THE JOURNAL OF THE ROYAL ASTRONOMICAL SOCIETY OF CANADA

JOURNAL DE LA SOCIÉTÉ ROYALE D'ASTRONOMIE DU CANADA

Vol. 83, No. 2 APRIL 1989 Whole No. 617

DETAILED RECORDS OF MANY UNRECOVERED METEORITES IN WESTERN CANADA FOR WHICH FURTHER SEARCHES ARE RECOMMENDED

BY IAN HALLIDAY, ALAN T. BLACKWELL AND ARTHUR A. GRIFFIN

Herzberg Institute of Astrophysics, National Research Council Canada, Ottawa, Ontario, Canada

(Received September 1, 1988)

ABSTRACT

The meteoritic fireballs observed with the Canadian camera network between 1971 and 1985 are studied to obtain a record of the essential data for those events that are believed to have dropped significant meteorites. The mass of the largest surviving fragment for each event is estimated from the dynamic data near the end of the photographic trail. Three groups are identified as follows: (1) all events, 28 in number, for which the largest fragment is larger than 0.5 kg, including three events with mass estimates near 10 kg and also including the recovered Innisfree meteorite; (2) 16 events with mass estimates from 0.1 to 0.5 kg for which the location might be favourable for recovery; (3) 12 other events in the smaller mass range for which the location is unfavourable.

Each of the 44 events in groups 1 and 2 is described briefly, with emphasis on the probable degree of fragmentation during flight and the effects of flight geometry plus upper atmospheric winds on the expected "ellipse of fall" distribution on the ground. Data on height, velocity, brightness, ground location and the orbit are given for each of these events. For the 12 events in group 3 only the ground position and estimated mass are given.

It is shown that any meteorite exhibiting only moderate weathering that may be found within an area of about 20 km^2 near the predicted impact sites is very likely to be related to the MORP object rather than to some unrelated event. It is hoped that the availability of the data on these objects will lead to further searches and educational campaigns that may increase the small number of meteorites for which details of both the orbit and the atmospheric encounter are known.

RÉSUMÉ

Les bolides météoritiques qui ont été observés à l'aide du réseau photographique du Canada entre 1971 et 1985 ont été étudiés pour obtenir un enregistrement de ces évènements que l'on croit avoir lancé des météorites importants. La masse du plus grand fragment restant pour chaque évènement est estimée à partir des données dynamiques près de la fin de la traînée photographique. Trois groupes ont été identifiés de la manière suivante: (1) Tous les évènements, c'est-à-dire un nombre de 28, pour lesquels le plus grand fragment pèse plus de 0.5 kg, y compris trois évènements avec des masses estimées à près de 10 kg et aussi le météorite Innisfree, qui a été récupéré; (2) 16 évènements avec des masses estimées de 0.1 à 0.5 kg pour lesquels les positions pourrait convenir à la récupération; (3) 12 autres évènements à masses plus petites pour lesquels les positions ne conviennent pas.

Chacun de ces 44 évènements dans les groupes 1 et 2 sont décrits brèvement en soulignant le degré probable de fragmentation pendant le vol et les effets de géométrie de vol et des vents atmosphériques supérieurs sur la distribution de l' "ellipse de tombée" au sol. Des données de hauteur, vélocité, brillance, position au sol et l'orbite sont données pour chacun de ces évènements. Pour les 12 évènements dans le groupe 3 seulement la position au sol et la masse estimée sont données.

On montre que chaque météorite qui semble avoir été peu usé et qui pouvait se trouver dans une superficie de 20 km^2 près du point de chute est très probablement en rapport avec l'objet PORM plutôt qu'à n'importe quel autre évènement sans rapport. On espère que la disponibilité de ces données pour ces objets conduira à d'autres recherches et des campagnes d'éducation qui pourrait augmenter le petit nombre de météorites pour lesquels l'on connaît quelque chose de l'orbite et de la rencontre atmosphérique.

1. *Introduction.* Meteorites may be classified into many different mineralogical classes but all meteorites may also be divided between "falls" and "finds". A meteorite is a "fall" if the date and time of its arrival on Earth are known, even if the recovery of the specimen is days or years after the event itself. A "find" is a meteorite for which the information on its arrival is lacking. For finds, the geographic location is usually known and some estimate of its "residence" time on Earth may be attempted from the amount of weathering or from sophisticated measures of the decay of radioactive isotopes.

While all meteorites are of great interest scientifically, falls are generally of more value since their history is more complete. Detailed descriptions of a fall by eyewitnesses may provide the radiant direction in the sky from which the object approached the Earth and some information on fragmentation during flight, plus accompanying sonic phenomena. Visual observations are not sufficiently precise, however, to determine the entry velocity into the atmosphere, an essential parameter together with the time and direction of motion, required for the determination of the meteoroid's orbit in the solar system.

Networks of cameras have been used in an attempt to solve this problem, since cameras equipped with a precisely-timed occulting device can provide accurate velocity data for any meteor photographed from at least two suitable locations. Three major networks have operated in recent years: the Prairie Network in the central United States from 1964 to 1974; the European Network in Czechoslovakia and the Federal Republic of Germany from 1964 to the present; and the Meteorite Observation and Recovery Project (MORP) in western Canada from 1971 to 1985. Each network has photographed many hundreds of bright meteors, undoubtedly including dozens of events that dropped a small meteorite. Because of the great difficulty in locating meteorites on the ground, however, only three have been recovered from the networks, one each in Czechoslovakia, the United States and Canada. Details of the fall and recovery of the Innisfree, Alberta, meteorite in February, 1977, were described by the present authors, together with a description of the MORP network (Halliday *et al.* 1978, 1981).

A total of 46 meteorites have been recovered in Canada, of which 11 are falls and 35 are finds, a normal ratio between the two classes. Only two new finds have appeared in the past decade and, as of mid-1988, it is more than 11 years since the Innisfree event, which remains the most recent recovered fall. This is the longest interval without the recovery of a new fall in Canada during the past half century, a period that has seen the recovery of eight witnessed falls, beginning with the large fall near Dresden, Ontario, in July 1939.

The MORP network has photographed its share of unrecovered meteorite falls and there is a possibility that some of these may be recovered in the future. If they could be associated confidently with MORP events, then they would become important falls rather than mere meteorite finds. The photographic records would provide not only the time of each event but also details about the brightness, range of heights for the fireball, data on the extent of atmospheric fragmentation, plus the velocity and deceleration. Most importantly, the MORP data provide a reliable orbit for each object, which is currently available for only the three meteorites mentioned above. The purposes of this paper, then, are to document many of the more significant MORP fireballs that are believed to have dropped meteorites and, it is hoped, to stimulate interest in further searches and educational campaigns that could lead to the recovery of more of these intriguing objects that contain exciting clues to the early history of our solar system.

2. *Observational Data.* In order to list those fireball events for which a significant meteorite fall is expected, it is necessary to have a method of estimating the terminal mass that may remain when the meteoroid has decelerated so much that it is no longer luminous. It is possible to estimate a *dynamic mass* at any point on a meteor path where the deceleration due to atmospheric drag is large enough to be measured with some confidence. The other quantities required are the velocity, atmospheric density at the observed height, some reasonable assumptions about the shape and density of the meteoroid, and a value for the drag coefficient. The method has been used for many years and our normal assumptions have been a density of 3.5 g cm^{-3} for a presumed stone meteorite, a drag coefficient of 1.0, and a brick-like shape with ratios of the sides of 2:3:5, oriented for maximum drag (Halliday *et al.* 1981, 1984). These assumptions were shown to agree well with the behaviour of individual fragments of the Innisfree meteorite, from which it was inferred that dynamic masses were normally within a factor of 2 of the true masses, but might occasionally differ by a factor of 3. The sources of error in both dynamic and photometric mass estimates were discussed in a recent paper on Geminid

fireballs observed with the MORP network (Halliday 1988).

Estimates of dynamic mass were calculated late in the trail for essentially all MORP fireballs that penetrated below a height of 40 km and a total of 79 events were identified for which a terminal mass of at least 50 g was indicated for the largest fragment. We select three groups from this sample, as follows: (1) all 28 events for which the dynamic mass of the main fragment exceeds 0.5 kg; (2) 16 lesser events where there is a reasonable chance that a small meteorite might be located; (3) the remaining 12 events for which the dynamic mass estimate is at least 0.1 kg.

Table I documents the dynamic and photometric data for the 28 largest events. The selection is unbiased in the sense that it includes all MORP objects that met the dynamic mass criterion, but it is likely to contain a high proportion of very bright fireballs because they will be detected at greater ranges from the camera stations than would less luminous fireballs.

The first column is the MORP number, generally in chronological order except when (as for no. 925) a number was assigned before the films for lesser meteors had been studied. The quantity λ is the geographic longitude (west) of the predicted impact point, listed here to facilitate the location of the corresponding description of the event, since the descriptions are arranged in order of longitude. The next columns indicate the year, month, day, hour and minute of the time of appearance, in U.T. In most cases the exact time is unknown and the quantity E in minutes, defines the maximum error in the listed time, i.e. the fireball may have appeared as much as E minutes before or after the listed time. The effect of this uncertainty is discussed later in connection with the orbits.

