THE MILLMAN FIREBALL ARCHIVE II: "SOUND REPORTS"

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Abstract. A total of 3878 report cards pertaining to 2131 fireball events observed from across Canada, in the time interval from 1912 to 1989, are contained within the Millman Fireball Archive. A further 410 report cards relate to 315 fireball events recorded by observers in the United States. Of these reports 153 mention the occurrence of sonic booms, 97 mention the presence of simultaneous (electrophonic) sounds, and 12 mention seismic effects. We find that the combined data suggest that sonic booms are most likely to be reported from fireballs observed in February and August, while simultaneous sounds are most often reported from fireballs observed in April and August. The generally enhanced number of sound generating fireballs reported between the months of January and April is keyed, we suggest, to the meteorite fall rate, which is also enhanced over the same time interval. We find some evidence to suggest that bright August Perseid meteoroids might produce short duration (so-called burster) simultaneous sounds. The typical reported characteristics of sound producing fireballs are found to be as follows. Of the simultaneous sound producing fireballs some two-thirds are brighter than magnitude −10; about half have durations lasting between $1 \leq D(sec) \leq 5$; about half constitute single non-fragmenting fireballs that show no obvious bursts or flares, and of those fireballs that do fragment some two-thirds break into four or more components. Of the sonic boom generating fireballs some seven-eighths of events are brighter than magnitude −10; about half have durations lasting between $1 \leq D(sec) \leq 5$; about half constitute single non-fragmenting fireballs that show no obvious bursts or flares, with some one-third of the remainder displaying just one observed burst or flare. If fragmentation does occur in a sonic boom generating fireball then some three-quarters of such events produce four or more observable fragments.

Résumé. Les archives Millman contiennent 3 878 rapports au sujet de 2 131 chutes de bolides observés à travers le Canada durant la période de 1912 à 1989. Quelques 410 comptes rendu additionnels concernent 315 chutes de bolides faits par des observateurs aux États-Unis. Parmi ces rapports, 153 mentionnent des circonstances de grondements soniques, 97 mentionnent la présence de grondements simultanés (électrophoniques) et 12 autres mentionnent des effets séismiques. Basé sur toutes ces données, nous trouvons que les rapports de grondements soniques sont plus probables durant les chutes de bolides ayant lieu aux mois de février et d'août, tandis que les grondements simultanés sont plus souvent mentionnés lors des chutes de bolides observés en avril et en août. Nous suggérons que le nombre croissant de mentions de bolides soniques durant les mois de janvier à avril est lié au taux aussi croissant de tombées de météorites durant cette période de l'année. Il nous paraît évident qu'une forte tombée des Perséides au mois d'août pourrait produire des grondements simultanés de courte durée (soit-disant éclat de son). Les caractéristiques typiques des bolides produisant des sons sont décrites comme suit : Quelques deux-tiers des bolides produisant des grondements simultanés sont plus brillants que magnitude −10 ; environ la moitié de ces cas ont une durée d'entre 1 # D(sec) # 5 ; aussi, près de la moitié sont des bolides non-fragmentés, indiquant aucun éclat ou flamboiement évident ; parmi les bolides qui se fragmentent, les deux-tiers se cassent en quatre morceaux ou plus. Quelques sept-huitièmes des chutes de bolides produisant des grondements soniques sont plus brillants que magnitude −10 ; environ la moitié de ces cas ont une durée d'entre 1 # D(sec) # 5 ; près de la moitié sont des bolides non-fragmentés sans aucun éclat ou flamboiement évident, et un tier du reste produisent seulement un éclat ou flamboiement. Si la fragmentation de bolides produisant des grondements soniques a bien lieu, les trois-quarts de ces chutes produisent quatres morceaux ou plus.

What is this sound and rumour? What is this that all men hear,
Like the wind in hollow valleys when the storm is drawing near?
— William Morris

1. Introduction

The Millman Fireball archive (MFA) constitutes a series of fireball observation records mostly gathered from across Canada in the time interval from January 1962 to October 1989, although several historical reports date as far back as 1912. The Archive is named in honour of Dr. Peter Millman who oversaw its initial organization in the early 1960s (Beech 2003; Halliday 1991). The Archive was originally maintained at the National Research Council (NRC) in Ottawa, Canada and was administered through the Associate Committee on Meteorites (ACOM), now the Meteorites and Impacts Advisory Committee (MIAC)[1] to the Canadian Space Agency.

