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# The Potential Danger to Space Platforms from Meteor Storm Activity

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## SUMMARY

The probabilities of impact of stream meteoroids on space platforms in low Earth orbit are calculated. It is found that at times of meteor storm activity, the meteoroid impact probability increases by factors in excess of $10^4$ over that from the sporadic background of meteoroids. A review of the historic record suggests that since the second millennium AD, a lower bound to the meteor storm rate per century is one or two. The meteor storm rate during the last two centuries seems to have been anomalously high. It is not entirely clear if this anomaly is purely an artifact of the incompleteness of the historical record. A review of the presently active meteoroid streams suggests that at least six streams may undergo storm or outburst activity in the next 6 years, the most likely stream being the Leonids. The impact shielding presently incorporated into space platform design may not be adequate under meteor storm conditions. Several Risk Curtailment Scenarios are open to space platform operators. An analysis of space platform impact probabilities from meteoroids within the Perseid stream suggests that the critical shielding concept outlined for the proposed Space Station will result, even under the most extreme of circumstances, in probabilities of no penetrative impacts above 99·98 per cent.

## 1 INTRODUCTION AND BACKGROUND

All Earth-orbiting space platforms are at risk from impacts. The primary sources of the impacting particles are the meteoroid complex, and the Earth-orbiting population of space debris. While the cloud of space debris in Earth-orbit is produced artificially in the process of Solar System exploration and the commercialization of the near-Earth environment, the meteoroid complex is the natural result of our Solar System's dynamic dust balance.

The space debris environment has been the subject of several recent symposia and reviews (ESA 1988, 1993, Kessler 1991, Flury 1993), and the population of Low-Earth-Orbit (LEO) impactors has been investigated with the Long Duration Exposure Facility (Love & Brownlee 1993). Despite the fact that several long-running programmes have been funded to assess the threat posed to space platforms from collisions with space debris, the threat to space platform integrity during times of enhanced meteor activity has only recently been investigated.

Space platforms in Earth orbit are subject to impacts from a background population of sporadic meteoroids, and a complex of several dozen reasonably well-defined meteoroid streams (Cook 1973). These meteoroid streams are typically active for a day or so, and are distinguished only because their orbits happen to intersect that of the Earth's at present. The idea that hypervelocity meteoroid impacts might cause substantial damage to space platforms and deep-space probes was first realized in the early 1950s (Whipple 1952, see also Cour-Palais 1969). Of primary interest to our study is the time evolution of the meteoric complex in the near Earth environment. Several detailed sporadic meteoroid flux models are now available for the region at 1 AU from the Sun (Grün *et al.* 1985, Laurance & Brownlee 1986, Divine 1993).

It is now well-observed that the number density of sporadic meteoroids in the near-Earth environment is so small that the probability of a catastrophic meteoroid impact (i.e. an impact of sufficient magnitude to compromise a satellite's mission) is small compared with a satellite's typical mission life time (Cour-Palais 1969). In assessing the probability of meteoroid impacts, researchers traditionally assume that collisions will occur with meteoroids from the sporadic background. Recently, however, it has been realized that there are occasions when the space platform impact probability is dominated by the flux of stream meteoroids (Beech & Brown 1993, 1994).

The influx of stream meteoroids is known to be highly variable. Stream activity is typically described in terms of the visually observed Zenithal Hourly Rate (ZHR). The ZHR is defined as the number of meteors that an average observer would see from a given meteor shower under perfect conditions if the radiant were directly overhead and the faintest visible star at the zenith was $M_v = +6{\cdot}5$. The peak ZHR is often found to vary from year to year, and from one meteor shower to another. Typically, however, the range of peak stream ZHRs varies from just a few meteors per hour to approximately 100 meteors per hour (Kronk 1988). The observed ZHR for a given meteor shower is related in a non-trivial way to the spatial number density of stream meteoroids. In general the ZHR will increase in proportion to the meteoroid spatial number density. When a meteor shower is active, the spatial number density of meteoroids is higher in the near-Earth environment than at those times when no substantive shower activity is present. The likelihood of a space platform sustaining some form of impact damage is not greatly increased when a typical meteor shower is active. This need not be the case, however, if a meteor shower undergoes an outburst or a storm. The distinctions between an outburst and a storm can be found in Section 2. Visual observations indicate that meteor showers can undergo unexpected outbursts as the Orionids did, for example, in 1993 (IAUC 5884), and unexpected storms as did the Andromedids in 1872 (Kronk 1988).