The position of the geocentric radiant, corrected for zenith attaction and diurnal aberration, is shown by α_R and δ_R. The quantity Z_R is the zenith distance of the *apparent* radiant, uncorrected for these effects, since this defines the slope of the actual trajectory in the atmosphere. A_R is the azimuth of the radiant, measured north through east, i.e. the direction from which the meteor approached. In the absence of atmospheric winds one would expect smaller fragments to be displaced in this direction relative to large ones, i.e. this should approximate the orientation of the major axis of the "ellipse of fall". Nearly all stone meteorites break up in the atmosphere and the approximately elliptical area on the ground is a result of differential drag effects among the fragments during the late stages of flight. Repeated fragmentation events along the trail will complicate the result but, typically, if there is an appreciable slope to the path, the larger fragments will be found furthest along the direction of flight. The "ellipse" may become very long and narrow for a nearly horizontal path. The Bruderheim fall in 1960 produced a typical ellipse of fall for a major event, with hundreds of recovered fragments in an area of 16 km^2 (Folinsbee and Bayrock 1961). The individual descriptions of the MORP events usually indicate what distortion of the axis

TABLE I

DATA FOR 28 EVENTS WITH SUBSTANTIAL TERMINAL MASS

No.	λ	y	m	d	h	m	E	α_R	δ_R	Z_R	A_R	DU	H_B	H_E	v_∞	v_E	R_1	R_2	M_{pan}	H_p	v_p	log L	m_p	m_t	m_∞
123	112.34	74	08	12	06	58	28	295.0	-12.6	56.2	197	5.8	81.0	32.6	16.3	8.7	75D	201C	- 7.1	51	15.8	3.25	0.67	0.74	1.4
172	108.64	75	04	11	05	52	24	181.6	33.3	14.8	165	3.1	66.5	31.2	12.5	8.1	236C	308L	- 7.9	52	12.4	3.31	1.17	0.62	1.8
174	109.62	75	05	10	09	24	24	47.6	71.4	47.2	13	3.3	72.1	32.3	19.1	12.3	192C	291A	- 8.5	46	17.6	3.74	1.7	1.2	2.9
189	105.20	75	09	14	07	56	9	319.2	-21.6	67.0	222	10.1	75.5	27.9	14.5	4.8	80L	150G	- 8.8	56	14.0	4.19	8.1	0.59	8.7
204	100.79	75	11	13	04	09	37	49.8	-21.1	57.2	144	4.8	61.9	29.5	13.0	8.7	270H	461G	- 8.1	40	12.6	3.71	2.9	3.9	6.8
207	109.56	75	11	16	06	58	26	14.3	37.6	23.6	259	3.6	77.2	25.9	17.9	6.5	153F	189E	- 9.5	44	16.7	3.99	3.4	0.56	4.0
223	109.70	75	12	16	14	40	0	86.9	31.7	70.2	302	6.4	77.7	27.1	27.1	9.5	77C	197D	-14.7	50	27.0	6.25	232.	3.4	235.
261	106.07	76	11	01	02	00	35	303.2	-25.1	54.5	198	4.1	59.0	34.4	12.4	7.8	87G	158H	-	43	10.5	-	-	0.52	-
276	101.65	76	12	20	04	17	62	110.5	79.4	32.9	162	3.3	81.8	24.4	23.5	6.5	186J	192H	-10.3	33	18.2	4.33	4.8	0.50	5.3
285	111.34	77	02	06	02	18	0	6.7	66.2	22.2	320	4.1	62.4	19.8	14.5	2.7	52C	194D	-12.1	35	13.4	4.97	46.	2.1	48.
288	109.28	77	02	17	07	25	32	67.7	27.8	44.2	280	6.3	68.6	20.2	12.4	4.1	248C	288B	-10.0	30	10.5	4.45	13.	6.2	19.
307	99.12	77	05	01	09	06	0	224.7	4.0	48.8	220	4.6	78.2	22.0	21.0	3.8	28J	161I	- 9.2	36	19.6	4.14	3.5	1.2	4.7
331	105.33	77	10	25	09	10	6	166.6	18.5	61.8	72	7.1	71.4	31.0	13.3	7.0	111L	150G	- 9.1	52	12.8	4.13	7.6	1.3	8.9
341	103.86	77	11	16	00	31	22	357.5	-16.8	54.8	141	5.3	70.8	31.9	12.8	8.5	51H	152I	- 7.2	71	12.8	3.30	1.1	1.6	2.7
364	106.00	78	03	30	03	40	0	55.4	38.1	32.9	291	4.8	65.8	25.4	11.3	5.3	75G	231F	-10.5	46	11.0	4.56	18.	1.4	19.
544	112.78	80	02	04	09	14	37	89.9	11.8	54.4	261	6.8	75.1	25.8	14.4	6.2	73D	265E	- 9.5	44	13.4	4.23	8.8	5.9	15.
545	104.29	80	02	06	02	11	16	30.5	72.1	19.2	339	2.6	63.1	30.0	14.7	9.9	129L	217A	- 7.6	45	13.9	3.19	0.76	1.8	2.6
565	107.67	80	07	01	08	50	40	283.4	32.3	16.8	226	2.6	64.6	34.8	13.2	10.7	115G	267H	- 8.7	50	13.2	3.71	2.7	0.92	3.6
580	111.63	80	09	01	08	10	5	229.3	9.7	78.2	302	17.9	70.1	28.0	14.2	5.2	284B	288D	-10.5	46	12.9	5.16	72.	11.	83.
626	101.86	80	11	25	02	54	41	349.7	1.7	39.7	198	3.0	62.3	33.5	13.5	10.0	136I	182L	- 7.1	47	13.0	2.99	0.54	0.77	1.3
672	108.44	81	04	18	09	02	44	114.5	47.0	54.7	323	4.3	65.5	32.7	13.7	8.8	229F	277E	- 9.2	34	10.2	3.95	5.2	0.60	5.8
687	112.13	82	01	16	03	24	2	314.4	17.2	70.2	288	10.5	77.3	28.9	16.7	5.9	74E	203D	- 8.1	48	15.5	3.62	1.6	1.6	3.2
792	98.34	82	06	11	07	28	29	143.3	64.7	50.0	338	4.8	76.1	28.9	17.3	7.7	98J	184K	- 8.2	50	16.7	3.71	1.8	0.88	2.7
872	104.13	83	07	12	04	45	27	239.5	10.9	32.1	205	4.3	67.7	20.8	14.8	5.8	285H	386I	-12.6	28	11.3	5.20	80.	10.	90.
886	106.29	83	09	07	07	31	10	297.1	- 4.8	56.4	237	5.8	72.0	32.0	13.8	7.4	92G	180F	- 7.4	51	13.2	3.37	1.2	1.1	2.3
897	109.68	83	10	27	07	53	48	250.9	58.7	60.8	345	3.8	73.6	31.6	25.1	16.2	317A	341D	-10.0	52	24.4	4.30	3.2	4.4	7.6
925	119.18	84	02	23	02	06	0	155.9	- 0.7	81.5	90	30.1	91.2	29.8	26.5	4.2	140C	308D	-14.9	48	24.9	6.90	1230.	12.	1240.
930	109.64	84	02	08	08	57	41	80.8	10.5	57.9	269	5.3	71.0	35.6	13.4	9.5	97F	112E	- 7.2	48	12.8	3.29	1.08	0.52	1.6

of the ellipse of fall is to be expected as a result of the wind at the time of the fall.

The next column lists the maximum duration in seconds of the photographed trails. Frequently this is greater than recorded at any single station since the station that records the highest beginning point may not be the one with most detail at the end point. The observed beginning and end heights, in kilometres above sea level, are listed in the next columns. The observed velocity at the top of the atmosphere, v_∞, is the value employed in the orbit calculation. The end velocity, v_E, is the value found by extending the plot of local velocities along the trail to the end of the trail and is sensitive to the quality of the sky transparency low in the sky, to the range of the fireball from the camera and even to the phasing of the occulting shutter. R_1 and R_2 are the minimum ranges in km from the observed luminous trails to the two stations used in the geometric solution. R_1 is chosen as the closer of the two stations and the letters A to L after the actual range indicate which MORP station is involved (see Table I of Halliday *et al.* 1978).

The peak luminosity of the fireball is indicated by M_{pan}, the absolute panchromatic magnitude, defined as the brightness the fireball would have if observed in the zenith at a range of 100 km. It is derived from a comparison of the meteor image with the trailed images of stars and planets, applying corrections for atmospheric and photographic effects. Some of these bright events were observed under conditions of scattered cloud and haze which increase the uncertainty in the result. In these cases it is generally assumed the meteor occurred during the intervals of better transparency. If this was not actually the case, then the fireball must have been brighter than shown in the table.

The light curves for meteorite-related fireballs typically have a gradual rise, a rather flat maximum and a steep decline. The precise moment of peak luminosity is often poorly defined but H_p and v_p show the estimated height at peak luminosity and the corresponding velocity. The total light emitted by the fireball is indicated by log L where L is the area under the light curve in units of zero-magnitude seconds. For example, an object that maintained a magnitude of -10 for 5 sec would have $L = 5 \times 10^4$ or log $L = 4.70$.

The final three columns are mass estimates in kg. The photometric mass, m_p, is a measure of the mass lost by ablation and is calculated by assuming a luminous efficiency in order to determine the amount of mass that must have been lost at each point along the trail to produce the observed luminosity. The papers cited above in the discussion of dynamic masses also contain discussions of luminous efficiency and other references to the literature on this subject. We adopt a luminous efficiency of 0.04, independent of velocity, but we note that the mass loss required to produce a given luminosity is still inversely proportional to the square of the velocity, because of the velocity factor in the expression for kinetic energy. With this assumption, a mass of 4.0 kg must be ablated to maintain an absolute magnitude of -10 for 1 sec at a velocity of 15 km sec^{-1}. Earlier studies have shown that as a meteorite decelerates below about 12 km sec^{-1} the source of energy for the luminosity gradually shifts from ablated material to energy provided by deceleration of the meteoroid (ReVelle and Rajan 1979, Halliday *et al.* 1981). It is also known that the luminous efficiency itself decreases rapidly below about 10 km sec^{-1} so that quite large mass losses might be inferred if luminosity at the lowest velocities is attributed to ablation. We assume that the deceleration term dominates ablation below 10 km sec^{-1} and no contribution to the photometric mass is made at these low velocities. The choice of this limit may affect the estimates of m_p for the very slowest fireballs, i.e. for those cases where the values of v_p are less than about 12 km sec^{-1}

The dynamic mass near the end of the trail is taken to be the terminal mass of the main fragment, m_t. The final column, m_∞, is the sum of the previous two columns and represents the initial mass. One might increase this value in order to allow for the mass of all the surviving fragments that are smaller than the main mass. For Innisfree the total mass recovered was about twice the mass of the largest piece and, if this is typical, the final column might be $(m_p + 2m_t)$. For many of the smaller meteorites in this study, however, we doubt that the smaller pieces would double the total mass on the ground so we adopt the simpler expression and note that the difference is small compared with the uncertainties in estimating the initial masses of the meteoroids.

