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The Mazapil meteorite: From paradigm to periphery

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Abstract–The remarkable fact about the Mazapil meteorite is that it fell on the same night, in 1885, that the Andromedid meteor shower underwent a spectacular outburst. The simultaneity of these two events has driven speculation ever since. From ~1886 to ~1950 the circumstances of the Mazapil fall were taken, by a number of researchers, as the paradigm that demonstrated the fact that comets were actually swarms of meteoritic boulders. Beginning ~1950, however, most researchers began to adopted the stance that the timing of the Mazapil fall was nothing more than pure coincidence. The reason behind this change in interpretation stemmed from, amongst other factors, the fact that none of the prominent annual meteor showers could be clearly shown to deliver meteorites. Also, with the introduction of the icy-conglomerate model for cometary nuclei, by F. Whipple in the early 1950s, it became increasingly clear that only exceptional circumstances would allow for the presence of large meteoritic bodies in cometary streams. Further, by the mid 1960s it had been shown that meteorites could, in fact, be delivered to the Earth from the main belt asteroid region *via* gravitational resonances. With the removal of the dynamical "barrier" against the delivery of meteorites from the asteroid region, the idea that the Mazapil meteorite could have been part of the Andromedid stream fell into complete disfavor. This being said, we nonetheless present the results of a study concerning the possible properties of the parent object to the Mazapil meteorite based upon the assumption that it was a member of the Andromedid stream. This study is presented to illustrate the point that while cometary showers do not yield meteorites on the ground, this does not, in fact, substantiate the argument that no meteoritic bodies reside in cometary streams. Indeed, we find no good reason to suppose that an object with the characteristics of the Mazapil meteorite could not have been delivered from the Andromedid stream. However, we argue that upon the basis of the actual reported observations and upon the scientific maxim of minimized hypothesis and least assumption it must be concluded that the timing of the fall of the Mazapil meteorite and the occurrence of the Andromedid outburst were purely coincidental.

INTRODUCTION

Many meteorites have special histories and entertaining tales regarding their discovery and ownership. One meteorite that often makes the "out-of-the-ordinary" list is the Mazapil meteorite which fell in Zacatecas county, Mexico at U.T. 28.17 November, 1885 (Hidden, 1887). There is nothing particularly exceptional about the actual meteorite; Mazapil is a medium octahedrite iron meteorite (Wasson, 1970; Buchwald, 1975) that weighed in with a fall mass of 4.656 kg (see Fig. 1). What is remarkable about the Mazapil meteorite, however, is the date and time at which it fell. The meteorite touched Earth during the night of the 1885 outburst of the Andromedid meteor shower. The historical debate and interest in the Mazapil meteorite has centered entirely on the time of its fall and the possibility that it might have been part of the Andromedid stream, and hence, by default, that it was at some time part of the stream's parent comet, Comet 3D/Biela.

The circumstances surrounding the fall of the Mazapil meteorite do constitute a remarkable story, and during the past century the importance of the fall, with respect to meteoritic and cometary studies, has varied greatly. According to which author and epoch one considers the relevance of the Mazapil fall has varied from one of total irrelevance to one of great importance. Below we review how the circumstances of the fall of the Mazapil meteorite have been treated historically. We shall consider how the meteorite has been discussed in both popular and scholarly books and we shall look at peer-reviewed journal articles. Second, we ask whether the parent meteoroid of the Mazapil meteorite could have possibly been a member of the Andromedid stream, and thirdly, we consider what can be said about the parentage of the Mazapil meteorite from a strictly scientific perspective.

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FIG. 1. The 3546 g Vienna, Natural History Museum fragment of the Mazapil Meteorite. Wüfling (1897) indicates that within 12 years of its fall the Mazapil meteorite had been cut into at least seven fragments. The largest fragment has always been held in Vienna, while smaller fragments are now held in the Natural History Museum, London, the American Museum of Natural History, New York, and the Field Museum in Chicago. Image kindly provided by G. Kurat and reproduced courtesy of the Naturhistorisches Museum, Vienna.

CIRCUMSTANCES OF THE FALL

Professor Jose Bonilla (then Director of the Zacatecas Observatory, Mexico) first described the circumstances of the Mazapil fall in a letter to William Hidden (see Hidden, 1887). Bonilla did not witness the fall himself, put presents the contents of a letter submitted to him by Eulogio Mijares who did witness the fall. Mijares explained to Bonilla:

> "It was about nine in the evening when I went to the corral to feed certain horses, when suddenly I heard a loud sizzling noise, exactly as though something red-hot was being plunged into cold water, and almost instantly there followed a somewhat loud thud."

Mijares was soon joined in the corral by other startled ranch hands and a "hole in the ground" containing the hot iron meteorite was soon discovered. Mijares continued in his letter:

> "Looking up to the sky we saw from time to time exhalations or stars, which soon went out, but without noise.…All night it rained stars but we saw none fall to the ground as they seemed to be extinguished while still very high up."

Mijares's account is remarkable for a number of reasons. Firstly, he only reports hearing a "sizzling" sound and the impact "thud". No sonic booms are reported in the letter. Likewise, no direct mention of a fireball is made. Wylie (1933), however, *reads* Mijares's comment that "the corral was covered with a phosphorescent light" as indicating the presence of a bright, enduring fireball trail. In addition, and with respect to meteoritical oddities, the Mazapil iron meteorite was described as being warm to the touch when first found. The depth of the plunge pit was measured to be some 30 cm.

The account of the Mazapil fall, while remarkable in the detail that it does provide, is equally as remarkable in what it does not provide. The vital piece of missing information, indeed the one point that makes the Mazapil fall at once engaging and also infuriating, relates to its direction of atmospheric flight. Neither Mijares nor any of the other witnesses to the recovery of the meteorite reported seeing any visible atmospheric flight phenomena. Put simply, we do not know the radiant point of the Mazapil fireball. In this sense we have no physical observation to link the meteorite to the Andromedid shower, for which the radiant point was right ascension 1 h 40 m and declination +44° (Cook, 1973).

