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ASTRONOMY
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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: $\mathrm{ZHR} = \mathrm{ZHR}_{max} 10^{-B|\lambda_\odot - \lambda_\odot^{max}|}$. 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 $\sim$ 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.

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):

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

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):

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

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	≥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) $\pm 3^o$. 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. $m \leq +3$ 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).

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 ±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 ±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:

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

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:

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

$$\Delta t(AU) = 0.0152/B \tag{4}$$

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 ~ 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±3, B = 17±2, and

1995A&A...295..206J

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 $^o)^{-1}$	δ_{E-C} $^o)$	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 $9{:}35 \pm 02^m$ 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~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 of Δ_{E-C}, the minimum distance between the Earth and comet orbit. Values of Δ_{E-C} are listed in Table 1a.

The absolute level of activity during the 1933 and 1946 returns is debated, mainly because of the bad observing conditions during both returns (1933: rising moon at phase 0.7; 1946: full moon and, at some locations, cirrus clouds). Reported relative peak rates range from 3:1 in favor of the 1933 return to 1:2 in favor of the 1946 return (Lovell 1954; Kresak & Slancikova 1975). Absolute rates vary from 2,250 (Prentice 1947) to 30,000 (Cook 1973). My judgement of the observing conditions results in a similar level of activity for both years, about ZHR$_{max}$ = 10,000.

Low level activity of ZHR = 1-4 was observed before and after the main peak in 1985 (Fig. 2b). The Draconids do not normally have annual activity with ZHR>1 and rates remained below ZHR = 2 in 1986, suggesting that this extended background component is associated with the outburst. The background component is shown in Fig. 1b, assuming it has a similar shape as Eq. 3, and values for the exponent B and peak rate ZHR$_{max}$ are listed in Table 1c.

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 high activity are given in Fig. 2 and will be discussed chronologically. The profile from 1866 contains a sharp peak, which is symmetric and well represented by Eq. 3, where values of B are similar to those of the Draconid outbursts. In addition, there is a strong background component, well defined in the descending branch. A sum of two curves as Eq. 3 results in a good fit to the data. Some observers report an exponential increase of activity up to a 10-minute central time interval. However, those observers that recorded the time after which a constant number of meteors was counted (e.g. Dawes 1867, Schmidt 1873) invariably show signs of saturation, perhaps because of inaccurate notation times. Data obtained by this method are not included in the plot.

The profile of 1867 is less well determined due to bad observing conditions. The data are consistent with a scaled down version of the profile of 1866.

A century later, in 1966, the activity curve had a similar main peak, but the background component was less strong. Peak rates are usually quoted as ~ 150,000 (Milon 1969; Yeomans 1981), but this may be too high. Note that the visual counts of Milon

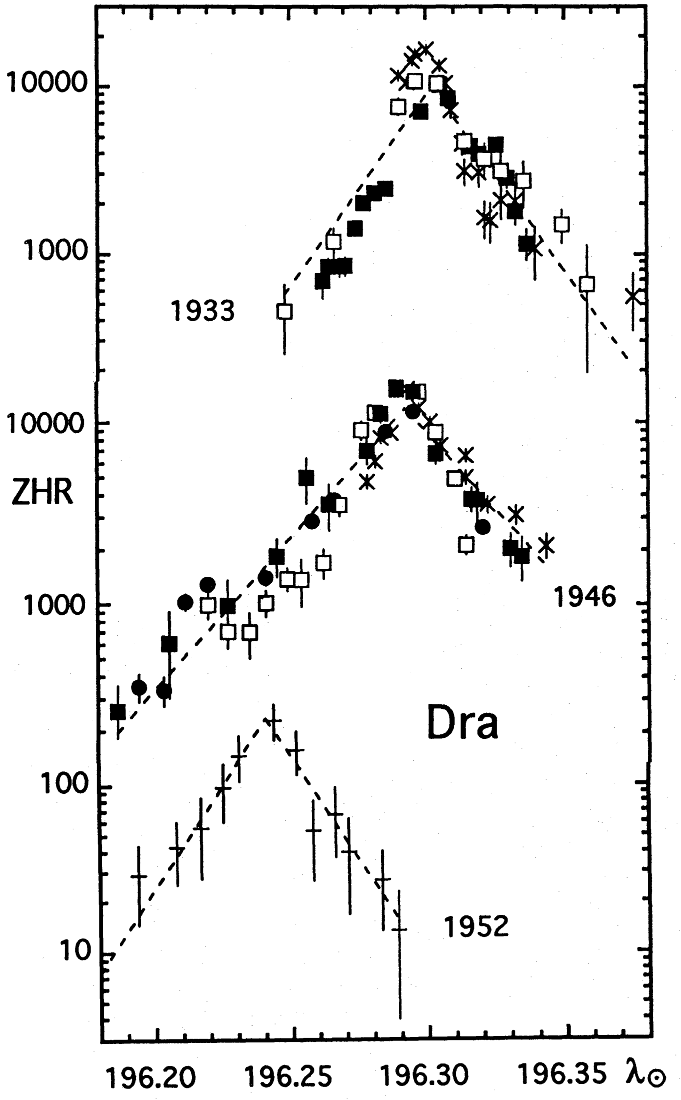

Fig. 1a. Activity curves of Draconid outbursts (1952: radar only). Note the typical triangular shape of the profiles on this log-normal scale. The observations are consistent with a single set of exponential slopes. **1933**: Data by F. De Roy at Mortsel by Antwerp (■ ; Lovell 1954), observers at Bergedorf (□ ; anonymous 1934), and observers Becker & Mueler in Potsdam (× ; anonymous 1934). **1946**: Data by Dutch observers in Groningen (□ ; Plaut 1948), AMS observer D. McKelly of the University of Oklahoma (● ; Olivier 1946), Mr. and Mrs. Averill + four observers in Wisconsin (× ; Averill 1946), and BAA observers Argus, Prentice, Ryves, and Burns (■ ; Prentice 1947). **1952**: Radar data by Davies & Lovell (1955)

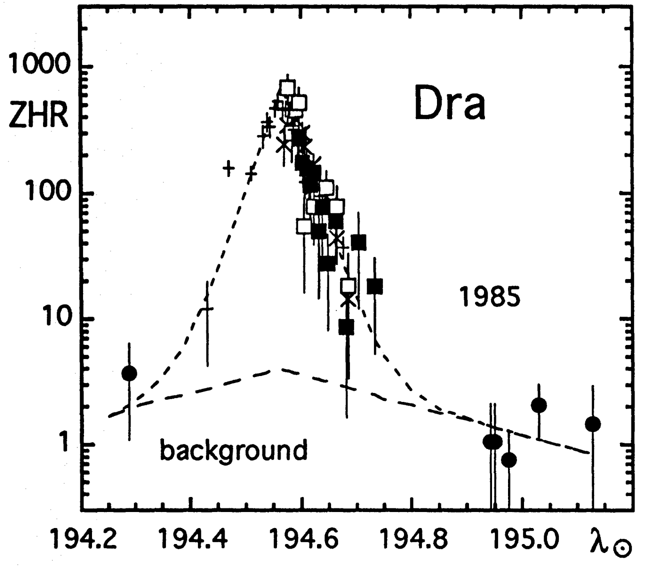

Fig. 1b. The profile of the 1985 outburst has a weak background that is associated with the outburst. **1985**: Visual data from NMS observers H. Tomioka from Japan (141E, +37N) (■ ; Nagasawa & Kawagoe 1987; Koseki 1990a), Y. Yabu (136E, +35N) (□), Mameta (×), and AKM observers J. Rendtel & R. Alt (●). Radar data by B.A. Lindblad (+ ; Lindblad 1987)

c.s., the only ones available to me, show a sudden increase of rates by a factor of 8 (Fig. 2b), coinciding with a change in observing technique at maximum. Instead of the regular counting, they opened the eyes for 1 second during a sweep of the head and counted projected (!) meteor trails. The sharp increase in rates is not seen in radar data (Plavcova 1968; Millman 1967a; McIntosh & Millman 1970), where the slopes of ascending and descending branch and the reduction procedure give no reason to assume that this is because of saturation in the radar data.

Therefore, I conclude that the main peak did not increase up to ZHR ~ 150,000 but only to some 15,000±3,000. Strength and duration of the main peak are similar to the outburst in 1866, suggesting again that the duration of the main peak is independent of Δ_{E-C}.

As late as 1969, an outburst was observed by visual observers in Canada (Millman 1969) and confirmed by radar (Porubcan 1974; Porubcan & Stohl 1992). This event was much less intense. Remarkably, the event was of the same duration as the main peak in 1966, suggesting that the stream duration is independent of E-C, the position of the comet in its orbit during the event (Fig. 3).

Other accounts of high Leonid activity result in gradually increasing or decreasing rates during the night without a well defined maximum. Fig. 2c shows such curves for 1898, 1901, and 1903. The available counts trace a broad component, superposed on annual activity, which retains the same slope in different returns but varies in absolute level. Rates were highest in 1901 (or perhaps in 1900). The slope of the broad component is somewhat less steep than the background below the peaks in 1866 and 1966 (Table 1c). A narrow peak may have been missed, because no observations cover the relevant 0.1 degree wide period of solar longitude. Indeed, Kazimirchak-Polonskaya et al. (1968) do report very high activity on Nov. 14, 1901 (given date off by 1 day?). On the other hand, in other years the narrow peak did not occur at all. For example, in 1961 and 1965 only a very broad (B ~ 0.9-1.5) increase in activity was observed both visually and by radar (Millman 1967a; McIntosh & Millman 1970). No series of visual counts are available to me in order to evaluate these profiles. An interesting aspect of the outbursts

Table 1c. The background component. Symbols as in Table 1b. In addition, the ratio of mass in the background component relative to the main peak is given as well as the sum of both mass estimates (M_{tot}; in 10^{15}g).

#	Name	Year	$\lambda_\odot^{max}$ (1950.0)	ZHR^b_{max}	B^{b+} $^o)^{-1}$	B^{b-} $^o)^{-1}$	M^b $\times 10^{15}$g	M^b/M^p	M_{tot} $\times 10^{15}$ g
			near-comet	type					
2	Pup	1982	32.552	3.3	0.09	-	0.16	100	0.16
5	Per	1863	(138.94)	300±50	-	9±3	0.008	4	0.010
8		1993	138.810	230±30	6.0±1.0	-			
12	Dra	1985	194.565	∼ 4	-	∼ 1.2	0.0008	0.1	0.007
15	Leo	1866	232.625	1,000	-	6±0.5	0.0002	30	0.0002
16		1867	232.713	350	6±2	-			
17		1868	233.122	(700)	-	4.5±0.5			
18		1898	(233.46)	1,100	-	4.1±1.0			
19		1901	(233.46)	7,000	3.2±0.6	3.8±0.6			
20		1903	(233.46)	1,400	3.5±0.4	-			
21		1966	234.468	150	∼6	∼6			
25	And	1885	246.645	100	∼0.30	∼1.4	0.2	8	0.2

in 1961-1965 is that the meteors were reportedly brighter than in the years after passage of the comet by the node (McIntosh & Millman 1970; Yeomans 1981), which is thought to be the result of radiation forces (Kresak 1976).

There are other scattered reports of high Leonid activity from 1831, 1832, and 1836 (Olivier 1925), 1868 (Grant 1869; Maclear 1869), 1900 (Kazimirchak-Polosnkaja et al. 1968), 1932 (Lovell 1954), and 1961 (McIntosh & Millman 1970). Most of these accounts relate to a broad component and are not easily interpreted because of a lack of several overlapping series of counts. For example, the observations of 1868 are consistent with a gradually decreasing level of activity during the night between $\lambda_\odot$ = 233.116 - 233.291 (Table 1b), but the two available series of counts (Grant 1869, Maclear 1869) show multiple peaks. Because the series do not overlap, it is impossible to check if these variations are merely due to variations in observing conditions, as I believe they are, or are a true feature of meteor stream activity.

3.1.3. The Perseids

A third example of near-comet type outbursts are those of the Perseid stream. The return of comet P/Swift-Tuttle 1862 III to perihelion was announced in 1980 and perfect observing conditions resulted in claims of enhanced *Perseid* activity (e.g. Russell 1982, 1984). However, the relative levels of Perseids and sporadic meteors in the available visual data do not confirm this claim (Jenniskens 1992). When the comet finally came in 1992, there were several outbursts of meteors. The first one occurred in 1991 (Koseki 1992; Shimoda et al. 1993; Watanabe et al. 1993), the second in 1992 (Marsden 1992). These were a prelude to the discovery of the comet on September 26, 1992 (Marsden & Green 1992). This is the first time that a meteor stream has been of guidance in finding the parent comet.

The profiles of the three events in 1991, 1992, and 1993 (Fig. 4) are symmetric and well represented by Eq. 3. There is no evidence of a wider component associated with the main peak, although the data of 1992 do allow for such a component up to a peak ZHR ∼ 10. The outbursts in 1991 and 1992 show similar peak activity and width of the stream, i.e. B = 25±7 and B = 22±4, but the event of 1993 is 4 times broader (B = 6±1). The duration of 1993 is similar to the background component that underlays the main peak of the Leonid outbursts. Perhaps, the 1991 and 1992 events sampled a "main peak" structure in the dust distribution, while the 1993 event sampled a "background" structure.

There is some indication that the same sequence of events happened during the previous return in 1862. The 1862 outburst on Aug. 10/11 was noted for its relatively short duration: "in the very first evening twilight, numerous stars fell intersectingly, mostly towards the southwest. This ceased after nightfall" (Tian-shan 1977), which suggests B>13. Accounts of the 1863 event have been gathered by Olson & Doesher (1993) and result in an activity curve that is not very accurate, but does suggest that the event in 1863 was of long duration as in 1993 (Fig. 4b). Accounts that go further back in time (e.g. Imoto & Hasegawa 1958; Tian-shan 1977; Dall'olmo 1978) do usually not coincide with the return of the comet to perihelion (Marsden et al. 1993; Yau et al. 1994) and the descriptions are consistent with annual activity.

3.1.4. The Andromedids

Andromedids, or Bielids after the parent comet P/Biela 1852 III, were first seen in 1741 (McKinley 1961; Cook 1973). Large numbers were seen in 1798, four years after a perturbation by Jupiter. Comet P/Biela split up prior to its return in 1846 and was lost after the next apparition in 1852. Major outbursts occurred again in the years 1872 and 1885. These latter events are well documented. The activity curves are shown in Fig. 5.

Again, the activity curves have exponentially increasing and decreasing branches, now with relatively shallow slopes: B = 10±1. The slope is nearly the same for both returns. However, the reported activity reaches a plateau at maximum in the profile

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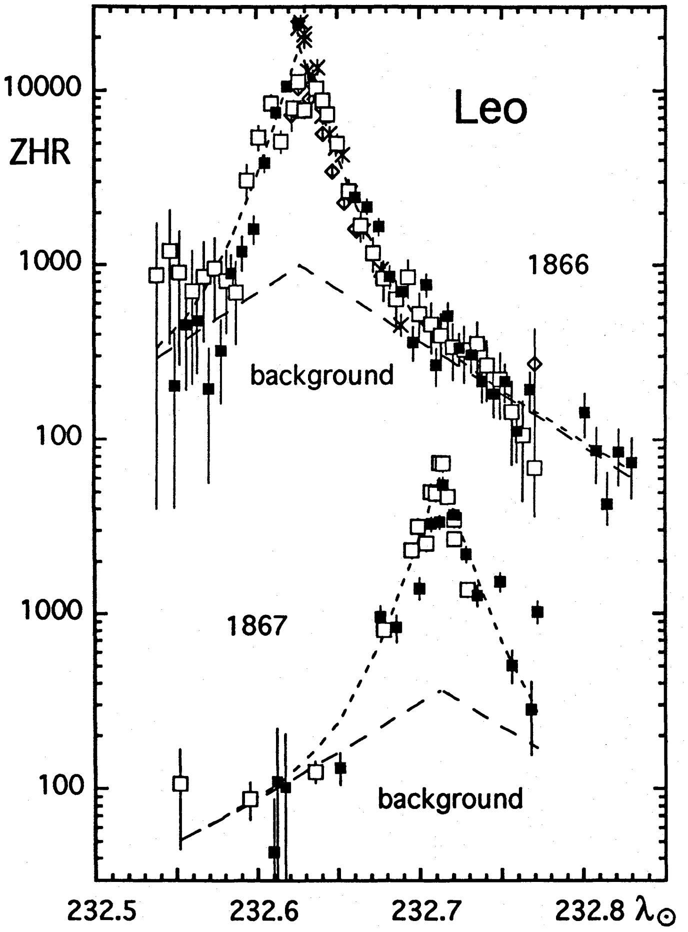

Fig. 2a. The profiles of the Leonids of 1866 and 1867 show a symmetrical main peak and a strong background. **1866**: Data are from Rev. R. Main in Oxford (□ ; Main 1867), G.W.H. Maclear at Cape Observatory (× ; Maclear 1867), A.S. Hershel in Greenwich (■ ; Hershel 1867), and P. Smyth in Edinburgh (◇ ; Smyth 1867). **1867**: Data are from Captain Stuart from Nassau (■ ; Stuart 1868) and a group of observers in Iowa (□ ; Leonard 1936)