The reasons for initiating a fireball archive in the early 1960s were to aid in the possible detection and recovery of new meteorites from within Canada. And, although not officially a part of the highly successful Meteorite Observation and Recovery Project (MORP;

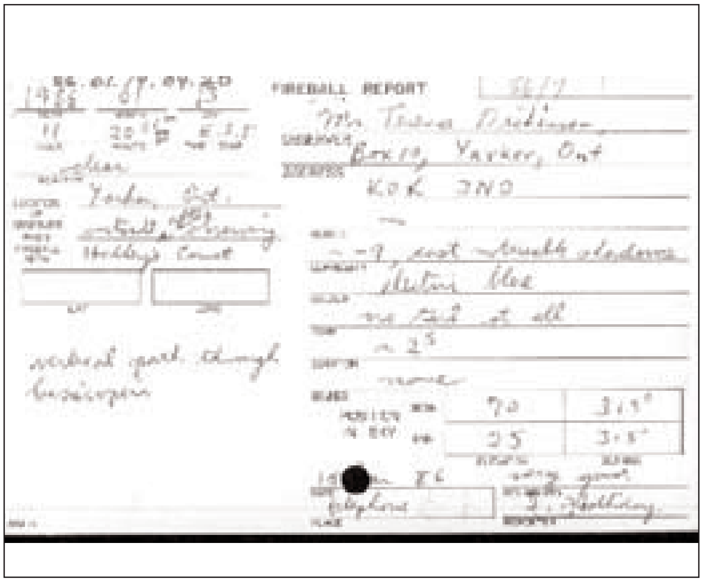
FIREBALL REPORT

Figure 1. — Scanned image of an MFA report card completed for a fireball witnessed (by a well-known astronomer) at 04:20 UT on January 14, 1986. The report was the seventh to be received in 1986 (see top right hand corner), and the observational details were recorded by Dr. Ian Halliday at the NRC. In this particular case no sounds were reported to accompany the fireball.

Halliday *et al.* 1996) the archive did, on occasion, provide additional eyewitness data on very bright, potentially meteorite dropping, fireball events. In particular, the eyewitness accounts could supplement the MORP camera data by providing information on occurrence time, trail duration, train colour, and sounds. Both sonic booms and simultaneous (also called electrophonic) sounds are described in the MFA, and in the sections below we discuss the general characteristics of the sound-generating fireballs. To give some idea of how the MFA is structured, Figure 1 shows a scanned copy of a report card (a so-called ACM-form 1 card). Reports on fireball events were received at the NRC via letter, telephone, telex, and through personal interviews with the observational details being transferred to a report card. The report cards were then archived according to the date and time of the event. Not every report card was fully completed and the various descriptions are often terse and occasionally rather cryptic. Many, but not all, of the cards within the MFA have complementary and detailed letters received from the eyewitness, and in our analysis it is both the letter and card information that we have examined.

2. Meteor Sounds

It is not our intention to review in detail here the mechanisms responsible for generating meteor sounds. Indeed, the mechanisms for sound generation are physically complex and in a number of aspects only poorly understood at the present time. The two main categories of fireball related sounds, however, are sonic and simultaneous (LaPaz 1958; Annett 1980; Ceplecha *et al.* 1998). The former are distinguished in that they are typically heard several minutes after the fireball has passed, while the latter are anomalous in that the fireball and sounds are witnessed concomitantly.

Sonic booms result from the generation of shock waves in the Earth's lower atmosphere. The essential picture is one of a fireball producing a cylindrical blast wave as it descends at hypersonic speeds through the Earth's atmosphere. The propagation of the shock waves and the distribution of the audibility zones, where the sonic booms might actually be heard, are determined by the local atmospheric conditions and prevailing winds (ReVelle 1975, 1997). Sustained simultaneous sounds, on the other hand, are believed to be generated via an interaction between the turbulent plasma column trailing behind an ablating meteoroid and the Earth's magnetic field (Keay 1980a, 1993; Bronshten 1983). This interaction, often described as a magnetic entanglement or "spaghetti" model, is believed capable of generating very low frequency (VLF) electromagnetic radiation. It is the transduction of the VLF electromagnetic radiation, by a suitable medium close to the observer, that ultimately results in the generation of audible, simultaneous sounds (Keay 1980b; Tatum & Stumpf 2000). In addition to the magnetic entanglement model, it has also been suggested that short duration, or "burster" simultaneous sounds (often described as sounding like "pops" and "vuts") might be generated as a consequence of shock waves propagating along the fireball's plasma column (Beech & Foschini 2001). It has become common practice, in recent years, to describe simultaneous sounds as being electrophonic. While the electrophonic label does express the apparent physical origin of such sounds, we shall continue to use the term simultaneous in this paper since it is the simultaneity between the sound and the passage of the fireball that is the key observable characteristic.

3. The MFA Sound Generating Fireballs

Table 1 is a summary of the number of fireball accounts within the MFA relating to sound phenomenon. The Canadian data relate to fireball events witnessed in the time interval 1912 to 1989. The US data relates to fireball events observed between 1962 and 1989.

Table 1.
Summary of data records and event counts contained in the MFA.

Country	Reports	Events	Sound reports (%)	Sound events (%)
Canada	3878	2131	268 (6.9)	143 (6.7)
United States	410	315	20 (4.9)	19 (6.0)

We have distinguish in Table 1 between "reports" and "events," such that, by "events" we mean the observation of a specific fireball and by "reports" we refer to the total number of report cards engendered by a particular event. Most "events" generated just one "report," but some very well observed "events" produced hundreds of "reports." The April 26, 1966 event, for example, generated a total of 246 "reports" from across Ontario and Quebec.