It was Edmond Weiss and Johann Galle who first noted in 1867 a similarity between the orbital elements of the Andromedid meteoroid stream and comet 3D/Biela. Observations of the Andromedid shower, however, date back to as early as 1714, when "large numbers" of meteors were reportedly seen from St. Petersburg on the night of November 25 (Fisher, 1926). Outstanding returns of the Andromedids were witnessed in 1872 and 1885, when the estimated hourly meteor rates at maximum were 7400 ± 500 and 6400 ± 600, respectively (Jenniskens, 1995). The maximum of the 1885 Andromedid storm occurred at U.T. November 27.8, and consequently the Mazapil meteorite fell some 9 h after the storm had peaked. At the time of the fall, the hourly rate of Andromedid meteors would have been ~10 per hour. The 1885 Andromedid activity profile is shown in Fig. 2.

To summarize, there is no good reason to doubt that the Mazapil meteorite fell, as described by Eulogio Mijares, on the night of U.T. 28.17 November, 1885. Likewise, we know that on the night of the fall of the meteorite the Andromedid meteor shower did produce a spectacular outburst. In the remainder of this article we shall consider a number of issues related to these basic observations.

METEORS, METEORITES AND COMETS

During his 1886 August 18th address to the American Association for the Advancement of Science, H. A. Newton commented (Newton, 1886):

> "We may reasonably believe that the bodies that cause the shooting-stars, the large fire-balls, and the stone producing meteor, all belong to one class. They differ in kind of material, in density and size. But from the faintest shooting star to the largest stone-meteor, we pass by such small graduation that no clear dividing line can separate them into classes"

Having made these statements, Newton considered just one objection to the idea that the streams that produce the annual meteor showers also contained meteorite-producing bodies. The objection concerned the observation that no meteorites had been observed to fall during neither the intense Leonid meteor storms of 1833 and 1866 nor during the Andromedid meteor storms of 1872 and 1885[1]. The fact that, as Newton put it, "this objection is plausible" required that he tackle it head-on. In fact, Newton argued that statistically no observed meteorite falls should be expected. Newton's counter argument is an interesting one and it is based upon the apparent annual rate of meteorite falls. First, Newton argued that "in the last hundred years five or six star-showers of considerable intensity" have occurred and that the total amount of meteors falling during these storms was equivalent to about one year's worth of "ordinary meteors". He then noted that the number of observed meteorite falls per year ran at a rate of some two or three[2]. With these details in place Newton summarized "to ask for more than two or three [meteorite falls] is to demand of star-shower meteors more than other meteors to give". From which he continued "the failure to get these two or three may have resulted from chance, or from some peculiarity in the nature of the rocks of Biela's and Tempel's comets". Accordingly, Newton felt confident in concluding that meteorites were derived from cometary meteoroid streams. Echoing the conclusion promoted by Newton, Bonilla wrote in his covering letter to Hidden (see Hidden, 1887) that "everything points to the belief that it [the Mazapil meteorite] belongs to a fragment of the comet of Biela–Gambart [3D/Biela], lost since 1852".

By the close of the nineteenth century it was commonly supposed that comets were loosely bound conglomerates of meteoritic material (Burke, 1986). Furthermore, since the formation of elongated, typically non-ecliptic streams did not fit well with respect to the Laplacian Nebular Hypothesis it was generally assumed that the streams (and hence comets) were captured by the Sun from interstellar space (Bailey *et al.*, 1986). The idea that the solar system could acquire material from interstellar space proved to be a particularly fertile one. Not only did it offer an explanation to the origin of comets, meteor showers and meteorites, but during the latter half of the nineteenth century it also presented a possible solution to the increasingly problematic debate concerning the relative ages of the Sun and the Earth (Thomson, 1862).

In his remarkable book *The Meteoritic Hypothesis,* Joseph N. Lockyer outlined a theory in which "all self-luminous astronomical bodies are composed of meteorites or of masses of meteoritic vapour" to which he also added "the existing distinction between stars, comets, and nebulae rests on no physical basis" (Lockyer, 1890). Lockyer's essential thesis was built around the idea of intersecting (interstellar) meteoroid streams, and the common features observed in stellar, cometary and meteor spectra. It is perhaps somewhat surprising therefore to find that Lockyer affords the Mazapil meteorite only brief notice. Lockyer's Figs. 1 and 2 are photographic reproductions taken directly from Hidden (1887) showing the Mazapil iron meteorite, but in the main body of the text his only comments relate to the fact that the circumstances of the fall are "trustworthy" and that it fell "during a star shower". Interestingly, Lockyer was apparently reluctant to mention any association between the Mazapil meteorite, the Andromedid