The masses in Table I are usually quoted to two significant figures, but occasionally to three figures in order to show the relative contributions of the photometric and terminal masses to the initial values. In all cases the potential errors are such that the second significant figure is in doubt.

The minimum terminal mass of 0.5 kg in Table I is an arbitrary value and with the expected errors in this quantity as large as they are, some events in Table I would no doubt be displaced by other events if the true values were known. Table II lists the same quantities as in Table I for 16 fireballs with terminal mass estimates between 0.1 and 0.5 kg. There were 28 such events observed by the network, but Table II contains only those cases where the impact location, or other factors, suggest there is some chance of an eventual recovery.

3. *Descriptions of 44 MORP Events*. Brief descriptions of each fireball in Tables I and II follow below. The heading for each event includes the MORP number, a geographic name, the U.T. date of the fireball event, and the geographic coordinates of the predicted impact point for the largest mass. The events are arranged in order of increasing westerly longitude. Figure 1 shows a selection of meteorite specimens from Canadian meteorites in the National Meteorite Collection of Canada. The masses of each fragment shown in the caption may be used as a guide to the expected size of the main mass from each of the unrecovered

TABLE II

DATA FOR 16 EVENTS WITH SMALLER TERMINAL MASS

No.	λ	y	m	d	h	m	E	α_R	δ_R	Z_R	A_R	DU	H_B	H_E	v_∞	v_E	R_1	R_2	M_{pan}	H_p	v_p	log L	m_p	m_t	m_∞
018	105.13	71	08	18	05	00	0	304.0	-10.7	55.4	169	5.4	75.5	27.6	18.4	5.7	82L	116H	- 9.8	41	15.5	4.25	5.6	0.30	5.9
171	112.22	75	04	02	06	45	19	196.6	1.6	46.5	156	3.3	70.2	33.7	18.1	11.3	129E	189F	- 7.3	48	16.4	3.22	0.57	0.16	0.73
195	108.98	75	09	26	06	12	0	7.0	- 2.8	52.3	157	3.7	77.6	30.4	25.2	7.6	90F	159G	-10.9	42	22.1	4.59	7.0	0.16	7.2
231	112.64	76	02	04	04	52	38	143.9	- 4.4	67.3	127	6.0	92.7	34.2	27.9	11.7	172F	198E	-10.2	56	27.3	4.53	4.3	0.18	4.5
303	108.97	77	04	15	10	37	43	124.8	57.2	51.5	333	4.1	67.3	34.9	14.1	8.2	112F	186G	- 9.2	53	13.7	3.84	3.5	0.11	3.6
345	104.01	77	11	22	11	07	44	52.4	31.3	47.4	278	3.6	73.3	34.3	17.4	10.6	181G	224I	- 6.9	58	17.4	3.03	0.38	0.21	0.59
346	109.53	77	11	22	05	01	17	16.7	48.7	4.3	270	2.3	64.1	31.0	15.7	8.5	183F	213E	- 8.6	54	15.6	3.50	1.3	0.12	1.4
498	106.07	79	10	19	03	36	2	255.5	-14.4	72.7	251	9.4	78.9	42.4	13.7	10.2	77A	130G	- 9.7	53	12.7	4.34	12.2	0.36	12.6
511	108.87	79	11	20	02	06	22	324.1	54.4	9.7	309	2.8	77.1	31.7	18.1	9.8	201F	445L	- 8.4	41	15.5	3.41	0.89	0.15	1.0
654	111.93	81	01	13	06	32	16	32.6	27.0	42.0	269	4.1	71.3	33.8	13.8	7.5	75C	115D	- 6.5	48	12.9	2.90	0.43	0.12	0.55
683	113.82	81	07	06	09	00	34	276.1	- 5.3	54.5	212	4.3	73.4	33.1	17.6	9.1	248E	348F	-10.4	45	16.3	4.46	9.6	0.23	9.8
751	109.32	81	11	23	04	25	31	342.4	61.6	20.3	317	3.1	78.7	30.5	18.9	8.9	99F	183E	- 7.2	46	17.5	3.01	0.32	0.28	0.60
840	103.55	82	12	12	12	35	0	261.6	71.2	41.1	29	3.4	77.2	27.7	23.6	6.1	174I	177K	-11.5	42	21.6	4.72	10.8	0.10	10.9
884	109.07	83	08	29	04	17	41	234.0	- 2.4	51.2	242	4.1	64.4	34.9	12.4	8.3	63F	186G	- 6.9	48	12.1	3.00	0.63	0.36	1.0
888	105.53	83	07	23	05	27	5	84.6	75.0	52.0	4	3.4	75.1	29.2	25.5	9.0	116H	120G	-10.2	48	24.1	4.38	4.3	0.17	4.5
977	110.18	84	11	20	05	51	19	26.4	55.5	6.2	312	2.1	71.5	29.4	23.3	9.4	103B	206D	- 9.6	42	20.9	3.68	1.1	0.16	1.3

FIG. 1—Upper photo, four stony meteorites recovered while the fusion crust was still fresh. Two pieces of the Innisfree meteorite are in the top row, with masses of 2 and 0.4 kg. The crust is chipped in some places and the end surface at extreme left shows a partial fusion crust. The two smaller specimens are from the Bruderheim, Alberta fall, with masses of 0.17 and 0.04 kg.

Lower photo, three stone meteorites showing moderately weathered surfaces. Left, the 2-kg Wynyard, Saskatchewan meteorite found in the late 1960s; centre, part of the Blithfield, Ontario meteorite found in 1910, weight 0.6 kg; right, a 1.4-kg piece of the Blaine Lake, Saskatchewan meteorite found in 1974, which also shows weathering on the interior surface that has been exposed by breaking the meteorite. The scale bars show centimetre marks. Specimens from the National Meteorite Collection of Canada, photos courtesy the Geological Survey of Canada, nos. 204845-A and B.

FIG. 2—Meteor 307 from one of two cameras at the Alonsa, Manitoba, station. The fireball entered the camera field at the left at a height of 27 km and ended, 1.1 second later, at 22 km. Five segments of the trail are recorded with eight separate fragments visible in the second segment on the original film.

events. Some indication of the effects of moderate weathering on the exterior appearance of stone meteorites may also be obtained in some cases.

No. 792 Spearhill, Manitoba 1982 June 11 98° 18′.3 51° 20′.4

The relatively unspectacular fireball that appears to have dropped a small meteorite near Spearhill showed a typical meteor wake between 64 and 61 km height and at least one trailing fragment between 54 and 46 km. A modest tailwind would tend to keep smaller fragments relatively close to the larger ones, but unfortunately the expected location is in swampy land about 4 km northeast of Spearhill.

No. 307 Alonsa, Manitoba 1977 May 1 99° 07′.4 50° 51′.5

The Alonsa event holds the record for a fireball that passed close to a MORP station that was in operation. The cameras at station J (also called Alonsa) were only 28 km from the luminous end point, while the predicted impact point is 17 km from the station. (Meteor 223 landed only 8 km from station B but the station was already shut down because of twilight.) Four stations recorded the Alonsa fireball and the time was recorded by the detector at station H.

As shown in figure 2, eight fragments are discernible on the photograph from camera J2, some of them at least five magnitudes fainter than the main piece but all surviving to heights of 25 km or less. Some wake appears at a height of 65 km followed by signs of fragmentation near 61 km, with continuously observable fragmentation below 47 km, reaching what appears to be peak activity at 29 km.

The fireball approached from the southwest but the fragments encountered a moderate crosswind from the northwest during the dark flight. The wind was apparently sufficient to stop the northerly component of motion, so the fragments were heading southeast before striking the ground. The impact area is rather sensitive to the assumed mass and to possible errors in the interpolated wind data. The position quoted above is for a 1.2 kg fragment, the best estimate for the main mass. A 5-kg mass should have landed nearly 4 km to the north while a 300-gram piece should have landed 2.5 km to the south. A search team spent three days in the area from May 11 to 13, 1977, and covered about 3 km^2 of ploughed fields and pastures, representing perhaps 10 per cent of the potential area of fall. Much of the area is densely covered with small trees and shrubs and could not be searched.

Nevertheless, there is no doubt that numerous fragments survived, so there is a chance one or more pieces might be located in the future.

No. 204 Findlay, Manitoba 1975 November 13 100° 47′.6 49° 36′.8

The two photographs suffer from excessive range to the fireball and from a very poor angle of intersection between the trails as seen from these stations. Nevertheless, it is clear that this is a much more interesting event than the photographs would indicate. In spite of the great range, there is some wake visible between heights of 55 and 43 km, possibly owing to fragmentation. The impact area is between Oak Lake and the highway from Reston to Souris, in farming land that includes some small lakes. A moderate headwind would tend to elongate the ellipse of fall with small fragments landing well to the southeast of large ones. An educational campaign among local residents might locate this object, one of the larger predicted falls from the MORP network.

No. 276 Langenburg, Sask. 1976 December 20 101° 39′.1 50° 47′.6

The sky contained scattered clouds during the exposures that recorded this fireball. The time is known relatively poorly and it is possible that the fireball was actually brighter than estimated if it was partially obscured by cloud. There is a modest wake between heights of 61 and 51 km but no definite signs of fragments. The moderate headwind would extend any ellipse of fall (to the south) more than would otherwise be expected. The impact area is about 6 km SE of Langenburg in an area that would permit a search to be attempted.

No. 626 Swan Plain, Sask. 1980 November 25 101° 51′.4 52° 06′.5

This modest fireball appears to have conserved its mass very well, much like the Ridgedale object (no. 545). There is no evidence of wake or fragmentation although the evidence could be obscured by moderate sky fog on both films. The impact area is about 14 km east of Swan Plain, in wooded country near the southern edge of the Porcupine Hills, but it is noted that the bush has been cleared for farming only 2 km east of the predicted position.