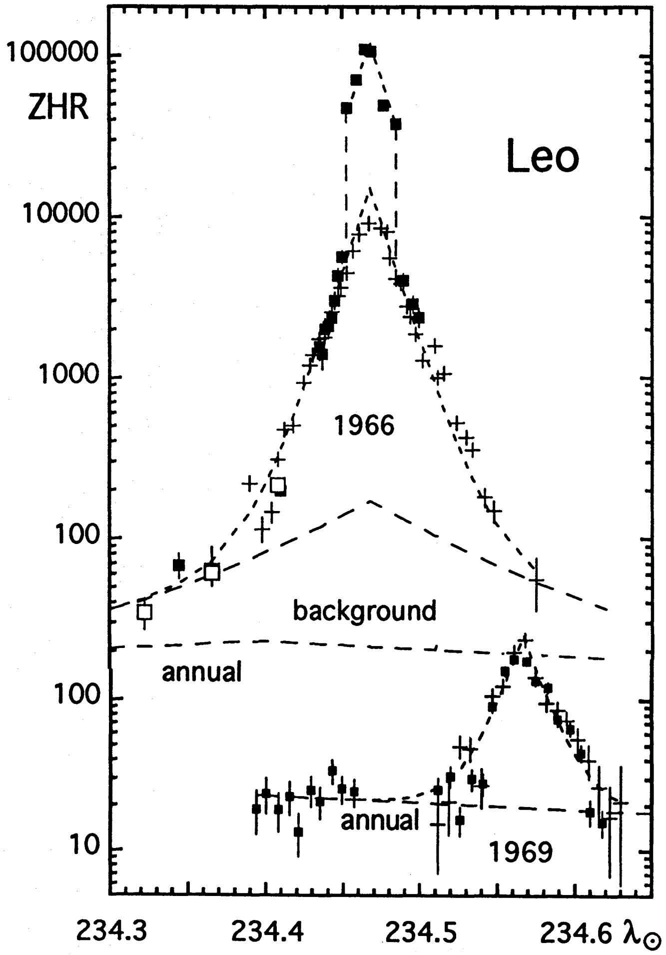

Fig. 2b. The jump in visual counts during maximum of the Leonids in 1966, by a factor of 8, coincides with a change in observing technique. The main peak has the same width as in 1866, but the background is much weaker. **1966**: Data from Milon c.s. at Kitt Peak Observatory (■ ; Milon 1967) and AMS observer K. Simmons (□ ; van Woerden 1967), as well as radar data by Z. Plavcová (+ ; Plavcova 1968). **1969**: Data from Millman c.s. (■ ; Millman 1969) and radar data by Porubcan & Stohl (1992)

of 1872. Perhaps my "twin exponential" model does not fit all the storms that occur, even to first order. This is the most clear example where the model appears to fail. Indeed, there is the (remote) possibility that the plateau is a real feature of the activity curve due to an irregular deposition of fresh material after the breakup of the comet. However, there are compelling reasons to believe that, instead, the plateau is due to a saturation of counts and the model fit does not fail. First of all, the Andromedids are exceptionally slow and persist for some time on the sky, which makes counting difficult at high rates. Secondly, some observers report a more saturated peak than others. Thirdly, it is probably justified to argue that, if the plateau is due to the breakup of the comet, a similar (or broader) plateau should have been observed in 1885, which is not the case.

A feature quite different from other outbursts is the asymmetry in the background. Cruls (1886) and Sawyer (1886) observed high rates of Andromedids in the night before Nov. 27/28, 1885 (Fig. 5b). E.F. Sawyer counted 37 Andromedids and 5 sporadics between 7 and 8 UT (*Universal Time*) on Nov. 26/27. This background has a B value characteristic of annual activity (Paper I). I do not know of an annual recurrence at this level. Similarly, during the previous return of 1798 high activity may have been observed on Dec. 4 and 5, a few days before the main peak on Dec. 6 (Tian-shan 1977). The unusually strong assymetry in the background may be related to the fast orbital evolution of the parent body, which had $d\Omega/dt = -0.18^{o}$/yr in the nineteenth century (Imoto & Hasegawa 1958), and suggest that the meteoroids in the background component evolve faster than the comet itself.

3.1.5. Comparison of near-comet outbursts

In comparing individual events of a stream, the duration of the main peak stands out as a stream characteristic. The duration, or stream width, does not vary much with Δ_{E-C}, the mini-

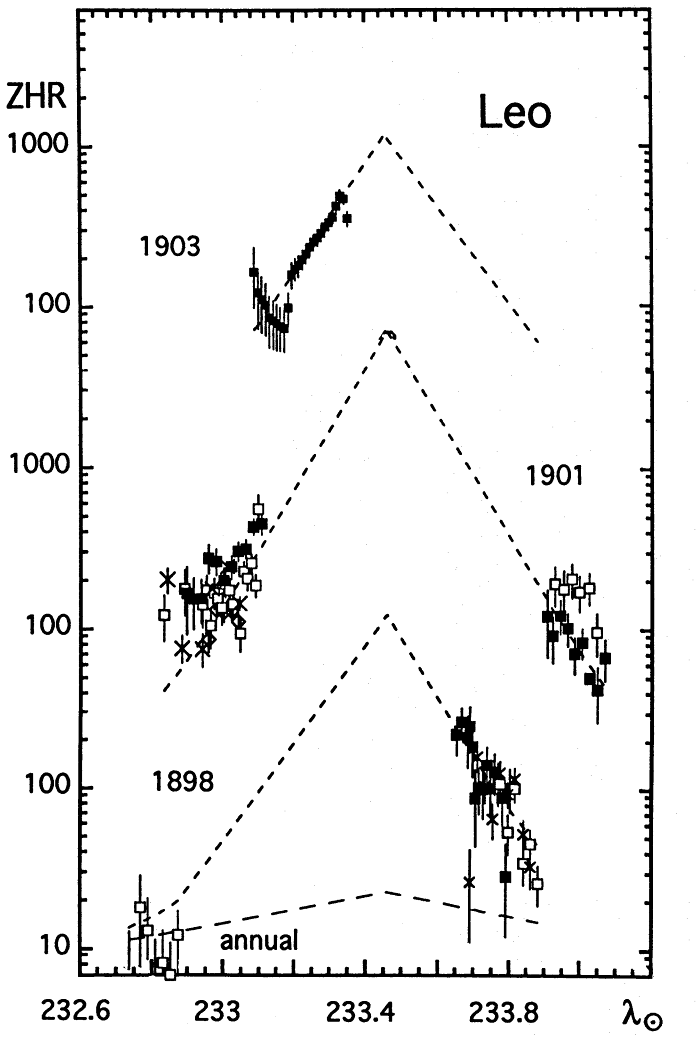

Fig. 2c. Leonid outbursts associated with the return of the comet in 1899. All activity curves fit to Eq. 3 with the same slope but a different peak activity. **1898**: Data from L.G. Weld from the State University of Iowa (× ; Weld 1899), F.G.J. from Claremont (CA) (□ ; Brackett 1899) and Prof. Keith at South Hadley (MA) (■ ; Wilson 1898). **1901**: Data from E.L. Larkin from Virginia (×; Denning 1902), Mr. Wilslow Upton from Providence (◇ ; Denning 1902), 3 observers at the University of Illinois (□ ; Brenke 1902), and F.P. Leavenworth c.s. at the University of Minnesota (■ ; Leavenworth 1902). **1903**: Data from BAA observer W.F. Denning at Bristol (1904).

mum distance between Earth and comet orbit, or with E-C, the position of the comet in its orbit during the event.

Table 1b lists the third parameter (Fig. 3) that is related to the position of the dust with respect to the comet orbit, and that is the time difference between the maximum of the outburst and passage of the node of the comet orbit (δ_{E-C}):

$$\delta_{E-C} = \lambda_{\odot}^{max} - \Omega_c \qquad (5)$$

I find that δ_{E-C} increases with increasing E-C away from zero in a series of events during one return. The meteor outbursts peak systematically earlier or later than the time that the Earth passes the comet's node. This feature is of value in predicting the time of occurrence of future outbursts.

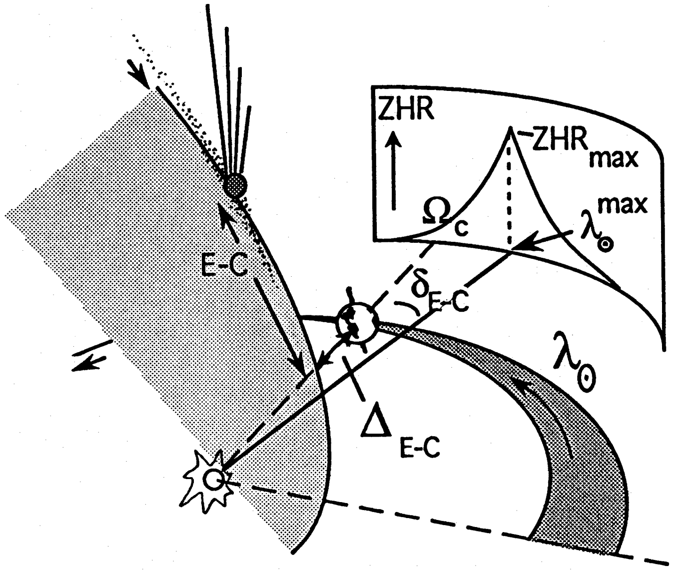

Fig. 3. This illustration shows the meaning of the parameters mentioned in the text that describe the distribution of dust relative to the comet position and orbit. The figure is not on scale

All near-comet type meteor outburst profiles show signs of a background component. The one possible exception, the Perseids, has a strong annual activity that can hide any background activity in the 1991 and 1992 profiles, but perhaps the wide stream seen in 1993 is due to such a "background" dust component. There is considerable variation in the relative contribution of the main peak and the background from return to return. Notably, the Leonids show a gradual broadening and a surprising increase in strength of the background component with increasing Δ_{E-C}. This concludes the section on near-comet type outbursts.

3.2. Far-comet type outbursts

I now turn to outbursts that occur when the parent comet is not near perihelion. The archetype of such far-comet outbursts is the Lyrid stream. This section also discusses the α Monocerotids and Aurigids. Other examples are given in Sect. 6.2.

3.2.1. The Lyrids

Because no approaching comet was there to give a warning, the 1982 Lyrid outburst came as a surprise to several independently working observers of the AMS and one fortunate observer of the British BAA-MS. A rare set of excellent observations is available from Norman M. McLeod and Jonathon Shanklin, who reported five and ten minute counts respectively (Adams 1982; Spalding 1982). The outburst duration was 0.64 hours. The event has been confirmed by radar from Springhill (Porubcan & McIntosh 1987) and Budrio (Porubcan & Cevolani 1985).

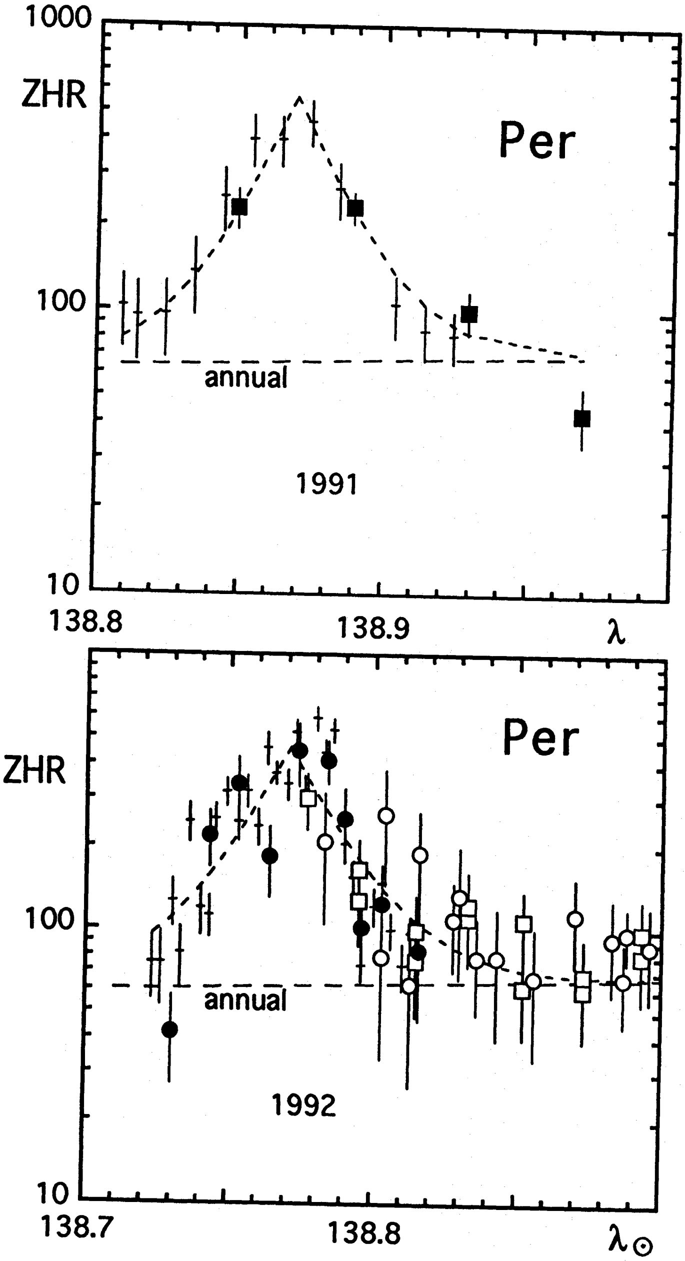

Fig. 4a. A strong annual component underlays the outbursts of the Perseids. The figure shows the two outbursts observed before perihelion passage in Dec. 1992. **1991**: Data by Yasuo Yabu from Japan (■) and radar data by Watanabe et al. (1993). **1992**: Data by Chinese observers Chen Wu from Tianjin and Ouyang Tianjing from Wuhan (● ; Xu Pin-xin 1992), Czechoslovakian observers I. Micek, T. Nasku, and Jan Kysely (□ ; Brown et al. 1992a; Znojil 1992), DMS observers Koen Miskotte at Harderwijk, and Marco Langbroek, and the author from Basel, Switzerland (O). 66 MHz radio MS data by BAA-MS observer J. Mason (+ ; Spalding 1992)

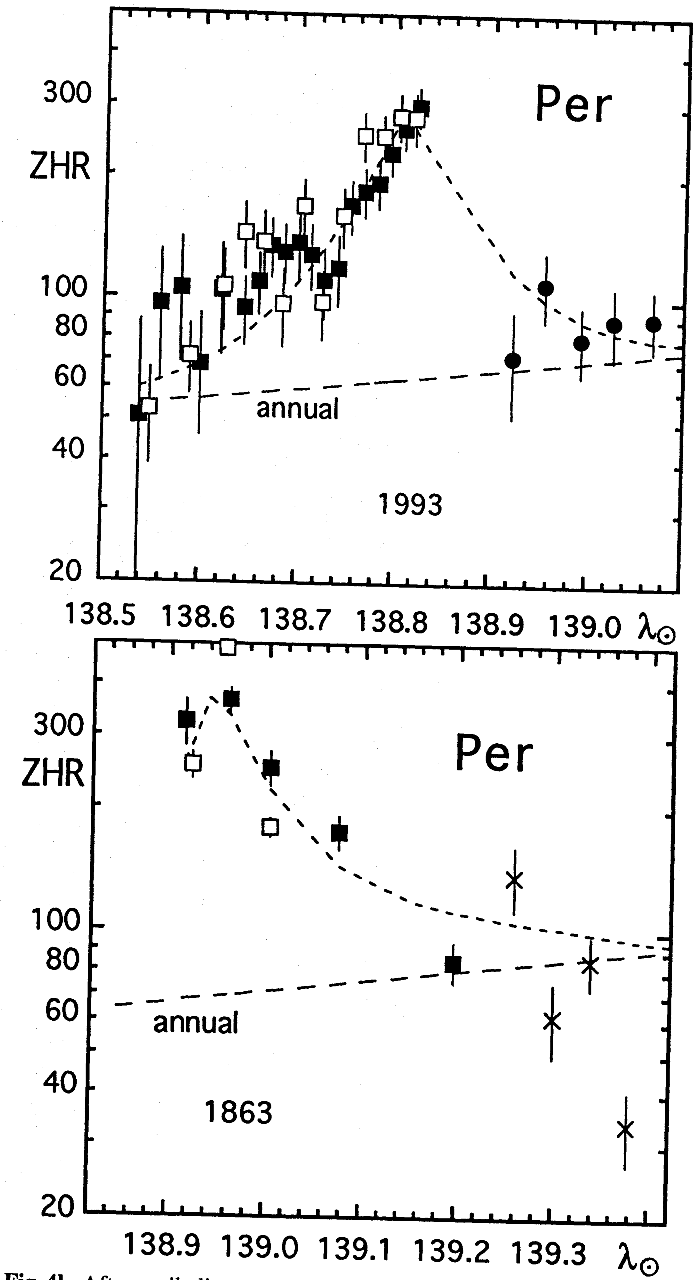

Fig. 4b. After perihelion passage, in 1993, the Perseid outburst lasted four times longer. Compare the X-axis scale with that of Fig. 4a. The event of 1863 occurred after perihelion, too, and data are consistent with a similar long duration. **1993**: Results of DMS observers Marco Langbroek and Koen Miskotte (■) and Marc de Lignie (□) from Puimichel near Digne in France, and the author (●) from Los Banos, CA. **1863**: Data from J.F. Julius Schmidt at Athens Observatory (■ ; Schmidt 1863), a group of observers in Germany as reported by E. Heis (□ ; Heis 1863), and from observers Andres Poey and Ricardo Zenoz from Havana, Cuba (× ; Poey 1864)

The resulting activity curve is shown in Fig. 6. Again, a curve as Eq. 3 is successfully fitted to the data.