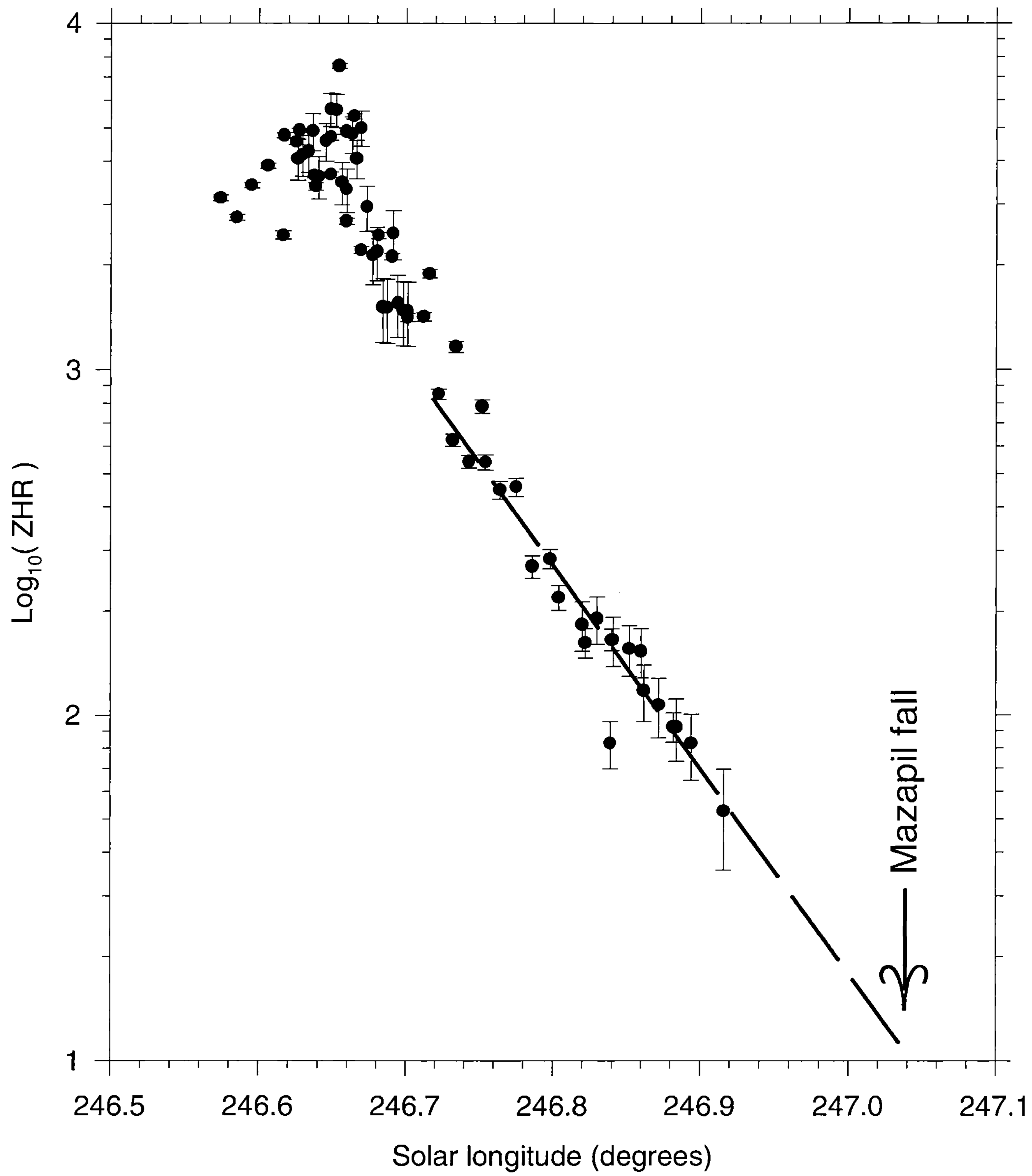

FIG. 2. Activity profile of the 1885 Andromedid meteor storm. The data for the zenithal hourly rates (ZHR) have been kindly provided by P. Jenniskens (pers. comm.). The ZHR is a reduced number and corresponds to the number of meteors brighter than magnitude +6.5 that would be seen, under perfect sky conditions, by an observer with the shower radiant in their zenith. The time axis is given in terms of solar longitude (epoch 1950). The Mazapil meteorite fell (see arrow) at $\lambda_{\odot} \approx 247.037$ some 9 h after the Andromedid maximum (Jenniskens, 1995). The dashed line is a linear extension of the ZHR rate to the time of the Mazapil meteorite fall. The estimated ZHR at the time of fall is ~10 meteors per hour.

stream and comet 3D/Biela. It is not obviously clear why Lockyer was so reserved upon this issue in his *Meteoritic Hypothesis*. This is especially so since he had earlier claimed that the "hint of a connection between comets and meteorites is one of the greatest discoveries of late years in the science of astronomy" (Lockyer, 1884). Lockyer's entire argument hinged upon there being meteoritic material in interstellar streams, and yet he made no attempt to build upon the circumstances of the Mazapil fall. At this point we may only conjecture that perhaps he believed that the meteorite–comet connection was best illustrated by spectroscopic observations, and perhaps Lockyer was uncomfortable about the missing radiant association information.

At about the same time that Lockyer published *The Meteoritic Hypothesis* William F. Denning (1891) published his *Telescopic Work for Starlight Evenings*. Within his book Denning argued that while fireballs and meteors differed greatly in size they nonetheless had a common origin. And, with respect to the Mazapil meteorite he noted,

> "The great display of meteors of Nov. 27, 1885, not only presented us with large and small members, but it also furnished us with a siderite or piece of iron, presumably from Comet Biela...this is the first observed instance in which a meteorite has actually reached the Earth's surface during the progress of a star-shower. If its identity with the meteors of Biela's comet is admitted, then all classes of meteoric phenomena would appear to have a commonality of origin."

Denning certainly takes the circumstances of the Mazapil fall at face value, and reservedly admits an association between meteorites, meteors and comets. We note that Denning bases his reservations upon the uncertain link between the Mazapil fireball and the Andromedid radiant. Denning later become less certain about the possibility of a common origin for the fireballs and ordinary shooting stars (Beech, 1991). Indeed, Denning (1894) noted "that there is a marked distinction in the general direction of motion of fireballs and ordinary shooting stars is a fact which has often impressed itself upon me". The implication, of course, is that the fireballs associated with meteorite-producing events need not be associated with meteor-producing cometary streams. The fact that fireballs have a different radiant distribution to that of the ordinary shooting stars is not fatal to the idea of a common origin, but it does imply that there can be a marked variation in the meteoroid size distribution from one cometary swarm to another.

FORGING A TENUOUS LINK

While Lockyer appears to have been somewhat ambivalent and Denning reserved about the circumstances of the fall of the Mazapil meteorite, other researchers proceeded to argue that numerous meteorites had, in fact, fallen when various annual meteor showers were active. For example, building upon the apparent association between the Mazapil meteorite and the Andromedids, Henry Ward (1905) argued that the Bath Furnace (1902 November 15), Saline Township (1898 November 15), Trenzano (1856 November 12) and Werchne Tzchirskaja (1843 November 12) meteorites were all derived from the Leonid stream. Ward's argument was based entirely upon the fact that the meteorites fell within a few days of the Leonid shower maximum and that they were all chondritic meteorites. Heinrich Bornitz (1900) went even further than Ward and suggested that some 143 known meteorite falls could be associated with various annual meteor showers. What Bornitz and Ward failed to fully appreciate, however, and what, for example, Arthur Harvey (1904) and William Monck[3] (1904) set out to critique, was the fact that the associations were based simply upon the time of fall, with no attempt being made to establish a radiant association. The lesson to be learnt, of course, was that on its own the time of fall argument cannot establish a physical connection between a meteorite and an active meteor shower. If one is purely interested in the time of fall then we note, for example, that the *Catalogue of Aerolites* published by Monck (1904) indicates that ten meteorites had actually fallen, in various years, between November 12 and 20 the time when the Leonid shower is most active. In spite of his mostly dismissive comments, Harvey (1904) appears to accept that the Mazapil meteorite was derived from the Andromedid stream—at least he did not come out strongly against an association. Monck (1904) argued, on the other hand, that there was no good evidence to link any known meteorite fall to any specific annual meteor shower, but he did concede that fireball (*i.e.*, meteorite) showers probably existed.