No. 840 Foam Lake, Sask. 1982 December 12 103° 32′.8 51° 37′.2

This very bright fireball is one of the four MORP meteorite candidates with a high orbital inclination, more than 30°. Some wake appears at a height of 66 km and a strong wake from 62 to 57 km probably includes some trailing fragments. Much later in the trail, between 40 and 33 km, a secondary fragment is also visible. The low terminal velocity indicates the survival of a meteorite although the mass is small. A moderately strong northwest wind was enough of a crosswind to rotate the major axis of an ellipse of fall to the ENE. The ground point is in cultivated land about 3 km northwest of the town of Foam Lake, although the exact location is sensitive to the small predicted mass and the nature of the wind.

No. 341 Qu'Appelle, Sask. 1977 November 16 103° 51'.6 50° 26'.3

This slow fireball had a unique light curve, appearing at peak luminosity followed by a considerable drop in intensity before staging a substantial recovery. A flare at a height of 50 km indicates some fragmentation with a major fragment visible from 49 to 40 km. The dynamic mass is large for the modest photometric mass, relatively high survival being aided by the low initial velocity. A moderate westerly wind would deflect smaller pieces to fall to the ESE of the predicted impact point, some 10 km south of the Trans-Canada Highway at Qu'Appelle.

No. 345 Weyburn, Sask. 1977 November 22 104° 00'.8 49° 39'.9

Neither observing station was close to this fireball so details of wake or fragmentation are obscured. There is a slight wake accompanying an early rise to peak brightness at 64 km height and two later ripples in the light curve may reflect modest fragmentation events. A moderately strong west wind was precisely a tailwind and should keep small fragments near the main piece, which itself is quite small. The impact area is 11 km due west of Weyburn, in open agricultural land.

No. 872 Sidney, Montana 1983 July 12 104° 07'.6 47° 46'.6

Local thunderstorms prevented observation of this spectacular fireball near the event itself but it was recorded from two stations in Saskatchewan where the sky was intermittently clear. Presumably because of the great range from the stations there is no evidence of wake or fragmentation but both photographs show a substantial drop in luminosity for 0.5 sec between heights of 33 and 30 km, just before peak intensity. This peak may be an indication of some major fragmentation.

The total luminosity, end height and terminal mass place the Sidney event among the three or four largest events observed by the network. There was only a modest westerly wind which would indicate smaller pieces should land to the south of the main mass and the ellipse of fall should be smaller than normal because of the rather steep path. The search area is in the valley on the western side of the Yellowstone River and on the grassy hillside marking the western limit of the valley, about 8 km NNE of Sidney and only 6 km west of the Montana-North Dakota border. The valley is cultivated intensively with numerous small, irrigated farms while the hillside is used for grazing cattle. A two-man team spent three days in the area during April 1984, showing meteorite specimens to many of the local residents. It would be useful to revive the local awareness of this meteorite fall from time to time.

No. 545 Ridgedale, Sask. 1980 February 6 104° 17'.6 53° 04'.2

Recovery of a meteorite from the Ridgedale event would be the most important discovery among all the meteorite falls described in this paper. It has been shown

(Halliday 1987) that the orbit was essentially identical to the Innisfree orbit and the meteoroid must have been another fragment from the same source. Various questions of considerable interest might be answered if the Ridgedale object could be found.

Like Innisfree, the atmospheric path was steep and the tailwind would carry smaller pieces further along the path, reversing the normal distribution of fragment sizes. The fall area should be small compared with that of Innisfree. The photographs reveal some normal wake between 56 and 46 km height but, in marked contrast to Innisfree, there is no clear evidence of fragmentation.

The search area is in good agricultural land about 10 km west of Ridgedale. Preliminary search efforts in 1987 by staff of the University of Saskatchewan suggest the object may have been obscured by ploughing but further searches are intended in the hope that it may be returned to the surface.

No. 018 Nokomis, Sask. 1971 August 18 105° 07′.8 51° 32′.4

The Nokomis fireball was photographed at 8 of the 12 stations and led to the first major search from the MORP network. Fragmentation is evident near 59 km with a major fragment visible at 41 km and two pieces trailing the main mass between heights of 33 and 29 km. A gentle westerly wind would tend to move small pieces southeast of larger ones with the main piece expected to fall about 8 km northwest of Nokomis. Although the predicted mass is small, this should be ideal terrain for a possible recovery.

No. 189 Middle Lake, Sask. 1975 September 14 105° 11′.7 52° 32′.2

This long-enduring fireball began near the middle of the camera network and followed a northeasterly path somewhat to the east of Saskatoon. It remains one of the better possibilities for a meteorite recovery in the future. Nine of the 12 MORP stations recorded the fireball, more than for any other of the thousand fireballs photographed. The most distant of the stations (Vegreville, Alberta) was at a range of 450 km from the fireball.

At a height of 64 km the Middle Lake fireball brightened dramatically and maintained essentially peak luminosity between heights of 60 and 37 km. There is considerable wake between the segments of the trail in the 64 to 54 km height range with an indication of trailing fragments near 60 and again at 54 km on all but the most distant cameras. The overexposed images at the closest stations show a slight flicker, at a frequency near 60 Hz, in the light production between 56 and 51 km, an indication that the meteoroid is oscillating (Halliday 1963, 1988). The closest station to the endpoint, near Watson, Sask., shows a slight wake late in the trail between 37 and 31 km, probably caused by small fragments although major fragmentation is not apparent at any point on the trail.

The predicted impact point is in the southern tip of Middle Lake, in the portion that frequently dries up. The search area extends several km into farmland to the

SSW from the position shown above, because of the combined effects of the relatively flat path and a moderate crosswind from the NW. A 230-gram object, for example, would have a predicted impact point at 105° 12′.6 W., 52° 30′.7 N. An educational campaign was conducted among local residents but would be worth repeating.

No. 331 Holdfast, Sask. 1977 October 25 105° 19′7 50° 57′.3

This is one of the most interesting of all MORP meteorite events since it is the only expected meteorite fall of a substantial mass from an Aten-type object. These are the rare objects with orbits smaller than that of the Earth. The Holdfast event occurred very near the aphelion point of its orbit where the geocentric velocity is very low, allowing the Earth's gravitational attraction to increase the probability of a collision.

A moderately strong wake is observed between the meteor segments from 59 down to 51 km height. Definite fragments appear at 42 km and are prominent between 39 and 37 km, with another one visible at 34 km in spite of the low velocity of the main mass which is below 8 km sec^{-1} at this point. The predicted impact point is in farm land about 6 km east of Holdfast. A headwind from the west would elongate the ellipse of fall for the observed fragments, so that an object with half the mass of the main mass would be expected to land about 3 km east and 0.5 km north of the largest piece. This interesting event deserves a continued attempt to recover at least one of the fragments.

No. 888 Crane Valley, Sask. 1983 July 23 105° 31′.9 49° 40′,1

Bright moonlight and evening twilight combined to produce considerable sky fog on the films from the six stations that recorded this bright fireball. The segments of the trail are generally quite clean with wake visible between 66 and 58 km and again from 43 to 40 km, the latter possibly indicative of small fragments. The impact area is 10 km south of Crane Valley in farming land and the moderate wind from the west would rotate the axis of the ellipse of fall to the NNE. An educational campaign was conducted among local residents shortly after the event.

No. 364 Craik, Sask. 1978 March 30 106° 00′.3 50° 57′.5

This is the slowest fireball recorded by the MORP network, barely above the Earth's escape velocity, with a small, low-inclination orbit. It was recorded at three camera stations but all suffered from scattered cloud near the time of the meteor so the brightness and photometric mass are quite insecure. At this velocity the photometric mass is especially sensitive to the contribution to the luminosity due to deceleration rather than ablation. The high ratio of photometric to dynamic masses in the table suggests that the photometric and initial masses may be seriously overestimated due to these effects.

There is minor fragmentation visible between 53 and 48 km height. The wind was from the direction of the radiant. Considering the modest zenith distance, the spread of fragments on the ground should be less than normal. The impact area is 15 km southwest of Craik, quite possibly in the valley created by Iskwao Creek.

No. 261 Old Wives Lake, Sask. 1976 November 1 106° 04′.3 50° 07′.9

A small meteorite appears to have landed in Old Wives Lake, possibly on ice if the lake was already frozen.

The slow fireball was observed through very poor sky conditions that revealed trailed images of the moon and only one or two stars. From these trails, the bolide must have been brighter than $M_{pan} = -5.4$, possibly much brighter. The impact area is in the western portion of the lake, about 3 km from the northern shoreline, but the lake level is quite variable. Because of several dry years, the level in 1988 is extremely low and the impact area may even be exposed, possibly permitting a search. A moderate crosswind from the west would deflect smaller fragments progressively more to the east of the path, so small pieces may generally lie to the south or SSE of the prime impact area.

No. 498 Allan, Sask. 1979 October 19 106° 04′.4 51° 48′.9

This long, slow fireball on a rather flat path, probably dropped a small meteorite. Very good sky conditions at station G permitted the meteor to be photographed while still quite faint. Below a height of 64 km there is continued fragmentation with minor maxima and minima in the light curve. Major fragments are seen from 60 to 58 km and at all points below 53 km. The trail runs off the edge of both cameras near 43 km but the meteor had faded so much it is likely that very little observable trail was missed.

A modest wind from somewhat south of west was almost precisely a tail wind, but the gentle slope of the path still produces a long narrow ellipse of fall. The expected impact point is 9 km south and 2 km west of Allan. A fragment of half the predicted main mass would be displaced 4 km to the WSW. Criteria that use the ablation and fragmentation history of a fireball to distinguish between irons, normal stones and carbonaceous chondrites suggest that this is the most probable MORP object for the survival of a carbonaceous chondrite, so it is unfortunate that the impact prediction is inferior owing to the flat path. The area is in farmland on the northern edge of the Allan Hills.

No. 886 Kenaston, Sask. 1983 September 7 106° 17′.6 51° 28′.2

Four camera stations recorded this fireball, although it was not among our brighter meteoritic events. The closest station revealed a faint wake between heights of 66 and 43 km, possibly indicative of minor fragmentation. Late in the trail there is a pronounced flicker with a frequency of about 40 Hz, attributed to oscillation of the meteoroid. The wind was a tailwind, which should reduce the spread of fragments on the ground. An educational campaign and a brief search were conducted in April, 1984 in the impact area, 4 km southwest of Kenaston. The area is cultivated land and further efforts to locate the meteorite would be warranted.