In 1922, a similar outburst was seen by observers in Poland (Gadomski 1929) and by H.N. Russell in Greece (Olivier 1935). Gadomski's report is not available to me, but Guth (1947) and Lindblad (1992) report that the Polish observers had peak activity at $\lambda_\odot = 31.294$ and $\mathrm{ZHR}_{max} \sim 600$. This is in good agreement with results from H.N. Russell's data, in spite of a low and climbing radiant, from which I have a peak in activity at $\lambda_\odot = 31.290 \pm 0.007$ and $\mathrm{ZHR}_{max} \sim 800$. The event in 1922

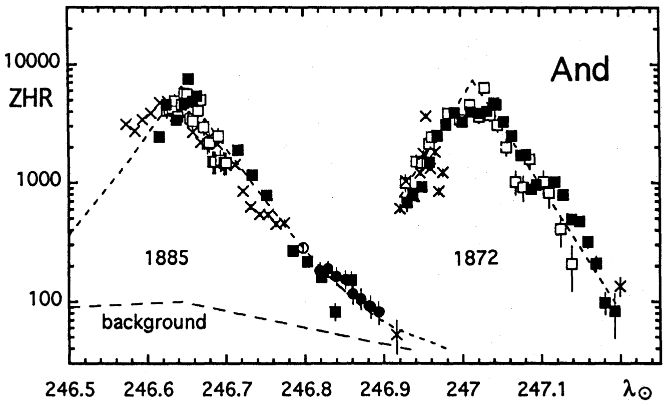

Fig. 5a. The meteor activity curve of 1872 has the same exponential slopes as in 1885, but an apparent saturation at maximum. This is interpreted as due to the observers having a hard time counting the slow Andromedid meteors during maximum. **1872**: Data by R. Grant (■ ; Grant 1872), E.J. Lowe from Nottingham (□ ; Hershel 1872), and J.G. Galle in Breslau (× ; Galle 1873). **1885**: Data by H. Urquhart (□ ; Grant 1886), Merino c.s. in Madrid (× ; Merino 1886), Hildebrand-Hildebrandsson & Charlier in Uppsala (■ ; 1886), E.F. Sawyer from Cambridgeport, MA (• ; Sawyer 1886), and Cruls from Rio de Janeiro (O ; Cruls 1886)

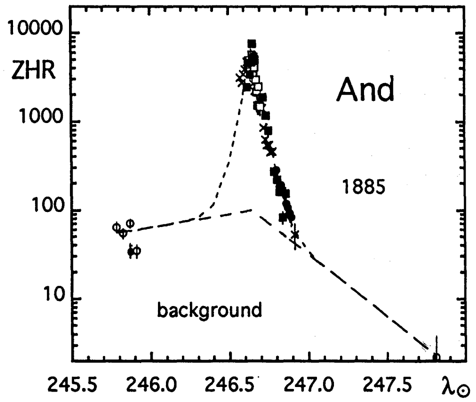

Fig. 5b. High rates in the night before and after the main peak of 1885 suggest that an asymmetric background component underlays the main peak of that year's activity curve. Symbols as in Fig. 5a

is consistent with an activity profile of the same duration as in 1982. The peak activity may have been a factor of 3-4 higher.

Many more accounts of increased Lyrid activity exist (Fischer 1931; Guth 1947; Spalding 1982a; Lindblad 1992). One rich display occurred in 1803 (Herrick 1838; Benzenberg 1838; Fisher 1931), lesser returns with peak ZHR's of order 30-100 were seen in 1838/39, 1850/51, 1863, 1934, and 1945/46, from which Guth (1947) determined a 12 year period. In 1994, 12 years after 1982, Robert Lunsford and the author observed the Lyrids between solar longitude 31.25 and 31.52 from California. But alas, no meteor outburst was observed (Fig. 6). This implies that meteor outbursts do not occur every 12 yrs. Instead, there is at best an enhanced probability of detecting an outburst every 12 years.

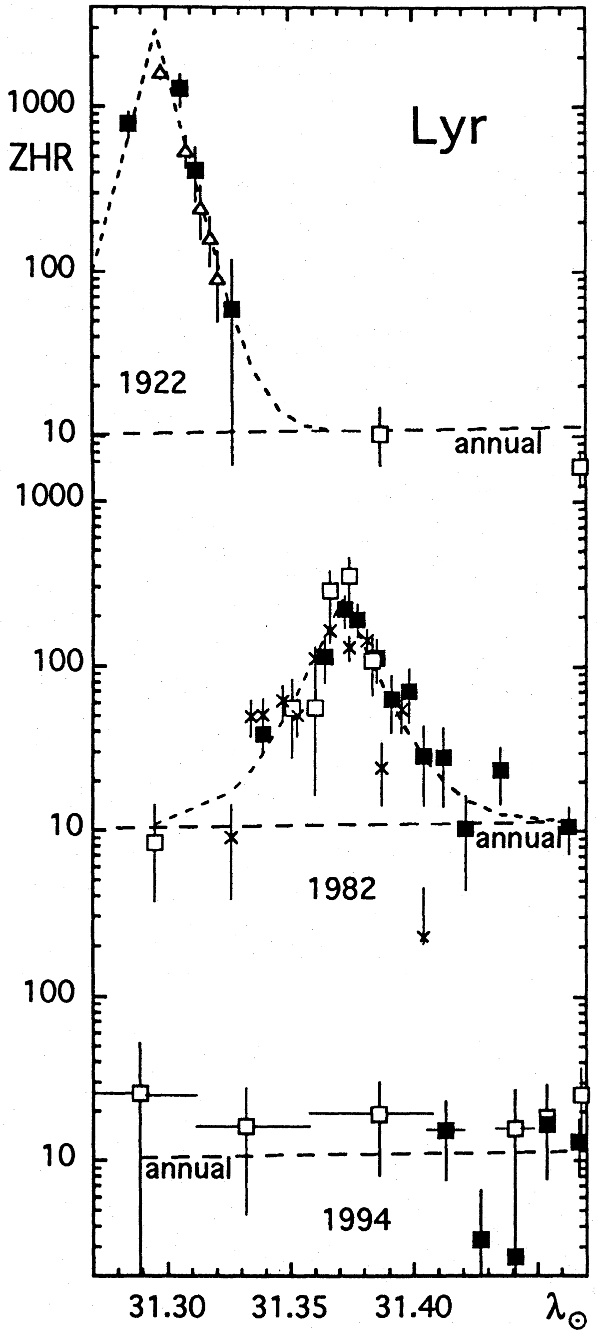

Fig. 6. The outburst of Lyrids in 1922 and 1982 were probably of about the same duration. There was no outburst in 1994. **1922**: Data by J.P.M. Prentice (□ ; Olivier 1935) and BAA observer Henry Norris Russell from "Greece" (■ ; Prentice 1930). **1985**: Data by AMS observer Norman M. McLeod from Ft. Myers (Fl) (■ ; Adams 1982), and BAA-MS observer Jonathon Shanklin (□ ; Spalding 1982), and radar data by Porubcan & Cevolani (+ ; 1986). **1994**:Observations by Robert Lunsford (■) from San Diego, CA, and the author (□) from Morgan Hill, CA. The atmospheric conditions changed considerably during the observations in 1994, because of an F = 0.7 moon before $\lambda_\odot \sim 31.47$. Lm typically was 5.5 in the beginning of the night and rose slowly just before moon set, after which Lm = 6.7

Many historic outbursts have been linked to the Lyrid stream. Events in 687 BC, 15 BC (Tian-shan 1977), 1040, 1096, 1122/23 (Dall'olmo 1978), and 1136 (Imoto & Hasegawa 1958) indicate that the node of the orbit was constant to $\pm 0.5^o$ over the past few millenia. More recent outbursts (Table 1b) occur within a 0.1^o interval from solar longitude $\lambda_\odot = 31.37$. Note that the four outbursts in the Middle Ages occurred at semi-regular intervals at the time of expected Lyrid outbursts, but the sequence of events had a period of 13.5-14 yrs (Dall'ollmo 1978). If these are Lyrids, then the periodicity is not stable over relatively short time scales. In any case, the recent accounts make it beyond doubt that the outburst event rate is much higher than suggested by the orbital period of the parent comet, P/Thatcher 1861 I, which is $P_c = 415$ yr.

3.2.2. The alpha Monocerotids

In November of 1985, Richard Ducoty (Capitola, CA) obtained four successive counts of α Monocerotids, or November Monocerotids (Ducoty 1986). This is an outstanding observation and resulted in the best documented activity profile of the stream to this date. Two previous events are known, one in 1925 and one in 1935. They are of a similar characteristically short duration (Olivier 1926; Hindley 1936; Olivier 1936). For example, in 1925 F.T. Bradley ran inside to get his cards etc. but discovered to his disappointment that the stream was over when he returned to continue his observations (Olivier 1926). No other known stream has such a narrow meteor activity profile. For the return in 1985, confirmed by Keith Baker at Lick Observatory, I estimate an effective duration of no more than 6 minutes.

The time of maximum $\lambda_\odot^{max}$ scatters significantly around $\lambda_\odot = 238.68$ by about 0.06^o. The sequence of events suggests a periodicity of 10 years (Olivier 1936). This is probably less than the orbital period of the parent comet Van Gent-Peltier-Daimaca, 1944I (Kresak 1958), which is not a short period comet of the Jupiter family and has not been observed since its return in 1944.

3.2.3. The theta Aurigids

In 1986, an outburst of *θ Aurigids* was reported by MMTEH observer I. Tepliczky from Hungary (Adams 1987; Tepliczky 1987). The observation remained unconfirmed, but was quickly accepted because of the similarity to a well known previous θ Aurigid outburst in 1935. That outburst was observed by C. Hoffmeister (Hoffmeister 1936) and confirmed by visual observers in Prague (Guth 1936). Duration and level of peak activity are about the same. The data scatter around solar longitude 157.88 with a spread of 0.07^o. An association of these outbursts with the annual stream of Aurigids (Aur), described in Paper I, is not certain because these refer to a rather diffuse radiant slightly more to the north. I adopt the name θ Aurigids.

Tian-shan (1977) links two previous events in 1037, Aug. 21, and 1063, Aug. 22, to this meteor stream. Indeed, the Chinees accounts are consistent with a relatively moderate activity of short duration from a stream with a radiant in the north-east: "several hundreds of stars glided southwestward" and "several

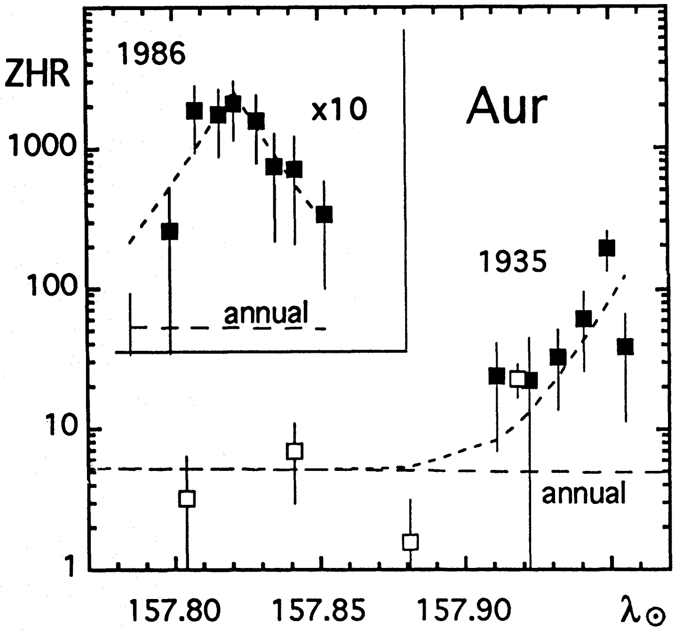

Fig. 7. Two outbursts of Aurigids are well documented, both are of similar magnitude and duration. **1935**: Data by Vrátník from the Stefanik Observatory in Prague (■ ; Guth 1936) and A. Teichgraeber and C. Hoffmeister in Sonneberg, Germany (□ ; Hoffmeister 1936). **1986**: Data by MMTEH observer Istvan Tepliczky from Tata, Hungary (18.4E, 47.7N) (Adams 1987)

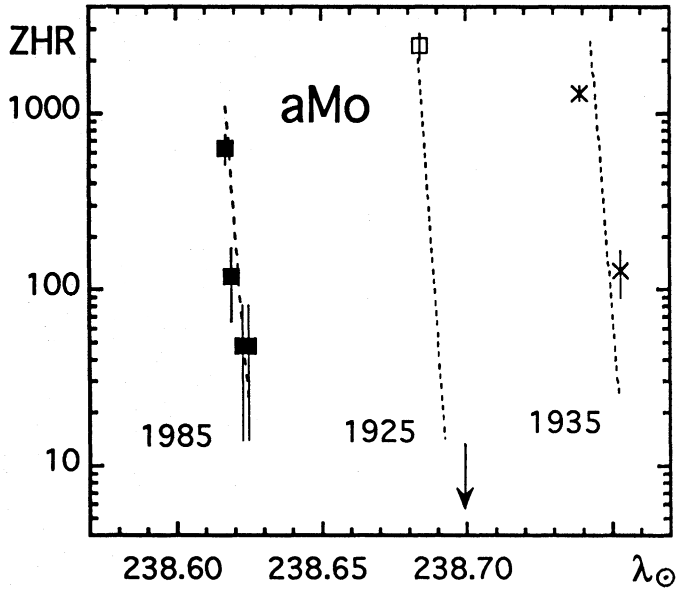

Fig. 8. Three outbursts of α Monocerotids had a characteristic short duration and high peak activity. **1925**: Data by F.T. Bradley from Crozet, VA (■ ; Olivier 1926), confirmed by two occasional observers at Charlottesville, VA. **1935**: Data from AMS observer Mohd. A.R. Khan from Begumpet, India (□ ; Hindley 1936), confirmed by the Commanding Officer of the US steamer Canopus from Manila Harbour. **1985**: Data by Richard Ducoty from Capitola, CA, (× ; Ducoty 1986), confirmed by Keith Baker, night assistant at Lick Observatory

hundreds of stars flew west". Tian-shan gives an "equivalent date" of 1900, Sept. 2, i.e. $\lambda_\odot = 158$, which is close to the current θ Aurigid maximum. Imoto & Hasegawa (1958) list two more accounts from Korea on the dates 1548, Aug. 24, and 1560, Aug. 24: "large and small meteors flew in all directions" and "many meteors flew in all directions like a shower". The data suggest a periodicity of 12.17 yrs for this sequence of events, which does line up with the θ Aurigid outbursts of 1935 and 1986. However, Imoto & Hasegawa give $\lambda_\odot = 166$ for these events. I have $\lambda_\odot$ = 166.8, 167.1, 166.7, and 166.7 (±0.3) respectively. Note that Tian-shan uses a correction of $\Delta t(days) = 0.01416 \times (1900 - yr)$, which does not appropriately account for the step of 10 days during the transformation of Julian to Gregorian calender in 1582 and the subsequent lack of leap-year days in 1700, 1800, and 1900. However, the Gregorian calender was introduced in China only in 1912. Amidst this confusion, I conclude that it is likely that these four outbursts are due to a single stream, probably of far-comet type, but this may not be the θ Aurigid stream.

Given only the accounts of 1935 and 1986, I conclude that the events occur much more frequently than suggested by the orbital period of the parent comet, P/Kiess 1911 II (Guth 1936), which has $P_c \sim 1900$ yr (Lindsey 1932).

3.2.4. The Ursids

A special case in the family of far-comet type outbursts is the Ursid stream, which has produced outbursts on occasions that the parent comet P/Tuttle 1939 X (= 1980 XIII) was near aphelion. The stream is also exceptional in that the comet orbit has a short period ($P_c = 13.6$ yr) and remains relatively far outside the Earth's orbit at the point of closest approach.

In 1986, an unexpected outburst of Ursids was observed by two independently working amateur observers of the Norwegian NAS-MS, Lars Trygve Heen and Kai Gaarder, who were doing routine observations of this annual stream under extremely cold conditions (Hillestadt 1987). Most of the observations of Kai Gaarder were initially interpreted incorrectly as to cover the outburst, which would imply a duration of more than 4 hours. However, Gaarder'Us high sporadic rates during the event and during the summer of 1986, as well as his high counts of Ursids in 1987, make it beyond doubt that he has a high perception coefficient ($c_p = 2.2$). From that, it follows that he saw only the onset of the outburst in 1986 (Jenniskens & Hillestadt 1988). Indeed, the shorter period of about 1.2 hours is confirmed by forward scatter radio data by K. Maeda from Japan (Koseki 1990) and V. K. Lehtoranta from Finland (Fig. 10).