In addition to questioning the timing and radiant association data, Monck (1904) also raised an important point about initial velocities. What Monck noted was that because of their great speed stream meteoroids typically carry more than enough kinetic energy for their complete destruction in the Earth's atmosphere. This observation essentially built upon the earlier analysis by James Joule[4] (1848). While entry velocities had not been well measured at the time that Monck was writing it was generally clear that fireballs typically had much lower velocities than shower meteors. He noted "I do not think a Perseid or a Leonid (unless the mass was enormous) could reach the [E]arth as a stone". With respect to the Andromedids, however, he was not so sure and commented "I neither affirm nor deny" the possibility of their surviving passage through the Earth's atmosphere. While Monck does not mention the Mazapil meteorite by name, his argument with respect to the Andromedids is presumable tempered by the possibility that it was a stream member. Monck is of course correct with respect to the impossibility of meteorites being deposited by the Perseid and Leonid streams (even if they did reside in the stream) for which the initial velocities are 59 and 71 km/s, respectively. The point about entry velocity requirements is a genuinely important one, and reminds us of the fact that in most cases the lack of meteorite falls during meteor showers is not actually evidence against meteoritic bodies residing in cometary streams (Campins and Swindle, 1998; see also appendix B).

In spite of the objections raised by Harvey and Monck, William H. Pickering (1909, 1910 and 1919), of Harvard College Observatory, proceeded to use time-of-fall data alone to "establish" a theory of meteorite origins. On this basis Pickering concluded that iron meteorites were most likely derived from comets, but that stone meteorites were terrestrial in origin, being placed into orbit "during the great cataclysm that occurred at the time that the Moon separated from the Earth"[5]. To Pickering the Mazapil fall was the classic paradigm that demonstrated the association between comets and iron meteorites. He also suggested that the Rowton iron meteorite, which fell on 1885 April 20, was derived from Comet 1861 G1 (Thatcher), the parent to the Lyrid meteor shower[6]. Pickering makes no mention of Ward's (1905) paper in which it had been argued that stone meteorites had fallen at various times during the annual Leonid meteor shower.

Farrington (1915), Curator of Geology at the Field Museum of Natural History, in his *Meteorites: Their Structure, Composition and Terrestrial Relations* picked up on the themes developed by Newton (1886) and Pickering (1909) and roundly rejected them. In contrast to Newton, Farrington suggested, in an unsupported argument, that if meteorite-producing objects did reside in cometary streams then large numbers of meteorites should fall during annual meteor showers. Farrington did mention the Mazapil fall but suggested it was an isolated case that could be accounted for as being purely coincidental. Interestingly, Farrington did not actually question whether the Mazapil meteorite was really a component of the Andromedid shower. Likewise, and in contrast to Pickering (1909), Farrington felt that if comets did produce meteorites then the meteorite-producing comets must be of a very different nature to those that produced ordinary meteor showers. Farrington appeared, in fact, to favour the idea that meteorites were derived from a shattered planet or planetoid.

C. P. Olivier (1925) in his classic text *Meteors* reiterated Monck's velocity limiting argument about the possibility of meteorite delivery from annual meteor showers. He could not, however, bring himself to completely dismiss the Mazapil fall, and commented "the chances for a meteorite falling on any given night are so small that many high authorities speak most confidently of this iron mass as being a piece of Biela's comet".

While in the mid 1920s Olivier felt that the circumstances of the fall of the Mazapil meteorite were at least worthy of mention, we find absolutely no discussion of it in Fletcher Watson's popular text *Between the Planets* (Watson, 1941). Indeed, Watson comments that "we know of no meteorite which has fallen from [a nighttime meteor] shower". Clearly in the 16 years time interval between the publication of the books by Olivier and Watson the circumstances of the Mazapil fall had gone from one of at least passing interest to one of compete disregard. Why was this? To begin to answer this question we have to look more closely at the then prevailing ideas on cometary structure.

COMETS AS METEOROID SWARMS

The standard "picture" of a comet changed but very little during the first half of the twentieth century. In their classic text *Astronomy* (volume 1), Russell *et al.* (1945) give the following description:

> "The accepted view of the nature of comets...is that they are loose swarms of separate particles (probably of very different size) separated by distances great in comparison with their own diameters and accompanied by more or less dust and gas."

The picture outlined by Russell *et al.* is often described as the "sand-bank" or "gravel-bank" model, although this appellation, as pointed out by Lyttleton (1972), gives a very poor image of what was actually envisioned. To give some example numbers, Russell *et al.* calculated that the mass of Halley's comet was some 2.5×10^9 kg. This result followed from an estimate of the coma volume (5.5×10^{12} km^3) and the number of 1 cm diameter particles (some 1.6×10^{13}) required to produce the observed brightness by pure reflection (the particle albedo being assumed similar to that of the Moon). This mass, volume and particle number estimate implied that the swarm that constituted Halley's comet had a number density of three particles per cubic kilometer. These same numbers also imply a bulk density of 4.2×10^{-12} kg/m^3 for Halley's comet.

With respect to meteoroid streams, Russell *et al.* (1945) argued that they were formed by the gradual disintegration of cometary swarms. They also noted that it is "by no means necessary that a meteor swarm should ever have been dense enough to have had enough gas and dust associated with it to form a visible comet". In this fashion they account for those annual meteor showers that have no recognized cometary parent. By way of a reader exercise, Russell *et al.* deduced that the number density of sporadic meteoroids is $\sim 6 \times 10^{-8}$/km^3. Thus comets represented a local enhancement of 50×10^6 over the sporadic background. Interestingly, the sporadic background exercise set by Russell *et al.* was "lifted" straight from Young's (1899) *General Astronomy*, even though this was one of the texts that Russell and co-writers had set out to update. Apparently Russell *et al.* saw no reason, 46 years on from Young's publication, to modify the ideas relating to the sporadic meteoroid background. While Russell *et al.* do mention comet 3D/Biela and the Andromedid meteor shower, and include a fairly lengthy section on meteorites, they make no mention of the Mazapil fall. It would seem, therefore, that Russell *et al.* did not consider the circumstances of the Mazapil fall to be either of general interest or relevant to the discussion on meteorites or cometary stream structure. In contrast, Young in his *General Astronomy* includes a short but specific section on the Mazapil fall (his section 784), although he is somewhat reserved about their being any possibility of an association between the meteorite and comet 3D/Biela.