Visual observations indicate that on those occasions when a meteor shower has undergone an outburst or a storm, the observed ZHRs can increase by factors of between 10 and $10^4$ (this is discussed at greater length in Section 4). Given such large increases in the observed ZHR, the implied increase in the spatial number density of meteoroids at the Earth may be sufficiently high that the space platform impact probability is significantly increased.

During the past several years the Perseid meteor shower has undergone a series of outbursts (Roggemans 1989, Koschack & Roggemans 1991a, b, Koschack, Arlt & Rëndtel 1993). Activity from this shower has been monitored carefully by the International Meteor Organization (IMO), and a short-lived, high-activity ZHR 'spike' has been recorded in the solar longitude interval 139·4° to 139·7° (epoch 2000·0). It has been suggested that the high-activity 'spike' is composed of material ejected by the stream's parent comet, Comet P/Swift-Tuttle, during its last perihelion passage (Wu & Williams 1993, Lindblad & Porubčan 1994, Jones, Brown & Beech 1995). This 'new' meteoroidal material is presently being sampled at the Earth as a consequence of Comet P/Swift-Tuttle's recent perihelion passage (Marsden *et al.* 1994).

Acting upon the possibility that the 1993 return of the Perseid meteoroid stream might result in enhanced meteor activity, Beech & Brown (1993) noted that should the Perseid ZHR increase by a factor of order $10^3$ above the normal annual level, for a time span of the order of 1000 sec, then an impact probability of 0·1 per cent would be realized for a space platform with a surface area of $100\,\mathrm{m}^2$. In comparison the impact probability with a meteoroid from the sporadic meteoroid background during the same 1000-sec interval is of the order of $10^{-5}$ per cent.

To minimize the probability of meteoroid impacts, engineers at the Space Telescope Institute chose to orientate the main body of the Hubble Space Telescope (HST) towards the Perseid stream radiant on the night of the stream maximum. The solar arrays were also feathered to minimize the surface area they presented to the stream (Petro, personal communication). Similar manoeuvres were performed for the Compton Gamma Ray Observatory, and the Extreme Ultraviolet Explorer (Sky and Telescope 1993). Also reacting to the possibility of a high flux of Perseid meteoroids, NASA officials delayed the nominal launch date of Space Shuttle Discovery (STS-51) to August 12 (Talent, personal communication).

Visual observations collected by the IMO indicate that a Perseid outburst occurred on the night of 1993 August 12. The outburst lasted about 1 h, and a maximum ZHR of about 300 was recorded (Brown & Rëndtel 1994). During the night of the Perseid outburst cosmonauts onboard the MIR-1 Space Station reported audible meteoroid strikes, and space flight controllers subsequently announced that MIR-1 experienced between 60 and 70 meteoroid impacts. It also appears that one of the MIR-1 solar panels received substantive damage on the night of the maximum (Lenorovitz 1993). Furthermore, it has been reported that the MIR-1 station recorded 2000 impacts during the 24-h period centred about the Perseid maximum in 1993 as compared with a nominal daily impact rate of 30–40 (Johnston, personal communication). Damage leading to mission termination was also received by the Olympus satellite on the night of the Perseid outburst. It is believed that the Olympus satellite operated by the European Space Agency (ESA) lost pointing control after a Perseid meteoroid impacted upon its south solar array (Caswell, personal communication).

The events surrounding the 1993 Perseid outburst highlight the potential threat of hypervelocity impact damage to Earth-orbiting space platforms during times of enhanced meteor shower activity. Not only are expensive satellites at risk during the times of stream outbursts and storms (the Olympus satellite damage, for example, was estimated to be in excess of $800 million), but in the not-so-distant future, with the construction of large space stations, human lives will also be at risk. Clearly, in the light of such risks, it is important that some assessment of the near-term possibilities for meteor storms be made.

## 2 METEOR SHOWER OUTBURSTS AND STORMS

A meteor shower occurs whenever the Earth passes through a coherent stream of meteoroids all moving along similar heliocentric orbits (Williams 1993). The characteristics of an observed meteor display will vary according to the Earth-meteoroid stream intersection geometry, the physical composition of the meteoroids' parent body, and the distribution of meteoroids around the stream. Comets are widely regarded as the parent bodies of meteoroid streams.

In the cometary model of meteoroid stream formation it is envisioned that meteoroids are injected into independent stream orbits as the parent comet nears perihelion. Meteoroids will be ejected both ahead of, and behind the parent comet, and they will gradually diffuse around the stream orbit. The time for a given injection of meteoroids to spread uniformly around the stream orbit is typically of the order of 20 to 100 $P_c$, where $P_c$ is the orbital period of the parent comet.