Two outbursts have been observed before. A Japanese chronicle relates that "stars fell like rain" on Dec. 20/21, 1795 (Imoto & Hasegawa 1958). Only after another outburst occurred in 1945, the Ursid stream was recognized as an annual stream (Ceplecha 1951). That year, three Czechoslovakian observers from Ondrejov Observatory saw 167 Ursids in a period of about 1.5 hours. The first meteors were observed in twilight at 16:30 UT. The first count in Fig. 9 - 1945 data - starts at 16:45 UT. No raw data have been published. Instead, ZHR data are derived from ZHRs calculated by Ceplecha (1951). I suspect that the first three counts have been overcorrected for the limiting magnitude decrease due to twilight. Only in that case are the data consistent with a profile that is similar to the event in 1986.

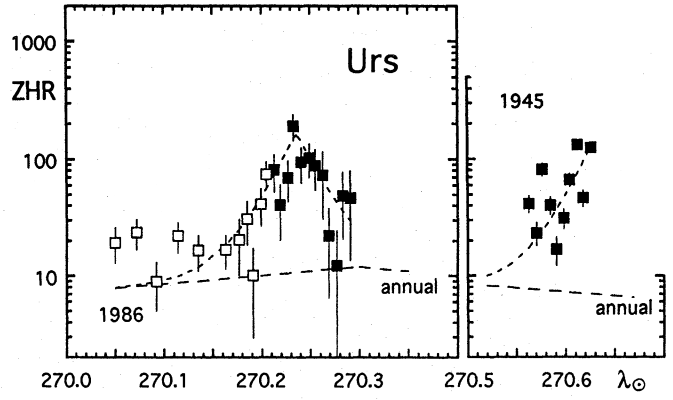

Fig. 9. Two outbursts of Ursids at a time that the comet was near aphelion. **1945**: Data by a group of observers at Ondrejov observatory (Ceplecha 1951). **1986**: Data by NAS-MS observers Kai Gaarder (□) and Lars Trygve-Heen (■)

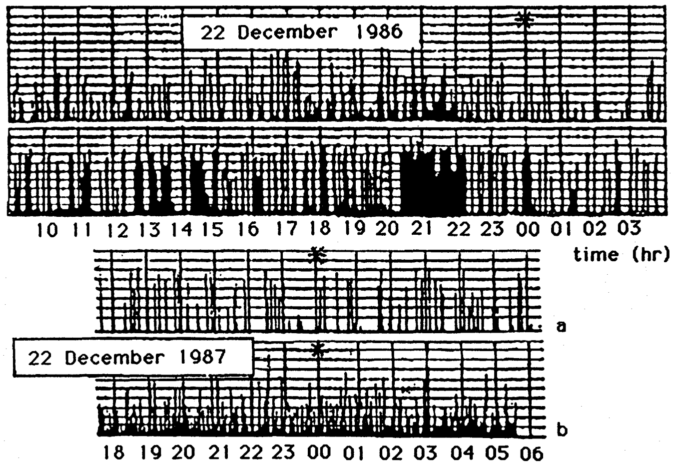

Fig. 10. The duration of the Ursid outburst of 1986 is confirmed by Radio MS observations at 89 MHz by Väinö K. Lehtoranta (Jokela, Finland). The upper graph shows recorded reflections on December 22/23, 1986. In 1987, no outburst was recorded during the same span of solar longitude (lower graph - time in UT). The figure shows paper recordings of the output of two antenna systems, an omnidirectional antenna (**a**) and a favourably oriented antenna beaming west (**b**)

The times of maximum suggest a nodal regression of $d\Omega/dt = -0.0051$ °/yr and a significant scatter around the mean of about 0.1°. This relatively strong regression is related to the short period of the comet orbit. Fox (1986) calculated an average regression of -0.0054 °/yr over the past 1000 yrs, in good agreement.

3.2.5. A comparison of far-comet type outbursts

Far-comet type outbursts have a well defined width and a peak ZHR in the range of 10-1000. The occurrences cluster around a given position in solar longitude but there is a significant spread

1995A&A...295..206J

of some $\Delta\lambda_\odot = \pm 0.1^o$. The periodicity of observed events suggests that there is an enhanced probability of occurrence every 10-15 years. The event rate is much higher than suggested by the orbital period of the comet.

While near-comet type outbursts have $\Delta_{E-C} < 0.04$ AU (Table 1a), far-comet outbursts can occur when Δ_{E-C} is as large as 0.12 (Urs) or even 0.18 AU (Ori - Sect. 6.2). The cross section of the meteoroid stream is smaller than this. For example, a duration of 1.2 hours for the Ursids corresponds to $\Delta t = 0.0009$ AU (Eq. 4). Therefore, the cross section of the meteoroid stream near the Earth is not cylindrically symmetric with respect to the comet's orbit.

The occurrence of outbursts when the comet is far from the Earth, even when the comet is in aphelion, implies that the dust density falls off only slowly away from the comet and is distributed along its orbit.

4. Discussion

4.1. Filamentary structure

The representation of meteor activity curves by a single set of exponentials is somewhat surprising in light of the substructure in the Leonid activity curve reported by Hershel (1967) and the filamentary structure found by Lovell (1954) in a comparison of radar, visual, and photographic data. Accounts of filamentary structure are numerous. Most recently, such "fine structure" was reported in the Draconid 1985 radar profile by Simek (1994).

Filamentary structure can perhaps result from the non-homogeneous ejection of dust from the comet surface. Ejection of matter occurs in the form of jets. Indeed, details in the coma of comets suggests that filamentary structure may exist on a scale of up to 2 Earth radii, corresponding to some 15 minutes in time along the Earth's path in the case of the Draconids. It is less clear whether filamentary structure is expected on a larger scale.

Let us define *filamentary structure* in a meteor outburst activity curve as enhancements in the flux that stand out significantly from Eq. 3 at a time scale smaller than the outburst duration. Statistically significant enhancements are expected to correspond to structures in the three dimensional distribution of the meteoroids. For a true filament, the length of such structure should be much larger than the width. The width determines whether the structure is seen at different positions on Earth at the same time. Here I assume that the width is comparable to the duration of the event as seen in the activity curve, which implies for most meteor outbursts that features should be seen nearly simultaneously at all positions on Earth where the stream can be observed. The two examples above represent probably the strongest case for filamentary structure and will be discussed here in some detail.

In Hershel's curve (Fig. 11a), valleys and peaks deviate by only ± 20% from a curve like Eq. 3. Such small deviations are surpressed by the logaritmic scale on the Y-axis in most figures in this paper. The question remains if the structure as shown in Hershel's drawing is significant. Comparisson of the data with counts from other observers at independent sites in the UK do not confirm the substructure. Counts by Rev. R. Main (1867) at Oxford and P. Smyth (1867) at Edinburgh are shown superposed on Hershel's data in Fig. 11a. There is no agreement on any of the submaxima or subminima in the profile. Therefore, the observed enhancements in rates do not correspond to a three dimensional density structure in the meteoroid stream, but may be due to statistical fluctuations in the meteoroid density or concentration variations of the observers.

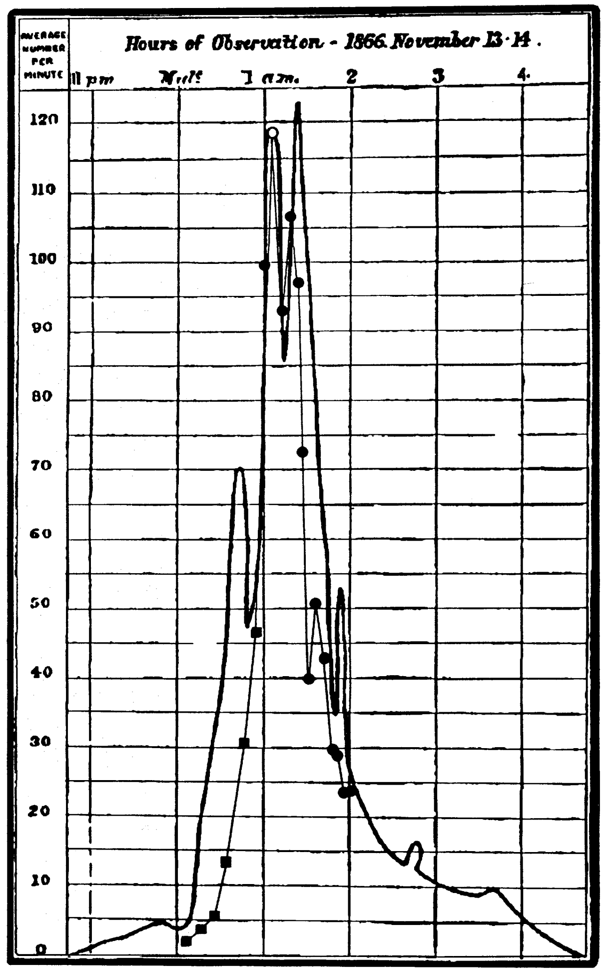

Fig. 11a. This well known historical presentation of the Leonid outburst of 1866 suggests filamentary structure on a scale of more than 15 minutes. Note that the scale on the Y-axis is linear as opposed to other figures in this paper. Data are by A.S. Hershel at Greenwich - the figure is reproduced from Monthly Notices of the Royal Astron. Soc. Vol 27, (1867) 54. This filamentary structure is not confirmed by other observers in the UK at that time. For example, I have added similar counts by P. Smyth at Edinburgh (Smyth 1867) and Rev. R. Main at Oxford (Main 1867). Smyth's 1-minute counts are averaged per 5 minute intervals and scaled to the main peak of Hershel (× factor 2.6). Main provided 10 minute counts that are similarly scaled to match Hershel's peak (× 0.17)

The case for substructure in the Draconid profile of 1946 was first made by Lovell (1954) and Davies & Lovell (1955), who found that the maximum in radar activity was displaced

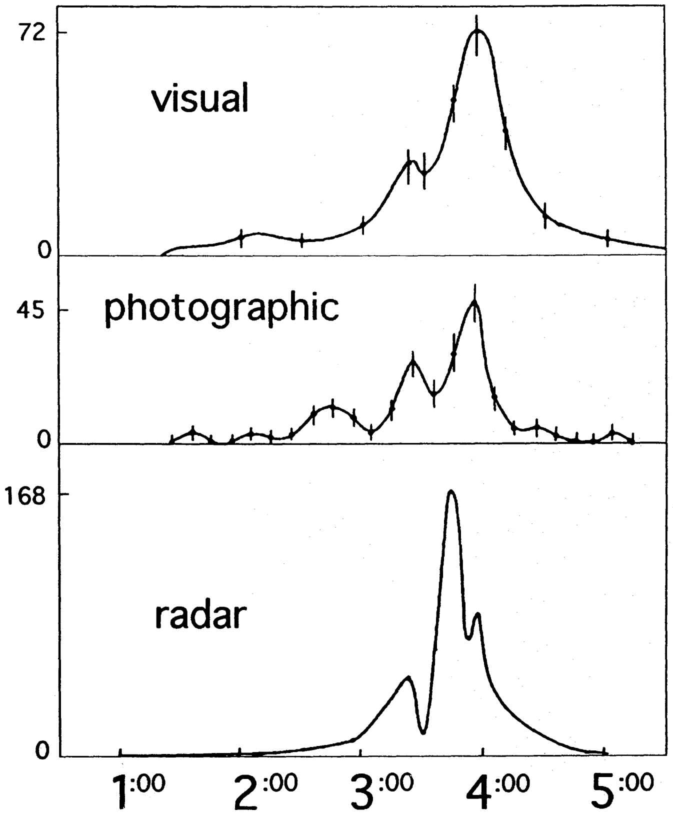

Fig. 11b. The Draconids of 1946. Visual data by Wylie (1946), photographic data by Jacchia et al. 1950), and radar data by Lovell (1954) - the figure is reproduced from: A.C.B. Lovell, 1954, *Meteor Astronomy*, Oxford University Press. I have added error bars in visual and photographic data, which show that these data are perfectly consistent with a smooth increase and decrease. Note the fast decrease after maximum in visual and photographic data, due to a rising full moon and increasing sky background brightness

from the peak in the visual observations by 13 minutes. In addition, they found two submaxima in the radar activity curve that coincided with maxima in the visual and photographic curves (Fig. 11b). Kresak & Slancikova (1975) elaborated on this and concluded that the center of the stream consists of a few layers of dust. I have added error bars to the visual (C. Wylie 1946) and photographic (Jacchia et al. 1950) data and find that a smooth equation like Eq. 3 fits through most of the 1 sigma error bars. There is no good coincidence in both activity curves that would imply substructure. The evidence for filamentary structure in the 1946 Draconid profile depends on the radar data by Lovell (1954), which are not well enough documented in the literature available to me to allow a discussion. No error bars are given. The minimum before the peak and the maximum after the peak stand out strongly. Strong enough to be recorded in Fig. 1. Radar peak rates are as high as 168 echoes per minute. At this level some problems with saturation due to long enduring trains or a changing background may be expected (Paper I). In a different set of data, Lovell et al. (1947) have a peak rate of only 9 counts per minute and no filamentary structure, although these counts are perhaps too sparsely sampled. A reassessment of the data from the original recordings may shed some light on these differences. Interesting, but unrelated, is the asymmetry found in all three profiles. The asymmetry in the visual and photographic counts is due to a rising full moon, which increases the brightness of the sky background, decreases the limiting magnitude, and darkens the photographic negatives. Very suggestive, but surprising to me, the radar data also show an asymmetry. Lovell et al. (1947) have $B^+ = 13$ and $B^- = 19$ (if peak at 03:40 UT). It is not clear if a changing geometry between meteors and radar antenna could have caused this. Perhaps, this also affected the time of maximum.

Most recently, Simek (1994) published an example of fine structure in a meteor activity profile from poorer radar data than usual. Radar observations of the Draconids of 1985 at lower culmination resulted in an activity curve with a number of peaks and valleys that have a width that reflects the width of the smoothing function. The background is ill defined. The profile is asymmetric, which is not in agreement with data quoted in Sect. 3.1.1. There is no agreement in the positions of individual activity peaks as seen in overdense and underdense echoes. Only two out of 12 maxima reported by Simek coincide with the 7 reported maxima by Koseki (1990). Moreover, from his radio-MS observations J. Mason derived a smooth profile with no apparent filamentary structure (Bone 1993).

The presence of filamentary structure in outburst profiles is an open problem in meteor astronomy. At some relative level of activity, substructure is bound to exist. Until good alignment of statistically significant activity variations are observed from two or more independent sites, I will consider the evidence as inconclusive. Equation 3 is at present a sufficient representation of activity variations.

4.2. *On the two activity curve components in near-comet outbursts*

The one feature that does stand out clearly is a background component seen in several near-comet type outbursts.

The near-comet outbursts of the Leonids are by far the best observed. There is a remarkable systematic behavior in the relative contribution of the background component in different returns. In the "best" meteor year, the shape of the activity curve is a sensitive function of Δ_{E-C}, the minimum distance between Earth and comet orbit. With increasing Δ_{E-C} the background component broadens and becomes stronger with respect to the main component, while the width of the main component does not vary. Thus, there is not a gradual change from one component into the other. These components must be due to distinct structures in the dust distribution near the comet.

The dust components must bear some relation to the cometary dust trails observed by IRAS (Sykes et al. 1986; Sykes & Walker 1992). The Earth does not intersect the IRAS dust trail itself, because the expected meteor fluxes are orders of magnitude higher than observed and the chance that the Earth actually crosses the IRAS dust trail is small (Sykes et al. 1986). Kresak (1993) emphasised, however, the common features between meteor outbursts and IRAS dust trails. The duration of an outburst is similar to that expected when the Earth would pass a trail, the duration does not vary much with E-C, and meteor activity falls off away from the comet in a manner consistent with that observed for cometary dust trails. Kresak, therefore, suggested that the Earth passed the dust trail, but slightly outside the boundary of the IRAS dust trail itself.

This picture is probably correct, except that the Earth does not pass through a cylindrically symmetric dust structure. The main peak duration is almost independent of Δ_{E-C} and the peak activity falls off much less fast with Δ_{E-C} than suggested by the duration of the outburst. For example, a comparison of the Draconid peak rates in 1985 and 1946, ZHR_{max} = 700 and 12,000 respectively, suggests that B equals 0.69 degree^{-1} perpendicular to the Earth's path, while B is 28 times larger along the Earth's path, i.e. B = 19±6. Instead, the observations of the main component in near-comet type outbursts are consistent with the presence of a sheet of dust that emanates from the IRAS dust trail. The sheet is almost in the plane of the comet, but deviates from that further away from the position of the comet (increasing values of δ_{E-C}). This sheet is perhaps related to the anti-tail sometimes seen in cometary ejecta. Only in some special cases will a near-comet type outburst be a direct result of the crossing of an IRAS dust trail, thereby offering the prospect of high meteor rates.