Harvey Nininger (1952) writing in his *Out of the Sky: An Introduction to Meteorites* revived the idea that the Mazapil meteorite was derived from the Andromedid stream and commented that "science is not yet ready to discard the concept of a comet–meteorite relationship". Nininger's views on the origin of at least some meteorites, however, were apparently not those of his contemporaries. While the "sand-bank" model was still highly regarded during the 1950s and 1960s, one of its main exponents R. A. Lyttleton (writing in Richter, 1963) actually argued that large, potentially meteorite-producing fragments, should not exist within cometary streams. Lyttleton wrote:

> "I see no reason to suppose that a comet necessarily contains large chunks of rock. Meteor showers have occurred injecting countless millions of meteors into the Earth's atmosphere without a single large object of meteoritic proportions coming in at the same time on the same path."

Because Lyttleton is rightly insisting upon a clear association between the fireball and the shower radiant, he is entirely justified in not mentioning the fall of the Mazapil meteorite. Lyttleton's refinement of the "sand-bank" model with respect to the non-delivery of meteorites, however, was a rather trivial addendum to a theory that, throughout the 1960s and 1970s, became increasingly embroiled in controversy.

NEW COMETARY MODELS

The "loose swarm of particles" model of cometary structure was brought directly into question by the introduction of two new ideas in 1950. First, F. L.Whipple (1950) introduced his idea that cometary nuclei were solid structures, mostly composed of water ice. And second, J. Oort (1950) introduced the idea of a vast reservoir of cometary nuclei that encircled the solar system and stretched almost halfway to the nearest stars.

Whipple's icy-conglomerate model does not *per se* rule out the possibility of there being large, potentially meteorite-producing, meteoroids within cometary streams. However, in order for such objects to be placed into meteoroid streams they must first be incorporated into the parent nucleus. In this respect, large meteoroids may be either "picked up" when and where cometary nuclei form, or they must be accreted at later times. The former possibility was discussed, for example, by E. J. Opik (1966) who argued, on dynamical grounds that meteorite-producing bodies must have originated at the same time as the comets and consequently were imbedded in their nuclei at the time of formation. Harwit (1968), on the other hand, suggested that cometary outbursts and nuclear fragmentation as well as accretion might be explained through collisions with interplanetary "boulders". The reader is referred to appendix A for a discussion on the possibility that comet 3D/Biela accreted the Mazapil parent object while traversing the main belt asteroid region. Needless to say the probability of a cometary nucleus "picking up" a meter-sized, potentially meteorite-producing body while in the main belt asteroid region is very small, but it is equally as important to note that it is not zero.

ESTABLISHING THE ASTEROID CONNECTION

With the introduction of the compact cometary nucleus model the question of how meteorites might be delivered to the Earth became more problematic. The association between meteorite-producing fireballs and comets had been historically supported by the observation that they both moved along highly elliptical orbits. A minor planet origin for meteorites was considered unlikely because the minor planets moved on predominantly circular orbits. Opik (1966), for example, specifically noted that the encounter velocities between asteroids were typically too low to place any collision fragments into Earth crossing orbits, and consequently he proposed his "meteorites mixed-in" cometary model.

Building upon the perturbation approximation techniques developed by Opik (1951), Arnold (1965a,b) produced a series of detailed numerical models, the results of which suggested that meteorites could be effectively transported from the main belt asteroid region without the aid of large velocity increments. Indeed, Arnold (1965b) concluded that all of the available evidence implied that iron meteorites were derived from the main belt asteroid region. He was not so sure about chondritic meteorites, because of their deduced exposure ages and his model timescale requirements, but he did suggest that an asteroidal origin was probable. Later works by numerous researchers have improved upon the orbital calculations of Arnold. It is now well established that the ν_6 secular resonance (Wetherill, 1974) and the 3:1 mean-motion resonance with Jupiter (Wisdom, 1985) are capable of rapidly "pumping" the orbital eccentricities of meteorite parent bodies to such levels that Earth-orbit intersections are possible (Morbidelli and Gladman, 1998; Vokrouhlicky and Farinella, 2000).

With the establishment of the "dirty snowball" model for cometary nuclei and the realization that meteorite-producing bodies can be delivered to Earth from the main belt asteroid region *via* resonances, it became much less likely that the Mazapil meteorite had any physical connection with comet 3D/Biela. Indeed, most research papers and specialist textbooks published since ~1970 either make no mention of the Mazapil fall, or consider it to be a complete coincidence. McCall (1973), for example, suggests that the fall of the Mazapil meteorite "may be a fortuitous coincidence", but concedes the somewhat unlikely possibility of a "shared" orbit between the meteorite and the Andromedid stream. Wetherill and Chapman (1988) note that the Mazapil fall "is now regarded simply as a coincidence". And in recent times, Campins and Swindle (1998) without actually mentioning that it is the Mazapil event comment that "one coincidental iron" has fallen during a meteor shower.

COULD MAZAPIL HAVE BEEN AN ANDROMEDID?

Although the modern-day consensus is that meteorites are predominantly derived from the main belt asteroid region (Marvin, 1996; McSween, 1999), cometary streams may nonetheless contain meteoritic material. Campins and Swindle (1998) have given a comprehensive review of the characteristics that might be expected of cometary meteorites, but conclude that none are presently held within any meteorite collection. Padevet and Jakes (1993) have argued that the observed fireball data (*e.g.*, mass, atmospheric penetration and orbital characteristics) indicate that chondritic boulders may be present in at least some cometary streams. Padevet and Jakes (1993) further argue that the precursors of the H, L, C2 and C1 chondrite meteorite types are probably present in cometary nuclei. Anders (1981) has also argued that "super-carbonaceous chondrites" with a complement of ices are more than likely present in cometary nuclei.

