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Meteor stream activity

II. Meteor outbursts*

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Abstract. In the past two centuries, alert amateur and professional meteor astronomers have documented 35 outbursts of 17 individual meteor streams well enough to allow the construction of a homogeneous set of activity curves. These curves add to similar profiles of the annual streams in a previous paper (Paper I). This paper attempts to define the type and range of phenomena that classify as meteor outbursts from which the following is concluded:

Outbursts are associated with the return of the comet to perihelion (near-comet type outburst), but occur also when the parent comet is far from perihelion and far from the Earth (far-comet type). All outbursts of a given stream are of one type only, depending on encounter geometry.

The activity curves, expressed in terms of Zenith Hourly Rates (ZHR), have a shape that is usually well described by: ZHR = $\mathrm{ZHR}_{max} 10^{-B|\lambda_\odot - \lambda_\odot^{max}|}$. The steepness of the slopes varies from an exponent of B = 7 to B = 220 per degree of solar longitude, with a typical value of B = 30. In addition, most near-comet type outbursts have a broader component underlying the main peak with B ~ 1-7.

The duration ($\Delta t \sim 1/B$) of the main peak is almost independent of location near the comet, while the background component varies considerably in duration and relative intensity from one return to another. The two components in the activity curve are due to two distinct structures in the dust distribution near the parent comet, where the main component can be due to a sheet of dust that emanates from the IRAS dust trail. This brings the total number of distinct structures in meteor streams to four, including the two structures found from the annual stream activity curves in Paper I.

Key words: meteors: meteoroids

1. Introduction

Annual stream activity (e.g. Jenniskens 1994 - Paper I) is not the only manifestation of meteor streams. Some streams are known from occasional intense outbursts of meteors and others have a non-annual low-level activity. Some annual streams, too, have significant variations in activity that are intrinsic to the distribution of dust in the meteoroid debris.

Events of this nature occur quite frequently. In the twelve years from 1982 to 1993, 12 meteor outbursts have been reported. For the purpose of this paper, *meteor outbursts* are defined as all those events of enhanced meteor stream activity that stand out significantly above the random variation of annual activity (if any). I will not use popular synonyms like 'meteor storm', 'rain', ' blizzard', or 'shower', because these terms are not very appropriate for some of the smaller events and, also, because the level of activity - implicit in these descriptions - is not a unique discriminator of the structures that may be present in the meteoroid distribution.

Meteor outbursts feature prominently in the history of meteor astronomy, most notably the succession of Leonid outbursts in 1799, 1833, and 1866. The discovery of the radiant in 1799, established in 1833, and its fixed position with respect to the stars during the night made it clear that there is such an entity as a meteor stream, and the periodicity of the event established the meteoroids as cometary debris (e.g. Olivier 1925; Lovell 1954; McKinley 1961; Hughes 1982).

Meteor outbursts are thought to be due to the recent ejecta of comets that have not yet spread in a wide area around the orbit of the parent body. Studies of this early stage of meteoroid debris evolution rely on activity curves obtained during outbursts (e.g. Plavec 1955; Plavec 1957; Sekanina 1974; Kresak 1993). *Meteor activity curves* depict the meteor rate as a function of the Earth's position in its orbit. Such curves are needed for as many as possible different paths of the Earth through the meteoroid stream, where each return potentially gives a different profile because the dust density varies over short length scales.

Meteor activity curves of outbursts have been published from visual observations by the unassisted eye (e.g. Hershel

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* Tables 1a-c are also available in electronic form: see the editorial in A& A 1993, Vol. 280 No 3, page E1. Part of this work was done while at Leiden Observatory.

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1867; Wood 1982; Spalding 1992), from radar backscattering observations (e.g. Lovell et al. 1947; Porubcan & Cevolani 1985; Lindblad 1987), and from radio forward meteor scatter - MS - observations (e.g. Mason 1992; Koseki 1990a). However, these curves have not been reduced to an influx rate consistently and inadequate corrections have occasionally led to disagreement on the level of activity and on the shape of the curves.

This paper presents a homogeneous set of meteor activity curves and searches for common features that will help predict future events and shed light on how dust is distributed near the parent comet. The available data are those accounts of outbursts in the literature that give a series of successive meteor counts. These counts are transformed into a consistent measure of influx. The emphasis is on counts from visual observations, which are reduced to Zenith Hourly Rates using the experience gathered in paper I, while radar and MS rates, if available, are scaled to the visual data. The method of approach is described in Sect. 2. Section 3 presents the results for a number of well observed meteor outbursts. These results are summarized and discussed in Sect. 4. The Zenith Hourly Rates are transformed into estimates of mass density and total mass of the meteoroid stream in Sect. 5. Finally, Sect. 6 to Sect. 8 present data on less well documented outbursts that add to, but do not alter, the picture drawn in Sect. 4. The paper briefly discusses the data in the context of meteor stream evolution, but the emphasis is on defining the appearance, in type and variation, of events that classify as a meteor outburst.

2. The reduction to zenith hourly rates

The reduction of the meteor counts per unit time (N/T_{eff}) to Zenith Hourly Rates (ZHR) is analog to Paper I and includes a correction for radiant altitude (h_r) dilution, a correction for sky limiting magnitude (Lm), and a normalisation to a standard observer perception (c_p):

$$ZHR = \frac{N}{T_{eff}} \frac{r^{6.5-Lm}}{c_p \; sin(h_r)^{\gamma}} \qquad (1)$$

where I assume that $\gamma = 1.4$ and r equals the magnitude distribution index χ.

The evaluation of accounts of outbursts, therefore, involves an estimate of the atmospheric condition (Lm), an estimate of the perception coefficient (c_p) from observed sporadic rates, and an estimate of the magnitude distribution index (χ) from the observed meteor magnitude distribution. Unfortunately, the accounts in the literature often do not contain a well defined estimate of sky condition, mention few if any sporadic meteors, and are from a very non-homogeneous group of observers. Magnitude distributions are not routinely reported, while data from annual streams are of no help because the magnitude distribution index may be quite different.