The background component in near-comet type outbursts is, perhaps, due to planetary perturbations of the IRAS dust trail. There are always meteoroids present at the point closest to Jupiter when it passes the orbit of the comet. The orbit of these particles is much stronger affected than that of the comet itself and, for that matter, much of the dust trail. The larger perturbation of meteoroids in the background structure is suggested by the broader width of the background component (larger spread in Ω) and also by the strongly asymmetric background observed for the Andromedids, where the outburst component extends in the general direction of the perturbation, that is to smaller longitude. Meteoroids in the broad component should have significantly different orbital elements than those of meteoroids in the main component.

I know of only one case where orbital elements of the background structure may have been obtained. In 1953, two meteors were multi-station photographed, 0.7° earlier in solar longitude than the outburst in 1952. The two meteors occurred one hour apart, had very similar orbits (little dispersion), and anomalously high fragmentation (Jacchia 1963; Jacchia et al. 1967), suggesting they were relatively recent ejecta. They were part of a low level activity that, I suspect, may have been due to a background structure. The orbital elements are given in Table 3 and are compared to the orbit of the parent comet and meteors in the outburst of 1946. Indeed, while the outburst in 1946 was caused by particles in nearly identical orbit as comet P/Giacobini-Zinner, the particles in 1953 had a significantly deviating orbit. This result should be confirmed by photographic studies of future outbursts.

Table 3. The orbital elements of two multi-station photographed Draconids, on October 9th 1953 (Jacchia & Whipple 1961), are compared to the orbit of the parent comet P/Giacobini-Zinner. Orbital elements for 1953 are from predictions by Dinwoodie (1952). Columns list the true radiant, the true geocentric velocity, the semi-major axis (a), the perihelion distance (q), inclination (i), ascending node (Ω) and argument of perihelion (π). All data are in equinox 1950.0.

Object	Year	RA,DEC (1950.0)	V_G km/s	a AU	q AU	i °)	Ω °)	π °)
HV8943	1953	270.9,+47.2	17.2	3.37	0.998	24.6	195.5	12.5
HV8951	1953	270.8,+47.3	17.1	3.29	0.998	24.6	195.6	12.5
comet	1952	262.0,+54.4	20.4	3.50	0.989	30.8	196.2	8.1
Dra 1946	1946	262.1,+54.1 ±0.1	20 ±1.5	(3.51)	0.996	30.7	196.3	8.1
comet	1946	262.0,+54.2	20.4	3.51	0.996	30.7	196.3	8.1

4.3. *Far-comet type outbursts and the IRAS dust trail*

Far-comet outbursts are not likely due to a sheet of matter, since these events are not observed annually, while the intensity of the sheet of the main-peak component in near-comet type outbursts falls off quickly in intensity away from the comet's position. A clue to the nature of far-comet type outbursts may be the occurrence of outbursts in semi-regular intervals of 10-14 yrs, which perhaps implies some influence by Jupiter (P = 11.9 yrs). Guth (1947) observed that in years of rich displays of Lyrids, the planets Jupiter or Saturn are in conjuction with the stream.

The peak activity of far-comet type outbursts is consistent with an origin in the IRAS dust trail itself. In that respect, far-comet outbursts may differ from most near-comet outbursts. The duration of the outbursts is not much different from that of near-type outbursts and the chance that the Earth passes the trail is small. There are ways, however, to enhance this probability without invoking a sheet-like distribution of dust. It is perhaps possible that Jupiter causes small orbital perturbations of the path of individual meteoroids in such a way that they are occasionally directed to the Earth. The orbital period of Jupiter causes a modulation of orbital elements, which may be reflected in the encounter probability. This modulation of movement at the position of the Earth perpendicular to the trail is not necessarily a modulation in density of particles as suggested by Guth (1947). A useful metaphor is the water from a hose used to water a distant flower: the probability that the flower receives water is greatly enhanced by moving the hose up and down.

Some evidence for this model is provided by the observation that there is significant scatter between the time of maximum and a given solar longitude, about twice the duration of the outburst. The Lyrid maxima scatter around $\lambda_\odot$ = 31.37 within an interval of 0.1°. The duration of the outburst corresponds to 0.026°. A random path movement over an area of similar extent perpendicular to the Earth's path than along the path would bring a cylindrical stream in collision with the Earth approxi-

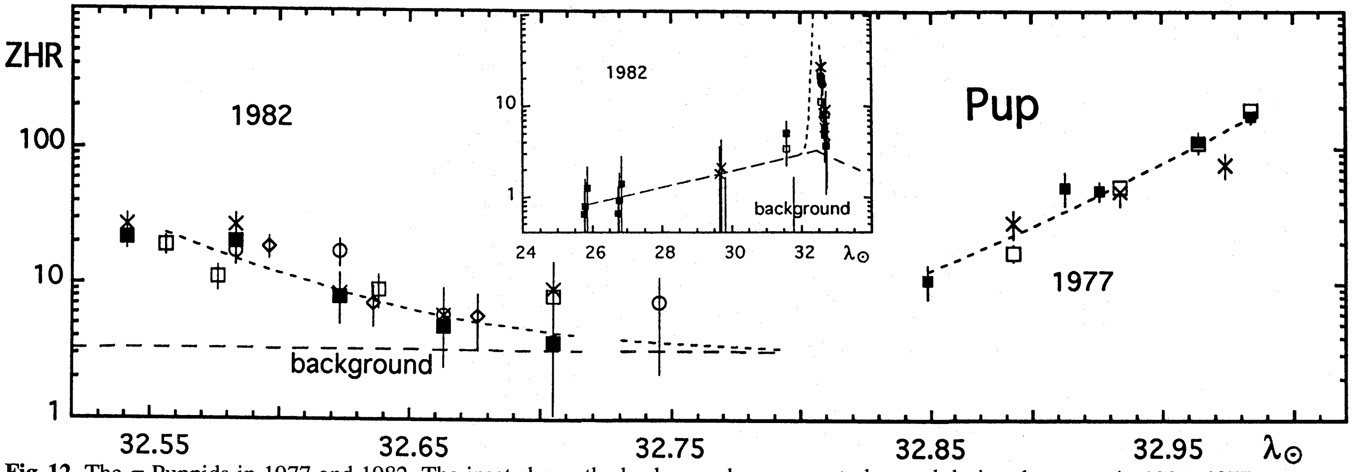

Fig. 12. The π Puppids in 1977 and 1982. The inset shows the background component observed during the return in 1982. **1977**: Data from Australian observers at Perth (■) and Eucla (□) (Buhagiar 1977) and Jeff Wood, Alex Saare, and Glenn Blencowe at Chidlows (×, Wood 1979). **1982**: Data by WAMS observers Jeff Wood (■), Darren Ferdinandez (×), Clem Foley (O), Nicolas Harvey (□), and Craigh Willoughby (◇) (Wood 1982; Simmons 1982)

mately once every $(0.1)^2/(0.026)^2 = 15$ years, which is close to the observed value of once every 12 yrs. Then again, the movement is not random, which would cause a random occurrence of outbursts. The good correspondence in this case probably implies that the scatter perpendicular to the Earth's orbit is of similar size as that along the Earth's orbit.

However, it is at present unclear what effect the proposed orbital modulation has on the dispersion of the trail over long timescales, that is, does the trail exist long enough if such effect has the necessary magnitude? Before being accepted, this model should be tested by numerical simulations, which are beyond the scope of this paper.

4.4. Relation to orbital elements

Each stream has only one of either type of meteor outburst: near-comet type or far-comet type. This can be related to the fact that the two types of event are associated with comets with different orbital elements. Table 1b shows that the near-comet type outbursts have $\omega \sim 0{,}180$ and $q \sim 1.00$ (or small i - And), while far-comet type outbursts do not. If this observation applies in general, it can be used to determine whether streams without a known parent body are of near-comet or far-comet type.

In the case of near-comet type outbursts, the Earth can come close to the perihelion position of the comet. This suggests that the sheet of dust responsible for the main component is due to forces that affect the perihelion distance of the meteoroid orbit.

4.5. Relation to annual stream activity

The annual stream activity does not usually increase significantly during meteor outbursts, suggesting that the supply of matter from the IRAS trail to the annual stream is not restricted to the most dense region near the position of the comet.

5. Mass estimates

The calculation of total mass for the matter in each dust component is analogous to that in Paper I. The calculation assumes a cylindrical geometry, a dependence of mass versus magnitude $M \sim m^{-0.62}$, and mass integration from 10^{-6} to 10^{2} gram. These assumptions may not be valid in light of future evidence, but transformation of the mass estimates into another system of assumptions is straightforward.

The assumption of cylindrical geometry is bound to be incorrect, but better assumptions can perhaps be made in the future. I allow for only one additional correction. For some near-comet type outbursts, matter is concentrated near the parent comet. Assuming that the Earth passes a sheet of dust in each return, the decrease away from the comet can be estimated. The Draconid observations are consistent with a dust density falling off with an effective duration of about 0.23 year, while the Leonids fall of with an effective duration of 1.8 yr behind the comet and perhaps 0.3 yr before. These values should be compared to the orbital period of the comet and show that the total mass is overestimated by a factor of about 30 when this effect is not taken into account. Therefore, instead of multiplying M_{1yr}, the mass passing through the stream cross section near the Earth per second, with the period of the stream to arrive at the total mass M_{tot} (Appendix - Paper I), the multiplication is done with a fraction of 1/30 of the orbital period. This applies to all mass estimates of matter in structures causing near-comet type outbursts. On the other hand, for far-comet type outbursts I chose to multiply with the period of the comet, since there is no indication that the observed dust is concentrated in part of the orbit only. As in Paper I, I assume P = 200 years, if only a parabolic orbit has been derived for the parent comet or no parent is known.

The mass estimates are given in Table 1b. The calculated values are in the range 10^{10} to 10^{13} g for the outburst main peak component and 10^{11} to 10^{14} g for the background component. This compares to 10^{14} to 10^{16} g for the annual streams. Individ-

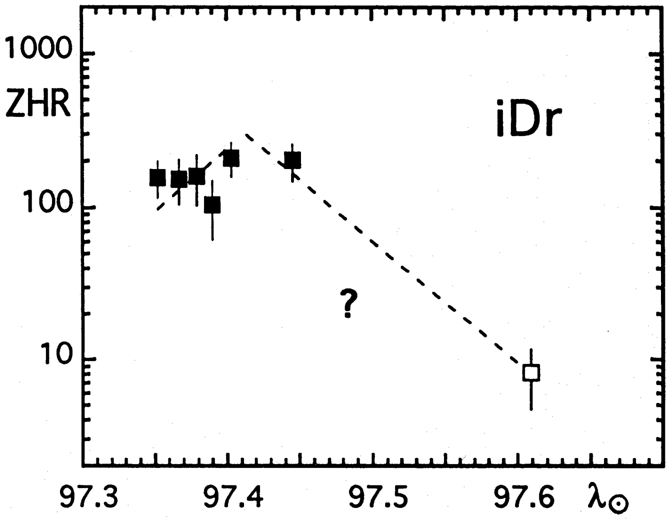

Fig. 13. Uncertain results of the i Draconids in **1916**: Data by W.F. Denning at Bristol (■ ; 1917) and AMS observer Brooks (□ ; Olivier 1917)

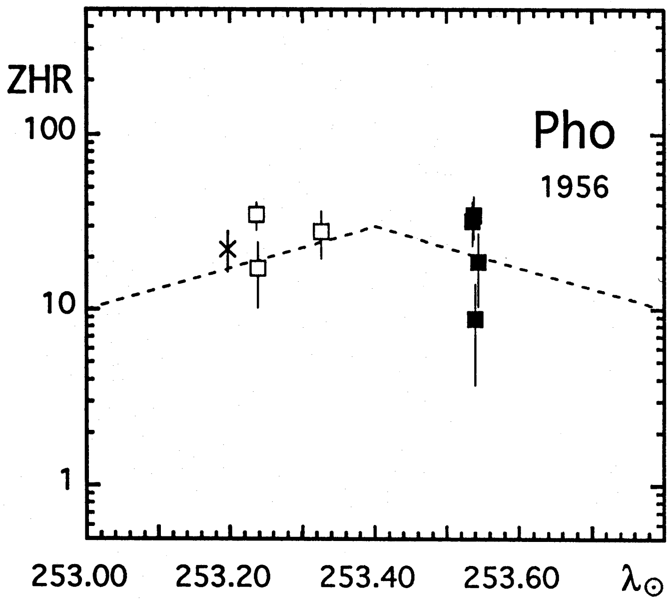

Fig. 14. Uncertain results of the Phoenicid outburst in **1956**: Data by observers in Australia (×, □) and South Africa (■) (Ridley 1961). There is no series of counts available that spans a significant part of the activity curve. A broad maximum is suggested

ual estimates are uncertain by one or two orders of magnitude. The relative uncertainty may be less when comparing these estimates from outburst activity with similar estimates from annual activity (see the discussion in Paper I), but depend on the assumptions related to the dust distribution geometry.

6. Some results of other streams

There are more reports of outbursts, both confirmed and unconfirmed, that add to the picture emerging from the previous sections but do not significantly alter it. These events are discussed now, in the order that they are listed in Table 1. These historic accounts provide valuable information on what to expect from the future outbursts of these streams.

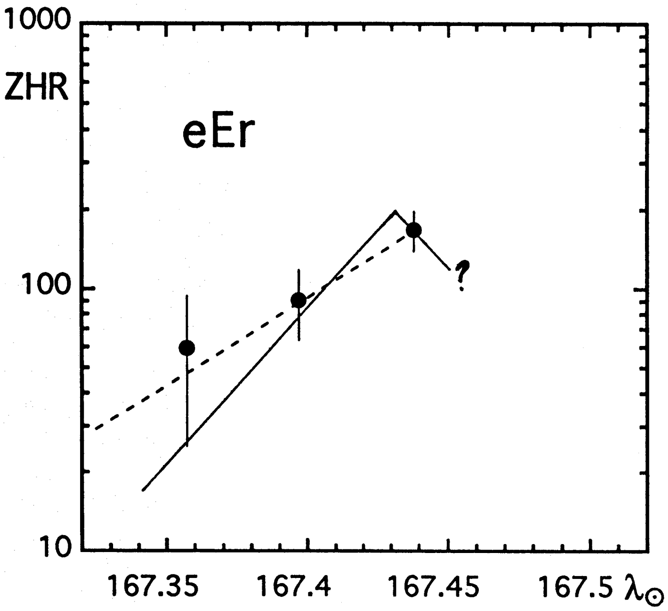

Fig. 15. One hour counts by Murray Gayski (Wood 1981) of πEridanids in **1981**. Two possible activity curves are shown

6.1. Near-comet type outbursts

Comet P/Grigg-Skjellerup 1972 II has produced many more meteors on Earth than the disappointingly small number of meteoroids detected by the satellite Giotto during its 1992 visit of the comet. A rapidly changing orbit brought the comet near the Earth's orbit a few times after a perturbation by Jupiter in 1964. In subsequent returns, there was clear evidence of meteor activity with an interesting behaviour. Weak π *Puppid* activity was first reported in 1972, both by radar and unassisted eye (Baggaley 1973; Ridley 1972). There were significant outbursts in 1977 and 1982 (Buhagiar 1977; Wood 1982; Simmons 1982; Lindblad 1987a). The duration of both events was similar (Fig. 12). In 1982, WAMS observers saw only the tail of the activity profile. Peak activity may have occurred 5-7 hours before the onset of the observations, based on a few other accounts from Bolivia and Hawaii (Wood 1982). A very broad activity component, with a duration similar to an annual stream was also detected, with $\mathrm{ZHR_{max}} = 3.3$, and seen again in 1983, $\mathrm{ZHR_{max}} \sim 13$, and in 1984, $\mathrm{ZHR}_{max} \sim 3$, but not in 1985 and 1986 ($\mathrm{ZHR}_{max} < 1$). No π Puppids were observed in 1987 during 50 hours of observing, covering April 22 11-12:20 UT and April 23 9:35-14:25 UT (Wood 1987). In 1990 some weak activity was observed around April 22/23 when rates peaked at $\mathrm{ZHR}_{max} \sim 1$ (Wood 1991). In 1992 weak activity covered a few days around April 23/24, $\mathrm{ZHR}_{max} = 2.3 \pm 1.2$ (Wood 1992). These results may hint to an annual stream in the making.