If, for the sake of argument, we allow that the Mazapil meteorite was at one time a member of the Andromedid stream, we can constrain the characteristics of its parent body to some high order of accuracy. Specifically, any simulation has to produce a ground fragment of 4.656 kg (the collected mass), and since we know the meteorite is an iron the bulk density of its parent will be 7900 kg/m^3. There is no evidence to indicate that the Mazapil meteorite was part of an extensive strewn field and consequently it is reasonable to assume that it was derived from a non-fragmenting parent object. The atmospheric entry velocity of the Mazapil parent object would be 16.5 km/s (appropriate to that of Andromedid stream) and its zenith angle would have been 22°. The zenith angle is based upon the radiant altitude at the stated time of fall (9 P.M. local time on the night of November 27).

The characteristics of the Mazapil parent object may be constrained by solving the equations of meteoroid ablation (see *e.g.*, Hughes, 1978), with the initial conditions discussed above, under the constraint that the final mass is that of the recovered meteorite. We have numerically integrated the mass loss and deceleration equations with a standard Earth atmosphere model, treating the initial mass as the independent variable. Our solution uses an ablation coefficient of $\sigma = 7.43 \times 10^{-8}$ s^2/km^2 (ReVelle and Ceplecha, 1994) and we assume that the parent object was spherical. Our "best-fit" Andromedid stream-derived Mazapil meteorite has a parent of initial mass 1.25×10^5 kg (diameter = 3.1 m). A maximum brightness of magnitude −19 is indicated by our model (assuming a 0.1% luminous efficiency) and the fireball was brighter than magnitude −10 for 5.1 s. In addition, the numerical model indicates a dark flight time (set according to the velocity being <2 km/s) of 7.0 s. The atmospheric ram pressure ($P_{\mathrm{ram}} \approx \rho_{\mathrm{atm}} V^2$) computed for the "best-fit" model did not at any time exceed the breakup condition set by the Weibull crushing strength law (see appendix B) and consequently no fragmentation is implied.

Figure 3 shows the approximate domains, in the initial mass *vs.* initial velocity plane, for which fragmentation and complete ablation of iron meteoroids are expected (see appendix B). Our calculations suggest that the limiting mass for an iron meteoroid, assumed to be within the Andomedid stream, to deliver a single, non-fragmented meteorite to the ground is $\sim 4 \times 10^5$ kg. Parent objects more massive than this limit will undergo break-up at heights above 10 km. Our calculations also suggest that any iron meteoroids more massive than ~250 kg in the Andromedid stream might potentially yield meteorites on the ground. The greatest initial velocity for which a single, non-fragmenting iron meteorite might be delivered to the ground is found to be ~20 km/s. Iron meteoroids traveling more rapidly than this limit will either fragment in the Earth's upper atmosphere (to deliver a meteorite shower), or be completely ablated. Our findings are similar to those of Passey and Melosh (1980) who note that "iron meteoroids with initial masses ranging from 10^5 to 10^{10} kg are the most likely ones to produce crater fields". We note, however, that Passey and Melosh (1980) used in their calculations an ablation coefficient some 2.7× larger than that suggested by ReVelle and Ceplecha (1994), and that they also assumed a constant crushing strength with S_0 being either 10^7 or 5×10^8 Pa.

The results of our numerical simulation are reasonably clear. If there was an $\sim 1.25 \times 10^5$ kg iron meteoroid in the Andromedid stream then there is no reason to suppose that it could not have produced a meteorite with the characteristics of the Mazapil iron meteorite.

DISCUSSION

In broad-brush form the circumstances surrounding the fall of the Mazapil meteorite are such that from at least ~1886 to ~1950 it was considered by at least some researchers to be an example of a meteorite actually derived from a cometary stream. From ~1950 onwards, however, it was increasingly questioned whether meteorites in general and Mazapil specifically might truly be associated with cometary streams. Bornitz (1900), Ward (1905) and Pickering (1909) tried to establish meteorite associations with the Perseid, Leonid, Lyrid and other annual meteor showers, but their arguments were based entirely upon time-of-fall data. They failed, as we would now expect them to, to establish any clear radiant association. From ~1965 onwards, with the growing acceptance of the icy-conglomerate model of cometary structure and as a result of the publication of detailed dynamical studies, the idea that cometary streams might contained large meteoritic bodies (especially iron ones) fell into complete disfavor.