In order to arrive at a reliable activity profile, I use the fact that most of the uncertainties are multiplicative and systematic during the time span of the outburst. By plotting the data logarithmically, any systematic error in one of the corrections involving Lm, χ, or c_p, is evident from a systematic shift of the data. The method demands the availability of a series of successive counts by a single (group of) observer(s). Ten or twenty minute counts are usually sufficient to show the true width of the stream. This is the main selection criterion that determines which data are suitable for analysis.

The following general considerations determine the choice of parameters in Eq. 1. Firstly, estimates of atmospheric conditions are often based on quite general remarks given in the accounts. These are interpreted from personal experience and results of Paper I. For example, haze (cirrus or fog) on moonless nights typically decreases Lm to 5.5 or less. The presence of moonlight decreases the limiting magnitude to Lm = 5.5-5.0, while high level cirrus clouds in combination with moonlight can decrease Lm to 3.0 or less. If no information is available, I adopt a standard atmosphere, that is Lm = 6.5. Each drop of Lm by 1 affects the rates by a factor 2-4, depending on the magnitude distribution index.

Secondly, the observer perception c_p is derived by comparing the observed sporadic rates - HR = $N_s \times 3.4^{6.5-Lm}/T_{eff}$ - with the expected sporadic rate seen by a standard observer (HR_{exp}). HR_{exp} equals ten meteors per hour at 0^h local time in August seen from the northern hemisphere or 10 meteors per hour at 0^h local time in February seen from the southern hemisphere, or correspondingly scaled values according to the annual and daily variations of sporadic activity (e.g. Lovell 1954). c_p is defined such that $c_p = HR/HR_{exp}$. The ZHRs from those observers for whom basic information on perception and limiting magnitude are missing are scaled to those of observers who do provide such information. The scaling factor should not exceed a factor of 2.5, since c_p is in the range 0.4-2.5 for most current observers.

Group counts can not be reduced to single-observer rates without knowledge of the relative viewing directions. I assume that in such cases the observers were watching in different azimuthal directions, and the correction factors of Millman & McKinley (1963) apply: c_p = 1.8 for a group of 2 observers, c_p = 2.4 for 3 observers, and c_p = 2.9 for 4 observers.

Thirdly, the magnitude distribution index χ may deviate from that of the annual stream (if such exists). It affects the ZHR in the case of non-standard atmospheric conditions. More importantly, χ strongly affects the mass calculations. Its value is derived from meteor magnitude distributions (or mean magnitudes) provided by the observers, either by correcting the observed magnitude distribution N(m) for a standard probability function P(m) (Kresakova 1966):

$$\chi = n(m+1)/n(m) = \frac{N(m+1)}{P(m+1)} \frac{P(m)}{N(m)} \qquad (2)$$

or by plotting the log of the ratio of stream and sporadic meteors versus magnitude. In either case, the χ values reported are on a scale with χ = 3.4 for sporadic meteors (Kresakova

Table 1a. Basic data of meteor outbursts. The Table lists the date of maximum activity, the true radiant position (RA,DEC; equinox 1950.0, corrected for zenith attraction), apparent entry velocity ($V_\infty = \sqrt{V_G^2 + (11.2)^2}$ km/s), and the magnitude distribution index (χ). Also, the number of people who observed the event and (between brackets) the number of reports useful for evaluating the activity profile. The final columns list the time in days that the Earth follows (+) or leads (-) the comet at passing the node (E-C) and the minimum distance that the comet passes outside (+) or inside (-) the Earth's orbit (Δ_{E-C}). Data for E-C and Δ_{E-C} are from D.K. Yeomans (Leonids - Yeomans 1981; Draconids - in Spalding 1982; and Perseids - in Rao 1993), and from Porter (1952) and Drummond (1981).