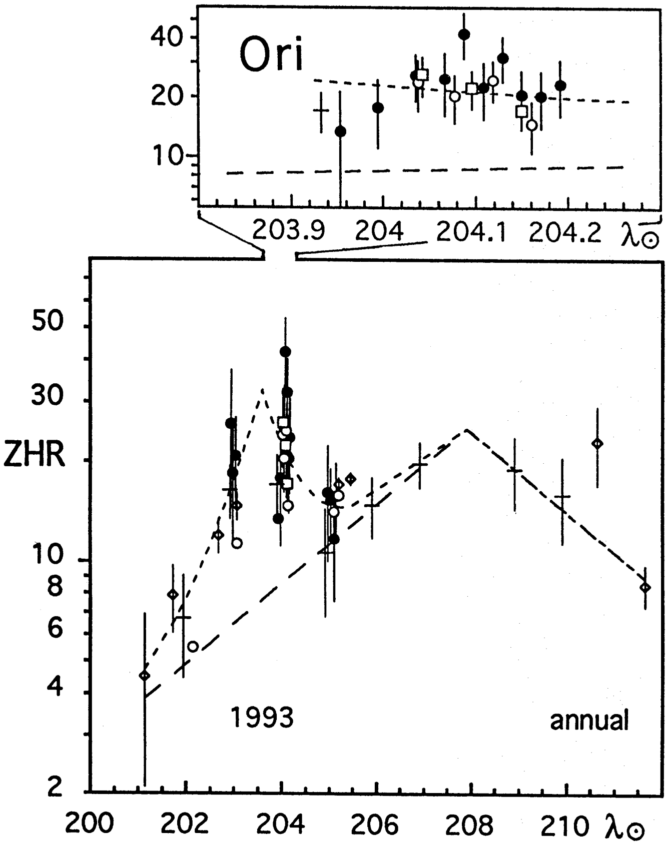

Fig. 16a. High activity of Orionids in 1993 persisted in two consecutive nights, Oct. 16/17 and Oct. 17/18. Data by Koen Miskotte (□), Juergen Rendtel and Andre Knoefel (■) and several other observers listed in Rendtel & Betlem (◇, 1993). Radio MS data at 80.7 MHz by K. Shibata, Sapporo Japan

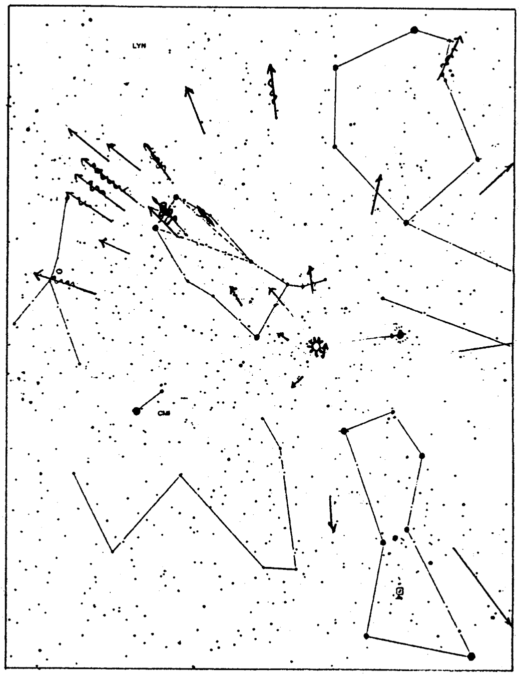

Fig. 16b. Orionids plotted on a gnomonic map by Koen Miskotte during the night Oct. 17/18, 1993. Meteors close to the radiant suggest a center of activity at (91.3,+13.5), south of the radiant of the annual activity (91.0,+15.5) (*)

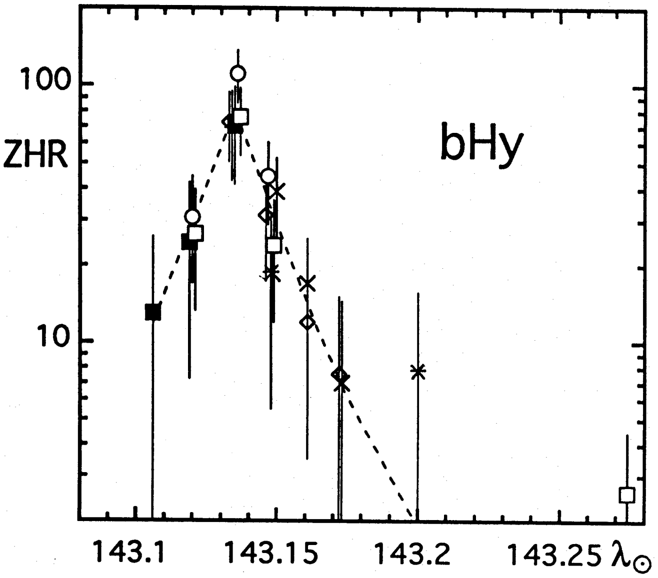

Fig. 17. The β Hydrusids were noticed by many occasional observers and members of NAPO-MS. **1985**: Data from Brian Macauley from Brickley (■), Jason Tame (□) and Simon Evans (O) at Kalumunda, Paul Rawlings at Belmont (×), and Joh-Ann Borrows (∗), Megan Clay (◇) from Byford, all in Western Australia (Wood 1986 a,b)

Iotta Draconids, or June-Draconids, were observed by W.F. Denning (1916) and confirmed by H.W. Raisin and two other occasional observers in Boscombe (GBr.). There is no clear activity variation over the period that Denning observed. Evaluation of the curve depends on one estimate by D. Brooks in Washington DC (Olivier 1917) and an observer who saw nearly 100 i Draconids between 11-12 UT, which may have been the peak of the outburst (Fig. 13). Meteors are from comet P/Pons-Winnecke 1915 III. The comet came close to the Earth's orbit only briefly. Some meteors were seen in 1921 (6 per hour, Hoffmeister 1921) and 1927 (Astapovich 1928).

Occasionally, the annual *Phoenicids* (ZHR $\sim$ 2.8) have significant surges of activity up to ZHR $\sim 20 - 50$ (Wood 1980a). The stream was discovered during an outburst on Dec. 3/4 in 1887 by V. Williams from Sydney (Austr.). Other outbursts of the stream had a similar peak ZHR of about 20-50 and occurred on Dec. 5, 1938 (Captain Murray), in 1956 (Weiss 1958, Ridley 1961), and in 1972 (M.J. Buhagiar). Meager data from 1956 result in a broad maximum (Fig. 14). These results are uncertain, because they are a compilation of independent observations under a range of observing conditions and by a range of observers. The sequence of events suggests a period of 17 years or a fraction thereof. The sequence aligns with the single observed return to perihelion of the proposed parent body, comet P/Blanpain 1819 IV (e.g. Drummond 1981). The comet passed the Earth within 0.11 AU on Oct. 31, 1819, but has not been seen since (Belyaev et al. 1986). Note that meteors occur on December 5th, while

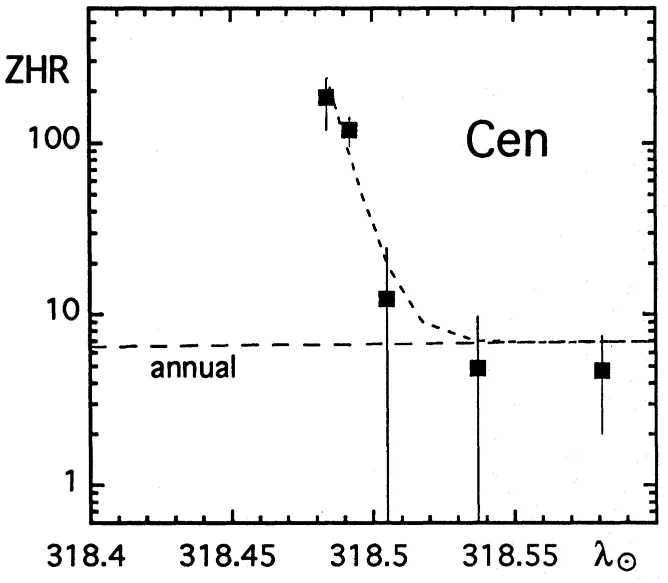

Fig. 18. Another conspicuous event observed by many occasional observers. The α Centaurids in **1980**: Data from WAMS observers Niel Freckelton and Glenn Blencowe at Redcliff and Craigh Willoughby at Busselton (Wood 1980)

a theoretical maximum is predicted for either Nov. 6 or Jan. 4. In the period between the predicted times of maximum, the comet is never far from the Earth's orbit (Drummond 1981). If the outbursts occur only when the comet returns to perihelion, then the orbital period of the comet is close to 5.67 yr instead of a value of 5.10 yr derived from the 1819 observations of the comet (Marsden 1983). This may help recover the comet.

6.2. Far-comet type outbursts

In 1981 WAMS observer Murray Gayski reported high activity from Eridanus in the night of September 10/11 (Wood 1981). This outburst is perhaps linked to the annual π Eridanids (Paper I). Conditions were unfavourable (moon, low radiant position and clouds). Only three one-hour counts are available. Two possible activity curves are shown in Fig. 15. Wood (1981) associated the event with the possibly elliptic comet Klinkerfues, 1854 III, which has a theoretical radiant at (54,-16) on Sept. 10 (Drummond 1981) (NB: not Klinkerfues 1853 III as I erroneously stated in Sect. 5.1 of Paper I). No related events are known.

In 1993, DMS observer Koen Miskotte first reported unusual high Orionid activity in the night October 16/17 (Miskotte 1993). A number of bright Orionids appeared, some of them brighter than m_v = -2, a rarity among annual Orionids. The outburst persisted in the next night, when AKM observers Juergen Rendtel and Andre Knoefel confirmed high rates of bright Orionids and DMS observer Hans Betlem photographed 27 Orionids in 100 hours of exposure time with a battery of F1.8/50mm cameras, as compared to only 9 Orionids in 96 hours during the night October 18/19 in similar observing conditions. Radio MS data by K. Shibata from Sapporo, Japan, confirm that there was high meteor activity on both Oct. 16/17 and Oct. 17/18 (Fig. 16a). Unfortunately, the relative orientation of radio station and receiver allowed to observe the stream only between 20 and 02 UT, so that the radio observations can not confirm the expected peak on Oct. 17. The parent comet, P/Halley 1986 III, came to perihelion back in 1986, which makes this a far-comet type outburst. As for other far-comet type outbursts, these events may happen more frequently. Indeed, Rendtel & Betlem (1993) report that similar events may have happened in 1957 and 1966. When marking the highest daily mean rates in the Ottawa radar observations of Hajduk (1970) for the 5 hour period of 8 to 13 UT from October 15 to 30, they found highest numbers of long duration echoes for October 17 in the years 1957 and 1966, while in the years 1959-1965 peak rates occurred on Oct. 21 or 22. Lovell (1954) reports a maximum of Orionid radar rates on Oct. 18 in 1946 ($\lambda_\odot \sim$ 204.3) and 1951 (203.3), while in other years from 1946 to 1952 rates peaked on Oct 20-23. Rates did not surge in 1930, 1933, and 1936 (Lovell 1954). The events in 1946, 1957, and 1993 are consistent with a 12 yr periodicity, but possible events in 1951 and 1966 may indicate a more frequent event rate. Again, the event rate is higher than suggested by the orbital period of the comet P_c = 76 yrs, that is, if any of these observations truely refer to a meteor outburst. In 1993, the outburst lasted exceptionally long (B$\sim$0.6) and occurred far from the peak of the annual activity. This is perhaps related to the fact that Orionids are observed exceptionally far from the orbit of P/Halley. Visual plots of Miskotte suggest a sub-radiant slightly south of the mean annual radiant (Fig. 16b), but it is not clear if this is the radiant of the outburst meteors because some bright meteors come from the annual radiant.

6.3. Outbursts of unknown type

In the night of July 17/18, 1986, while the nearly full moon was almost in the zenith, WAMS observers Niel Inwood and Paul Stacey from Karnet (116.1E,-32.5S) noted unexpected meteor activity from κ Pavonis (Wood 1986c; MacKenzie 1986). Between 11:50 and 13:00 UT, they saw 26 and 30 *κ-Pavonids* and 4 and 6 sporadic meteors respectively. This is probably the full duration of the event. No ten minute counts are given, nor is there information on rate evolution. The parent comet has not been identified. On August 16, 1985, an outburst of *β Hydrusids* lead to reports to media and police. Several WAMS observers obtained an excellent series of 20 minute counts (Wood 1986a,b). These result in a characteristic activity profile (Fig. 17). No annual activity is known, no previous events, and no parent comet. Another account by Jeff Wood relates that in 1980 many people in Western Australia observed conspicuous activity of the α *Centaurids* (Wood 1980). This is an annual stream with a peak activity of about ZHR = 7. No parent comet is known. The activity curve of the outburst is not well determined because only one-hour counts are available (Fig. 18).

A rare instrumental recording of an outburst, without visual observations, was obtained during the systematic survey of meteor activity by the Harvard SuperSchmidt project in the early fifties. Five meteors with nearly identical orbits were pho-

Table 4. Photographic multi-station data on the μPegasids of Nov. 12, 1952 (McCrosky & Posen 1961, Jacchia & Whipple 1961). m_{pg} is the absolute photographic magnitude. True radiant and velocity. $\Omega = 229.7$. The orbital elements are compared to those of comet 1351 (Hasegawa 1979, Marsden 1983) and P/Hartley 2 1985 XVI which has Ω = 226.1 (Marsden 1985). Radiant by McNaught (1986).

Date	m_{pg}	RA,DEC	V_G	a	q	i	π
12.18	1.5	341,+21	10.1	3.04	0.97	7	69
12.19	1.5	338,+24	13.6	13.34	0.97	10	68
12.19	1.3	335,+21	10.9	3.86	0.97	8	65
12.19	2.1	342,+22	10.9	3.49	0.96	8	70
12.26	2.7	342,+23	9.7	2.80	0.97	7	70
comet	*1351*	-	-	(∞)	1.01	7	68
comet	*1985 XVI*	299,+14	11.3	3.38	0.96	9	41

tographed in a two hour span between 04:15 and 06:15 h UT, Nov. 12 1952, with a marked concentration near 04:35 UT (Table 4, McCrosky & Posen 1961). No annual activity is known of this stream of μ *Pegasids*, which makes this a certain outburst. The orbital elements suggest that this is a near-comet type outburst (small i, $\omega \sim 180$). The outburst may be related to events on Nov. 10/11 1883 and 1893, both described as "At night stars fell like rain" (Tian-shan 1977). Tian-shan suggested from general direction indications that the outburst may be of Taurids. But, there is no other evidence of meteor outbursts associated with this stream. On the other hand, these outbursts occur at almost the same solar longitude as the μ Pegasids with a radiant nearby. The sequence of events suggests a 10 year period. The photographed meteors have low inclination and short period orbit (P$\sim$7 yrs). If the association with μ Pegasids is correct, then I expect that the comet was close to perihelion in 1883, 1893, and 1952 and has orbital elements a $\sim$ 4.6, q $\sim$ 0.97, i $\sim$ 8 and π $\sim$ 68. This may prove enough information to recover the object. From Marsden's (1983) catalogue, I find that comet 1351 is a candidate parent body. But its orbit is based on only 3 approximate observations in one week and has Ω = 263 instead of Ω = 230 (Hasegawa 1979). Alternatively, the event may be related to comet P/Hartley 2. The current node of this comet is at Ω = 226.1 (Table 4).

6.4. Doubtful events

Several more accounts of possible meteor outbursts are listed in Table 5 and Table 6. These include a number of Chinese accounts that could not be linked to one of the streams mentioned previously. Some of these observations may be due to mere fluctuations in sporadic activity, bad classification (Monocerotids/Geminids? - Egintis 1899), or better than usual observing conditions. As a rule, there are no five or ten minute counts available to evaluate the activity curve. Perhaps, future observations of related outbursts will put these accounts in a proper perspective.

One particular case, the recent report of an outburst on Nov. 5th 1991 (Green 1991; Brown et al. 1992), was studied in detail, because the "outburst" was recorded on two CCD frames (I band) of the same part of the sky at CFHT (Hawaii). On request, B. Fort kindly made the frames available for analysis at Leiden Observatory. The two images were taken during two consecutive half hour intervals and show a pattern of bands made up of short stripes. Comparison of the two images shows that the pattern is nearly identical and slightly shifted with respect to the stars and the CCD frame. These observations exclude the possibility that the stripes are due to meteors (Jenniskens et al. 1993).

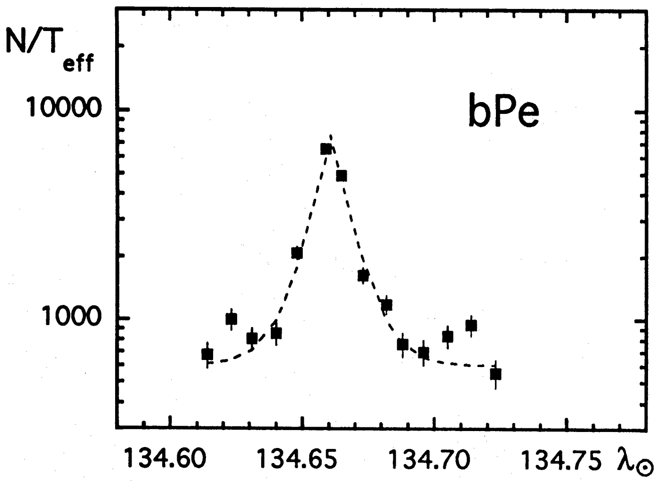

Fig. 19a. A possible faint-meteor stream of β Perseids. Raw counts only. A narrow spike is superposed on a high background of activity. Unassisted eye observations by S. Holm from Silkeborg, Denmark (Nielsen 1936)

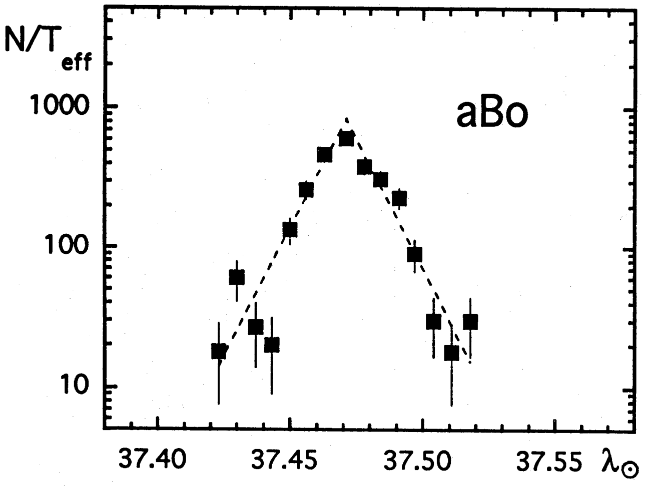

Fig. 19b. The possible faint-meteor stream of αBootids. Raw counts only. Telescopic observations by DMS observer F. Witte from Hengelo, The Netherlands

7. Possible outbursts of faint meteors

There are currently at least three accounts that describe outbursts of faint (telescopic) meteors. Uncorrected rates are shown in Fig. 19. These accounts have not been confirmed by independent observers, or only tentatively, and should be considered with caution.

