June 28, $1^{\rm h}05^{\rm m}$ UT.

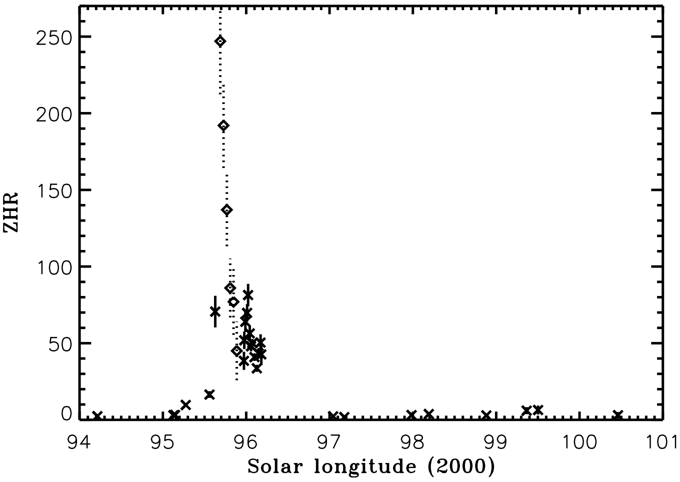

Figure 6. ZHR-profile of the 1998 June Boötids as derived from visual observations. The diamonds with dotted error margins are the results of a single observer.

The most striking feature of the ZHR-graph is the long duration of high activity for about 12 hours. The decreasing branch of activity is covered by a good sample of observations. Additional observations are given in Hashimoto & Osada (1998) made by 'a beginner in meteor observations but an experienced amateur', R. Shimoji, for which we re-calculated the ZHRs. They cover the solar longitude range from 95°.67 to 95°.95 (Jun 27, $12^{\rm h}$–$19^{\rm h}$ UT) with gradually decreasing ZHRs starting above 200 and ending up at about 50. The full width at half maximum of the outburst is 3–4 hours according to this single-observer record, but it must be underlined that estimates of a single observer can bear substantial systematic errors, and the resulting ZHRs are specially marked in Figs. 6 and 7.

Estimates of the flux of particles producing meteors brighter than 6.5 mag are between 0.02 and 0.04 per km^2 and per hour. The strong sensitivity of visual fluxes on the population index results in large uncertainties of at least a factor of two.

Table 3. Activity profile of the 1998 June Boötids. Only regular meteor observations are used. A radiant position of $\alpha = 230°$, $\delta = +47°$ and the population index profile shown in Fig. 4 were applied for the analysis. Solar longitudes refer to eq. 2000.0; times are rounded to the nearest ten minutes.

Date	Time (UT)	$\lambda_\odot$	$n_{\rm JBO}$	ZHR	r
Jun 26	0000	94°.215	2	2.4±1.4	2.77
Jun 26	2230	95°.128	32	3.0±0.5	2.77
Jun 27	0000	95°.147	43	3.2±0.5	2.77
Jun 27	0200	95°.275	65	9.7±1.2	2.72
Jun 27	0920	95°.560	53	16.5±2.2	2.68
Jun 27	1100	95°.629	46	70.6±10	2.64
Jun 27	1940	95°.973	42	38.5±5.9	2.00
Jun 27	1950	95°.977	81	51.9±5.7	2.00
Jun 27	2000	95°.990	90	64.0±6.7	2.02
Jun 27	2040	96°.011	148	69.8±5.7	2.04
Jun 27	2100	96°.023	124	81.4±7.3	2.05
Jun 27	2120	96°.043	125	56.4±5.0	2.07
Jun 27	2130	96°.044	110	55.0±5.2	2.07
Jun 27	2150	96°.059	212	48.0±3.3	2.13
Jun 27	2210	96°.074	371	50.1±2.6	2.15
Jun 27	2250	96°.100	264	40.9±2.5	2.27
Jun 27	2330	96°.128	206	33.6±2.3	2.31
Jun 28	0000	96°.149	166	43.4±3.4	2.23
Jun 28	0040	96°.173	87	50.4±5.4	2.17
Jun 28	0100	96°.182	36	42.7±7.0	2.17
Jun 28	2240	97°.044	35	2.3±0.4	2.22
Jun 29	0200	97°.178	35	1.8±0.3	2.44
Jun 29	2220	97°.985	46	3.1±0.5	3.48
Jun 30	0330	98°.192	48	3.8±0.5	3.50
Jun 30	2050	98°.883	4	2.9±1.3	3.50
Jul 01	0900	99°.366	6	6.0±2.3	3.50
Jul 01	1230	99°.503	4	6.4±2.9	3.50
Jul 02	1240	100°.462	1	3.0±2.1	3.50