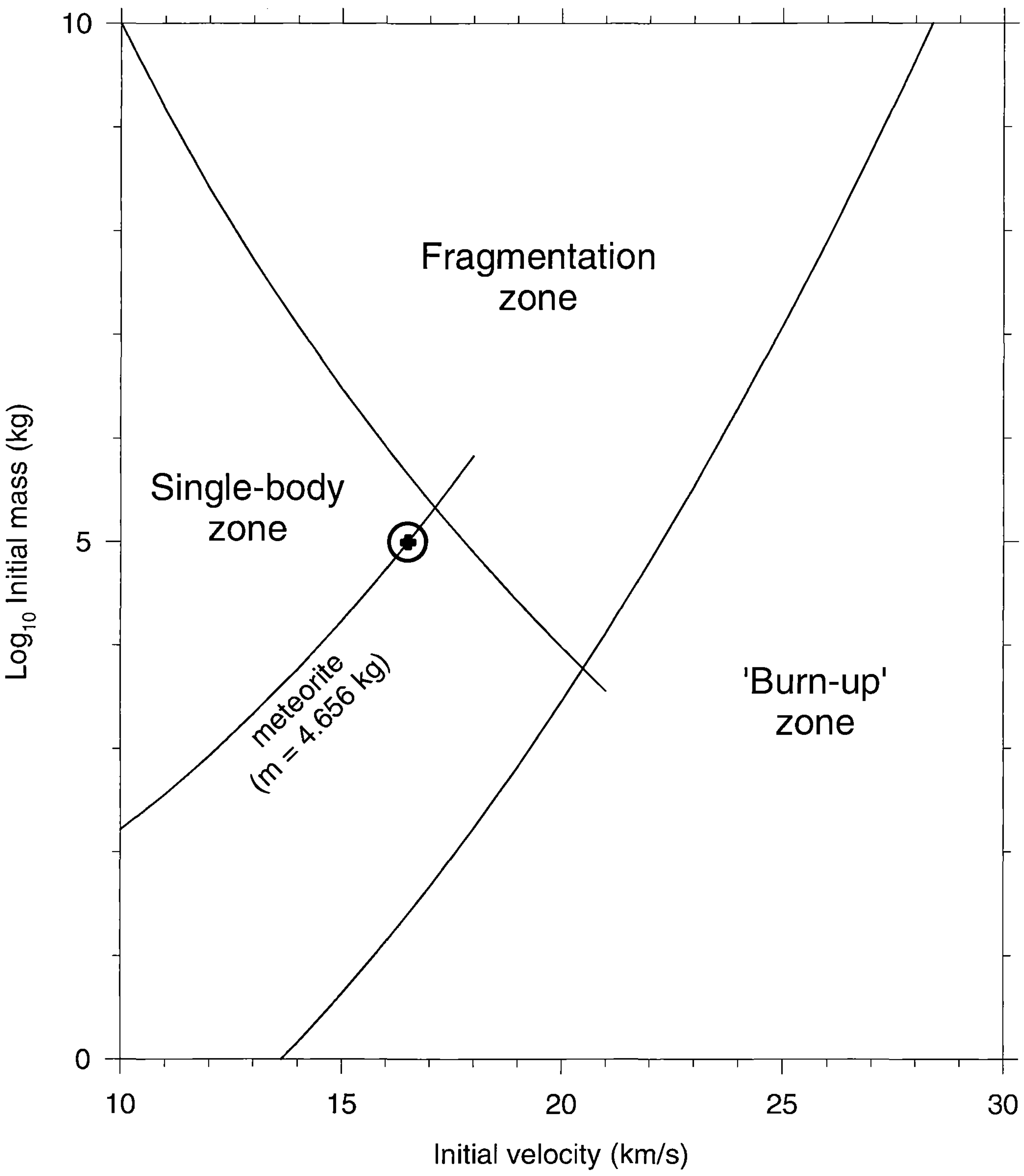

FIG. 3. Total ablation and fragmentation zones for iron meteoroids. The "Fragmentation zone" indicates those values of initial mass and velocity for which the parent object would break apart, before 10 km altitude, due to atmospheric ram pressure. The "Single-body zone" gives those values of initial mass and velocity for which no breakup will occur. To the right of the line separating off the "Burn-up zone" the parent meteoroid is totally consumed by ablation, whereas to the left of the line a meteorite fall is possible. The line marked "meteorite (m = 4.656 kg)" shows the range of initial masses and velocities for which single iron meteorites of mass 4.656 kg are delivered to the Earth's surface. The hypothetical Mazapil meteorite parent (*i.e.*, assuming it to be a member of the Andromedid stream) is marked on the diagram by a circled cross. The estimated initial mass of the hypothetical Andromedid Mazapil parent is of the order 100 tonne (diameter ≈ 3 m). See appendix B for details concerning the calculation of the zone boundaries.

Our present-day understanding of the formation of cometary nuclei and of meteorites allows for no commonality of origin. Each will have formed at different times, in different locations and under very different circumstances within the solar system. In broad terms, cometary nuclei will have formed beyond the "ice-line" situated some 3 to 4 AU from the protosun, while meteorites are splinter fragments produced when asteroids collide. Also, as an iron meteorite, Mazapil has at some stage undergone considerable heat processing. Indeed, Choi *et al.* (1995) have classified the Mazapil meteorite as an anomalous IAB iron meteorite, and argue that such meteorites were formed in impact generated melt pools.

Within the framework of present-day understanding, therefore, there are only two possibly hypothesis to account for the circumstances surrounding the Mazapil meteorite fall.

H1: The Coincidence Option–The parent object to the Mazapil meteorite was in no manner connected to the Andromedid stream and the fall was entirely coincidental.

H2: The Stream Option–The parent object to the Mazapil meteorite was part of the Andromedid stream and at one time was embedded in the nucleus of comet 3D/Biela.

We have argued above that there is no physical reason why an iron meteoroid, if it were in the Andromedid stream and of sufficient size, could not deposit a meteorite on the ground. This result certainly bolsters hypothesis H2. However, there is no direct observational evidence linking the Mazapil fireball to the Andromedid radiant. In addition, while it is not impossible for comet 3D/Biela to have "picked up" an iron meteoroid while traversing the main belt asteroid region, it is exceedingly unlikely that it did so (see appendix A). In this respect hypothesis H2 is based upon an assumed radiant association and a highly improbable capture argument. In contrast to the situation with H2, hypothesis H1 simply builds upon the known facts that meteorites fall, and that they can fall at any time and from random directions on the sky. Adherence therefore to the basic tenants of the scientific method expressed under the guise of Occam's razor, which entrains us to seek explanations with the least number of assumptions and "complications", drives us to the necessary adoption of hypothesis H1.

In conclusion, unless, or until, further information about the fall of the Mazapil meteorite becomes available (*e.g.*, through previously unknown written accounts), and if the scientific method (as expressed by William of Occam's *Entia non sumit multiplicanda praeter necessitatem*) is to stand for anything meaningful, we must conclude that the fall of the Mazapil meteorite during the 1885 Andromedid storm was, more likely than not, nothing more than a noteworthy coincidence. Akin to the smile of the Cheshire cat in Carroll's (1865) *Alice's Adventures in Wonderland*, we must be resigned to the fact that the circumstances of the fall of the Mazapil meteorite are interesting, but ones that, in their present form, are ultimately devoid of substance and significant meaning.

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NOTES

1. The fall of the Mazapil meteorite on the night of the 1885 Andromedid outburst had not been made public at the time that Newton was preparing his review. Hidden (1887), in fact, made the announcement of the fall to the New York Academy of Sciences on 1887 January 17.

2. The annual fall rate of meteorites was remarkably constant during the nineteenth century, and we find from a survey of the *Catalogue of Meteorites* (Grady, 2000) that some 3.6 ± 2.3 meteorites fell per year during that epoch.