No. 565 Neville, Sask. 1980 July 1 107° 39′.6 49° 50′.4

The photographic trail runs off the edge of the camera field at the nearer station so details of the final second of trail depend on the more distant station. This may account for the apparent lack of fragmentation, except for the hint of one small piece at 52 km height. Winds were quite light and from the west but sufficient to move a smaller 300-gram piece to a predicted location 800 metres due south of the main piece. The expected ground point for the main piece is about 14 km south of Neville, in open agricultural land.

No. 672 Savoy, Montana 1981 April 18 108° 26′.2 48° 30′.3

This is the smaller of two significant events in Montana that were recorded by the MORP network. Although there is no sign of fragments on the photographs, a minor flare just before the end of the trail may well indicate a fragmentation event. The impact area is in cattle-grazing range land, about 9 km NE of the small settlement of Savoy. A westerly wind would tend to rotate the ellipse of fall so that the axis would lie in a NNW-SSE direction.

No. 172 Edam, Sask. 1975 April 11 108° 38′.2 53° 13′.9

This fireball was quite distant from all three stations where it was recorded which may explain the lack of any observable fragments. The atmospheric path is steep and the modest wind was from slightly north of west. Smaller fragments would tend to fall to the east of the main mass. The impact area is about 10 km northeast of Edam in a partially wooded area between two small lakes, but much of the area would be suitable for a search.

No. 511 Claydon, Sask. 1979 November 20 108° 52′.4 49° 09′.9

The radiant for this fireball was very close to the zenith, which may account for the apparent survival of a small meteorite from a small initial mass. Fragmentation begins near a height of 54 km and its effects are visible down to about 36 km. The nearly vertical path should reduce the uncertainty in the impact position due to drag, while a light westerly wind might move smaller pieces to land east of the prime location, which is 5 km south of Claydon. Although the estimated mass is small, other factors are favourable for a possible recovery.

No. 303 Edgell, Sask. 1977 April 15 108° 58′.4 49° 40′.0

The photographs of this fireball show a moderate wake between 56 and 48 km and suggest that two very nearly equal fragments travelled close together below 40 km and each probably survived as a small meteorite. A very light wind from south of west was a crosswind and the impact area is in elevated range land, with a few cultivated fields, about 18 km south of Edgell. Although the predicted masses are small, the area might be very suitable for a search at some seasons when growth is negligible.

No. 195 Coleville, Sask. 1975 September 26 108° 58′.9 51° 41′.0

Although this object was fast for a meteorite, it decelerated to a low velocity and at least three small fragments probably survived. There is considerable fragmentation between 67 and 60 km and again between heights of 38 and 33 km where three distinct pieces are visible. A light westerly wind would rotate the axis of the ellipse of fall to approximately a NW-SE direction. The impact area consists of farms, some 18 km east and 3 km south of the town of Coleville.

No. 884 Great Sand Hills, Sask. 1983 August 29 109° 04′.0 50° 33′.1

A small meteorite appears to have survived from this modest fireball, probably because of its very low entry velocity. Some fragmentation appears near 50 km and is more pronounced between 42 and 40 km height. Hazy sky conditions make the photometric estimates more uncertain than normal.

The location of the fall is in the Great Sand Hills, perhaps the most interesting landscape of any potential MORP search. The area is extremely dry with sparse vegetation, although it does support a few cattle and many deer. There are no surface rocks and a dark meteorite would be quite visible in most locations. Hills in the predicted impact area are smaller than elsewhere, typically a few metres in height although they may be quite steep with scrubby bush on the northern slopes. At the time of the fall a modest tailwind from the southwest would reduce the scatter among individual fragments. A two-man search team spent two days in the area in April 1984, including a search from a light aircraft flying about 25 metres above ground level. The area is frequented by hunters in the fall and it is possible the meteorite might be located in the future.

No. 288 Primrose, Sask. 1977 February 17 109° 16′.5 55° 14′.6

Although five camera stations recorded this slow fireball, all were far to the south of its easterly path. There is some normal wake between 59 and 55 km but no evidence of fragmentation, although the large distance would reduce the chance of recording small fragments. There can be no doubt that a substantial meteorite survived and it is interesting to note the fireball was on the same day that the first piece of the Innisfree meteorite was recovered. Unfortunately, the Primrose event was in northern bush country, within the Primrose Lake military range, and the chance of any recovery is slight.

No. 751 Maple Creek, Sask. 1981 November 23 109° 19′.0 50° 01′.1

This fireball showed very little wake and no clear evidence of fragmentation. The path was steep and the solution indicates the end point of the luminous trail is located with abnormal precision. A modest westerly wind was approximately a tailwind but sufficient to move smaller pieces to land northeast of the predicted main mass. The impact point should be well determined for such a small meteorite, about 17 km northeast of Maple Creek and 4 km north of the Trans-Canada Highway. An educational campaign and search are recommended to locate this object.

No. 346 Consul, Sask. 1977 November 22 109° 31′.7 49° 16′.7

The path of this object was very nearly vertical so the duration was quite short. Both photographs suffer from sky haze but there is some evidence of at least minor fragmentation between 52 and 47 km height. The impact area is 2 km SSW of Consul, in farmland south of Battle Creek. A moderately strong westerly wind would disperse smaller fragments to the east of larger ones.

No. 207 Cypress Hills, Sask. 1975 November 16 109° 33′.3 49° 35′.2

This bright object fell on a steep atmospheric path and decelerated smoothly without noticeable fragmentation. A modest wake appears between 62 and 53 km. The westerly wind would compensate for the gently sloping path so any fragments should not be widely dispersed. The impact area is in hilly country about 6 km south of Cypress Hills Provincial Park, but the area would be suitable for a search since the only wooded parts are in the narrow valleys.

No. 174 Whelan, Sask. 1975 May 10 109° 37′.5 54° 07′.5

A visual observer near Saskatoon described the fireball as bright green and breaking into three pieces. The photograph from station C exhibits fragmentation below 38 km. The predicted impact point is in bush country about 12 km northwest of Whelan, although air photographs indicate numerous clear areas, probably meadows, throughout the bush.

No. 930 Golden Prairie, Sask. 1984 February 8 109° 38′.5 50° 09′.6

This fireball was relatively close to two camera stations, with a visible wake between 59 and 55 km height and one or more trailing fragments from 52 down to 40 km. The search area is mostly cultivated land, about 7 km south of Golden Prairie. The wind appears to have been light, from the northwest, so smaller fragments should lie to the west of larger ones. Local residents were shown meteorite samples and a modest search was conducted, but there remains a reasonable chance for a recovery in this case.

No. 897 Mudie Lake, Sask. 1983 October 27 109° 40′.7 54° 10′.0

This fireball approached from the north at very low elevations as seen from the two camera stations. The great range would obscure most evidence of wake or fragmentation and none is visible. A moderately strong westerly wind would push small fragments to the east so that any ellipse of fall might be oriented slightly east of north whereas the radiant was somewhat west of north. The impact area is in bush, 3 km southeast of the southerly tip of Mudie Lake and only 8 km northwest of the impact point for the Whelan event. It is unlikely that meteorites will be found from either event but the separation is probably sufficient to avoid confusion in identification.

No. 223 Manito Lake, Sask. 1975 December 16 109° 42′.3 52° 42′.7

One of the most luminous objects photographed by the MORP cameras, the Manito Lake fireball appeared during bright morning twilight. The sun was only 8° below the horizon at the two stations in Alberta that secured photographs. The Lousana station was at a greater distance but had more transparent sky conditions than Vegreville, although the trail at Lousana was divided between two cameras with a loss of 2 seconds of trail between them. Weak trails of the very brightest stars enabled photometric comparisons to be made. There is a moderate wake between heights of 67 and 50 km but no clear evidence for separate fragments.

Many visual observations were reported from Edmonton and at least one observer confirmed the fireball was still luminous after crossing into Saskatchewan, beyond the range of the photos. The velocity on entry into the atmosphere was near the upper limit for survival of a meteorite, but a small fraction of the entry mass survived to such low velocities that a meteorite fall is indicated. There was a rather strong tailwind in the upper atmosphere (3 to 20 km height) which would tend to reduce the spread of fragments along the path. The predicted impact point is on the shore of one of two major points that project out from the south shore of Manito Lake. A light aircraft was used to search the winter ice of the lake not long after the fall and a ground search was conducted before spring breakup but no meteorites were located. Further ground searches on the peninsulas and southern or southeastern shores of the lake might be productive.

No. 977 Altario, Alberta 1984 November 20 110° 10′.6 51° 53′.6

A fireball of short duration but essentially vertical path penetrated quite deep into the atmosphere without any sign of appreciable fragmentation. There is a slight wake discernible all along the trail. A moderate westerly wind would move small pieces to land east of larger ones. The impact area is 3 km southwest of Altario and a brief educational campaign was conducted in the area.

No. 285 Innisfree, Alberta 1977 February 6 111° 20′.2 53° 24′.9

The Innisfree meteorite fall (an LL5-6 chondrite) is included here for the sake of completeness. Details of the extensive atmospheric fragmentation were well recorded by the nearer of the two camera stations. The terminal mass in the table is the recovered mass of the largest fragment; a total of 4.58 kg was recovered in nine separate masses. The steep path with a modest tailwind confined the fragments to a maximum separation of 1 km and, as reported previously, it is believed that all major fragments were recovered. Small fragments, less than 100 grams, might well remain undiscovered. The cultivated soil contains many grey stones, however, and weathered chondritic material might not be easily recognized.

No. 580 Fork Lake, Alberta 1980 September 1 111° 37′.9 54° 26′.3

The Fork Lake fireball had the second longest duration of any event recorded by the MORP network, 18 seconds in flight in spite of the great distance of all four camera stations from the object. The path was, of course, quite flat for such a long duration to be possible and the light curve showed a long, broad maximum. Fragmentation is observable below 37 km height and at times it is quite severe. Two subsidiary fragments are observed almost to the end, in spite of the great range, so we must be dealing with an ellipse of fall containing at least several pieces.