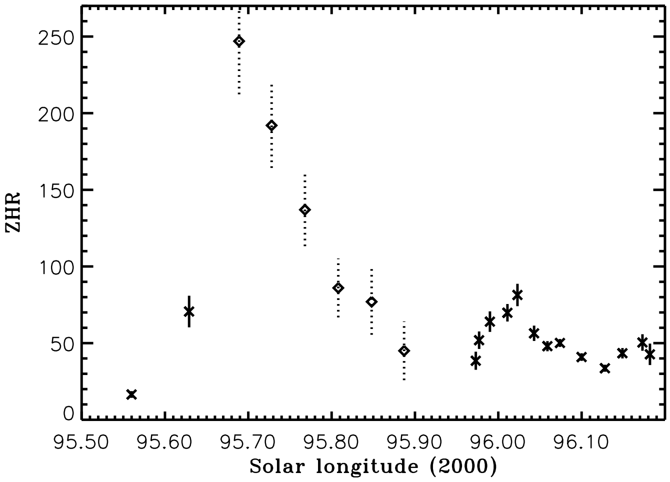

Figure 7. Magnification of the ZHR-profile of the 1998 June Boötids given in Fig. 6. The diamonds are again based on only one observer.

3.3 Radiant analysis

Software for the analysis of visual meteor plots was developed by Arlt (1992) and is available as RADIANT 1.41. Three different methods of radiant determination are implemented in this package: (i) traditional backward tracings of meteor paths resulting in a density distribution of individual meteor prolongations, (ii) the density distribution of intersection points, and (iii) the computation of probability functions for each meteor.

The first two methods are considered traditional; they were improved by applying the angular-speed information recorded by the observer to the prolongation arc on the sky. Path and angular-velocity errors of experienced observers were determined in Koschack (1992). The speed error is used to select a certain section of each backward prolongation as a valid radiant range of the meteor.

The last method is the most thorough way of radiant mapping, yielding reliable radiant distributions from small meteor samples. According to the error distribution of the path and the angular velocity, a whole area of probabilities behind a meteor is computed instead of a backward prolongation. Each point behind a meteor is associated with some probability of being its true radiant location, expressed by two Gaussian functions

$$p = \exp\left(-\frac{(\omega-\omega_0)^2}{2\sigma_\omega^2}\right) \times \exp\left(-\frac{\Delta^2}{2\sigma_{\mathrm{path}}^2}\right), \qquad (3)$$

where ω means the observed angular velocity, ω_0 is the theoretical angular speed at that distance for a given atmospheric velocity and σ_ω is the typical standard deviation of such estimates (depending on the speed itself). In the second term, Δ is the distance to the great circle on which the plotted meteor path lies, and σ_{plot} is the standard deviation of the plot in terms of 'error at the radiant'. Probability areas of all meteors are accumulated giving a radiant distribution.

Zenithal attraction is the shifting of a meteor radiant towards the local zenith by the gravity of the Earth. This is an effect which is usually negligible for observations obtained with visual accuracy. However, the zenithal attractions of shower meteoroids with extremely low geocentric velocities can amount to several degrees according to

$$\Delta z = 2 \arctan\left(\frac{v_\infty - v_{\mathrm{g}}}{v_\infty + v_{\mathrm{g}}} \tan\frac{z}{2}\right), \qquad (4)$$

where z is the geometrical zenith distance of the apparent radiant. This distance depends on the time when the meteor appeared; hence, the correction of a radiant *after* its determination from meteor plots of a night is only applicable if the zenith distance has not changed considerably. Therefore, the RADIANT software corrects each meteor individually for zenithal attraction. It assumes a most probable radiant of a single meteor according to path length and speed and changes the position of the meteor in a way that the distance of the new radiant to the original one fulfills the zenithal attraction. We used the same method of individual meteor correction for the diurnal aberration, which gives an additional shift of up to 1.°5 for the June Boötid radiant. The shift $\Delta\beta$ on a meridian running through the east and west points at the horizon, is calculated by

$$\sin\Delta\beta = \frac{\sin\beta\cos\phi\, v_{\mathrm{e}}}{v_\infty} \qquad (5)$$

where β is the distance of the apparent radiant from the east point, ϕ is the geographical latitude and v_{e} is the rotational velocity at the Earth's equator.