The βPerseids were recorded visually by S. Holm (Nielsen 1936; Hindley 1936). The meteors had short tracks and were mostly very faint, of +5 and +6 magnitude brightness, with only 6-8 meteors brighter than +4 in each 5 minute count. Observing conditions must have been excellent (Lm = 7.2) and $\chi > 5$. Raw counts by Holm peak at an amazing 548 meteors in a 5 minute interval centered at 23h15m MET. There is a tentative confirmation. An observer 35 km from Silkeborg (at Brabrand near Aaarhus) noted "a large intensity of weak meteors at 23h MET, but not at all as many as reported by Holm" (Nielsen 1936).

DMS observer Frank Witte (Hengelo, The Netherlands) reported an outburst of meteors during a telescopic watch on April 27/28, 1984, from a radiant immediately next to α Bootes (215,+19). Witte used a 6cm F700mm refractor with a field of view of about 1 degree (23mm Huygens ocular), for which he estimated a limiting magnitude close to +11. Slow and short trails of 433 meteors and "point meteors" from a radiant of diameter less than 1 degree were classified as α Bootids, 12 others as sporadics. Witte's peak rate was as high as 102 Bootids per 10 minutes between 01:11 and 01:20 UT (Veltman 1984; Witte 1984). Cook (1973) lists a minor stream of αBootids that has a radiant at (218,+19) and V_∞ = 23 km/s during this night. However, the stream is of long duration ($B \sim 0.05$), the radiant is diffuse (6 degree diameter), and the orbit has a short period (P = 4.3 yr) which, perhaps, makes it an atypical stream for outbursts. Witte's telescopic observation followed after he noticed Bootid activity from this minor radiant during regular visual observations on extremely clear nights between April 22nd and 25th. No magnitude estimates were made during the outburst. In the night of April 26/27, Witte classified 26 telescopic meteors as "alpha-Bootids" and 6 as sporadics in 0.55 hours effective observing time. Those 26 "alpha-Bootids" had a magnitude distribution from +11 down: 0,5,4,11, 3,1,2. Judging the difficulty of classifying meteors in such a small field of view, all of these meteors may have been sporadics. Witte started occasional telescopic watches in 1983 and had just set out to do some serious telescopic observing with a new observing form that recorded total numbers per time interval only. Visual observer Klaas Jobse (Paper I) did not see a single α Bootid (sic) during the telescopic outburst while observing under perfect conditions (Lm = 6.3, 8 sporadics between 00:40-01:40 UT). The telescopic observation has not been confirmed.

One final account of a telescopic outburst of meteors is associated with the 1933 return of the Draconids. G. Delf (Bedburg, Germany) noticed hundreds of light points flaring up and disappearing again while setting up his telescope to the region near μ and ν Draconids. He reportedly noticed that the meteors were difficult to observe with the naked eye (Graff 1933; Kresak & Slancikova 1975). However, other observers had visual counts of 5-8 Draconids per minute at this time, 19h50m MEZ, one hour and 15 minutes before the peak of the shower.

Future observations of related events may put these observations in a proper perspective.

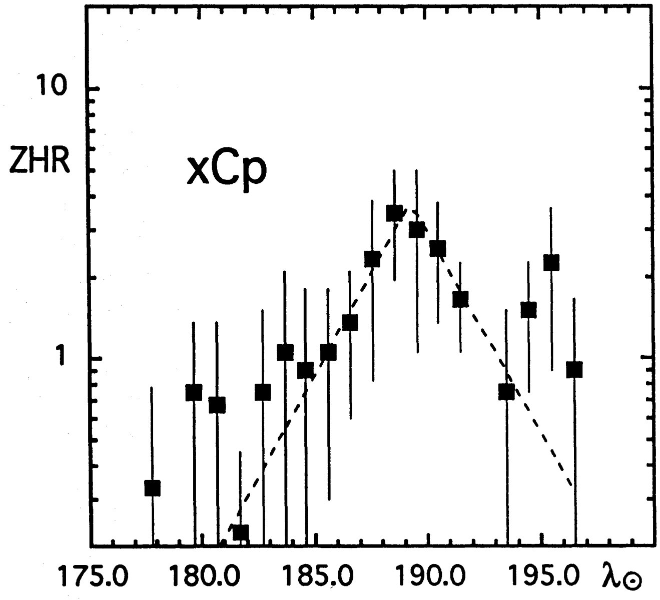

Fig. 20. The transient annual stream of ξ Capricornids, from a compilation of WAMS data between 1978 and 1987. ZHR data by Wood (1988)

8. A matter of definition: a transient annual stream

As a final result, I want to point out that in some instances the dust component that is usually responsible for annual activity may also cause an event that, when first noted, might be classified as a meteor outburst. For some streams, there is no such thing as a stable annual activity.

Due to planetary perturbations, the Bootids and Geminids are swept by the Earth's path over a timescale of 100 yr (Murray et al. 1980; Fox et al. 1982). In some other cases the stream evolution is even faster and meteor activity occurs only in one or a few years. One example is reported by Wood (1988): the ξ *Capriconids* or October Capricornids.

Comet P/Haneda-Campos 1978 XX (P = 5.97 yr – Marsden 1983) is severely disturbed by Jupiter and had a gradually decreasing perihelion distance during the past century (q = 1.57 in 1900, 1.21 in 1954, 1.12 in 1962). In 1972, q had decreased to 1.100, and two observers, Dennis Rann and Derek Johns, in Western Australia noticed ten bright and slow ξ Capriconids in 35 minutes on Oct. 2/3 that year. This may have been an outburst of relatively short duration (Table 5). In subsequent years it was noticed that slow meteors radiate from (302,-9) annually. The meteors are mostly yellow or orange and 4% left a persistent train. The magnitude distribution of all 138 observed meteors results in $\chi = 2.8$ (Wood 1988).

Fig. 19 shows the activity curve derived by Jeff Wood from all observations of the NAPO-MS between 1978 and 1987. Wood calculated rates for $\gamma = 1$ and these have been multiplied by 1.5 to roughly equal rates with $\gamma = 1.4$. The curve suggests a typical annual profile, with B = 0.15 and $\mathrm{ZHR}_{max} = 4\pm1$ at solar longitude $\lambda_\odot = 189.3$.

1995A&A...295..206J

Table 5. Possible meteor outbursts. Symbols as in Table 1.

#	Code	Name	Year	Date	RA,DEC (1950.0)	V_∞ km/s	χ	$\lambda_\odot^{max}$ (1950.0)	ZHR$_{max}$	B^p °)$^{-1}$	P yr	q, i, ω
		near-comet type?										
50	tHe	τ Herculids	1930	June 8/9	228,+39	18	-	77.3	50?	-	5.4	0.99, 17, 192
51	Cor	Corvids	1937	June 26/27	192,-19	15	1.9	94.9	13	0.2-20	4.0	1.01, 3, 8
52	xCp	ξ Capricornids	1972	Oct. 2/3	302,-9	16	~ 2	≤189.04	≥8	~20	7.4	0.99, 3, 193
		far-comet type?										
53	aBo	α Bootids	1984	Apr. 27/28	219,+19	23	>4	37.471	-	37±5	4.3	0.73, 18, 249
54	aCi	α Circinids	1977	June 3/4	220,-65	~28	-	73.25	-	80±40	∞	0.84, 29, 49
55	gDe	γ Delphinids	1930	June 10/11	312,+17	~60	(2.5)	79.72	≥200	≥60	∞	0.84, 117, 227
56	bPe	β Perseids	1935	Aug. 7/8	52,+40	~67	>5	134.661	-	60±20	∞	0.86, 143, 135
57	oOr	ωOrionids	1964	Nov. 25/26	85,+04	~45	(2.3)	243.42	≥140	1-30	∞	0.23, 43, 123
58	-	Monocerotids	1896	Dec. 12/13	88,+7	~43	-	-	-	-	145	0.19, 35, 129

Table 6. Chinese references to miscellaneous meteor outbursts between 1793 and 1993 (Tian-shan 1977). The moon phase is mentioned, where F_{moon} = 0.0 indicates a new moon. The exact time of each event is usually uncertain, hence $\lambda_\odot$ has an uncertainty of ± 0.3°.

#	Year	Date	$\lambda_\odot$	F_{moon}	Description:	Association:
59	1799	Feb. 2/3	316.0	0.0	"Stars criss-crossed as though weaving"	1939 III?
60	1842	Feb. 10/11	323.1	0.0	"Stars glided as though weaving"	-
61	1861	Aug. 14/15	143.1	0.7	"At night stars fell like rain"	1862II? Per?
62	1858	Nov. 1/2	220.6	0.1	"In daytime (8am-noon), moving from W to E"	1639?
63	1885	Nov. 2/3	221.3	0.2	"Stars glided as though weaving"	1639?
64	1885	Nov. 14/15	233.5	0.5	"From midnight to cockcrow, stars fell like rain"	Leo?
65	1891	Nov. 17/18	235.9	1.0	"Full Moon. "Stars fell like rain"	-
66	1882	Dec. 7/8	256.5	0.1	"Many stars glided from SE to E, fell like rain"	1941 IV?
67	1799	Dec. 18/19	268.9	0.6	"Stars fell like rain"	Urs?
68	1885	Dec. 26/27	276.1	0.7	"Meteors filled the sky, moving from NW to SE"	-

References and notes to Table 5

50 Activity associated with discovery of P/Schwassmann - Wachmann 3 1930 VI, which made a close passage by the Earth on May 30, 1930 (Δ = 0.062AU) (Kresak 1980, Smith 1932). Hoffmeister gives references to S. Sibata (1930; Kyoto Bulletin 172) and K. Nakamura (1930; MN 91, 204). Multi-station meteors photographed between May 19-June 14 in other years (Cook 1973). Δ_{E-C} = +0.0055 (Porter 1952).

51 109 slow meteors seen in the period June 25-30, 1937, by Hoffmeister (1948). χ from Levin (1955). No activity observed from this stream by the author from San Jose (CA) at 07-08 UT on June 24/25, 25/26, and 26/27, 1994.

52 8 bright meteors in 35 minutes by one observer (Derek Johns). Observations truncated by clouds. Observer M. Buhagiar saw only two meteors in a period directly after this interval, although watching in a direction opposite to the radiant.

53 Telescopic observation. Field of view on the radiant; therefore, many point meteors and short tracks.

54 Amateurs in Australia saw large number of meteors between 8:30-9:20 UT, of which 15 came from α Circini (Ottewell 1994 - no source reference available). Radiant is probably apparent radiant.

55 51 meteors in 30 minutes (39:+1; 10:+0). Observers Paul S. Watson, Frank Oertle, and Joseph Field from Baltimore (MD). Full moon, transparent sky, very low radiant altitude (Simmons 1980).

56 Observations by unassisted eye. "5-6th magnitude meteors with only 6-8 meteors within each 5 minute count brighter than +4" (Nielssen 1936). Radiant determined long after observations.

57 25 meteors ("many 0-1 magn") in 10-15 minutes. "Late during night shower was still in action" at Pretoria, South Africa (Warner 1965).

58 50 meteors, of which were 22 plotted; same time only 4 Geminids plotted. Observers D.E. Egintis, Terzakis, Hazapis (Egintis 1899). Association with Monocerotids uncertain.

The perihelion distance will increase again in the near future, and the new meteor stream will soon be lost.

9. How often can outbursts be observed?

This ends the listing of (possible) meteor outbursts. Tables 1, 5, and 6 form a catalog of such events that can be used to estimate how often meteor outbursts occur. Such estimate depends on the completeness of the catalog, which is likely far from exhaustive.

In this paper are listed a total of 49 certain outbursts that occurred between 1793 and 1993, which implies an event rate of about once every four years. 12 events are from the period 1982 to 1993, which saw the foundation and bloom of several of the amateur meteor organisations listed in Table 2. This suggests that the actual rate of events is higher, at least one event per year.

Yet, this estimate is probably still too low. In the distribution of accounts over the year, there is a concentration of events in the months October through December as compared to January through May. The months October through December are favoured months for observing meteors in the northern hemisphere. This suggests that the actual rate of events may be even higher, perhaps up to 2 events per year and that a number of meteor streams that have caused previous outbursts in the past two centuries has not been identified yet. This calls for more observing outside the periods of the main streams.

10. Summary and conclusions

In conclusion, meteor outbursts occur at a rate of more than 1 event a year. Still, only some 35 outbursts of 17 streams have been well enough documented over the past two centuries to give useful information about the meteor activity curve.

The 17 streams are divided into two groups that have been discussed separately: near-comet type outbursts that are associated with the return of the comet to perihelion, and far-comet type outbursts that occur when the comet is far from the Earth. Each meteor stream in this sample has only one type of outburst, depending on encounter geometry, where near-comet type outbursts occur when the Earth comes relatively close to the perihelion position, i.e. $\omega \sim 0{,}180^o$ and q $\sim$ 1.0 (or small inclination).

In order to characterise the activity profiles with the smallest possible number of parameters, each activity curve is fitted by a symmetric function as Eq. 3. The resulting values for the exponent B, level of peak actitivity ZHR_{max}, and time of maximum $\lambda_\odot^{max}$ are listed in Table 1b. Values of B vary from 7 to 220 as compared to annual streams: B = 0.05 - 0.7 (Paper I).

It is found that Eq. 3 is presently sufficient to describe available meteor outburst activity profiles. There is no solid evidence for a plateau at maximum, nor for the presence of substructure (filamentary structure) at the resolution of the present data, which is of the order of 15 minutes in time and at best 20% in activity.

The feature that does stand out clearly in several activity curves of near-comet type outbursts is an underlying component that is related to the outburst event. This background component can be described by an additional curve as Eq. 3. Values of B vary from 0.09 to 7 (Table 1c). 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. There is no gradual change from one component into the other. Therefore, main peak and background are due to two different structures in the meteoroid density distribution.

The presence of both a main peak and a background component has thus far only been established in near-comet type outbursts. For a series of subsequent returns, the main peak and background components behave quite differently. The duration and peak activity of the main peak do not depend strongly on the minimum distance between Earth and comet orbit Δ_{E-C} or the position of the comet in its orbit E-C (Fig. 3). The stream width is typically much less than Δ_{E-C}. Outbursts of a single return (for both type of outbursts) tend to occur systematically short of or later than the point of closest passage, resulting in positive or negative values of δ_{E-C}. This may help predict the time of occurrence of future events. The background component varies in strength and width relative to the main peak component. The Leonids show a progressive increase in width and strength for returns with increasing values of Δ_{E-C} (if this pattern holds for future returns, then the Leonids in 1998/1999 should have a relatively strong background component).

Far-comet type outbursts have a characteristic duration. The level of activity of "good" events comes out at about the same level in different returns. The outbursts do not occur annually. Instead, there appears to be an enhanced probability of a meteor outburst every 10-14 years. The rate of events is larger than suggested by the orbital period of the parent comet. There is a significant scatter of the time of maximum activity around a given position in solar longitude.

The main peak in near-comet outbursts can be due to a sheet-like distribution of dust. The width of the sheet is similar to the IRAS dust trail from which it likely emanates. The dust sheet falls off in density away from the comet position in E-C similar to the dust trail, and extends to tens of times further into the plane of the comet than its width.

The relatively large stream width of the background component of near-comet type outbursts, the orbital elements of some stray Draconids photographed in 1953, and the presence of the strong asymmetric background observed for the fast evolving Andromedid meteoroid stream indicate that this background component, perhaps, contains meteoroids that are strongly perturbed by the planets.

Far-comet type outbursts can be perhaps due to a direct passage of the Earth through the IRAS dust trail. In order to enhance the likelyhood that the Earth crosses the trail itself, it is suggested that periodic planetary perturbations cause a modulation in orbital elements. The beam of dust, perhaps, behaves much like a beam of water from a garden hose that is moved up and down to water a distant flower.

The total ejected mass in the "main peak" component is of order 10^{10} to 10^{13} gram. This compares to a factor of 100-1000 larger masses in the annual component (Paper I). The annual activity does not increase when the comet is nearby, suggesting that the transfer of dust from trail to annual stream is not constrained to the dense region near the comet.