It is highly unlikely that the meteoroid ejection process and the mechanisms responsible for orbital evolution will result in a truly uniform distribution of meteoroids around a stream's orbit. Times of enhanced meteor activity, i.e. outbursts, can therefore be expected from every meteoroid stream. We shall define an outburst in a stream specific manner. If, at a given solar longitude, $\lambda_\odot$, a meteor shower has an annual average ZHR of $Z(\lambda_\odot)$, then an outburst will have occurred at $\lambda_\odot$ if the observed ZHR exceeds a value of $Z(\lambda_\odot) + 5\sigma_s$, where $\sigma_s$ is the standard error deviation of the stream's annual mean. Thus the Perseids, for example, have a typical annual peak ZHR of $110 \pm 10$; an outburst occurs by our definition if the peak ZHR exceeds 160.

Since new meteoroids are injected into a stream orbit each time the parent comet passes perihelion, it is to be expected that the number density of stream meteoroids will be at its greatest value close to the cometary nucleus. Should the Earth happen to pass through the meteoroid stream shortly after, or shortly before the parent comet has passed through the node of its orbit, the likelihood of enhanced meteor activity is high. The important factors that determine the observable outcome of such close encounters are: (1) the distribution of the meteoroids in the near-cometary nucleus environment; and (2) the Earth–meteoroid stream encounter geometry.

Let the Earth make its closest approach to the node of a parent comet at a solar longitude of $L_n$, and let the observed annual average ZHR at this time be $Z(L_n)$. At the times when the Earth passes the node shortly after, or shortly before the parent comet, then the observed ZHR will be $F \times \mathrm{ZHR}(L_n)$. The available observations, which are discussed more fully in the next section, indicate that $F$ can vary anywhere between 1 and roughly $10^4$. If the Earth–meteoroid stream encounter geometry is not favourable, then $F$ will be of order unity, and no obvious increase in the meteor rate will be observed at $L_n$.

Historically, a large range of possible responses to close cometary-node-Earth encounters have been observed. In 1983, for example, Comet IRAS-Araki-Alcock passed closer to the Earth than any other comet within the last 200 years (Yeomans 1991), but no strong meteor activity has been associated

TABLE I

*Well documented meteor storms since 1799. The storm ZHR values are taken from Kresák (1993, 1980). The non-storm, yearly averaged ZHR is taken from McBeath (1993).* F *is the storm enhancement factor*

| Date | Shower | ZHR (storm) | ZHR (max) | *F* |
|---|---|---|---|---|
| 1799 | Leonids | 30000 | 15 | 2000 |
| 1803 | Lyrids | 1500 | 20 | 75 |
| 1832 | Leonids | 20000 | 15 | 1300 |
| 1833 | Leonids | 100000 | 15 | 6700 |
| 1866 | Leonids | 6000 | 15 | 400 |
| 1867 | Leonids | 5000 | 15 | 330 |
| 1872 | Andromedids | 8000 | 10 | 800 |
| 1885 | Andromedids | 15000 | 10 | 1500 |
| 1933 | Draconids | 20000 | 10 | 2000 |
| 1946 | Draconids | 7000 | 10 | 700 |
| 1965 | Leonids | 5000 | 15 | 330 |
| 1966 | Leonids | 150000 | 15 | 10000 |

with this comet (Ohtsuka 1991). Conversely, Comet P/Pons-Winnecke produced an outburst of meteor activity in 1916, and again in 1921 after close passages by the Earth in 1915 and 1921 (Roggemans 1989), though no substantial meteor activity has been linked to this comet since. In contrast to the situation observed with Comet P/Pons-Winnecke, when the Earth made its closest approach to the node of Comet P/Tempel-Tuttle in 1966, some 561 days after the comet had passed through the node, the strongest meteor storm ever documented occurred. Clearly, the dust distribution about any given comet is unique.

There is no well-defined ZHR that signifies the onset of a meteor storm. Kresák (1993) has adopted a ZHR of 3600, i.e. 1 meteor every sec, as the minimum ZHR to constitute a storm. Brown & Jones (1993), on the other hand, consider ZHRs in excess of 500, i.e. 1 meteor every 8 sec, to signify the onset of a meteor storm in the context of the Leonid meteor shower. Given the great difficulty in actually calculating ZHRs under storm conditions (Koschack & Hawkes 1993) a strict definition of a storm ZHR is, in reality, a little redundant. Our working criterion for the onset of a meteor storm will be the attainment of a ZHR in excess of 1000. For those meteoroid streams that have produced meteor storms in the past, our storm criterion requires enhancement factors *F* of between 50 and $10^4$ (see Table I above). In contrast to our definition of an outburst, the criterion for the onset of a meteor storm is set independently of the average ZHR at a given solar longitude.