The probability method needs information about the angular velocities of the meteors, information that was not given by the majority of observers at the beginning of this century. Fig. 8 shows the backward prolongations of meteors observed and reported by Denning (1916c) with a main radiant at $\alpha = 229°$, $\delta = +55°$ The 1998 position derived by the probability method from a number of precisely plotted meteors is found at $\alpha = 226.°2$, $\delta = +46.°1$ (Fig. 9). The application of the zenithal-attraction correction considerably reduces the radiant size.

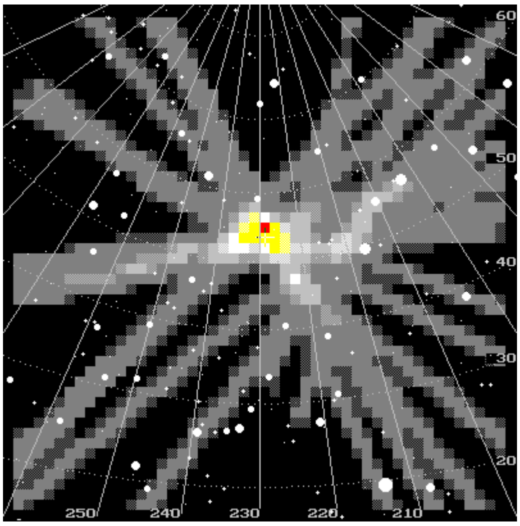

Figure 8. The June Boötid radiant derived from the meteor plots of Denning (1916c).

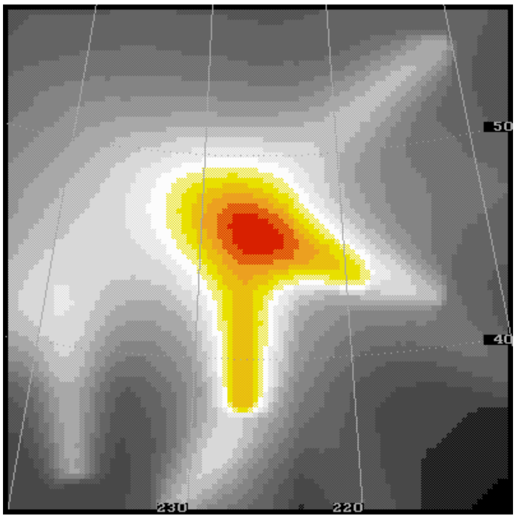

Figure 9. The 1998 June Boötid radiant derived from meteor plots of Velkov and Rashkova. The radiant shown here is based on 59 plots and corrected for zenith attraction and diurnal aberration.

3.4 Photographic data

A sample of seven single-station June Boötids was photographed by Velkov at Avren, Bulgaria, which are very well distributed in a fan-like structure around the radiant. The apparent radiant position is $\alpha = 229.°6$, $\delta = +48.°1$, which reduces to a geocentric radiant at $\alpha = 225.°2$, $\delta = +48.°4$ according to zenith attraction and diurnal aberration assuming a pre-atmospheric velocity of $v_\infty = 18$ km s^{-1}. The photo-

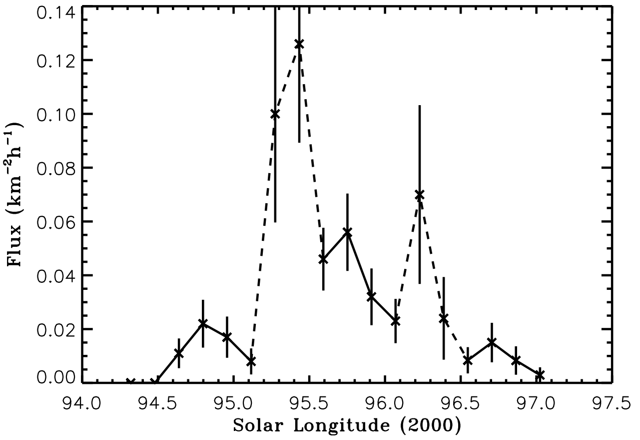

Figure 10. Flux profile derived from the SkiYmet radar on 1998 June 27. Dashed lines indicate four points suffering from a strong correction due to small collecting areas.