The expected landing site for the main mass is about 4 km southwest of the most southerly tip of Fork Lake, near the southern bank of the Beaver River. The separation of fragments by size is likely to be severe, because of the flat path; for example a 2.5 kg piece would be expected to fall 9 km northwest of the main piece. Although the radiant direction is essentially WNW, the westerly wind would move small pieces further east than normal, partially offsetting the increased drag and rotating the expected direction of the axis of the ellipse of fall to a NW-SE direction. There is considerable farming in this area and an educational campaign was conducted among local residents.

No. 654 Wavy Lake, Alberta 1981 January 13 111° 56′.0 52° 54′.8

This appears to be the least luminous of all the events described in this paper. Two stations were close to the fireball and the closer one showed the trail beautifully, near the centre of the field among the stars of Orion. There appears to be some fragmentation from 48 to 46 km and below 37 km there is a subsidiary fragment accompanying the main one. Although the mass is small, the low end velocity indicates some material survived, presumably from both fragments. The wind was from the WNW, somewhat north of the radiant direction, which would carry the predicted main mass to a point 9 km east of the northern tip of Wavy Lake, in farmland well suited to a search. Smaller pieces would fall to the southwest of larger ones.

No. 687 Vauxhall, Alberta 1982 January 16 112° 07′.9 50° 01′.6

This long-enduring fireball was photographed from only two stations that happened to be nearly coplanar with the fireball path, so much calculation was done by hand, based on matching details of the light curve. Minor fragmentation occurred between 54 and 44 km height with a more pronounced fragment visible from 33 to 31 km. The impact area is 5 km SSW of the town of Vauxhall, in agricultural land. A rather strong wind from slightly north of NW would reduce the spread of fragments along the ground and would likely align the ellipse of fall almost due west to east. A search was conducted in the area, particularly on the ice of a reservoir 3 km west of the prime area, and meteorite samples were shown to local residents.

No. 171 Endiang, Alberta 1975 April 2 112° 13′.4 51° 53′.6

A rather minor event probably dropped a small meteorite about 10 km southeast of the search area for no. 123. There is a slight wake near 53 km height but no clear evidence of fragments. A modest wind from the WNW was approximately a headwind. The predicted landing area is 9 km southwest of Endiang.

No. 123 Byemoor, Alberta 1974 August 12 112° 20′.2 51° 57′.1

The fireball was close to station D but ran off the edge of the camera field shortly before its end. Peak brightness was near 51 km with a major fragment visible between heights of 53 and 42 km and a lesser fragment at 40 km. The atmospheric winds were exceptionally calm. The impact area is about 5 km southwest of Byemoor in an area with numerous sloughs (ponds) that may dry up completely in some years.

No. 231 Meeting Creek, Alberta 1976 February 4 112° 38′.7 52° 41′.9

This fireball is the fastest of all those believed to have dropped a meteorite of at least 100 grams. Some normal wake begins at a height of 82 km and is quite intense between 63 and 60 km, possibly due to a mixture of fragments and coasting gas. The predicted impact point is 6 km ENE of the village of Meeting Creek, just south of two small lakes in agricultural land. It is only 11 km southeast of the much larger Edberg object which fell exactly four years later. A modest wind from the north combined with the rather flat path would elongate any ellipse of fall and rotate its major axis to a direction south of southeast.

No. 544 Edberg, Alberta 1980 February 4 112° 46′.6 52° 45′.0

This is one of the better candidates for further searches. The closest of the three camera stations recorded at least three stages of fragmentation, from 58 to 50 km, 33 to 31 km and again at 28 km. The major surviving fragment is estimated to be among the five largest observed by the network. The wind was perhaps less than normal in intensity from somewhat north of the direction to the radiant, so the fragments should not be too widely dispersed. The impact area is in agricultural land 4 km south of Edberg where a local educational campaign was undertaken after the fall, but renewed efforts would be justified.

No. 683 Lacombe, Alberta 1981 July 6 113° 49′.2 52° 29′.2

Three stations recorded this fireball but the closest one observed only a short trail through a break in heavy clouds. There is some wake beginning as high as 66 km and the close station confirms fragmentation near 56 km. There is a further suggestion of fragments from 39 to 37 km and an irregularity in the light production is suggestive of repeated minor fragmentation. Most of the mass has been consumed in this activity but a small residue appears to have survived to land about 6 km northwest of Lacombe, in excellent farming land. A moderately strong wind from the southwest was nearly a tail wind so the dispersion of fragments on the ground should not be excessive.

No. 925 Grande Prairie, Alberta 1984 February 23 119° 11′.0 54° 56′.3

The record for long duration of a MORP fireball is the Grande Prairie event which lasted for somewhat more than 30 seconds. Only the first 17 seconds were recorded by the camera network but visual reports were combined with the photographic data to reconstruct the entire trail (Halliday 1985). As far as we are aware, this is the longest duration of any fireball photographed in Canada and it is comparable with the event of 1966 April 25 which began over Virginia and ended southwest of Montreal (McIntosh and Douglas 1967, Griffin 1968). The earlier paper on Grande Prairie documents the presence of wake and moderate fragmentation as recorded by the photographs while the visual observers described a major fragmentation late in the trail, near a height of 30 km.

The large photometric mass shown in Table I exceeds the earlier estimate by a factor of 2.3. The smaller value was based on a dynamic mass at a height of 49 km and then extrapolated back to the beginning using a higher luminous efficiency than adopted in this paper. The discrepancy is only partially explained by the differing assumptions for luminous efficiency. Other factors could be difficulties in the photometric estimates, more severe fragmentation between heights of 40 and 30 km than was inferred from the visual data, or an unusually thin shape for the meteoroid which would make the dynamic mass estimate less than the true value.

A fast fireball on a flat trajectory suffers severe ablation so the surviving meteorites from the Grande Prairie fireball are probably only 1 or 2 percent of the initial mass. Meteorites between 1 and 10 kg probably landed southwest of Grande Prairie and small fragments may have survived considerably to the east. Large meteorites would be inconsistent with visual observations of the fragments. A 5-kg meteorite would be expected to land 4 km southwest of the hamlet of Wapiti or 36

TABLE III
DATES AND LOCATIONS FOR 12 OTHER EVENTS

No.	*y*	*m*	*d*	*h*	*m*	λ		φ		m_t
937	84	06	04	06	32	97°	36′.4	51°	27′.2	0.38
313	77	07	06	06	14	99	49.5	52	33.6	0.27
503	79	11	12	07	16	107	42.3	54	25.0	0.24
245	76	06	21	07	57	109	03.4	51	53.2	0.12
268	76	12	10	02	00	109	06.2	53	49.7	0.25
669	81	03	31	05	56	109	13.0	53	20.4	0.12
844	82	12	15	05	01	110	06.1	54	07.3	0.27
205	75	11	12	05	20	111	24.2	54	10.3	0.12
771	81	12	31	11	35	111	38.8	53	20.0	0.16
299	77	04	06	09	37	115	35.6	52	26.7	0.16
567	80	07	06	09	25	116	03.3	53	37.2	0.27
219	75	12	12	04	48	116	08.0	52	16.0	0.11

km southwest of Grande Prairie. Owing to the modest headwind and the flat trajectory, a 1-kg object would land 13 km east of a 5-kg piece, so we expect the meteorites to be spread out in a long narrow band whose latitude is rather well determined. The prime area is partly agricultural land and more bush is being cleared for agriculture. At least two search campaigns have been conducted but there remains a chance that one or more pieces of this exciting object may still be found.

Table III lists the MORP number, time of appearance, terminal mass, m_t (kg), and the expected impact location (λ, φ) for the remaining 12 fireballs omitted from Table II because of a poor chance of recovery. Displacements due to wind have been included in the dark-flight calculations in each case. Essentially all the parameters in Tables I and II plus the orbital data will appear in future lists of MORP data, so if a meteorite should be recovered and associated with a fireball in Table III, the pertinent data could still be located. This table is also arranged in order of increasing west longitude.

4. *Orbits*. Tables IV and V present the orbital data for the fireballs in Tables I and II respectively. Successive columns list the MORP number, the semi-major axis of the orbit in AU; the eccentricity; the inclination of the orbit to the ecliptic; the perihelion distance, q, and the aphelion distance, q', in AU; the argument of perihelion, ω, defined as the angular distance in degrees from the ascending node to the perihelion point, measured in the orbit plane in the direction of motion; the longitude of the ascending node, θ, measured eastward in the ecliptic from the First Point of Aries. The final column indicates by an A or D whether the meteoroid was at the ascending or descending node of its orbit when it encountered the Earth.

TABLE IV
ORBITAL ELEMENTS FOR OBJECTS IN TABLE I

No.	*a*	*e*	*i*	*q*	*q'*	ω	θ	A/D
123	1.98	0.558	3.1	0.875	3.08	231.6	138.9	D
172	1.27	0.236	5.1	0.970	1.57	213.5	20.4	D
174	2.05	0.555	19.9	0.913	3.19	137.0	48.8	D
189	1.93	0.518	1.5	0.928	2.93	39.3	350.5	A
204	1.12	0.205	7.2	0.890	1.35	66.0	49.8	A
207	2.39	0.638	11.0	0.865	3.91	227.3	232.9	D
223	2.51	0.798	7.2	0.506	4.51	275.4	263.6	D
261	1.70	0.415	0.8	0.992	2.40	357.7	38.6	A
276	1.58	0.483	31.1	0.819	2.35	241.0	268.0	D
285	1.87	0.473	12.3	0.986	2.76	178.0	316.8	D
288	1.76	0.438	1.0	0.987	2.53	184.7	328.0	D
307	1.51	0.563	11.9	0.661	2.36	267.4	40.5	D
331	0.757	0.338	3.2	0.501	1.01	18.5	211.7	D
341	1.66	0.411	2.4	0.976	2.34	17.3	53.2	A
364	1.17	0.162	1.5	0.984	1.36	153.1	8.7	D
544	2.15	0.560	3.0	0.947	3.35	27.4	134.3	A
545	1.87	0.475	12.3	0.984	2.76	186.7	316.0	D
565	1.01	0.140	11.7	0.868	1.15	281.9	99.3	D
580	2.45	0.591	6.5	1.000	3.90	167.4	158.6	D
626	2.26	0.567	1.2	0.980	3.54	191.8	242.4	D
672	2.29	0.563	5.4	1.001	3.58	172.6	27.8	D
687	2.11	0.577	11.1	0.892	3.32	138.3	295.2	D
792	2.46	0.608	15.4	0.966	3.96	150.5	79.6	D
872	2.28	0.566	7.9	0.991	3.57	201.6	108.9	D
886	1.90	0.494	3.8	0.962	2.84	210.2	163.7	D
897	2.32	0.579	36.4	0.977	3.66	162.7	212.9	D
925	1.93	0.733	8.4	0.515	3.35	97.6	153.2	A
930	2.02	0.520	2.7	0.971	3.07	17.3	138.4	A

At the moderately high northern latitude of the camera stations, most of the sky is north of the ecliptic so most radiants are also on the northern side, i.e. collisions with the earth are usually at the descending node.