The reported characteristics of the MFA sound-producing fireball events will not be given in tabulated form in this paper, but the data may be accessed from the MIAC Web page[2]. We have distinguished between "sonic booms" and "simultaneous" sounds, as best we can, according to the descriptions given in the reports. Comments such as "booms," "rumbling like thunder," "roaring like a jet aircraft," "explosions," and "bangs" are taken to be sonic booms, and especially so if there was a delay in hearing such retorts. In contrast, when comments like "crackling," "popping noise," "hissing," "screeching," "like a sky rocket," and "air rushing noise" are used we count the description as being simultaneous and especially so when the sound was stated as being heard concurrent to the passage of the fireball.

In our earlier, general analysis paper on the MFA (Beech 2003) it was noted that the average yearly percentage of fireball events generating some "sound" phenomenon was remarkably constant at 7.6 ± 3.5 percent. Further to this, we note here that Norton (2002), without supporting references, comments that "between 4 and 8%" of fireball events are accompanied by sound phenomena. The implications are, therefore, that of order one in thirteen fireball events has some associated "sound" characteristic. Sears (1978) presents data on the sound generating characteristics of 20 fireballs associated with meteorite falls. Although only a small sample was considered, Sears finds that 17 (85%) of the events were accompanied by "explosions," presumably related to sonic booms. In addition, 9 (45%) of the fall events were accompanied by simultaneous sounds. During the time interval over which the MFA was actively maintained a total of four meteorite falls occurred in Canada[3]. Of these events, 3 (75%) produced MFA reports that specifically mention either sonic booms and/or simultaneous sounds. The one event that has no MFA reports signifying the occurrence of sounds was the Innisfree meteorite fall of February 5, 1977. Other eyewitness accounts not contained in the MFA do clearly indicate, however, that distinct simultaneous sounds did accompany the passage of the Innisfree fireball (Halliday *et al.* 1978). Indeed, with respect to organizing meteorite fall searches, McCall (1973) argues that only those "reports of falls which do include descriptions of sound effects are worth following up." While the general consensus appears to be that meteorite-dropping fireballs are highly likely to be accompanied by sound phenomena, it is not necessarily the case that every sound generating fireball results in the delivery of a meteorite.

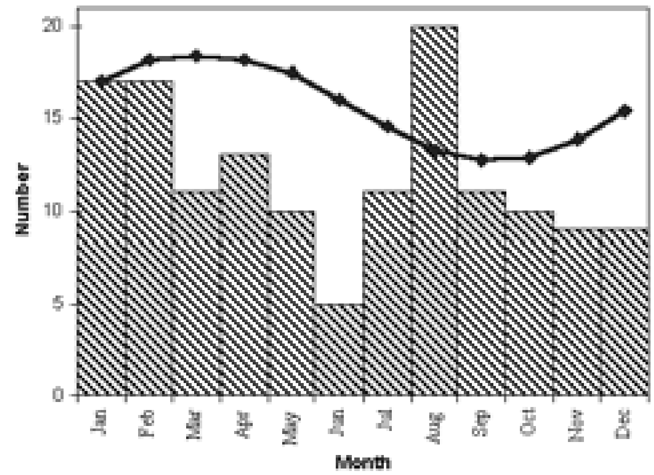

Figure 2. — The monthly distribution of "sound-" generating fireball events. The solid line shows the predicted variation in the relative meteorite fall rate, for latitude 52° N, as calculated by Halliday & Griffin (1982) and arbitrarily normalized to the January fireball count. The relative monthly variation in the histogram data would follow that of the curve derived by Halliday and Griffin if there were no seasonal selection effects in observing fireballs (and if all sound-generating fireballs were due to meteorite dropping events). As it is, the late fall and early spring observations suggest under sampling of sound-generating fireballs — this is presumably a "poor weather" related selection effect. The August observations are relatively "over" sampled but may also include a contribution related to sound-generating fireballs from the Perseid stream.

4. Seasonal variation of events

The monthly distribution of sound generating fireball events is shown in Figure 2. Two reasonably distinctive peaks are discernible in the monthly data with one broad peak running from January through February, and the other occurring in August. A distinctive minimum is evident in June. The monthly distribution of sonic and simultaneous sound events is compared in Table 2 along with the simultaneous sound data reviewed by Kaznev (1994) who studied an extensive fireball data set gathered by Russian observers.