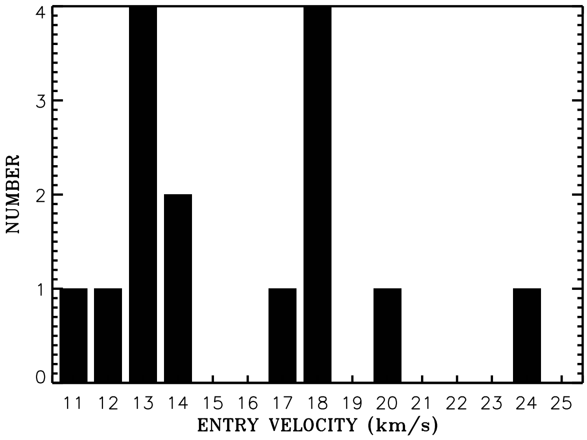

Figure 12. Distribution of pre-atmospheric velocities of 15 accurately measured June Boötids.

graphic meteors appeared between $20^{\rm h}35^{\rm m}$ and $22^{\rm h}10^{\rm m}$ UT on 1998 June 27.

The European Fireball Network (EN) photographed a $-8^{\rm m}$ June Boötid on 1998 June 27, $21^{\rm h}23^{\rm m}04^{\rm s}$ UT from two stations (Spurný & Borovička 1998). The geocentric radiant was found to be $\alpha = 222\overset{\circ}{.}88 \pm 0\overset{\circ}{.}16$, $\delta = +47\overset{\circ}{.}60 \pm 0\overset{\circ}{.}06$.

4 ACTIVITY FROM RADAR RECORDS

In addition to the visual observations of the Boötid outburst, radar records of the event were obtained. In particular, the SkiYmet Interferometric Radar observed the outburst from Saskatoon, Canada (52.1N, 106.4W). The SkiYmet Radar is a 6-kW peak power, 5-receiver system operating at 35.24 MHz using a three-element vertically directed Yagi for transmit and one two-element Yagi for each receiver. The limiting sensitivity of the system is near an equivalent limiting magnitude +7, or an electron line density approaching 1.5×10^{13} m^{-1}. The interferometric capability of the radar permits identification of the echo direction in the sky from an average meteor to within $1\overset{\circ}{.}5$ of the true location. As the gain pattern for the system is very broad, the system has nearly all-sky detection capability down to an elevation of 20°. As a result, the Boötid radiant was visible for all hours except from $2^{\rm h}$–$5^{\rm h}30^{\rm m}$ UT daily when the radiant elevation is too high to allow any echo detection above 20° elevation. However, as the slow velocity of the Boötids leads to a very large zenithal attraction effect, the apparent location of the radiant in equatorial coordinates varies by nearly 10° throughout the day. Thus any attempt to use the radiant mapping technique of Jones & Morton (1977) will lead to a smeared-out radiant region. To minimize this effect, Fig. 11 shows the radiant map using all echoes from $23^{\rm h}$–$8^{\rm h}$ UT daily when the radiant is above 50° elevation and the zenithal attraction effects are less than 5°, comparable with the estimated spread due to the intrinsic phase errors alone. The best-fitting radiant position from these data is $\alpha = 229^\circ \pm 3^\circ$ and $\delta = +48^\circ \pm 3^\circ$. Diurnal aberration of the radiant is not considered here.