Code	Name	Year	Date	RA,DEC (1950.0)	V_∞ (km/s)	χ	n_{obs}	E-C	Δ_{E-C} (AU)	#
	near-comet type									
Pup	π Puppids	1977	Apr. 23/24	110, -45	19	$\geq$1.6	many(2)	+12 d	-0.0012	1
		1982	Apr. 23/24	-	"	1.9	many(6)	-21 d	-0.0163	2
iDr	i Draconids	1916	June 28/29	238,+55	19	~ 1.7	5(2)	-79 d	-0.0408	3
Per	Perseids	1862	Aug. 10/11	-	61	-	(2)	-33 d	+0.0050	4
		1863	Aug. 10/11	(47,+58)	"	-	(3)	+332 d	+0.0050	5
		1991	Aug. 11/12	45.6 +57.2	"	1.9	many(2)	-507 d	+0.00094	6
		1992	Aug. 11/12	-	"	2.1	many(8)	-141 d	+0.00094	7
		1993	Aug. 11/12	45.9,+57.3	"	2.2	many(3)	+224 d	+0.00094	8
Dra	Draconids	1933	Oct. 9/10	262.4,+54.9	23	3.6	many(3)	+80 d	+0.0054	9
		1946	Oct. 9/10	262.1,+54.1	"	3.2	many(4)	+15 d	+0.0015	10
		1952	Oct. 9	262, +54	"	-	radar	-196 d	-0.0057	11
		1985	Oct. 8/9	262.4,+55.8	"	3.4	many(3)	+27 d	+0.0329	12
Leo	Leonids	1799	Nov. 11/12	-	71	-	many(1)	-116.9 d	-0.0032	13
		1833	Nov. 12/13	-	"	-	many(1)	+308 d	-0.0013	14
		1866	Nov. 13/14	149.3 +22.0	"	~2.5	many(3)	+299 d	-0.0065	15
		1867	Nov. 13/14	-	"	-	many(2)	+664 d	-0.0066	16
		1868	Nov. 13/14	-	"	-	3(2)	+1030 d	-0.0065	17
		1898	Nov. 14/15	151.7 +22.4	"	-	many(3)	-235 d	-0.0117	18
		1901	Nov. 14/15	151.5,+23.2	"	3.1	many(4)	+861 d	-0.0117	19
		1903	Nov. 15/16	152, +22	"	~2.5	many(1)	+1591 d	-0.0117	20
		1966	Nov. 16/17	152.5,+21.3	"	2.9	many(1)	+561 d	-0.0031	21
		1969	Nov. 16/17	-	"	3.0	11(2)	+1656 d	-0.0032	22
And	Andromedids	1798	Dec. 6/7	-	20	-	many(2)	-118 d	+0.018	23
		1872	Nov. 27/28	24.3,+43.6	"	~3.6	many(3)	-10 d	+0.0051	24
		1885	Nov. 27/28	24.5,+43.6	"	3.6	many(4)	-105 d	+0.0004	25
Pho	Phoenicids	1887	Dec. 3/4	24,-55*	~17	~3	1	-	-	26
		1938	Dec. 5/6	23,-57*	"	-	1	-	-	27
		1956	Dec. 5/6	15,-58	"	2.9	10(1)	-	-	28
		1972	Dec. 4/5	25,-57*	"	-	1	-	-	29
	far-comet type									
Lyr	Lyrids	1803	Apr. 19/20	-	48	-	many(1)	-58 y	-0.0021	30
		1922	Apr. 20/21	(271,+34)	"	-	2	+62 y	-0.0021	31
		1945	Apr. 21/22	-	"	-	1	+84 y	-0.0021	32
		1982	Apr. 21/22	-	"	2.9	many(3)	+121 y	-0.0021	33
tAr	θ Aurigids	1935	Aug. 31/32	87,+41	66	2.2	3(2)	+24 y	+0.0041	34
		1986	Aug. 31/32	94.3,+36.3	"	~1.3	1	+75 y	+0.0041	35
eEr	π Eridanids	1981	Sep. 10/11	56,-14	~57	2.6	1	+127 y	+0.014	36
Ori	Orionids	1993	Oct. 17/18	91.0,+15.5	68	2.0	many(3)	+7 y	+0.181	37
aMo	α Monocerotids	1925	Nov. 20/21	-	~60	-	3(1)	-18.1 y	-0.0338	38
		1935	Nov. 21/22	110,-5	"	~3	1	-8.1 y	-0.0338	39
		1985	Nov. 21/22	109,-7	"	2.7	2(1)	+41.9 y	-0.0338	40
Urs	Ursids	1795	Dec. 20/21	-	35	-	(1)	+5.9 y	+0.122	41
		1945	Dec. 22/23	217.1,+75.8	"	-	several(1)	+6.1 y	+0.091	42
		1986	Dec. 22/23	-	"	2.8	3(2)	+6.0 y	+0.089	43
	unknown type									
kPa	κ Pavonids	1986	July 17/18	275,-67*	~25	2.2	2	-	-	44
bHy	β Hydrusids	1985	Aug. 16/17	23,-76	~24	2.1	many(1)	-	-	45
mPe	μ Pegasids	1883	Nov. 10/11	-	16	-	1	-	-	46
		1893	Nov. 10/11	-	"	-	(1)	-	-	47
		1952	Nov. 11/12	339,+22	"	-	(1)	-	-	48
aCe	α Centaurids	1980	Feb. 8/9	210,-58	~60	2.2	many(3)	-	-	49

Notes and references to Table 1a

1 Bright meteors with long enduring trains (m_v = -4: 200^s).

2 Magnitude distribution N(m) (Lm = 6.7, from +6 down): 5,21, 62,99,103,76,39,19,12,8,3. Read this as: 5 between +6.5 and +5.5, 21 between +5.5 and +4.5, etc. All meteors of -3 left a train, and about half of 0 meteors. Mainly orange and yellow (Wood 1982).

3 "bright" (χ = 1.5-2.5). The radiant is derived from meteor positions given by Denning (1916). The rather general indication of "meteors radiating from a point between ζUMa and ηUMa" suggests a radiant at (209,+53), which is more close to the theoretical radiant of P/Pons-Winnecke (208,+56) (Drummond 1981). Indeed, Astapovich (1928) has (204,+56) from observations in 1927/28.

6 MS data consist of 83% (annual activity: 20-40%) long enduring trains (T>10s) (Koseki 1992, Shimoda et al. 1993). Large fraction of photographed meteors suggests also a smaller than annual χ.

7 Chen and Ouyang report (Lm = 5.5, from +2 down): N(m) = 3,4,14,20, 38,22,5,5,2 and 7,4,11,4, 6,6,4,0,1 respectively. Jan Kysely has between 19:30 and 21:10 UT (Lm = 5.5, +6 down): 1,0.5,1,3,5.5,3,4, 0,6,5,2 (read this as: one meteor between +6.5 and +5.5, one meteor of +4.5, one meteor between 4.5 and 3.5, etc.) and for sporadics during the whole night: 0,1,9.5, 9,1.5,4.5,0.5, 1.5,0.5,0,0, from which Znojil (1992) finds χ = 1.96±0.24, compared to χ = 2.22±0.26 later in the night.

8 Mean radiant from 15 multi-station photographic meteors from preliminary results by de Lignie & Betlem (1995).

9 χ from N(m) of De Roy. F.G. Watson (1934) has χ = 2.5. Photographic radiant of Millman (1936).

10 A discussion of χ is given in Kresak & Slancikova (1975). Prentice (1947) gives χ = 3.3 (I find 2.7). P.M. Millman finds χ = 2.5 (Jacchia et al. 1950). Photographic radiant by Millman et al. (Jacchia et al. 1950, Lovell 1954). Hey et al. (1947) have V_∞ = 22.9±1.3 km/s (radar).