10.1. Future work

Have we seen the full range of outburst phenomena? Probably not. Future events may offer surprising perspectives. In order to observe these phenomena systematically, a continuous monitoring system at several locations on Earth is called for.

In the next decade, dedicated observations can be planned for among others the Perseids in 1994 and 1995, the α Monocerotids in 1995, and the Leonids in 1994-2001. In any event, visual observers should try to gather 2 or 5 minute counts for as long a period of time as possible and should also mention the rate of sporadic meteors. If such counts are obtained at several independent sites, they may give information on the presence of filamentary structure. There is currently a conspicuous lack of orbital elements of meteoroids belonging to the outburst dust component and multi-station photography should be attempted.

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References

anonymous, 1934, AN 250, nr. 5984, 137
anonymous, 1967, Sky & Tel. 33, 4
Adams M.T., 1982, Meteor News nr. 58
Adams M.T., 1987, Meteor News nr. 76, 1
Astapovich I., 1928, Astron. Bulletin 23, 1
Averill L., 1946, Pop. Astronomy 54, 485
Baggaley W.J., 1973, Observer 93, 23
Bellot Rubio L.R., 1994, WGN 22, 13
Belyaev N.A., Kresak L., Pittich E.M., Pushkarev A.N., 1986, *Catalogue of short-period comets*, Astr. Inst. of Slovak Academy of Sci., Bratislava
Benzenberg J.F., 1838, AN 355, 325
Bone N., 1993, *Meteors*, Sky Publishing Co., Cambridge (MA), p. 156
Brackett P., 1899, Pop. Astronomy 7, 30
Brenke W.C., 1902, Pop. Astronomy 10, 105
Brown P., Asher D., Steel D., 1992, WGN 20, 28
Brown P., Gijssens M., Rendtel J., 1992a, WGN 20, 192
Buhagiar M., 1977, *WAMS Bulletin* no. 88
Burritt E.H., 1840, *The Geography of the Heavens*, F.J. Huntington & Co, New York, p. 160
Ceplecha Z., 1951, BAC 2, 156
di Cicco D., 1992, Sky & Telescope (Febr.), 225
Clegg J.A., Hughes V.A., Lovell A.C.B., 1948, JBAA 58, 134
Cook A.F., 1973, *A working list of meteor streams* in *Evolutionary and Physical Properties of Meteoroids*, NASA-SP 319, Washington DC, 183
Cruls L., 1886, AN 114, 99
Dall'olmo U., 1978, JHA 9,123
Davies J.G., Lovell A.C.B., 1955, MNRAS 115, 23
Davies J.G., 1955, in *Meteors*, Special Suppl. to J. Atmosph. Terr. Phys., p. 177
Davies J.G., Turski W., 1962, MNRAS 123, 459
Dawes W.R., 1867, MNRAS 27, 47
Denning W.F., 1902, MNRAS 62, 299
Denning W.F., 1904, MNRAS 64, 125
Denning W.F., 1916, The Observatory 39, 356
Denning W.F., 1917, The Observatory 40, 95
Denning W.F., 1927, MNRAS 87, 104
Dinwoodie C., 1952, Brit. Astr. Assoc. Handbook, p. 44
Drummond J., 1981, ICARUS 47, 500
Ducoty R., 1986, Meteor News nr. 73, 6
Egintis D.E., 1899, Ann. Obs. Nat. Athens 2, 41
Fisher W.J., Olmsted M., 1929, Bull. Harv. Coll. Obs. 870, 7
Fisher W.F., 1931, Pop. Astronomy 39, 256
Foersster W., 1886, AN 114, 112
Fox K.A., Hughes D.W., Williams I.P., 1982, MNRAS 200, 313
Fox K.A., 1985, in *Asteroids, Comets, Meteors II*, C.-I. Lagerkvist et al. (eds.), Uppsala, p. 521.
Gadomski J., 1929, Publ. Astron. Obs. Warzawa Univ. 5, 69
Galle J.G., 1873, AN 80, 279
Graff K., 1933, AN 250, 248
Grant R., 1869, MNRAS 29, 60
Grant R., 1872, MNRAS 33, 78
Grant R., 1886, MNRAS 46, 64
Green D., 1991, IAU Astron. Telegram (Nov.).
Guth V., 1936, AN 258, 27
Guth V., 1947, BAC 1, 1
Hagen J.G., 1892, AJ 12, 145
Hajduk A., 1970, BAC 21, 37
Hasegawa I., 1979, J.A.S. Japan 31, 257
Heis E., 1863, Wochenschrift für Astronomie, p. 363
Herrick E.C., 1838, Am. Journ. Sci. and Arts 34, 398
Hershel A.S., 1867, MNRAS 27, 54
Hershel A.S. 1872, MNRAS 32, 355
Hey J.S., Parsons S.J., Stewart G.S., 1947, MNRAS 107, 176
Hildebrand–Hildebrandsson H., Charlier C.V.L., 1886, AN 113, no. 2697
Hillestadt T.E., 1987, *N.A.S. Annual Report 1986*
Hindley A.K., 1936, The Observatory 59, 26
Hindley A.K., 1936a, The Observatory 59, 67
Hoffmeister C., 1921, AN 215, 455
Hoffmeister C., 1936, AN 258, 25
Hoffmeister C., 1948, *Meteorströme*, Johann Ambrosius Barth, Leipzig.
Hughes D.W., Thompson D.A., 1973, MNRAS 163, 3p
Hughes D.W., 1982, Vistas in Astronomy 26, 325
Hussey W.J., 1892, AJ 12, 176

Imoto S., Hasegawa I., 1958, Smits. Contr. Astrophys. 2, 131

Jacchia L.G., Kopal Z., Millman P.M., 1950, ApJ 111, 104

Jacchia L.G., Whipple F.L., 1961, Smits. Contr. Astrophys. 4, 97

Jacchia L.G., 1963, in *The Moon, Meteorites, and Comets*, B.M. Middlehurst, G.P. Kuiper (eds.), Chicago, 1963, Vol IV, Ch. 22, p. 774.

Jacchia L.G., Verniani F., Briggs R.E., 1967, Smits. Contr. Astrophys. 10,1

Jenkins P.W., 1899, Pop. Astronomy 7, 47

Jenkins P.W., 1902, Pop. Astronomy 10, 220

Jenniskens P., Hillestadt T.E., 1988, Radiant 10, 23

Jenniskens P., 1992, Radiant 14, 55

Jenniskens P., Cailloux M., de Lignie M., Kuiper J., 1993, WGN 21, 32

Jenniskens P., 1994, A& A 287, 990 - Paper I

Katz B., 1987, Meteor News 77

Kazimirchak-Polonskaya E.I., Beljaev N.A., Astapovich I.S., Terenteva A.K., 1968, in *Physics and Dynamics of Meteors*, L. Kresak & P.M. Millman (eds.) (Reidel, Dordrecht)

Kock A.C., 1934, Hemel & Dampkring 32, 44

Koschack R., Alt R., Rendtel J., 1993, WGN 21, 152

Koseki M., 1990, ACM III, p. 543

Koseki M., 1990a, ICARUS 88, 122

Koseki M., 1992, Radiant 14, 21

Kresak L., 1958, BAC 9, 88

Kresak L., 1975, BAC 26, 327

Kresak L., 1976, BAC 27, 35

Kresak L., 1980, in *Solid Particles in the Solar System*, I. Halliday & B.A. McIntosh (eds.), p. 211-222.

Kresak L., 1987, BAC 38, 65

Kresak L., Slancikova J., 1975, BAC 26, 327

Kresak L., 1993, A& A 279, 646

Kresakova M., 1966, Contr. Ast. Obs. Skalnate Pleso 3, 75

Leavenworth F.P., 1902, Pop. Astronomy 10, 161

Leonard N.R., 1936, Pop. Astronomy 44, 560

Levin B.J., 1955, in *Meteors*, T.R. Kaiser (ed.), Pergamon Press, p. 131

de Lignie M.C., Betlem H., 1995, A& A (in prep.)

Lindblad B.A., 1987, A& A 187, 928

Lindblad B.A., 1987a, A& A 187, 931

Lindblad B.A., 1987b, WGN 15, 154

Lindblad B.A., 1992, *Asteroids, Comets, Meteors 1991*, A.W. Harris, E. Bowel (eds.), Lunar and Planetary Institute, Houston, 367

Lindsey L., 1932, A.J. 42, 109

Lovell A.C.B., Banwell C.J., Clegg J.A., 1947, MNRAS 107, 164

Lovell A.C.B., 1954, *Meteor Astronomy*, Oxford University Press, New York, 463 pp

MacKenzie R., 1986, Meteoros 16, 70

Maclear G.W.H., 1867, MNRAS 27, 65

Maclear G.W.H., 1869, MNRAS 29, 233

MacNaught R.H., 1986, Meteor News 74

Main R., 1867, MNRAS 27, 39

Marsden B.G., 1983, *Catalog of Cometary Orbits*

Marsden B.G., 1985, IAUC 4200+5304

Marsden B.G., 1992 IAUC 5586

Marsden B.G., Green D., 1992, IAUC 5620

Marsden B.G., 1993a, IAUC 5636

Marsden B.G., Williams G.V., Kronk G.W., Waddington W.G.,1993, ICARUS 105, 420

Mason J.W., 1986, in *Proc. 20th ESLAB Symp.*, ESA-SP 250, p. 379

Mason J.W., 1992, BAA Newsletter nr. 44 (Oct.)

McCrosky R.E., Posen A., 1961, Smits. Contr. Astrophys. 4,15

McIntosh B.A., Millman P.M., 1970, Meteoritics 5, 1

McKinley D.W.R., 1961, *Meteor Science and Engineering*, McGraw-Hill, New York, 309 pp

Merino M., 1886, AN 114, 101

Millman P.M., 1934, J. Roy. Soc. Canada 28, 137

Millman P.M., 1936, J. Roy. Soc. Canada 30, 293

Millman P.M., 1962, J. Roy. Soc. Canada 56, 215 + 257

Millman P.M., McKinley D.W.R., 1963 in *The Moon, Meteorites and Comets*, B.M. Middlehurst & G.P. Kuiper (eds.), p 674.

Millman P.M., 1967, J. Roy. Soc. Canada 61, 89

Millman P.M., 1967a, in *The Zodiacal Light and the Interplanetary Medium*, J.L. Weinberg (eds.), NASA-SP 150, 399

Millman P.M., 1970, J. Roy. Astron. Soc. Canada 64, 55

Milon D., 1967, JBAA 77, 89

Miskotte K., 1993, Radiant 15, 139

Moore R., Morrow M., 1982, Meteor News no. 57

Murray C.D., Hughes D.W., Williams I.P., 1980, MNRAS 190, 733

Nagasawa K., Kanda T., 1986, Tokyo Astron. Bull., Second Ser., 274, 3159.

Nagasawa K., Kawagoe A., 1987, ICARUS 70, 138

Nielsen A.V., 1936, Die Himmelswelt 46, 34

Ohtsuka K., 1986, Meteoros 16, 45

Olivier C.P., 1917, MNRAS 77, 71

Olivier C.P., 1925, *Meteors*, The Williams & Wilkins Co., Baltimore, 276 pp

Olivier C.P., 1926, Pop. Astronomy 34, 165

Olivier C.P., 1935, Publ. Leander McCormick Obs., 5, 24

Olivier C.P., 1936, Pop. Astronomy 44, 88

Olivier C.P., 1946, Pop. Astronomy 54, 475

Olivier C.P., 1946a, Pop. Astronomy 54, 305

Olson D.W., Doesher R.L., 1993, WGN 21, 175

Ottewell G., 1994, Astronomical Calendar, Furman University, Greenville SCa, p. 60

Plaut L., 1948, Hemel en Dampkring 46, 39

Plavec M., 1955, BAC 6, 20

Plavec M., 1957, BAC 30, 1

Plavcová Z., 1968 , IAU-symp. 33, 432-439

Poey A., 1864, Comptes Rendus 58, 119

Porter J., 1952, *Comets and meteor streams*, J. Wiley & Sons New York

Porubcan V., 1974, BAC 25, 353

Porubcan V., 1986, Contr. Ast. Obs. Skalnate Pleso 14, 105

Porubcan V., Stohl J., 1983, Contr. Ast. Obs. Skalnate Pleso 11, 169

Porubcan V., Cevolani G., 1985, Contr. Ast. Obs. Skalnate Pleso 13, 247

Porubcan V., McIntosh B.A., 1987, BAC 38, 313

Porubcan V., Stohl J., 1992, in ACM 1991 (Lunar and Planetary Institute, Houston), p. 469

Prentice J.P.M., 1930, JBAA 40, 136

Prentice J.P.M., 1934, JBAA 44, 108

Prentice J.P.M., 1947, JBAA 57, 86

Rao J., 1993, WGN 21, 110

Rees, 1892, AJ 12, 128

Rendtel J., Betlem H., 1993, WGN 21, 264

Ridley H.B., 1961, JBAA 72, 266

Ridley H.B., 1972, JBAA 82, 95

Russell J.E., 1982, Sky & Telescope 63, 10

Russell J.A., 1984, Meteoritics 19, 305

Sawyer E.F., 1886, The Observatory 9, 95

Sawyer E.F., 1892, AJ 12, 146

Sekanina Z., 1973, Icarus 18, 253

Schmidt J.F.J., 1863, Wochenschrift für Astronomie, Oct. 7, 314

Schmidt J.F.J., 1873, AN 80, 289

Schönfeld E., 1886, AN 113, 120
Shain C.A., 1957, The Observatory 77, 27
Shimoda C., Suzuki K., Maeda K., 1993, WGN 21, 130
Simek M., 1986, BAC 37, 246
Simek M., 1987, BAC 38, 80
Simek M., 1994, A& A 284, 276
Simmons K., 1980, Meteor News nr. 51, 2
Simmons K., 1982, Meteor News nr. 58, 7
Smith F.W., 1932, MNRAS 93, 156
Simpson J.A., Sagdeev R.Z., Tuzzolino A.J., et al., 1986, Nature 321, 278
Smyth P., 1867, MNRAS 27, 22
Spalding G.A., 1982, BAA Newsletter nr. 9 (June)
Spalding G.A., 1982a, BAA Newsletter nr. 10 (Sept.)
Spalding G.A., 1985, JBAA 95, 211
Spalding G.A., 1992, BAA Newsletter 44 (Oct.)
Stuart Capt., 1868, MNRAS 28, 54
Sykes M.V., Lebofsky L.A., Hunten D.M., Low F.J., 1986, Science 232, 1115
Sykes M.V., Walker R.G., 1992, ICARUS 95, 180
Tepliczky I., 1987, WGN 15, 28
Tian-shan Z., 1977, Chinese Astronomy 1, 197
Veltman R., 1984, Radiant 6, 81
Veltman R., Jenniskens P., 1985, Radiant 7, 107
van Vliet M., 1993, Radiant 15, 19
Warner B., 1965, MNRAAS 24, 126
Watanabe J.-I., Nakamura T., Tsutsumi M., Tsuda T., 1993, Publ. Astr. Soc. Japan, 44, 677
Watson F.G., 1934, Bull. Harv. Coll. Obs. no. 895, 9
Weiss A.A., 1958, Austr. J. Phys. 11, 113
Weld L.G., 1899, Pop. Astronomy 7, 17
Witte F., 1984, Radiant 6, 101
Wilson H.C., 1898, Pop. Astron. 6, 568
van Woerden H., 1967, Hemel & Dampkring 65, 28
Wood J., 1979, Meteoros 10, 3
Wood J., 1980, Radiant 2, 135
Wood J., 1980a, WAMS Bulletin no. 157
Wood J., 1981, WAMS Bulletin no. 167
Wood J., 1982, WAMS Bulletin no. 180
Wood J., 1986a, NAPO-MS Bulletin no. 121 and 118
Wood J., 1986b, Radiant 8, 75
Wood J., 1986c, NAPO-MS Bulletin, no. 150
Wood J., 1987, NAPO-MS Bulletin no. 184
Wood J., 1988, NAPO-MS Bulletin no. 200 (Radiant 10, 71)
Wood J., 1991, WGN 19, 161
Wood J., 1992, WGN 20, 240
Wylie C., 1946, Sky & Tel. 6, 11
Xu Pin-Xin, 1992, WGN 20, 198
Yau K., Yeomans D., Weissman P., 1994, MNRAS 266, 305
Yabu Y., 1985, *Great Meteor Display of the Draconids in Japan* (mimeographed report, Nippon Meteor Society)
Yeomans D.K., 1981, ICARUS 47, 492
Young C.A., 1899, Pop. Astronomy 7, 17
Znojil V., 1992, WGN 20, 244

Note added in proof: The library of the Royal Astronomical Society made available to me a copy of Gadomski (1929). Gadomski's counts are shown in Fig. 6 by triangles. The following parameters for the Lyrid outburst of 1922 replace those in Table 1b: $\lambda_0 = 31.296$, $\mathrm{ZHR}_{\mathrm{max}} \sim 2900$, $B = 57 \pm 8$, $\delta_{\mathrm{E-C}} = +0.126$.