To attempt to measure the flux from the shower, all data were binned into one-hour intervals. Using the best estimate of the geocentric radiant from photographic data (Spurný & Borovička 1998, photographs by Velkov) of $\alpha = 224^\circ$ and $\delta = +48^\circ$, an iterative procedure was adopted whereby the apparent radiant position at the mid-point of each hour was calculated and the 'apparent' radiant then used to sift June Boötids from the sporadic background. This was done by selecting those meteor echoes which were within ±3° of the specular point from the 'apparent' radiant within the one-hour interval. This was performed for all hours for June 26–28 (when the radar ceased gathering data). The echo collecting area for the Boötids was then calculated using standard techniques (cf. Brown et al. 1998) and the data binned into 4-hour increments to improve the statistical reliability. The final flux profile (which assumes $r = 2.2$ as found from the visual observations) is shown in Fig. 10. Error margins refer to the 95%-confidence interval due to the mere statistical number errors $\pm 2/\sqrt{n_{\rm JBO}}$.

There is a very definite beginning to the shower activity near $\lambda_\odot = 94\overset{\circ}{.}6$, the previous 12 hours showing absolutely no echoes from the Boötid radiant. A slow buildup in activity occurs from this point forward. Note that the data points closest to the $2^{\rm h}$–$5^{\rm h}30^{\rm m}$ UT intervals are subject to large uncertainties due to the much smaller collecting areas involved. Additional systematic errors of the analysis procedure may add to the statistical errors given in Fig. 10. The large increase near $\lambda_\odot = 95\overset{\circ}{.}2$–$95\overset{\circ}{.}4$ may be overstated due to this effect, but the large number of echoes from the Boötid radiant in this long interval (close to 1 every 2 minutes for several hours) is strong evidence of significantly heightened activity, probably higher than any other period where radar observations are available. The sub-maximum near $\lambda_\odot = 95\overset{\circ}{.}7$ corresponds to the region of maximum activity observed visually and is far from any 'edge' effects near to the time of radiant transit and is thus also likely real. The additional peak near $\lambda_\odot = 96\overset{\circ}{.}2$ occurs just after radiant transit when a large number of apparent Boötids (17) were seen in just one hour – this may be a real feature rather than a statistical anomaly, though again close to the time of smallest collecting areas.