Given the high probability that a meteorite-preceding fireball will produce some accompanying sounds (Sears 1978; McCall 1973), one might expect a correlation between the monthly meteorite fall rate and the sound generating fireball distribution shown in Figure 2. Hughes (1981) has analyzed the "observed" monthly meteorite fall rate and finds that it is maximized between April and mid-October and minimized between November and March. This result, however, does require careful interpretation with respect to numerous selection effects. Indeed, Halliday & Griffin (1982) show that the meteorite fall rate actually maximizes between November and March and is at a minimum between July and October (as indicated by the solid line in Figure 2). It appears, therefore, that while the longer nighttime hours in the winter months favour fireball observations, the harsher weather conditions hamper the recovery of meteorites even though the recovery conditions are perhaps at their best when the ground is frozen and vegetation is sparse. The enhanced numbers of sound producing fireball events for January through April probably relate, therefore, to the relatively enhanced arrival rate of meteorites to the Earth in those months. The relative dearth of sound producing fireball events in November and December, in turn, probably reflect the generally poor observing conditions prevalent in those months.

Judging from the Table 2 data it would appear that the August peak is related to enhanced rates of both sonic and simultaneous sound-generating fireballs. The August peak is also clearly represented in the simultaneous sound data gathered by Kaznev (1994). Since the well known, and well observed, Perseid meteor shower occurs in mid-August it might be suggested that it is responsible for the enhanced numbers of sound generating fireballs. We find, however, that this is unlikely. The collected data indicate that 7 out of the 28 sound generating fireball events observed in the month of August occurred within a seven day window centered on August 13, the time of the Perseid shower maximum. This "window" should capture events possible derived from the Perseid stream. Of the 7 events reported, 5 produced sonic booms and 2 were simultaneous. Since, however, Perseid meteoroids are cometary in origin (*i.e.,* derived from comet 109P/Swift-Tuttle) it is unlikely that they can penetrate deep enough into the Earth's atmosphere to produce sonic booms[4]. We suggest, therefore, that the August peak is probably the result of an observational selection effect. Essentially, we would argue, more people go out observing at the time of the Perseids, because the weather is typically fine and because it is known that a good "show" is likely to be seen. Since more people are out observing at the time of the Perseids, a greater number of non-Perseid fireball events will be observed and reported. In this respect, we note that the enhanced August reporting trend is also present in the overall fireball reporting rate (see column 9 of Table 3 in Beech 2003). The two simultaneous sound-producing fireballs in our seven day "Perseid window" are perhaps deserving of a little more attention since both occurred close to the time of the Perseid maximum. The events were observed on August 12, 1969 at

03:35 UT and August 12, 1979 at 09:30 UT. The first event was described as lasting for 3 seconds and was "brighter than Mars." The second event was described as lasting for a "few seconds" and being "very bright." We immediately run into difficulties with the duration times given for these two events since, we note, of the 27 MORP camera-detected Perseid fireballs not one lasted longer than one second. Hence, we are either dealing with exceptional Perseid fireballs (and the sound associations possibly support this supposition) or the duration estimates contain some considerable error (see below). With the above being said we note that the reported speed and direction of the 1969 event are consistent with it having been a Perseid shower member. The meteor apparently left a trail that lasted for some 10 seconds, and the report card indicates a "faint crack heard during mid-flight." The 1979 event was described as sounding "like [a] rocket taking off," but it is not clear from the report if it was truly a Perseid shower member. We note here, for comparison purposes, that the short duration, simultaneous sound event recorded by Beech *et al.* (1995) was observed at the time of the Perseid maximum on August 11, 1994. While large, tens of centimeter-sized Perseid meteoroids might conceivably produce simultaneous sounds, a survey by Beech & Nikolova (1999a) concluded that such large meteoroids must, at best, be a very rare commodity within the Perseid stream. Barabanov et al. (1996) have reported, however, upon the telescopic detection of multi-metre-sized objects within the Perseid stream (seen while they were passing Earth by outside of its atmosphere), but a similar telescopic survey by Beech *et al.* (2003), found no supporting evidence for the existence of such large meteoroids.

In addition to the August peak, a distinctive maximum in the number of simultaneous sound events is evident for April (see Table 2 and Figure 2). The April peak in the MFA data is not, however, apparent in Kaznev's study; this is possibly a result of the comparatively lower number statistics prevalent in the MFA data. Two of the April observed simultaneous sound-producing events were recorded on the night of the Lyrid meteor shower maximum (April 22/23). While there is some evidence to suggest that short-duration simultaneous sounds were heard during the 1803 Lyrid outburst (Beech & Nikolova, 1999b), neither of the events contained in the MFA can be sensibly linked to the shower. Hughes (1981) interestingly finds a distinct peak in the observed meteorite fall rate in April, which is close to the March maximum (see the solid line in Figure 2) predicted by the analysis of Halliday & Griffin (1982). The April peak is probably, therefore, related to the enhanced meteorite fall rate during the spring months and the generally improving weather conditions at that time.

A June minimum is present in all three of the data sets shown in Table 2, and it is clearly evident in Figure 2. Indeed, the minimum is also present in the over all MFA fireball data count (Beech 2003). The most likely explanation for the June minimum is the reduction of nighttime observing hours at the time of the Summer Solstice. That the June minimum is probably a short nighttime selection effect is further underscored by the fact that no similar minimum is seen in the observed meteorite fall data (Hughes 1981), and nor is it seen in the arrival rate of satellite-detected fireballs (Tagliaferri, *et al.* 1994).