12 Mameta (Lm = 6.0, +5 down:) 8,45,89,41,11,14,4,0,1; H. Tomioka (Lm = 6.5, +6 down:) 6,6,5,12,19,3,1,1,2 (Yabu 1985; Nagasawa & Kawagoe 1987). Simek (1986) has from radar data: χ = 2.48±0.14. Photographic radiant from 4 single station meteors by Ohtsuka (1986). Seven video trails give (262.2,+55.3) (Nagasawa & Kanda 1986). Simek (1994) has for overdense echoes: χ = 2.78 ± 0.13.

18 P.W. Jenkins (1899) from Indianola (IA) gives magnitude estimates, but these have an unusual distribution and are unreliable (see 1901 return). Photographic radiant from single station results (Lovell 1954).

19 Magnitude distribution by Larkin (Denning 1902) gives $2.6 < \chi < 3.8$ and I have χ = 3.3 from Brenke (1902). P.W. Jenkins' (1902) data are rejected because he systematically finds an anomalous proportion of weak meteors and has low total rates. Photographic radiant from single station results (Fisher & Olmsted 1929).

20 Denning (1904) finds meteors to be "bright, nearly all of first and second magnitude few though brighter than -4", with "no weaker meteors like for the Per and And".

21 Millman (1934) gives χ = 2.25±0.15 for a total of 167 Leonids seen in 1933, and χ = 2.60±0.20 for 322 sporadic meteors. The ratio of Leonids over sporadics as a function of magnitude gives χ_l/χ_s = 0.85, i.e. χ_l = 2.9. In 1966, Springhill Meteor Observatory radar: χ = 3.0±0.5 (Plavcova 1968, McIntosh & Millman 1970). In 1965: χ = 1.8±0.3 (McIntosh & Millman 1970).

24 Athen observers have average magnitude of 4.22 (Lm = 6.8-7.2) from 515 Andromedids, i.e. $\chi > 3.5$ (Schmidt 1873). Meteors faint: "seldom as bright as a star of 1st magnitude" (Grant 1872). W.F. Denning reports 20 out of 33,000 brighter than Jupiter and 188 out of 14,000 brighter than or equal to first magnitude. Dr. Kowalczyk has 1/10-1/15 of meteors +1, 1/2 of meteors 2-3, and rest 4-6.

25 E.F. Sawyer (1886) gives magnitude distribution. Many meteors have persistent train for 2-3^s (Grant 1886). Radiant position in 1872 and 1885 by Foersster (1886).

26 Meteors of medium brightness and long yellow streaks.

27 Radiating from Achernar (α Eri).

28 Meteors are yellow, orange, and red. J.H. Botham and S.C. Venter from South Africa have from +5 down: 4,15,14,5,16,5,2 meteors and apparent radiant at (10,-45) and (15,-45) respectively, from which Shain (1957) has (15,-58) after correction for zenith attraction. Meteors plotted far from radiant. However, good agreement with radiant determined by radar using range-time envelope method by Weiss (1958) at Adelaide, who has (15,-58) ±3°. 59 Phoenicid reflections included very few bright radio meteors.

31 Radiant from Prentice, but not obtained during outburst.

33 Lyrids "faint, but not less brilliant than in other years" (may refer to bright meteors only). McLeod: (Lm = 6.6, +6 down) 13,19,16,11,8,5,4,1,2. In period 1971-1980 under similar Lm he has: 7,28,37,32,25,16,13,2,2,3,1. m≤+3 gives χ=2.9, but excess +5 and +6 meteors (more favourable conditions than indicated?). Porubcan (1986) has low number of short duration echoes during outburst, which implies small χ. Porubcan & Stohl (1992): $\chi \sim$ 2.4.

34 Vrátník has (Lm = 6.0, +5 down): 1,4,9,14,2,2. Radiant from few plotted meteors, but good agreement between Praque and Sonneberg. 48% persistent trains.

35 Tepliczky has (+4 down): 1,1,6,3,7,5,0,0,1. "Bright yellow meteors, all of them leaving persistent trains for 1-3 seconds. Not so fast as Perseids."

36 Fast yellow orange meteors. N(m) (Lm = 5.6, +5 down): 1,3,8,11, 10,7,4,1,2,1; 44% left a train.

37 Koen Miskotte (KMH) has (Lm = 6.6, +5 down) 4,28,30,18,12,7, 4,1,2,1,1 for the Orionids and 6,29,25,9,0 for sporadics. Excess of bright meteors in single station photography. During outburst χ was 1.8-2.0, after outburst χ was 2.5-2.8 (Rendtel & Betlem 1993). Radiant from visual observations KMH.

38 Radiant "below Orion".

39 "Several were of first magnitude." Confusion about radiant position because of mix-up of stars γ and α Monoceros. Khan's latest position is adopted (Olivier 1936).

40 Eighteen meteors of magnitude 2-4. Very quick and of short duration, with no persistent trains (Baker). Brightest meteors 0 to -2, quite fast, little slower than Leonids (Ducoty 1986).

42 Photographic radiant from three trails (Ceplecha 1951).

43 Heen (8E,+58N) has χ = 3.4. Gaarder (11E,+60N) has χ = 2.7 (mostly annual activity). Average magnitude of Ursids and sporadics are: Heen has 2.61 and 2.50 respectively, Gaarder has 1.90 and 2.73. N(m) (+6 down), Heen has (Lm = 6.0): 8,11,14, 10,13,6, 7,1,2, 1,2,1 Ursids and 10,82,69, 58,58,57, 32,13,17, 3,2,0 sporadics in summer months, while Gaarder has (Lm = 6.3): 3,7,14, 20,17,11, 7,5,4, 3,2,1 Ursids and 40,201,338, 377,230,109, 63,34,15, 8,2,0 sporadics (Hillestadt 1987). 17% left persistent train with duration (from 0 down:) 0.6,0.6,0.8,1.1, 1.8,3.0 seconds.