## 3 METEOR STORMS: THE HISTORICAL RECORD

Spectacular meteor storms have been documented throughout recorded history. While most past accounts offer nothing of value concerning the characteristics of a meteor storm, i.e. the observed meteor rates and the storm duration, they do offer valuable markers for the times of occurrence. In principle, a lower bound to the rate of meteor storms per century can be extracted from the historical record. Many difficulties are encountered in

TABLE II

*Meteor storms since the second millennium* AD. *References are (1) Hasegawa (1993), (2) Tian-Shan (1977), (3) Rada & Stephenson (1992), (4) Dall'olmo (1978) and (5) Kresák (1993). See text for details*

| | | Chronicles | | |
|---|---|---|---|---|
| Dates | Oriental Refs.: 1, 2 | Arabic 3 | European/US 4, 5 | Rate/century |
| 1000–1100 | | | 1 | 1 |
| 1100–1200 | 1 | | 1 | 2 |
| 1200–1300 | 1 | 1 | 1 | 3 |
| 1300–1400 | | | | 0 |
| 1400–1500 | | | | 0 |
| 1500–1600 | 2 | | | 2 |
| 1600–1700 | 1 | | | 1 |
| 1700–1800 | | | 1 | 1 |
| 1800–1900 | 4 | | 7 | 11 |
| 1900–2000 | | | 4 | > 4 (?) |

attempting such an exercise, among these are the incompleteness of the historical records, and the manner in which the records themselves are to be interpreted.

Useful meteor rates, and storm duration statistics are not available prior to 1800. Table I is a summary of the meteor storms that have been reasonably well-documented since 1799. This table reveals that just four meteoroid streams are responsible for producing the contemporary storm record. We defer to Section 4 the detailed discussion of these meteoroid streams. The only storms ever associated with the Andromedid and Draconid meteoroid streams are those listed in Table I. Shower activity and storm events have, in contrast, been associated with the Lyrid and Leonid streams for the past several thousand years.

Table II represents an attempt to extract from the historical record the meteor storm rate per century since the second millennium AD. Table II has been compiled from data collected by Hasegawa (1993), Kresák (1993), Rada & Stephenson (1992), Dall'olmo (1978) and Tian-Shan (1977). In extracting the candidate storm events we have looked for key phrases such as 'uncountable meteors', 'innumerable stars flew', 'more than thousands of stars fell', 'swarms of stars fell', and 'stars waved and scattered like locusts'. Other phrases, such as 'stars fell like rain', 'many stars flew', and 'stars throwing themselves forth' are taken to infer the observation of an annual meteor shower, or simply enhanced activity, as opposed to storm conditions.

Many accounts in the historical records are ambiguous (Hasegawa, personal communication, Yau, personal communication 1993) and it is not clear to us how comments such as, 'in daytime, meteors fell like rain' should be interpreted. Accounts of this nature, if taken at face value, might suggest a meteor storm, since to be aware of the appearance of many meteors under daylight conditions certainly implies that the meteor rate must be very high. On the other hand if the observations were made in twilight then the account could simply refer to an annual meteor shower, or it could refer to a fragmenting fireball event seen in daylight. We have therefore not included such accounts in our list of storm candidates. At present we can say very little about the incompleteness of the historical record except that the record does contain large gaps in which no meteor data are recorded. It is highly unlikely that these gaps truly indicate the cessation of meteor activity, storms or otherwise. The historical record is not only limited in its temporal structure, it is also biased by the fact that the observations are collected locally, rather than globally. Correcting for this bias is a non-trivial, if not impossible task. As an example, even under the most favourable conditions, that is, beginning at midnight, and lasting for just a few tens of minutes, a storm will be visible only from a fraction at least equal to:

$$A_{\mathrm{storm}} = (1 - \sin\theta)/2 \tag{1}$$

of the Earth's surface, where $\theta$ is the minimum local altitude that the radiant must be above an observer's horizon for meteors to be conspicuous. With $\theta = 25°$, the storm will be visible from about 30 per cent of the Earth's surface.

Our method for selecting 'candidate' meteor storms from the historical record is certainly not foolproof, and the meteor storm rate per century shown in column 5 of Table II is probably a lower bound only. The apparent meteor storm rate per century since AD 1000, that can be inferred from Table II shows several interesting characteristics. Typically, it would seem that a meteor storm rate of one or two (plus or minus one or two) per century has been experienced for most of the past millennium. The meteor storm rate during the 19th century, however, appears to have been abnormally high, and quite exceptional. While the increase in the number of meteor storms recorded in the 19th century may reflect a true increase in the meteor storm rate, it is also possible that the increase is linked to the birth of meteor astronomy itself (Beech 1988). Four of the entries prior to 1700 in Table II involve storms from the Leonid meteoroid stream (1202, 1238, 1533, 1594) and one storm is due to the Lyrid meteoroid stream (1122).