Seismic phenomena were reported to accompany twelve of the sound-producing fireball events described in the MFA. These observations were presumably the result of sonic-boom related shock waves impinging upon the ground with the effect of producing surface-propagating seismic waves (see *e.g.*, Anglin & Haddon, 1987; Hildebrand *et al.* 1997). In principle the seismic data provides a valuable constraint upon the energy released during the fireball event (*e.g.*, Brown *et al.* 2003), and this, again in principle, can constrain the initial mass estimate of the incoming meteoroid. As far as can be gauged none of the MFA seismic-related fireball events were observed with sufficient detail to enable useful data on the parent meteoroid to be extracted.

Table 2.

Comparison of the monthly distribution of sound-generating fireball events. Columns 2 through 5 give the number and percentages (rounded to the nearest integer value) for the simultaneous and sonic-boom generating events catalogued in the MFA. The last two columns reproduce the data given by Kaznev (1994).

Month	Simultaneous	%	Sonic	%	Kaznev	%
January	9	12	8	12	56	10.5
February	5	7	12	18	47	8.8
March	7	9	4	6	32	6.0
April	10	13	3	5	33	6.2
May	4	5	6	9	44	8.2
June	4	5	1	2	40	7.5
July	8	10	3	5	49	9.2
August	10	13	10	15	74	13.9
September	9	12	2	3	42	7.9
October	7	9	3	5	39	7.3
November	1	1	8	12	41	7.7
December	3	4	6	9	37	6.9
	Σ = 77		Σ = 66		Σ = 534	

5. Typical event characteristics

There is probably no such thing as a typical sound-producing fireball event, but since the production of sonic and simultaneous sounds does require that certain physical conditions be satisfied we shall attempt to see what conditions favour the production of meteor sounds. We also derive the characteristics of a "control group" of 360 randomly selected, non-sound-generating fireballs. We note here that since many of the report cards were not fully completed the sample sizes being compared will vary according to the category under investigation.

Table 3 is a summary of the reported brightness estimates for those fireball events that were accompanied by sound phenomena. Given, however, that the majority of the reports in the MFA were produced by inexperienced observers we do encounter some difficulty in interpreting the comments relating to brightness. Observers, for example, commonly use expressions such as "bright," "very bright" and "extremely bright," "like lightning," or "like a welding arc," and the placement of a numerical magnitude upon such expressions is problematic. In the cases where observers used expressions such as "like Venus," or "like planets" we suggest that they are describing fireballs in the magnitude range −1 to −5. When observers use expressions such as "like the Moon" or "half as bright as the Moon" we have taken the magnitude to be in the range −5 to −10. It is our guess that expressions such as "bright," and "very bright" also fall somewhere in the magnitude range -5 to −10, but we have collated such accounts separately. When an expression such as "brighter than the Full Moon" has been used we ascribe to it a magnitude in the range −10 to −15. Events described as being "like daylight," or "the sky lit up like daytime" are given a magnitude in the range −20 to −25. We find that some 36% of simultaneous sound-producing fireballs have estimated magnitudes less than −10, while only 14% of sonic-boom-generating fireballs fall into the same brightness range. In general Table 3 appears to indicate that fireballs producing sonic booms tend to brighter than those fireballs that produce solely simultaneous sounds. Some 11% of the fireballs that produce sonic booms fall into the "like daylight" category (−20 ≤ mag ≤ −25), a value that is twice that derived for the fireballs producing simultaneous sounds. Likewise, column 4 of Table 3 indicates that in general fireballs that produce some accompanying sound phenomena tend to be brighter than those fireballs that apparently produce no sound.

Table 3.

Brightness estimates of "sound-" generating fireballs. The category "other" includes estimates such as "like lightning," blinding," and "welding arc." Columns 2 and 3 give the number of reports and in brackets the percentage (rounded to the nearest integer value) of reports for each of the brightness categories. The last column is a control sample, picked at random, of non-sound-generating fireball events. The last row shows the sample size for each category.

Brightness	Simultaneous	Sonic Booms	Control
−1 to −5 (Venus)	20 (30)	9 (9)	109 (30.8)
−5 to −10	4 (6)	5 (5)	56 (15.8)
−10 to −15 (Moon)	13 (19)	20 (21)	40 (11.3)
−15 to −20	0 (0)	2 (2)	11 (3.1)
−20 to −25 (Daylight)	4 (6)	11 (11)	2 (0.6)
Bright (Brilliant)	6 (9)	10 (10)	41 (11.6)
Very Bright (Ext. Bright)	14 (21)	23 (24)	61 (17.2)
Other	6 (9)	16 (17)	34 (9.6)
	Σ = 67	Σ = 96	Σ = 354