The uncertainty, E, in the time of appearance may produce significant changes in the orbit since it corresponds to a shift in the right ascension of the radiant with a corresponding change in the direction from which the meteoroid is assumed to have approached the earth. To investigate the problem, two additional orbit solutions were calculated whenever E exceeded $\pm 30^{m}$, one for the beginning and one for the end of the interval of uncertainty. The results are shown in Table VI which includes objects from both Tables IV and V.

The differences between the elements in Tables IV and V from those found in

TABLE V
ORBITAL ELEMENTS FOR OBJECTS IN TABLE II

No.	a	e	i	q	q'	ω	θ	A/D
018	2.42	0.655	3.7	0.833	4.00	236.4	144.3	D
171	1.19	0.444	3.9	0.661	1.72	275.9	11.6	D
195	2.04	0.740	4.2	0.531	3.55	96.1	2.2	A
231	1.48	0.715	17.4	0.423	2.54	111.7	134.1	A
303	2.29	0.562	8.1	1.003	3.57	176.6	25.0	D
345	1.33	0.469	5.3	0.705	1.95	264.0	239.6	D
346	1.60	0.443	11.5	0.892	2.31	226.8	239.4	D
498	2.07	0.530	1.9	0.972	3.16	158.3	204.7	D
511	2.58	0.623	19.5	0.973	4.19	196.4	236.7	D
654	2.61	0.625	2.9	0.979	4.24	189.2	292.5	D
683	1.49	0.483	7.8	0.769	2.20	255.4	103.8	D
751	2.31	0.590	21.0	0.945	3.67	207.7	240.3	D
840	1.65	0.407	35.3	0.981	2.33	189.6	259.7	D
884	1.69	0.404	2.8	1.009	2.38	175.2	154.8	D
888	1.11	0.397	39.5	0.668	1.55	78.1	119.4	D
977	2.98	0.732	22.3	0.797	5.16	237.1	237.6	D

"early" and "late" solutions were averaged and this maximum error due to uncertain time of appearance is indicated as a percentage of the quantity itself for a, e, q and q'. For i and ω the table shows the uncertainty in degrees.

Let us examine the uncertainty in each element due to large values of E. Only five entries appear to have a serious problem with the semi-major axis. There is no single cause, but the worst case (no. 231) is associated with the smallest perihelion distance. This orbit is poorly defined since the uncertainty in a is reflected in uncertain values of both q and q'. The eccentricity is usually well defined with two of the larger percentage uncertainties associated with unusually small values of the eccentricity itself. The perihelion distance, q, is well determined for the large proportion of meteoritic objects with perihelion not far inside the Earth's orbit. Thus q is not a problem even for no. 897 which has a high inclination and rather large aphelion distance. The larger (percentage) uncertainties in q are again associated with the smaller values of this quantity.

The aphelion distance, q', is quite sensitive to errors in the velocity of arrival, especially for moderately fast meteoroids, but here we are considering only the sensitivity to the time of appearance. Table VI suggests it is also the least reliable element due to this uncertainty. On the other hand, the inclination is very insensitive to a timing error and exceeds 1° only in the case of orbits with exceptionally high inclinations.

The argument of perihelion, ω, specifies the orientation of the major axis of the

TABLE VI
ORBITAL UNCERTAINTIES DUE TO LARGE E

No.	Δa	Δe	Δq	$\Delta q'$	Δi	$\Delta\omega$
204	7	14	3	9	0.6	15
231	47	5	30	50	0.3	21
261	2	3	0	3	0.2	4
276	9	8	1	12	1.3	4
288	2	3	0	3	0.1	4
303	2	2	0	3	0.4	4
345	20	9	11	23	0.6	18
544	16	11	2	19	0.1	7
565	7	10	8	6	0.2	27
626	5	3	1	6	0.8	6
672	1	1	0	2	0.2	5
683	20	11	9	25	0.4	16
751	2	1	1	2	0.4	4
884	2	4	0	4	0.4	6
897	32	21	2	40	1.4	10
930	10	8	1	13	0.2	7
977	24	7	4	26	0.1	6

ellipse in the orbit plane. Its value will be relatively uncertain when the eccentricity is low and this correlates with small values of a (since large a implies high e for Earth-crossing orbits). A few values of $\Delta\omega$ exceed 10° for this reason. There is no appreciable uncertainty in θ, the longitude of the node, for timing uncertainties of less than an hour so this element is not included in Table VI.

5. *Association of Meteorite Finds with MORP Events*. If a meteorite is found close to one of the predicted locations of this paper, what is the probability that it is part of the MORP event or that it is from an unrelated event whose ellipse of fall happens to overlap that of the MORP event? The question can be addressed by making a few reasonable assumptions.

In a study of the frequency of meteorite falls on the Earth, the authors (Halliday *et al.* 1984) used those MORP events that were observed in clear sky conditions to derive the following relation:

$$\log N = -0.689 \log m + 2.967 \tag{1}$$

In this equation, N is the number of events per year that drop meteorites with a total mass greater than m grams in an area of 10^6 km^2. It was assumed that the total mass of each event was twice the dynamic mass derived for the largest fragment. We now assume there are five significant fragments per event and divide the total mass between them in the proportions, 0.5, 0.2, and three fragments each with 0.1 of the total mass. By calculating the actual distribution of the total masses in a range of sizes and then distributing the fragments in "bins" of increasing size, we find that the relation describing the distribution of *fragment* masses is:

$$\log F = -0.689 \log p + 3.217 \quad (2)$$

where F is now the number of fragments of mass p grams or greater that arrive per year in 10^6 km^2.

We need to adopt some value for the "search area" relating to a MORP event. There are two aspects to this problem, namely the confidence in the location of the impact point for the main mass and, secondly, the expected spread of smaller pieces with respect to the largest. Errors in the primary location may arise from less than ideal geometry of the event with respect to the camera stations, poor location of the meteor image in the field of the camera, unusual shape effects that may make the actual dark flight deviate from the flight predicted by the drag equation, and wind conditions that differ from the values found by interpolation in time and position among the meteorological records. The error is likely to increase with increasing range of the event from the camera stations, with increasing zenith distance of the radiant, with greater end height of the luminous trail and with larger than normal wind forces. Larger meteorites are less affected by wind than small ones and are also likely to be observed to lower end heights. Because of drag effects, smaller pieces in the ellipse of fall will be spread over larger areas as the zenith distance of the radiant increases and may be moved large distances by atmospheric winds.

For primary masses greater than 0.5 kg (Table I) we would expect the predicted end point to be within 2 km of the actual point if Z_R does not exceed 60°, i.e. a search area of 13 km^2, but we adopt a more pessimistic value of 20 km^2 for a general case. Unrecovered MORP meteorites have now been weathered on the ground for an average of about ten years. The condition of a new recovery should be compatible with the fall date of a MORP meteorite if it is to be attributed to the event. We assume that more than 50 years of weathering would produce noticeable effects that could usually be distinguished from more recent falls so that only falls within the past 50 years are likely to cause confusion with MORP objects.

Given the uncertainty in dynamic mass estimates, m_t, any meteorite larger than 0.5 m_t might well be the main mass from a MORP event. (Meteorites much larger than 2 m_t might be suspiciously large to be considered from the MORP event, but their inclusion adds only 50 per cent to the total number that would be within a factor of 2 of m_t.) From equation (2) the expected number of meteorite pieces that might cause confusion in 20 km^2 in 50 years, i.e. all pieces larger than 0.5 m_t, is shown in Table VII for a range of values of m_t.

To interpret Table VII, consider meteor 886 in Table I, for which a terminal

TABLE VII
CONFUSION FROM UNRELATED METEORITES

m_t	Probability of one unrelated piece larger than $0.5\ m_t$ in 20 km^2 in 50 years
10 kg	0.0047
2	0.014
1	0.023
0.5	0.037
0.2	0.069

mass of 1 kg is predicted. Any object larger than 0.5 kg may reasonably be the main mass. We expect one such mass near the location given in the description of no. 886 and the Table states that the probability that a second such mass has fallen within a 50-year interval in an area of 20 km^2 is only 0.023. Thus the recovery of a suitably-weathered meteorite within these limits from the MORP prediction should be related to no. 886 with a confidence level of 98 percent. At this size the chance of confusion by an unrelated event would still be small if an interval of 200 years was considered.

We expect lesser fragments to accompany most falls and to be distributed in an ellipse of fall. Unless the ellipse is defined by the recovery of several pieces, the search area for smaller pieces will be larger than for the main mass. If the fragment is 0.1 of the total mass the area might be three times larger, but we assumed three fragments of this size would fall in each event, so the confidence in assigning such a recovery to the MORP event remains about as shown in Table VII. The confidence is less than for a larger piece but is still essentially determined by the size of the piece without regard to whether it is a fragment from a larger fall or the main mass of a small one.