3. I have focused on the exchange between Monk and Harvey and their interpretations of the catalogs by Bornitz since it characterizes the dialog on meteorite origins prevalent in the early 1900s. Arthur Harvey was a Fellow of the Royal Society of Canada, and at the time of the exchange with Monk was Director of the Institutio Solar Internacional, Monte Video. W. H. S. Monck (1839–1915), although ostensibly an amateur astronomer, was a recognized pioneer in the fields of stellar spectroscopy, stellar distributions and proper motions. He wrote extensively on many areas of astronomy and was one of the founding directors of the British Astronomical Association. I have found no accessible biographical data on Heinrich Bornitz. His published works and meteorite catalogs were certainly well known to Monck and Harvey and are listed in the *Astronomischer Jahresbericht* for 1900, 1901 and 1902. Of additional note, Harvey mentions in his paper that a cast of the Mazapil meteorite was to be presented to the Toronto Astronomical Society (later to become the Toronto Center of the Royal Astronomical Society of Canada). This cast now appears to be lost.

4. Hughes (1990) has suggested that Joule might reasonably be considered the "father" of meteor physics since he was the first researcher to describe the correct physical interactions between a meteoroid and the Earth's atmosphere.

5. In this argument Pickering (1909) gives reference to the hypothesis advanced by Chamberlin (1901) that the meteorite-producing bodies, comets and nebulae (now recognized to be galaxies) could have been formed by the tidal disruption of an ancient planet, ripped apart during the close approach of a passing star.

6. Pickering also makes note of a "Lyrid stream meteorite" that supposedly fell on 1095 April 4. This fall, however, is without substantiation (see *e.g.*, Grady, 2000).

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APPENDIX

APPENDIX A

The probability that a given cometary nucleus might "pick up" a metre-sized meteoroid while passing through the main belt asteroid region can be determined from its orbital characteristics and its size. For a cometary nucleus of radius R, the probability P of encountering an impactor of size d is

$$P = \int_d^D \frac{dN}{dr} P_\mathrm{i} (R + r)^2 \, dr$$

Where P_i is the intrinsic collision probability (as described by Wetherill, 1967), and dN/dr describes the impactor size distribution in the range from d to D. Gil-Hutton (2000) finds that for comet 3D/Biela the intrinsic collision probability was 1.45×10^{-24} m^2/years, with a mean collision velocity of 15.8 km/s. Introducing the absolute magnitude $\mathrm{H}_{10} = 7.5$ derived by Babadzhanov *et al.* (1991) into the formula by Hughes (1987) we estimate that the nuclear radius of comet 3D/Biela was $R \approx 2 \pm 1$ km assuming that 5% of the nuclear surface was undergoing active sublimation. With this estimate for the radius and substituting for the asteroid size distribution given by Bottke *et al.* (1995) we find that the probability of comet 3D/Biela "picking up" a 3 m diameter meteoroid (*i.e.*, one the size of the estimated Mazapil parent), while passing through the main belt asteroid region is of order 5×10^{-5} per orbit.

The depth to which an impactor might penetrate a cometary nucleus can be estimated from the equations presented by Cintala (1981) and Kadono (1999). At a velocity of 15.8 km/s, a 3 m diameter, iron impactor might penetrate some 750 m into the cometary nucleus according to Eq. (1) of Cintala. In contrast, Eq. (1) of Kadono indicates a penetration depth of ~75 m. Even though there is an order of magnitude uncertainty in the penetration depth it appears that any impactor would likely be well buried, and something along the lines of the complete breakup of the nucleus might be required to "release" it into an associated meteoroid stream.

APPENDIX B

The boundaries between the "burn-up", "single-body" and "fragmentation" zones in Fig. 3 are derived on the basis of a simplified theory. We begin by expressing the mass of an ablating meteoroid in terms of its actual atmospheric velocity V (see, *e.g.*, Bronshten, 1983)

$$M(V) = M_\infty \exp\left(\frac{\sigma}{2}\left[V_\infty^2 - V^2\right]\right)$$

Where V_∞ and M_∞ are the initial velocity and mass, and σ is the ablation coefficient. The boundary separating off the "burn-up" zone in Fig. 3 is calculated according to the final mass being $<10^{-3}$ kg at the onset of dark flight (which is achieved once $V < 2$ km/s) and consequently we obtain

$$\ln(M_\infty) = (0.0372)V_\infty^2(\mathrm{km/s}) - 7.0486$$

The arc labeled "meteorite (m = 4.656 kg)" is obtained by setting the mass at the onset of dark flight to be 4.565 kg (*i.e.*, the mass of the recovered Mazapil iron meteorite).

The boundary between the single-body and fragmentation zones is calculated according to the statistical strength theory of Weibull (see *e.g.*, Svetsov *et al.*, 1995). The Weibull limit is derived upon the basis that the larger a given body is, the greater the range of structural defects it contains. In this respect the crushing strength S decreases with increasing size. The crushing strength is taken to vary with the meteoroid mass as

$$S = S_0\,(M_0/M)^\alpha$$

where S_0 and M_0 are determined by experiment and typically $0.1 \leq \alpha \leq 0.3$. Svetsov *et al.* (1995) quote a value of $S_0 = 4.1 \times 10^8$ Pa for an $M_0 = 1$ kg polycrystal fragment of the Sikhote–Alin meteorite. While Sikhote–Alin is a coarse octahedrite meteorite we assume that it has similar crushing characteristics to the Mazapil iron meteorite. The fragmentation condition is determined according to the atmospheric ram pressure being equal to the crushing strength S. In this manner the breakup condition is

$$S = S_0\left(\frac{M_0}{M}\right)^\alpha = \rho_\mathrm{atm} V^2$$

where ρ_atm is the atmospheric density at the point of fragmentation. The boundary condition calculated is that corresponding to the maximum ram pressure and the minimum crushing strength at a height of 10 km. In this way the break-up condition conveniently becomes

$$M_\infty^\alpha = \frac{1000}{V_\infty^2(\mathrm{km/s})}$$

where the atmospheric density at 10 km has been taken to be 0.41 kg/m^3. We also assumed $\alpha = 0.1$ in our calculation for Fig. 3.