One striking feature discernible in column 2 of Table 3 is the large percentage of simultaneous sound-producing fireballs having an estimated brightness less than magnitude −5. Drobnock (1992, 2002) has argued (although see Beech *et al.* 1995) that apparently "ordinary" meteors[5] can produce detectable "pulses" of VLF electromagnetic radiation, but it is not clear that simultaneous sounds can proceed from such events. It has been generally asserted on theoretical grounds that only fireballs brighter than magnitude −8 to −10 are likely to generate sufficient electromagnetic energy to produce simultaneous sounds (Keay 1980a; Beech & Foschini 2001). While we do not claim that the theory of simultaneous sound generation is fully described, it is none-the-less difficult to understand how apparently "ordinary" meteors can produce "sounds." Interestingly Vinkovic *et al.* (2002) report that some 37% of the reports received at the Global Electrophonic Fireball Survey[6] are attributable to fireballs less bright than magnitude −5. This observation certainly requires further study, but will only likely be verified as "real," as opposed to being some magnitude-estimation bias, through the careful and calibrated instrument study of sound-producing fireball events.

The distribution of duration estimates for sound-generating fireballs is shown in Table 4. Again, since most of the eyewitness reports are from inexperienced observers there is no doubt that some error in the duration estimates exists. However, the reported data suggests that ~55% of the fireballs that generate simultaneous sounds and/or sonic booms endure for between 1 and 5 seconds. In general, columns two and three of Table 4 suggest that with respect to duration there is no significant difference in the flight times of fireballs that generate simultaneous sounds and those that produce sonic booms. The sound-generating fireballs do apparently have slightly longer durations (in the 5 to 25 second duration ranges) than those fireballs that produce no sound (but see below).

Some measure of the observational error associated with fireball duration estimates can be gauged from the last two columns of Table 4. The data in these two columns is taken from MORP camera survey data presented in Table 3 and Table 4 of Halliday *et al.* (1996). The "fireball" data column indicates that only one MORP recorded fireball had a measured duration in excess of 10 seconds. Likewise the "meteorite" data column indicates that just one of the potential meteorite-dropping fireball events observed with the MORP cameras had a measured duration in excess of 30 seconds. We would suggest, therefore, that the large number of sound-generating fireballs with estimated durations in excess of 20 seconds is most probably due to the "tail" of the error distribution associated with eyewitness timing estimates.

Table 4.

Estimated duration of "sound" generating fireballs. Events described as being a "flash" have been placed in the < 1 second category, while those events described as being "several," "few" and/or "brief" have been placed in the 1-5 second category. Columns 2 and 3 give the number of reports and in brackets the percentage (rounded to the nearest integer value) of reports for each of the duration categories. Column 4 is a control sample of non-sound generating fireball events. Columns 5 and 6 are based upon MORP camera data (Halliday *et al.* 1996) — see text for details. The last row shows the sample size for each category.

Duration (sec)	Simultaneous	Sonic Booms	Control	MORP fireball	MORP meteorite
< 1 (Flash)	0 (0.0)	8 (7)	24 (6.7)	80 (37.6)	0 (0)
1 – 5	42 (57)	59 (53)	226 (63.3)	123 (57.7)	33 (72)
5 – 10	14 (19)	23 (21)	59 (16.5)	9 (4.2)	9 (20)
10 – 15	8 (11)	7 (6) 23	(6.4)	1 (0.5)	1 (2)
15 – 20	1 (1)	5 (5)	8 (2.2)	0 (0)	2 (4)
20 – 25	2 (3)	1 (1)	5 (1.4)	0 (0)	0 (0)
25 – 30	1 (1)	0 (0)	7 (2.0)	0 (0)	0 (0)
> 30	6 (8)	9 (8)	5 (1.4)	0 (0)	1 (2)
	Σ = 74	Σ = 112	Σ = 357	Σ = 213	Σ = 46

A summary of burst and flare-like events[7] for sound-generating fireballs is given in Table 5. About 50% of both the simultaneous and sonic-boom generating fireballs are described as being single, continuous streaks of light with no apparent indication of flares, bursts and/or fragmentation events. Fireballs that generate sonic booms are about three times more likely to show a single burst or flare than those fireballs that generate simultaneous sounds, while simultaneous-sound-generating fireballs are some six times more likely than sonic-boom-generating fireballs to show "many" bursts.

Table 6 is a summary of the comments relating to fireball fragmentation. We distinguish between bursts and fragments on the basis that a burst need not result in multiple fireball components being produced[7]. It would appear that a fireball generating simultaneous sounds is about two times more likely to fragment into two or three components than a fireball that generates sonic booms. Also, a sound-

Table 5.

Burst observations for "sound-" generating fireballs. The row corresponding to "many" bursts was used to account for comments such as "bursting flames," "shower of sparks," "flares," and "pulsation." The last row shows the sample size for each category. The last column is a control sample of non-sound-generating fireball events.