If several pieces are recovered that belong to the same fall, then the association of the fall with a particular MORP fireball is strongly reinforced if the distribution on the ground is in accord with the expectation from the radiant direction and elevation, modified by wind, as indicated in the individual descriptions. A well-defined ellipse of fall in marked conflict with expectations would render the association with a MORP event quite doubtful.

6. *Future Recovery Programs*. As indicated above in the descriptions of the individual events, we recommend that further attempts to recover meteorites should be undertaken for many of the events in Tables I and II. It could become an organized activity for Centres of the R.A.S.C. to search for some of these meteorites in their region of the prairies or it could be a project for a smaller group

TABLE VIII
EVENTS RECOMMENDED FOR FURTHER SEARCHES

(1) Southern Manitoba:	204
(2) Southern Saskatchewan:	207, 276, 303, 331, 341, 345, 346, 364, 511, 565, 751, 884, 888, 930
(3) Central Saskatchewan:	018, 172, 189, 223, 498, 545, 840, 886
(4) Southern Alberta:	123, 171, 687, 977
(5) Central Alberta:	231, 544, 654, 683

of interested individuals. In all our dealings with rural residents we have found them to be uniformly helpful and cooperative once we have explained the nature of our interest and the importance of meteorites to science. There is no point in attempting to search fields where a growing crop obscures the soil so the best times for a search are likely to be spring and fall, choosing weather conditions that are sufficiently dry to avoid heavy mud. Even at these times it is strongly recommended to establish friendly relations with the owner of the land before conducting a search, especially since the owner will then become interested in locating meteorites himself or herself.

There is a guaranteed offer by the Geological Survey of Canada (Department of Energy, Mines and Resources) of a minimum purchase price of $500 for the first piece of any new Canadian meteorite. The Geological Survey owns the National Meteorite Collection of Canada and maintains cordial relations with researchers at Canadian universities and abroad for the exchange and study of meteorite specimens. Because of their special interest, most MORP meteorites might exceed the minimum offer in value. The owner of the land on which a meteorite is found is considered to be the owner of the meteorite, so a search team can offer the possibility of this financial benefit when seeking permission to search on farming land. The actual finder, however, receives a handsome framed certificate from the Associate Committee on Meteorites of the National Research Council of Canada in recognition of his or her achievement.

Table VIII is a selected list of those events we consider to be the better choices for further search efforts. It is divided geographically into five groups consisting approximately of the areas surrounding the five major cities in the Prairie Provinces. Astronomical groups in these cities, and R.A.S.C. Centres in particular, might consider organizing educational campaigns and actual searches in these areas, although there is no reason to restrict the efforts to the local area (or to the events in Table VIII) if a group is able to travel more broadly. It would be wise to study in advance the appearance of partially weathered meteorites and to obtain meteorite brochures for distribution to residents in prime search areas. Adequate maps of the search areas are required, of course, to plot the expected locations from the coordinates given with each description.

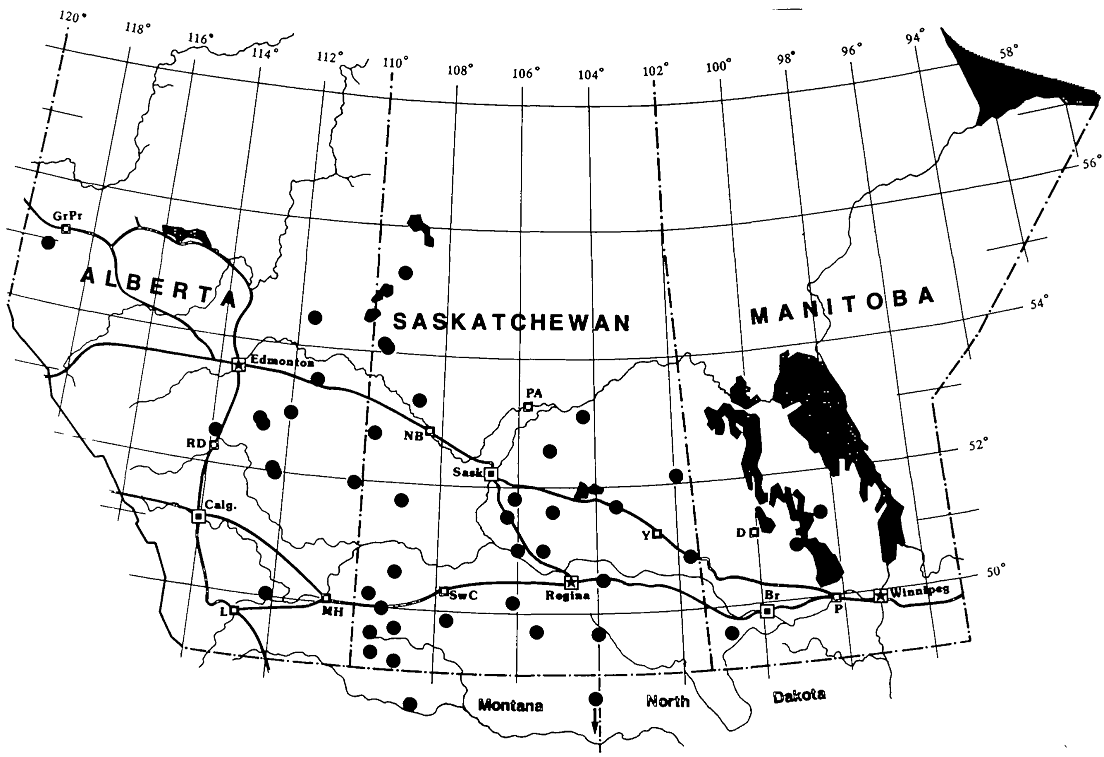

FIG. 3—Map of the Canadian prairies showing the locations of the 44 meteorite events described in this paper. There are three pairs of events for which the symbols overlap on the map, two in central Alberta and one in western Saskatchewan. The Sidney, Montana event would plot off the southern edge as indicated by the arrow. Some major highways, rivers and lakes are shown and the following cities and towns are indicated by one or more letters, in order of longitude: Winnipeg, Portage la Prairie, Brandon and Dauphin in Manitoba; Yorkton, Regina, Prince Albert, Saskatoon, Swift Current and North Battleford in Saskatchewan; Medicine Hat, Lethbridge, Edmonton, Red Deer, Calgary and Grande Prairie in Alberta.

Figure 3 is a map of the Prairie Provinces on which the locations of the 42 Canadian events described in this paper have been plotted. A few cities, highways, lakes and rivers have been indicated to assist with orientation. The distribution shows only 3 falls in Manitoba, 28 in Saskatchewan, 11 in Alberta and 2 events south of the international border, in Montana. The shape of the network and the large distance from the headquarters for service trips combined to make the coverage in Manitoba less efficient than elsewhere. The majority of the events are in Saskatchewan, with a chance concentration in the southwestern corner of the province. Although this area is remote from the major cities, there are some attractive possibilities here and it would be possible to visit several locations in a relatively short time to inform local residents of the need to be on the alert for meteorites. By chance, southern Alberta has very few possibilities although the entries in Table III show that the coverage was quite adequate for the western and northern fringes of the network where recovery conditions are poor.

Whenever a new meteorite is found in the area covered by the MORP network, a check should be made to see if it may be related to a MORP event. Since the descriptions of the events in this paper are arranged in order of increasing longitude, it is a simple procedure to check any new recovery against the events described. A check of the positions in Table III should also be made.

7. *Conclusions*. Recently fallen meteorites must exist at nearly all of the locations given in this paper for the 44 photographic events listed in Tables I and II. The data on behaviour of these objects in the atmosphere and on their orbits appear to provide the best descriptions available of the types of events that produce modest meteorite falls in the kilogram size range. Since, at the present time, only three recovered meteorites have such detailed information on both their orbits and atmospheric paths, the recovery of even one more meteorite from the MORP events would be a major addition. It is hoped that some of these meteorites will be recovered eventually, but the probability of this success will be considerably greater if astronomical groups in the region will take up the challenge!

Acknowledgements. The authors are indebted to Dr. Richard K. Herd of the Geological Survey of Canada, Ottawa, for providing Fig. 1. We thank Michael S. Webb of the Canadian Climate Centre, Atmospheric Environment Service, Downsview, Ontario, for assistance with the meteorological data required for the dark-flight calculations. We acknowledge numerous discussions with Dr. Bruce A. McIntosh and Dr. Peter M. Millman of the Herzberg Institute, both of whom also made helpful comments on the manuscript. Mrs. Denise Cardinal provided expert assistance with the computer reductions and, finally, we thank Norman Dyrvik and Eldon Hubbs for their years of conscientious service in maintaining the technical equipment of the MORP camera network.

Ian Halliday,
Arthur A. Griffin,
Herzberg Institute of Astrophysics,
National Research Council Canada,
Ottawa, Ontario,
K1A 0R6

Alan T. Blackwell,
Legal Services Office,
National Research Council Canada,
Ottawa, Ontario,
K1A 0R6

References

Folinsbee, R.E. and Bayrock, L.A., 1961, *J. Roy. Astron. Soc. Canada*, **55**, 218.
Griffin, A.A., 1968. *J. Roy. Astron. Soc. Canada*, **62**, 55.
Halliday, I., 1963, *Smithson. Contr. Astrophys.*, **7**, 161.
Halliday, I., 1985, *J. Roy. Astron. Soc. Canada*, **79**, 197.
Halliday, I., 1987, *Icarus*, **69**, 550.
Halliday, I., 1988, *Icarus*, **76**, 279.
Halliday, I., Blackwell, A.T. and Griffin, A.A., 1978, *J. Roy. Astron. Soc. Canada*, **72**, 15.
Halliday, I., Griffin, A.A. and Blackwell, A.T., 1981, *Meteoritics*, **16**, 153.
Halliday, I., Blackwell, A.T. and Griffin, A.A., 1984, *Science*, **223**, 1405.
McIntosh, B.A. and Douglas, J.A.V., 1967, *J. Roy. Astron. Soc. Canada*, **61**, 159.
ReVelle, D.O. and Rajan, R.S., 1979, *J. Geophys. Res.*, **84**, 6255.