The fact that some historically active meteoroid streams no longer intersect the Earth's orbit reflects the dynamical evolution taking place within the meteoroid complex. Sporadic and stream meteoroids are not only subject to gravitational perturbations from the planets, they are also over time susceptible to collisional disruption (Steel & Elford 1986), and perturbations caused by interactions with the Sun's radiation field (Burns, Lamy & Soter 1979). Therefore, the characteristics (e.g. the mass index, and the peak ZHR) of a meteoroid stream will vary with time, as will the condition that the Earth intersects the stream orbit. Hasegawa (1993) has found that 25 well-defined meteoroid streams can be identified within the historical record during the past two and a half millennia. Of these 25 streams, only 11 are currently active. We find that of the 14 'lost' meteoroid streams six appear historically to have produced meteor storms under our storm selection criteria.

In addition to the possibility of meteoroid streams being perturbed out of Earth-intersecting orbits, they can also be perturbed into orbits favourable for the production of 'new' annual meteor showers. One example of a 'newly arrived' meteor shower is that of the October Draconids. Activity from this shower was first noted in the second decade of this century, and the stream has subsequently produced two spectacular meteor storms.

Examples of singly occurring meteor showers are found within contemporary and historical records. Of such events the Corvid meteor shower is one well-known case. Corvid meteors have been observed just once on the nights of 1937 June 25–30. The lunar impact events recorded between 1975 June 16 and 27 (Duennebier *et al.* 1975) are another example of what appears to be a once-only recorded meteoroid stream. There is no direct evidence in the historical record that a meteor storm has occurred as a result of a lone encounter with an unknown meteoroid stream, but the potential certainly exists for such events.

Meteor storms may arise after the break-up of a cometary nucleus. This was the case, for instance, with the 1872 and 1885 Andromedid meteor storms. These storms followed in the wake of the break-up of comet Biela in 1846. At present the meteor activity from this stream is very low to non-existent. Meteor storms that result from the break-up of a cometary nucleus are likely to be sampled only a few times at the Earth.

## 4 THE NEAR-TERM OUTLOOK FOR OUTBURST AND STORM ACTIVITY

The material sampled during a meteor storm is derived from a population of meteoroids recently ejected from the parent comet. Since the cloud of storm meteoroids is composed of newly ejected material there will have been little time for the meteoroids to spread appreciably around the stream orbit. The population of storm meterolds can also be expected to contain a greater number of smaller mass meteoroids relative to that contained in the meteoroid population which produces the 'normal' annual activity. This is due to the fact that the Poynting–Robertson effect, and the influences of radiation pressure (Burns *et al.* 1979) will not have had sufficient time to remove the smaller particles from the newly ejected population of storm meteoroids. Porubčan & Štohl (1991) have found, for example, that the mass exponents derived for the 1969 Leonid, and the 1982 Lyrid outbursts were higher than their normal values, indicating a higher incidence of smaller mass particles.

The behaviour observed when Earth encounters the meteoroid storm cloud depends critically upon several stream formation and stream evolution mechanisms. The important factors are: (1) the orbital position of the comet when the material is ejected; (2) the initial ejection velocity; (3) the influence of planetary perturbations; and (4) the outgassing of residual volatiles from the parent comet.

Mechanism (4) is particularly important for its influence upon the ejection of smaller, lower mass meteoroids. Over long-time scales, as mentioned previously, radiation pressure and the Poynting–Robertson effect will also have an important influence on stream evolution. Meteoroid–meteoroid collisions are considered to be negligible during the short term evolution of the meteoroid storm cloud.