44 The two observers together have (Lm = 5.7, +4 down:) 2,7,11,13,9, 6,6,2. "Slow" meteors with $V_\infty \sim 20 - 25$ km/s. 14 % of the meteors left a persistent train.

45 Very slow meteors, "slower than Taurids, but not as slow as slowest meteors seen (i.e. 18-25 km/s). All observed meteors (Lm = 6.5, +5 down): 4,14,21,26,23,12,13,5,1,2 (Wood 1986).

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49 Radiant position from plots: 207,-58 (Blencowe), 208,-58 (Freckelton), and 213,-59 (Willoughby). Bright meteors: mean magnitudes of +0.14, +0.75 and +0.92 respectively. Total of all observers (Lm = 6.5, +6 down): 4,13,19,22,35,29,21,12,7,4,1,1,0,0,1.

1966). χ usually varies between 1.7 and 3.8. Magnitude distributions are affected by the atmospheric conditions (Paper I), the radiant altitude (Bellot Rubio 1994), and the distance between the center of vision and the radiant (Moore & Morrow 1982). These effects render the absolute values of χ seldom more accurate than $\pm 10\%$, which affects the ZHR by less than 20% but has strong effect on the total mass estimates. No variations of χ with position in the stream are well enough documented to allow being taken into account. However, for the outbursts of annual streams (e.g. Per, Ori) I assume χ from Paper I for the annual component.

The absolute error in the zenith hourly rate is, of course, dependent on the validity of the assumptions made. In general, rates derived from the visual observations should be accurate to within a factor of two and occasionally are better than $\pm 50\%$. The duration and shape of the activity curve is usually better defined than the absolute level of activity.

3. Results

A literature search in the library of Leiden Observatory and the archive of the Dutch Meteor Society revealed 49 accounts of meteor outbursts that occurred between 1793 and 1993. Basic data for each account are listed in Table 1a. Most recent accounts are from amateur meteor observers that are members of the organisations listed in Table 2. These outbursts are from 17 individual meteor streams. Only five accounts deal with single events that can not be linked to previous activity, including one northern hemisphere stream of a known comet with rapid orbital evolution (iDr) and four southern hemisphere streams of which one has annual activity (aCe). In total, a mere 8 out of these 17 streams have high enough annual activity (ZHR$_{max}$ >2) to be listed in Paper I.

Figures throughout this paper show the calculated ZHRs as a function of *solar longitude* ($\lambda_\odot$, Eq. 1950.0), which relates to the position of the Earth in the meteoroid stream at a given time. The annual activity from Paper I, if relevant, is indicated by a dashed line and labeled "annual", as opposed to any "background" component that is part of the meteor outburst. Radar data and radio forward meteor-scatter data, if available, are corrected for radiant altitude dilution $(sin(h_r)^{-1})$. The result is scaled to the visual data at the peak and the base of the profile, after subtraction of an annual and sporadic component as estimated from data before and after the outburst. Radar and radio MS data can be recognized in the figures by the symbol "+".

For the purpose of characterising the profiles by as small a set of parameters as possible, I have fitted an equation:

$$ZHR = ZHR_{max} 10^{-B|\lambda_\odot - \lambda_\odot^{max}|} \qquad (3)$$

The fit is shown by a dashed line in the figures and Table 1b summarizes values of peak activity ZHR$_{max}$, time of maximum $\lambda_\odot^{max}$, and steepness of the slope B. The fit assumes that ascending B$^+$ and decending B$^-$ branches have the same slope (B$^+$ = B$^-$ = B). B is directly related to the stream cross section (Δt; equivalent width, or 2 times 1/e duration), which is:

$$\Delta t(^o) = 0.869/B$$

$$\Delta t(AU) = 0.0152/B \qquad (4)$$

For some time now, it has been realised that some outbursts occur when the comet is far from perihelion (e.g. Guth 1947; Kresak 1958). I will group the outbursts in two types: the familiar events related to the return of a comet to perihelion (e.g. Leonids, Perseids) and outbursts that occur when the parent comet is far from the Sun. These outbursts sample dust close to the comet and far from the comet respectively. I will refer to these as *near-comet* type outbursts and *far-comet* type outbursts. In the next section, four representative cases of each type of event will show different aspects of these outbursts.

3.1. Near-comet type outbursts

Outbursts associated with the return of the comet to perihelion are the more familiar. This section will discuss the Draconids, the Leonids, the Perseids, and the Andromedids. Other such events will be given in Sect. 6.1. The discussion is started with the Draconids, because their meteor activity curves strike me as relatively simple.

3.1.1. The Draconids

The *Draconids*, or Giacobinids, have been watched carefully during every return of the parent comet P/Giacobini-Zinner 1913 V (= 1926 VI) to perihelion after Davidson & Crommelin suggested that the close passage to the Earth in 1926 could possibly result in detectable meteor activity (Lovell 1954). Indeed, Prentice observed the stream at a rate of ZHR $\sim$ 14 in 1926 (Denning 1927; Prentice 1934) and spectacular displays were observed in 1933, 1946, 1952, and 1985. These four events are shown in Fig. 1.

The Draconid activity curves are well represented by Eq. 3 (Veltman & Jenniskens 1985). There are no significant differences in the slope of the ascending (B$^+$) and descending branch (B$^-$). Note that among individual observers there is good agreement on the steepness of the slopes, but there is no agreement on substructure on a scale larger than 15 minutes (i.e. $\Delta\lambda_\odot > 0.01^o$), with the possible exception of a feature in the 1946 profile near $\lambda_\odot$ = 196.218.