The limiting sensitivity of the radar (+7 mag) is near

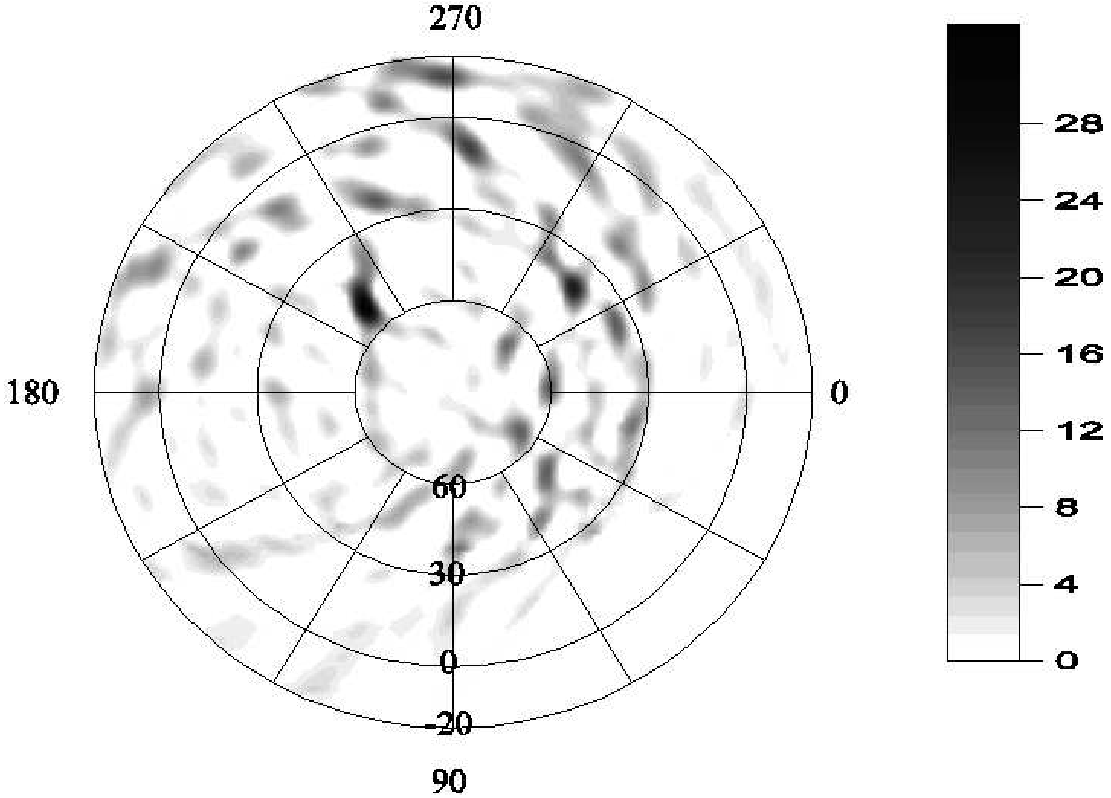

Figure 11. Map of radiation points derived from radar observations using the mapping technique described by Jones & Morton (1977).

the underdense–overdense transition region, and thus determination of mass-indices from the amplitude distribution of echoes is not applicable. The detection algorithm used is similar to that used for the CLOVAR meteor radar (cf. Brown et al. 1998) and hence discriminates detection against all but the shortest lived overdense echoes and thus duration distributions also do not provide a means for computing the mass index. The velocities of the echoes selected above were computed using a new spectral frequency technique based on the variation of the phase as the meteor crosses Fresnel zones (Hocking, in preparation). Of the 429 echoes of probable Boötid origin detected from June 26–28, 15 were of sufficient quality to allow for measurement using this new technique. Fig. 12 shows the distribution of velocities from the ensemble of selected Boötid echoes. A set of two possible peaks near 18 and 13 km s^{-1} is apparent, though the number statistics are very poor. The former is similar to the expected velocity of the Boötids and that measured by the one multi-station EN Boötid fireball (Spurný & Borovička, 1998), while the latter peak may represent Boötid echoes decelerated lower in the atmosphere or might be from another source entirely.

5 SUMMARY AND DISCUSSION

The activity of the June Boötids was exceptional in 1998. The highest activity with ZHR ≥ 40 was recorded between $\lambda_\odot = 95\overset{\circ}{.}6$ and $96\overset{\circ}{.}2$, that is, for more than 12 hours. According to radar and visual data, the peak time may be narrowed down to $\lambda_\odot = 95\overset{\circ}{.}7$ if we consider the second radar peak as the most reliable. The flux profile of particles producing meteors brighter than +6.5 mag is similar for visual and radar data. The apparently high flux of 0.126 $\mathrm{km^{-2}h^{-1}}$ in the radar data may be an artifact due to the very small collecting area at that particular time and does not coincide with high visual activity. The other values between 0.03 and 0.06 agree well with the visual fluxes between 0.02 and 0.04 $\mathrm{km^{-2}h^{-1}}$. A summary of individual radiant determinations of past and present records is given in Table 4. Radiant positions for the June Boötids were derived from visual, photographic and radar data. The visual and photographic radiants were corrected for zenith attraction and diurnal aberration; the radar radiant only involves zenith attraction. Giving a weight of 10 to the two-station EN fireball radiant, a weight of 5 to the photographic data obtained by Velkov and a weight of 1 each for the radar and visual radiants, we get an average radiant position at $\alpha = 224\overset{\circ}{.}12$, $\delta = +47\overset{\circ}{.}77$ (2000.0) for 1998 June 27.9 or $\lambda_\odot = 96\overset{\circ}{.}04$.

The 1916 June Boötid outburst happened 298 days behind the nodal passage of the parent comet 7P/Pons-Winnecke. Meteoroids released from the comet during the perihelion passage in 1915 were substantially disturbed by Jupiter between 1917 and 1919. The closest approach to Jupiter occurred in mid-May 1918 (0.719 AU). The comet and the particles of each ejection phase are disturbed by Jupiter in a different way. It is certainly a typical feature of short-period cometary meteoroid streams to show an activity behaviour which is decoupled from the orbital motion of the parent body. Perturbations from Jupiter are assumed to

Table 4. Radiants given for the June Boötids as given in historical records as well as in 1998 reports. If the column 'Z' is tagged, the radiant was corrected for zenithal attraction.