Currently, the most promising means of predicting the behaviour of a specific meteoroid storm cloud is through the numerical integration of hypothetical meteoroid orbits, whereby the development of the storm cloud can be followed in time. Yeomans (1981), Wu & Williams (1992) and Brown & Jones (1993) have specifically investigated the dynamical evolution of the Leonid meteoroid stream, the most active of the current meteor storm

TABLE III

*Near-term storm and outburst assessment. See Appendix for stream details*

| Date | Shower | Parent comet | Type |
|---|---|---|---|
| 1994 Apr. 22 | Lyrids | P/Thatcher | Outburst |
| 1994 Aug. 12 | Perseids | P/Swift-Tuttle | Outburst |
| 1995 Aug. 12 | Perseids | P/Swift-Tuttle | Outburst |
| 1995 Nov. 22 | Monocerotids | Comet 1944 I | Outburst (?) |
| 1996 Aug. 12 | Perseids | P/Swift-Tuttle | Outburst |
| 1997 Aug. 12 | Perseids | P/Swift-Tuttle | Outburst |
| 1997 Nov. 17 | Leonids | P/Tempel-Tuttle | Outburst |
| 1998 Apr. 23 | π-Puppids | P/Grigg-Skjellerup | Outburst (?) |
| 1998 Aug. 12 | Perseids | P/Swift-Tuttle | Outburst |
| 1998 Oct. 9 | Draconids | P/Giacobini-Zinner | Storm |
| 1998 Nov. 17 | Leonids | P/Tempel-Tuttle | Storm |
| 1999 Aug. 12 | Perseids | P/Swift-Tuttle | Outburst |
| 1999 Nov. 17 | Leonids | P/Tempel-Tuttle | Storm |
| 2000 Aug. 12 | Perseids | P/Swift-Tuttle | Outburst |
| 2000 Nov. 17 | Leonids | P/Tempel-Tuttle | Outburst |

producers. Davies & Turski (1962) have modelled the Draconid meteoroid stream, while Wu & Williams (1993) and Jones, Brown & Beech (1995) have modelled the evolution of the Perseid meteoroid stream.

Several numerical models have been developed to study the structure and evolution of meteoroid streams but none can presently boast a sufficient sophistication to predict absolutely, with consistent accuracy the time or even the occurrence of meteor storms or outbursts. The models do offer, however, some insight into the likelihood of such events occurring. The main deficiencies of the numerical models are the meteoroid ejection procedures, i.e. the modelling of the cometary decay process, and the limited number of stream particles that can be followed in a given mass range.

Given that only a few meteoroid streams, and meteoroid storm clouds, have been modelled numerically, the best guide to future storm and outburst activity is that provided by the visual meteor record. A survey of this record, and a knowledge of the times at which parent comets pass perihelion allows an assessment of the near-term meteor storm/outburst activity to be made. Table III is a summary of streams we expect to undergo storms and/or outbursts in the near future. Brief notes on each of the streams listed in Table III are given in the Appendix.

We have assigned each event in Table III a storm or outburst classification. The designation is based either upon previous stream behaviour, or upon numerical model predictions. One should bear in mind the possibility that a predicted outburst could produce a storm (although this is rather unlikely in the cases considered), and vice versa. It is also possible that neither a storm nor an outburst will materialize. A demonstration of the last mentioned situation was provided by the return of the 1972 Draconids. In 1972 Earth was to pass near the node of P/Giacobini-Zinner's orbit just 58·5 days after the comet, with the distance between the stream's orbit and that of the Earth's being a mere 100000 km. Contrary to these otherwise promising indicators only a very few Draconid meteors were observed that year (Millman 1973).

The circumstances surrounding the 1972 return of the Draconid meteoroid stream highlight one area of considerable uncertainty. At present our ability to predict the times at which meteor storms and/or outbursts might occur is severely constrained by the very limited data on the distribution of meteoroids in the near cometary nucleus environment. The two modest exceptions to this general rule are those of the Leonids and the Draconids. Work presented by Yeomans (1981) has shown that Leonid meteor storms are most likely to occur when the Earth passes the node outside and behind the orbit of Comet P/Tempel-Tuttle. In contrast the best Draconid displays appear to occur when the Earth passes the node behind, and inside the orbit of P/Giacobini-Zinner (Yeomans & Brandt 1985).

## 5 METEOR STORM CHARACTERISTICS

In order to assess the likelihood of meteoroid impacts on space platforms during times of enhanced meteor activity, some idea of the storm duration and the ZHR enhancement factor ($F$) are required. Table IV is a summary of the available data pertaining to meteor storms since 1799. The ZHR enhancement factors under storm conditions were previously given in Table I. Observations indicate that the enhancement factor $F$ is a sensitive function of the encounter geometry. This point is illustrated, for example, by the Leonid meteor storms for which the estimated $F$ values fall in the range $75 < F < 10000$. The variation, by nearly two orders of magnitude, in the individual Leonid storm $F$ values does not correlate in any obvious sense with the $\Delta T/P$ value of the encounter given in column 6 of Table IV which indicates the ratio of the time lapse between the closest approach of the Earth to, and the actual passage of the comet through the nodal point of the comet's orbit, and the orbital period of the comet. From the discussion in previous sections it might be expected that storms most often occur when the $\Delta T/P$ value is small. This is generally true for the Leonid and Draconid streams, but not obviously so for the Lyrid stream (see Appendix). The Andromedid storms are again a special case since these storms resulted from the nuclear break-up of Comet P/Biela.