No. of Burst	Simultaneous	Sonic Boom	Control
Single object	26 (49)	40 (47)	158 (53.4)
1	7 (13)	30 (35)	65 (21.9)
2	2 (4)	6 (7)	13 (4.4)
3	3 (6)	4 (5)	3 (1.0)
4	0 (0)	1 (1)	4 (1.4)
Many	15 (28)	4 (5)	29 (9.8)
	Σ = 53	Σ = 85	Σ = 272

generating fireball is some two times more likely to catastrophically break-up than a non-sound-generating fireball.

Table 6.

Fragmentation observations for "sound-" generating fireballs. The numbers in columns 2, 3 and 4 give the number of reports and in brackets the percentage (rounded to the nearest integer) of reports for each of the fragmentation categories. The last column is a control sample of non-sound-generating fireball events. The row corresponding to "many" was used to account for comments such as "broke into many pieces," "breaking fragments," and "following fragments." The last row indicates the sample size of each category.

No. of Fragments	Simultaneous	Sonic Boom	Control
2	5 (23)	3 (13)	9 (41)
3	3 (14)	2 (8)	5 (23)
4	1 (5)	2 (8)	1 (5)
Many	13 (59)	17 (71)	7 (32)
	Σ = 22	Σ = 24	Σ = 22

6. Discussion

For the typical casual observer of the nighttime sky the probability of witnessing a sound-producing fireball is very small. Indeed, Keay & Ceplecha (1994) suggest that with respect to simultaneous sounds it is literally a once in a lifetime experience. Not only does one need to be fortunate to witness the fireball, but one also needs to be in an appropriate location for hearing sounds. In the case of simultaneous sounds a local transducting medium is required (Keay 1980b), while in the case of sonic booms placement in an audibility zone is necessitated (ReVelle 1975). Based upon those MFA fireball events that produced more than ten eyewitness reports, Beech (2003) found that on average if sonic booms do accompany a fireball event then 12.8 ± 9.0 percent of the observers actually "hear" the "booms" at a sufficiently distinctive level to comment upon them. Likewise, if simultaneous sounds are reported to accompany a fireball event then 5.7 ± 1.8 percent of the observers actually "hear" them in a distinctive fashion. For comparison, we note that following the recent fall of the Morávka meteorite in the Czech Republic on May 6, 2000 some 2.5% of eyewitnesses reported hearing distinct simultaneous sounds (Borovička *et al.* 2003).

Keay & Ceplecha (1994) suggest that the number of simultaneous sound-producing events N_E, occurring over an area A in the time interval n_y is

$$N_E = \frac{1}{2}\left(\frac{A}{A_E}\right) C\, n_y\, H,$$

where A_E is the Earth's surface area (5.1×10^8 km^2), C is a cloud obscuration term (taken here to be 0.5), H is the global frequency of simultaneous sound-producing events and the factor of $^1/_2$ accounts for predominant nighttime observing. Keay & Ceplecha (1994) argue that $H \sim 11{,}000$ events/year. Across the total land mass of Canada, where $A \approx 9.0 \times 10^6$ km^2, we might expect there to have been some 1300 simultaneous sound-generating events in the 27 years over which the MFA data was gathered. If one accepts this estimate as reasonable then just 7 % of the possible simultaneous sound-producing events were apparently witnessed and reported by Canadian observers. Since many of the simultaneous sound-producing events might also have produced sonic booms, then perhaps of order 10% of the possible sound-producing events were reported. It is likely that the actual percentage of events witnessed is much higher than the values just derived, since the area of Canada over which people physically reside is much smaller than nine million square kilometers. Indeed, the detection rate could easily be closer to one in three events after allowing for a not unreasonable 1/3 reduction factor in the area A.

It is a certainty that some of the sound reports in the MFA are illusory. Just how many reports might be mistaken, however, is difficult to determine. Odd sounds occur all around us, all of the time, even in remote locations, and observers can unwittingly associate such sounds with a chance fireball event. Romig & Lamar (1963) discussed the possibility of "psychological suggestion" for the origin of simultaneous sounds, but came to no conclusions as to how often "suggestion" might occur. A nice example of psychological "forces" at work is found in the report by Robert Leslie (1885), who described the obmutescence of the 1885 Andromedid meteor storm in the following terms, "the silence of the display was almost oppressive, as one expected each moment to hear the bang of fireworks." Leslie "held" his expectations at bay, but his sentiments underscore the tendency of human observers to "see and hear" what they expect to "see and hear." A detailed discussion of the "power" of "psychological suggestion," with respect to the phenomenon of lunar meteors, where observers "found" what they expect to "find," is given in Beech & Hughes (2000). While we do believe that simultaneous sounds constitute a real physical phenomenon, it is our belief that the next major development in this area must follow from carefully constructed instrument-based surveys.