Striking feature of these profiles is the characteristic duration, noted before by Davies & Lovell (1955). For the returns in 1933, 1946, and 1952, I have B = 24$\pm$3, B = 17$\pm$2, and

Table 1b. Parameters that describe the main peak in the activity curve (Eq. 3). The ZHR data are decomposed into a main peak and an annual activity and/or background if present. The table lists values for the main peak. Subsequent columns list the peak position ($\lambda_{\odot}^{max}$), the peak rate (ZHR_{max}), the slope of ascending (B^+) and descending (B^-) branches, assuming that $B^+ = B^- = B$, the difference between time of maximum activity and the node of the comet $\delta_{E-C} = \lambda_{\odot}^{max} - \Omega_c$ (or between maximum activity and point of closest approach - marked $^{1)}$). Also given are the period of the comet (P_c), approximate orbital elements (i.e. perihelion distance q, inclination i, and argument of perihelion ω, where $a(1-e^2) \sim 1 \pm e \times cos(w)$ and $e = 1 - q/a$), the mass of a zero magnitude meteor M(0), the density of matter in the peak of the meteoroid stream (ρ; in g/cm^3), and the total mass (M_{tot}; in 10^{15} g.)

#	Name	Year	$\lambda_{\odot}^{max}$ (1950.0)	ZHR^p_{max}	B^p °)$^{-1}$	δ_{E-C} °)	P_c (yr)	q, i, ω (1950.0)	M(0) (g)	$\rho \times 10^{-24}$ (g/cm^3)	M^p_{tot} $\times 10^{15}$g
			near-comet	type							
1	Pup	1977	≥ 32.973	≥ 180 ± 60	10±1	≥ +0.33	5.12	1.00, 21, 359	12	1400	0.0016
2		1982	<32.556	>20	8.4±2.5	~ -0.33					
3	iDr	1916	97.413	300±80	8.0±1.6	-2.425	5.89	1.00, 18, 172	12	3000	0.006
4	Per	1862	(138.91)	≥250	≥13	~+0.22	135	0.93, 113, 150	0.13	40	0.0016
5		1863	(Tab. 1c)			~+0.26					
6		1991	138.869	500±100	25±7	+0.11					
7		1992	138.771	400±50	22±4	+0.013					
8		1993	(Tab. 1c)			+0.052					
9	Dra	1933	196.302	10,000±2,000	24±3	+0.059	6.59	1.00, 31, 172	6	11,000	0.006
10		1946	196.292	12,000±3,000	17±2	+0.001					
11		1952	196.241	(250)	25±3	+0.001					
12		1985	194.565	700±100	13±2	-0.147					
13	Leo	1799	(232.1)	>5,000	-	-	33.5	1.00, 162, 174	0.07	100	7E-6
14		1833	232.45	>5,000	-	<0.02					
15		1866	232.627	17,000±5,000	30±3	+0.055					
16		1867	232.713	6,000±2,000	30±6	+0.141					
17		1868	(Tab 1c)			≤+0.550					
18		1898	(Tab 1c)			-					
19		1901	(Tab 1c)			-					
20		1903	(Tab 1c)			-					
21		1966	234.468	15,000±3,000	30±2	+0.032					
22		1969	234.567	250±30	30±3	+0.131					
23	And	1798	257.1	like rain	-	(+3.5)	6.62	0.89,13, 222	10	15,000	0.03
24		1872	247.015	7,400±500	10.5±1.0	(+2.5)					
25		1885	246.645	6,400±600	9.5±0.8	(+4.3)					
26	Pho	1887	~252.2	~50	-	-	5.10	0.99, 16, 00	19	300	0.005
27		1938	~253.1?	-	-	-					
28		1956	~253.44	50±30	1.9±0.5	-					
29		1972	~252.4	~20	-	-					
			far-comet	type							
30	Lyr	1803	31.283	~860	-	+0.113	415	0.92, 80, 214	0.33	40	0.07
31		1922	31.290	~800	~35	+0.120					
32		1945	31.355	>97	-	~+0.185					
33		1982	31.371	250	33±8	+0.201					
34	tAr	1935	≥157.950	≥100	35±15	≤-0.014	1903	0.59, 153, 99	0.09	11	0.06
35		1986	157.821	250±30	33±8	-0.143					
36	eEr	1981	≥167.42	≥170±50	5-14	-1.58	∞	0.63, 109, 75	0.17	6	(0.09)
37	Ori	1993	203.6	25±5	0.6±0.1	-5.5	76	0.61, 164, 80	0.08	1.6	0.47
38	aMo	1925	238.684	≥2300	>115	-0.199$^{1)}$	∞	0.49, 110, 90	0.14	50'	(0.0009)
39		1935	238.740	≥1200	>69	-0.143$^{1)}$					
40		1985	238.617	≥600	220±50	-0.266$^{1)}$					
41	Urs	1795	271.1	like rain	-	+0.3	13.6	0.95, 53, 206	1.1	40	0.005
42		1945	≥270.627	≥120	17±5	≤0.787					
43		1986	270.236	160±40	17±3	+0.355					
			unknown	type							
44	kPa	1986	114.130	~60	30±15	-	∞	0.88, 24, 42	4	110	(0.04)
45	bHy	1985	143.133	80±20	30±6	-	~6	0.97, 32, 23	5	200	(0.002)
46	mPe	1883	229.9	-	-	-	7	0.98, 8, 199	24	~900	~0.005
47		1893	230.4	-	-	-					
48		1952	229.7	~100?	≥15	-					
49	aCe	1980	≤318.484	≥230±60	60±20	-	∞	0.99, 106, 01	0.14	16	(0.004)

Notes and references to Table 1b

1 Data recalculated from a ZHR curve by Buhagiar (1977), and counts by Wood (1979) (Lm = 6.5, c_p = 1). Radiant setting at end of observation. Low rates later that night from Brazil. In 1972, minor activity is seen by radar at 27MHz from (107.5,-45). The meteor stream was present on all four days, April 21-24 (Baggaley 1973).