That the ZHR enhancement factor is poorly constrained even in those cases where we know the encounter geometry reasonably well, once again illustrates the complexity of the problem at hand, and it also underscores the need for more detailed modelling of meteoroid stream evolution. Available observations of previous meteor storms do, however, suggest that ZHR enhancement factors of the order of $50$–$10^4$ can be expected during times of enhanced meteor activity.

The duration of a meteor storm, that is the time that the ZHR is above our adopted storm value of 1000/h, has proved a difficult parameter to gauge. Once the meteor rates increase above several hundred per hour it is difficult to determine accurate ZHRs (Koshack & Hawkes 1993); consequently the storm duration times shown in column 5 of Table IV are very approximate. The problem of estimating meteor storm durations is further exacerbated by the poor reporting of meteor storm characteristics prior to the turn of this century. In spite of the inherent uncertainty, the observations do suggest that meteor storm activity can last between $10^3$ and $10^4$ sec.

TABLE IV

*Characteristics of well-documented meteor storms. Data compiled from Kresák (1993), Lovell (1954), Kronk (1988) and Lindblad & Porubčan (1991). The ZHR and durations are order of magnitude estimates only*

| Shower | Year | Date | ZHR | Duration (sec) | $\Delta T/P$ |
|---|---|---|---|---|---|
| Leonids | 1799 | Nov. 12.5 | 30000 | 7200 | $-0{\cdot}010$ |
| | 1832 | Nov. 13.2 | 20000 | | $-0{\cdot}005$ |
| | 1833 | Nov. 13.4 | 100000 | 10000 | $+0{\cdot}026$ |
| | 1866 | Nov. 13.7 | 6000 | 7200 | $+0{\cdot}025$ |
| | 1867 | Nov. 13.8 | 5000 | 1200 | $+0{\cdot}055$ |
| | 1965 | Nov. 17.0 | 5000 | | $+0{\cdot}016$ |
| | 1966 | Nov. 17.4 | 150000 | 2000 | $+0{\cdot}046$ |
| Lyrids | 1803 | Apr. 19 | 1500 | 4000 | $-0{\cdot}140$ |
| Andromedids | 1872 | Nov. 27.8 | 8000 | 4000 | $+0{\cdot}036$ |
| | 1885 | Nov. 27.8 | 15000 | 4000 | $-0{\cdot}012$ |
| Draconids | 1933 | Oct. 9.9 | 20000 | 900 | $+0{\cdot}033$ |
| | 1946 | Oct. 10.2 | 7000 | 900 | $+0{\cdot}007$ |

TABLE V

*Average and extreme physical characteristics of shower meteoroids*

| Stream | $V_\infty$ (km sec$^{-1}$) | $\langle M_v \rangle$ | $\langle r \rangle$ (cm) | $\langle m \rangle$ (gm) | $R_c$ (km) | $r_{max}$ (cm) | $m_{max}$ (gm) |
|---|---|---|---|---|---|---|---|
| Lyrids | 49 | $+2{\cdot}5$ | $0{\cdot}1$ | $3\times10^{-3}$ | — | — | — |
| π-Puppids | 18 | $+2$ | $0{\cdot}5$ | $0{\cdot}4$ | 2 | $12{\cdot}5$ | $8{\cdot}3\times10^{3}$ |
| Perseids | 59 | $+2{\cdot}5$ | $0{\cdot}06$ | $1\times10^{-3}$ | 7 | $3{\cdot}6$ | 195 |
| Draconids | 20 | $+3$ | $0{\cdot}3$ | $0{\cdot}1$ | 1 | 25 | $6{\cdot}5\times10^{4}$ |
| α-Monocerotids | 60 | $+3{\cdot}5$ | $0{\cdot}05$ | $5\times10^{-4}$ | — | — | — |
| Leonids | 71 | $+2$ | $0{\cdot}08$ | $2\times10^{-3}$ | 3 | $8{\cdot}0$ | $2{\cdot}1\times10^{3}$ |