Date	α	δ	Source	Equinox	Z
1916 Jun 28	203°	+53°	observer at Birmingham; Olivier (1916)	–	
1916 Jun 28	221°	+56°	Denning (1923), no. 183	–	
1916 Jun 28	231°	+54°	Denning (1923), no. 184	–	
1916 Jun 28	213°	+53°	Denning (1923), no. 185a	–	
1916 Jun 28	223°	+41°	Denning (1923), no. 185	–	
1916 Jun 28	229°	+55°	Denning, this analysis	2000.0	
1921 Jun 28	212°	+49°	Nakamura (Yamamoto 1922)	–	
1921 Jun 28	228°	+58°	Denning (1923), no. 186	–	
1921 Jun 28/29	208°	+61°	Hoffmeister (1922); 12 meteors	1910.0	
1921 Jun 29/30	233°	+54°	Kanda (1922)	–	
1921 Jul 01	240°	+55°	Alenitch, 4 meteors (Malzev 1933)	1855.0	
1922 Jun 29	219°	+48°	Alenitch, 4 meteors (Malzev 1933)	1855.0	
1922 Jun 29	234°	+39°	Alenitch, 5 meteors (Malzev 1933)	1855.0	
1922 Jun 29	248°	+53°	Alenitch, 5 meteors (Malzev 1933)	1855.0	
1927 Jun 26.8	198°	+53°	3 observers, Tashkent (Sytinskaja 1928)	1927.0	√
1927 Jun 27	213°	+55°	Dole (King 1928)	–	
1927 Jun 27.8	198°	+54°	4 observers, Tashkent (Sytinskaja 1928)	1927.0	√
1927 Jun 28.8	198°	+54°	2 observers, Tashkent (Sytinskaja 1928)	1927.0	√
1927 Jun 29.7	200°	+54°	2 observers, Tashkent (Sytinskaja 1928)	1927.0	√
1927 Jun 30	218°	+60°	Dole (King 1928)	–	
1927 Jun 30.7	204°	+55°	1 observer, Tashkent (Sytinskaja 1928)	1927.0	√
— Jun 27–30	212°	+58°	Bakulin (1973), no. 18 (visual)	1950.0	
— Jun 13–Jul 02	229°	+48°	Bakulin (1973), no. 90 (photographic)	1950.0	
— Jul 01	209°	+56°	Bakulin (1973), no. 52	1950.0	
1942 Jul 06	206°	+54°	Bakulin (1973), no. 29 (telescopic)	1942.0	
1944 Jun 24	208°	+55°	Bakulin (1973), no. 30 (telescopic)	1900.0	
1987 Jun 27	229°	+44°	Velkov	1950.0	√
1998 Jun 27.6	218°	+53°	report by Vodicka and Marsh, radiant position corr. by McNaught (1998, MeteorObs mailing list)	2000.0	√
1998 Jun 27.60	229°	+48°	Brown and Hocking; radar	2000.0	
1998 Jun 27.89	222°.9	+47°.6	Spurný & Borovička (1998); double-station photograph	2000.0	√
1998 Jun 27.9	225°.2	+48°.4	7 photogr. meteors by Velkov	2000.0	√
1998 Jun 27.9	226°.2	+46°.1	Rashkova, Velkov	2000.0	√
1998 Jun 27.9	237°	+46°	Crivello (1998, pers. comm.)	2000.0	√
1998 Jun 27.9	240°	+50°	Gorelli (1998, IMO-news mailing list)	2000.0	
1998 Jun 27.9	224°	+50°	Haver (1998, IMO-news mailing list)	2000.0	
1998 Jun 27.9	220°	+59°	Stomeo (1998, IMO-news mailing list)	2000.0	

be the key mechanism which directs filaments of the stream closer to Earth at certain times. Since it is not the comet's perihelion passage but the encounter conditions with Jupiter which trigger an outburst, filaments ejected at different perihelion passages (being evolved quite differently) will be directed towards the Earth resulting in broad activity profiles and possibly large radiation areas.

Resonance effects as discussed for the Taurids (Asher & Izumi 1998) may act towards particle concentrations which encounter the Earth in intervals which are much different from the orbital period of the parent comet. In the case of 7P/Pons-Winnecke, this would be the 2:1 resonance with Jupiter. In the future, the orbit of the comet will be shifted back closer to the Earth's orbit (Asher, personal communication 1998). The June Boötid meteoroid stream will be an interesting subject for short-period stream evolution analysis.

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