2 Perception coefficients from averages over several years of observations (e.g. Paper I). Meteors first seen $\Delta\lambda_\odot = 0.35$ before the first Australian observations (58 between 02:00-03:35 UT - A. Beltran Bolivia). If peak at $\lambda_\odot$ = 32.305, then rates may have been as high as ZHR$_{max}$ = 2500.

3 Dennings had sporadic rate of only 2.5 per hour between June 23 and July 8, 1916. Brooks: Lm $\sim$ 6.5, $c_p \sim 1$.

5 No sporadic rates available. Data scaled to Schmidt's data, by assuming Lm=6.8 and c_p = 1.2 (as for his Andromedids of 1872). Rates uncertain by a factor of two.

6 Group of observers of Shinshu University Astro OB Club (137.49E, 35.95N) counted 64, 352, and 62 meteors in 1 hour intervals (Lm = 6.5) starting at 14:20 UT. Rates by Yasuo Yabu (128E, 27N) are consistent with the recorded number of trails on the pictures by Tatsuo Nakagawa and Haroshi Hayashi.

7 Adopted Lm for Chinese and Czechoslovakian observers is the value as observed by DMS members (see also van Vliet 1993): fast increase from Lm = 4.5 to 5.3 due to twilight and a constant low Lm = 5.5 rest of the night.

8 Position of peak consistent with observations reported by Marsden (1993).

9 Dutch data (Kock 1934) result in the same slope in the ZHR curve (Veltman & Jenniskens 1985).

10 Radar data: see Lovell et al. (1947), Lovell (1954), and McKinley (1961).

11 Radar data from Radiant Survey equipment at Jodrell Bank (Davies & Lovell 1955). Other system's data said to be unreliable.

12 Rates are scaled to sporadic data by H. Tomioka. MS data by J. Mason has centroid at 9:35 UT (saturated data) (Spalding 1992, Bone 1993). Lindblad (1987) finds $9{:}35\pm02^m$ UT from Onsala Space Observatory radar data. Data by Simek (1986) from Ondrejov radar are in error, because the data before and during maximum are obtained by a different recording method.

13 In 1799, Von Humboldt and co-observer M. Bompland in Venezuela had "thousands of meteors in four hours by 2 observers". They also said that "there was no space in the firmament equal in extent to three full moons not filled every instant with bolides or falling stars". Andrew Ellicott (about 83W,+25N) "woke at 3 o'clock" (Burritt 1840). Peak at 8 ± 1 UT, Nov. 12.

14 Anonymous observer in 1833 gives two rates: ZHR = 420 at $\lambda_\odot$ = 232.492 and ZHR = 3000 at $\lambda_\odot$ = 232.480. Increasing rates at $\lambda_\odot$ = 232.3 (Burritt 1840; Olivier 1925, Millman 1962). Cook (1973) quotes ZHR$_{max}$ = 14,000. Yeomans (1981) quotes ZHR$_{max}$ = 50,000.

15 Data scaled to sporadic rates by Maclear (before 13:15 UT the radiant was below the horizon). Hershel (1867) gives group counts or normalised data.

16 Full moon close to radiant. Sporadic rates by Iowa group.

17 Grant (1869) reports that activity increases at 4:30 UT but data after 05:00 UT show gradual decrease. Maclear gives sporadic rates and has twilight set in at 02:30 UT.

18 Prof. Keith at South Hadley (MA) and Prof. Payne at Northfield give sporadic rates (Wilson 1898).

19 Leavenworth (1902) and Denning (1902) give sporadic rates.

21 A report in *Sky & Telescope* (anonymous, 1967) quotes other observers having peak rates a factor of 4 less than those of Milon (1967). Radar data exist also from Springhill (Millman 1967a, McIntosh & Millman 1970). Perception coefficient of K. Simmons (AMS) is c_p = 1.0, from Perseid observations.

23 On Dec. 6th, between 7-9 pm local time, observers in China saw "stars fell like rain" (Tian-shan 1977). "Numerous stars glided southeastward as though weaving. They ceased after a while" (the rate of meteors?). In Japan "stars fell like snow" (Imoto & Hasegawa 1958). Brandes observed 400 meteors near Hamburg, while traveling on Dec. 7 (?), 1798 (Hershel 1872).

24 No information on sporadic rates. Data scaled to those of Grant, which results in reasonable c_p values (0.5-2.4). In the period that haze is present in Nottingham, rates notably drop. Schmidt's data saturate in peak (time noted after 100 meteors seen). Lovell (1954) quotes rates up to 2000-6000 per hour.

25 Some interference of moon. No sporadic rates. Data agree well, except for Sawyer and Cruls, which are scaled to other results. Lovell (1954) quotes rates up to 75000 per hour. In 1892 (Rees 1892; Hagen 1892; Hussey 1892) and in 1899 (Young 1899) Andromedids were detected up to ZHR = 500 and 20 respectively and a radiant at (25,+42) and (23,+42). No long enough series of counts available. S.J. Corrigan (in Lovell 1954) has $\delta_{E-C} = -0.53^o$.

26 "Nearly one meteor per minute" seen at Sydney, New South Wales.

27 "Large number".

28 Only total counts per observer given. Data uncertain by factor 2-3. Virtually all activity confined to one night Dec. 5/6. Radar rate equivalent to about ZHR$\sim$3-20 at $\lambda_\odot$ = 253.20 (Weiss 1958).

30 One count only by observer in Portsmouth (NH): Lm $\sim$ 6.5, $c_p \sim 1$.

31 Low radiant altitude.

32 Account by Koziro Kamaki from Kanaya, Japan, former president of NMS. 87 brightness estimates give a surprisingly low mean magnitude $< m >$ = 1.2 (Olivier 1946a). No sporadic estimates. In 1946, Czechoslovakian observers have ZHR = 23.6, 85.2, 29.2, 4.4, 47.0,40.2 respectively in 10 minute counts starting at 22:10 UT. One hour rates are 23.5, 38.6, 26.5 starting at 21:10 (Porubcan & Stohl 1983). Therefore, apart from spike of faint meteors, there is no typical outburst pattern.