There is a growing body of evidence, some instrumental but mostly anecdotal, that "sounds" can accompany annual meteor shower fireballs. A good number of cases exist for Perseid fireballs possibly producing "burster" simultaneous sounds, and there is some historical evidence to suggest that Lyrid meteor shower fireballs might also produce "burster" simultaneous sounds. In the case of the recent spectacular Leonid meteor storms, the reports relating to simultaneous sound production are of a very mixed quality. Indeed, it might very reasonably be argued that most of the recently reported Leonid events were simply "psychologically suggestive" in nature. This comment being made because the storms were well predicted, massively reported in the media, and viewed by countless multitudes of inexperienced observers. Furthermore, many media outlets and Web pages distinctly mentioned the possibility of sounds being associated with bright Leonid meteors, thereby instilling the expectation of hearing something in the minds of inexperienced observer. We note that the MFA contains no sound-producing fireball reports relating to the Leonid meteor storms of 1965 and 1966. All of the above being said, a few of the Leonid sound reports4 gathered over the last several years (*e.g.*, Drummond, *et al.* 2000), along with the historical reports from the 1833 and 1866 Leonid storms (Beech 1998; Beech & Foschini 2001), are suggestive of a real physical phenomena.

Keay (1985) has argued that according to the magnetic entanglement model, sustained simultaneous (electrophonic) sounds should accompany the re-entry of large artificial satellites. And on this point, a number of the report cards in the MFA do relate to satellite re-entry observations. One event, the infamous Cosmos 954 re-entry on January 24, 1978 generated five MFA reports and one report from the Hay River (N.W.T) area interestingly notes a "hissing noise on first appearance in the west." Heaps (1978) further describes several additional eyewitness accounts of sustained simultaneous sounds being heard during the Cosmos 954 re-entry. In more recent times, and also in apparent agreement with Keay's prediction, a distinct magnetic-field disturbance was detected during the re-entry of the Molniya 1-67 satellite over Western Australia (Verveer *et al.* 2000).

That sound-producing fireball events are described in the MFA is not at all surprising. Indeed, it would have been surprising if they had not been reported. We find that of order one in thirteen of the fireball events documented within the MFA had some associated sound characteristic. In common with previous studies we find that it is predominantly the brightest, long-duration fireball events that produce associated sounds. We find some intriguing, but tentative, evidence to suggest that "burster" simultaneous sounds can proceed from Perseid meteor shower fireballs. We also find tentative (but as yet unclear) evidence supporting the claim that apparently "ordinary" meteors[5] can produce simultaneous sounds. It is, perhaps this latter topic that most clearly indicates where the next major thrust in the understanding of simultaneous sounds must come from; namely through the development of instrument based surveys.

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Notes

[1]The MIAC Web page can be accessed via `miac.uquac.ca/MIAC/`.

[2]Data on the MFA and links to the tabulated data can be found directly at `hyperion.cc.uregina.ca/~astro/MIAC/MFA/Intro.html`.

[3]The meteorite events were the Peace River (AB) fall on March 31, 1963 the Revelstoke (BC) fall on March 31, 1965 the Vilna (AB) fall on February 5, 1967 and the Innisfree (AB) fall on February 5, 1977.

[4]The caveat to this statement is that sonic booms would not be expected unless an exceptionally large meteoroid encountered the Earth's atmosphere. Beech & Nikolova (1999a) estimate that an initial diameter in excess of 1-metre would be required before a Perseid meteoroid might produce sustained simultaneous sounds. A similar sized, or even larger, Perseid meteoroid would be required to produce a sonic boom. While sonic booms might not, in general, therefore, be expected to originate from fireballs in cometary streams, they can apparently produce infrasound waves. ReVelle & Whitaker (1999), for example, report on the infrasonic detection of a very bright Leonid fireball observed on November 17, 1998. A second very bright Leonid fireball (EN151101), recorded by the European Network of fireball cameras on November 15, 2001 was also found to generate a clear infrasound signal (P. Brown personal communication). Brief mention is made in Jenniskens *et al.* (2000) of a bright Leonid fireball, observed in 1998, that apparently generated a sonic boom, although the association is far from certain.

[5]By "ordinary" we mean meteors of peak visual brightness less than magnitude −5. The magnitude limit of −5 is somewhat arbitrary, but it is employed with respect to the standardized nomenclature adopted at the 1961 IAU General Assembly (Millman 1961). The IAU approved definition for the appellation of fireball corresponds to a meteor brighter than the brightest planet. In practical terms the planetary brightness limit is set by Venus, which can attain a maximum brightness of magnitude −4.7. Drobnock (1992) makes the extraordinary claim that meteors as faint as zero magnitude peak brightness can generate measurable VLF electromagnetic radiation transients. Based upon some 80 hours of VLF monitoring, however, Beech, Brown & Jones (1995) found no evidence to support such a claim.

[6]The Web page of the Global Electrophonic Fireball Survey can be found at `www.gefsproject.org`.

[7]A burst or flare corresponds to a transient increase in a meteor's brightness. The occurrence of bursts need not indicate that the parent meteoroid has completely broken apart, but they do indicate that numerous small and hence rapidly ablating particles have been released from the meteoroid. We have distinguished between bursts and fragments in the following way; bursts are short-lived brightness enhancements of the parent fireball, while fragmentation corresponds to the appearance of distinct, relatively long-lived daughter trails that follow the parent fireball in its path.

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