33 McLeod has c_p = 0.8. Shanklin: Lm $\sim$ 6.5, $c_p \sim 1$.

34 Increase shortly before dawn. Sporadic rates are reported.

35 Sporadic rates as well as magnitude distribution suggests an (inexperienced?) observer with low c_p or a low limiting magnitude. I assume c_p = 0.4 and Lm = 6.2. Observations started at 00:00 UT. Ten minute counts starting at 00:40 UT: 1,0,4,4,5,4,2,2,0,2,0,0 (Tepliczky 1987, Adams 1987).

36 Eridanid count per hour was 0,3,11, and 34 from 13:00 UT onward. Sporadic counts: -, 5,7,7. The radiant was below the horizon before 13:00. Lm = 5.6, $c_p \sim 2$.

37 Experienced observers. Data calculated from original reports.

38 No data on Lm or sporadic rates. Thirthy-seven meteors in 13 minutes. Meteors reported by Olivier ("bright, slow, leaving trains") are not part of this outburst.

39 Two 20 minute counts only: "more than 100" and 11 respectively. Khan is experienced AMS observer, c_p = 1.0. Hazy sky; therefore, I assume an optimistic Lm=5.5.

40 In four minute intervals starting at 11:41 UT: 27,5,2,2 meteors. Probably not obtained during regular watch. Ducoty: Lm$\sim$6.5, $c_p \sim 1$. "At about 11 o'clock pm", K. Baker at Lick Observatory saw 18 meteors in 7 minutes with a radiant in CMi. Next night only one possible stream member between 11:15-12:15 UT.

42 ZHR recalculated from Ceplecha (1951). First three 10-minute counts (starting at 16:45 UT) may be uncertain due to twilight. Clouds and moonrise interfered after 18:30 UT.

43 Number counted in ten minute intervals by Lars Trygve Heen (8E,+58N) starting at 21:00 UT on Dec. 21/22 is (Lm=6.3): 8,4,7,16,9,10 (Lm=6.5:) 7,6,2,1 (Lm = 6.0 to 5.5:) 1,3,2. Sporadic rates over 1986 indicate $c_p = 1.2$.

44 Peak at 11:40 UT. Between 11:50 and 13:00 UT Inwood and Stacy (116.1E, -32.5S) recorded 26 and 30 κ Pavonids respectively and 4 and 6 sporadic meteors. Lm = 5.7. Moon phase: 0.8, 80° altitude. Inwood has $c_p = 1.7$ from sporadic rates in July 1986 (Wood 1986a,b).

45 Raw 20 minute counts: BM (Lm = 6.5, $c_p = 0.7$) at (116,-31.9): 08:50 UT onward: 1,2,6. JT (Lm = 6.5, $c_p = 1.3$) at (116.1,-32.0): 9:10 UT onward: 4,12,4 and in 1 hour counts from 01:10 onward: 2,0,0. SE at (116.1,-32.0) (Lm = 6.5, $c_p = 1.4$) observed 5,19,8 from 9:10 onwards. JB (116.1,-32.0) (Lm = 6.8,$c_p = 1.1$) observed 11,5,2,1 from 9:30 onwards (last interval only 15 minutes. Also 10% clouds) and in same intervals MC (Lm = 6.8, $c_p = 1.2$) saw: 13,7,3,1.

48 Number of photographed meteors in comparison to the number of Geminids per unit interval suggests ZHR$\sim$100. Uncertain result; no visual observations.

49 Raw counts of Blencowe and Freckelton (115E,-34S) from 12:10-13:10 UT: 14 and 11 Centaurids, 9 and 8 sporadics (Lm = 6.5, $c_p \sim 1$). Towards the end of the hour, the activity declined. Centaurids were active before 12:10 UT. Freckelton saw one between 14:15 and 15:15 UT. During the end of the hour the activity ceased. Willoughby (Busselton) saw 8 and 2 per hour from 13:15 UT onward.

B = 25±3 respectively. In 1985, the Earth remained far from the comet orbit and the peak activity was modest. However, the duration of the outburst was, again, nearly the same as in 1946, i.e. B = 13±2. Therefore, stream duration is nearly independent

Table 2. National organisations of amateur meteor observers that contributed to the data discussed here and the corresponding abbreviations used in the text. "MS" stands for "Meteor Section".

	Organisation of amateur meteor observers.
AKM	Arbeitskreis Meteore e.V. of Germany
AMS	American Meteor Society
BAA-MS	British Astronomical Association
DMS	Dutch Meteor Society
MMTEH	Hungarian Meteor and Fireball Observing Network
NAPO-MS	North Australian Planetary Observers
NAS-MS	Norwegian Association for Amateur Astronomy
NMS	Nippon Meteor Society
WAMS	Western-Australian Meteor Society (now: NAPO)

3.1.2. The Leonids

Past *Leonid* outbursts are of special interest because of the upcoming 1998/1999 return of the parent comet P/Temple-Tuttle 1965 IV. Numerous accounts of Leonid outbursts exist as far back as 902 AD. They show that the node of the orbit changed over time by no more than $d\Omega/dt$ = +0.0008°/yr (Imoto & Hasegawa 1958; Tian-shan 1977). However, the information on meteor activity is very meager. Only in the past two centuries have counts been published. From that, the highest reported rates are given by Lovell (1954) and Kazimirchak-Polonskaya et al. (1968), and have been discussed by Yeomans (1981). Series of counts that give information on the activity curve were first published in 1866. Despite a high awareness of the possible occurrence of Leonid outbursts, the observations at any return seldom cover the full range of solar longitude due to bad November weather (e.g. Millman 1934).

The meteor activity curves from years of reportedly very