In addition to knowing when a meteor storm or outburst is going to occur, it is also desirable to know something about the characteristics of the stream meteoroids involved. Sekanina (1972), for example, has suggested that it is possible to estimate the radius of the largest meteoroid that might be encountered during a meteor shower. The maximum meteoroid radius is determined by balancing the cometary gas drag equation against the gravitational attraction of the cometary nucleus. Sekanina finds that the important factors controlling the meteoroid ejection process are the heliocentric distance, the nuclear radius, the nuclear temperature and the nuclear rotation rate. If we adopt a temperature of 200 K for the nucleus, a heliocentric distance of 1 AU, and ignore nuclear rotation we find that Sekanina's equation for the radius $r_{max}$ (cm) of the largest meteoroid to be ejected is given by:

$$r_{max} = 25/R_c, \tag{2}$$

where $R_c$ (km) is the nuclear radius. Sekanina's relation, which we estimate to be accurate within a factor of order two, requires some estimate of the cometary nuclear radius. Only one cometary nucleus, that of comet P/Halley, has been resolved visually (Keller, Kramm & Thomas 1988). Radii estimates for all other comets are based upon indirect measurements. Of the parent comets we are interested in four have reasonably well-constrained nuclear radii. We shall discuss these below.

Table V is a summary of the characteristics attributed to the meteoroids associated with the streams listed in Table III. While the geocentric velocities listed in column 2 of Table V are known to a reasonable accuracy of order $\pm 2{\cdot}0$ km $\mathrm{sec}^{-1}$, the other terms listed in Table V are poorly constrained. The average visual magnitude, $\langle M_v \rangle$, for each stream is based upon the observational accounts collected by Kronk (1988). Estimates given are probably accurate to within $\pm 1{\cdot}0$ $M_v$. We have used the relation of Verniani (1973) to calculate meteoroid masses for a given velocity and visual magnitude. Verniani's relation was derived originally for radio meteors, but we find it differs only slightly from the relation derived by Jacchia *et al.* (1965) for average Super-Schmidt photographic meteors. For ease of computation, therefore, we shall use Verniani's relation to determine meteoroid masses irrespective of the mass, velocity and magnitude range. We estimate that the masses calculated with Verniani's formula are accurate to within a factor of 5.

In order to determine $r_{\max}$, we have searched the literature for estimates to the various parent cometary nuclei. Sekanina (1985) estimates that the radius of comet P/Giacobini-Zinner is about 1 km. Marsden (personal communication) has suggested that the nucleus of comet P/Tempel-Tuttle is likely to be about 3 km, while Kamoun, Pettengill & Shapiro (1982) have quoted a value of 2 km for the radius of comet P/Grigg-Skjellerup. We have estimated the nuclear radius of comet P/Swift-Tuttle by first establishing the comet's $H_{10}$ value. $H_{10}$ is the apparent magnitude that the comet would have at distance of 1 AU from the Earth and the Sun, when the heliocentric brightness function is assumed to vary as $r^{-2{\cdot}0}$ (Hughes & Daniels 1983). From the published visual magnitude estimates we find $H_{10} = 5 \pm 1$ $M_v$ for P/Swift-Tuttle. Hughes (1987) has given a relation linking the nuclear radius to $H_{10}$. We find a radius of $7 \pm 2$ km for Comet P/Swift-Tuttle. The mass corresponding to the largest meteoroid radius has been calculated with the assumption that the density is 1 g $\mathrm{cm}^{-3}$. Since the radius of the largest meteoroid for a given stream is not well constrained, we did not deem it worthwhile to establish rigorously each stream's mean meteoroid density. We note, for example, that the Draconid meteoroids are remarkable for their 'fluffy' dust-ball-like quality. Beech (1986) found that the observations indicate a bulk density of the order of $0{\cdot}25$ g $\mathrm{cm}^{-3}$ for the Draconids. This lower Draconid meteoroid density suggests a maximum meteoroid mass one quarter of that given in column 8 of Table V. In contrast to the Draconids, Babadzhanov (1993) suggests that the Perseid meteoroids may have a bulk density of order 4 g $\mathrm{cm}^{-3}$. In this case, the maximum mass entry listed in Table V underestimates the mass of the largest Perseid meteoroid by a factor of order four. Bearing in mind all the qualifying factors discussed above, we suggest that the values presented in Table V should be viewed as representative rather than definitive.

## 6 IMPACT PROBABILITIES WITH SPACE PLATFORMS

The number of sporadic meteoroids, $N_{sp}$, that might be expected to strike a space platform of surface area $A$ (m$^2$) in a time interval $t$ (s), is given by the relation:

$$N_{sp} = \Phi(m, sp)\, At, \tag{3}$$

where $\Phi(m, sp)$ is the flux of sporadic meteoroids of mass $m$, or greater, at 1 AU from the Sun. Estimates of $\Phi(m, sp)$ have been presented by Grün *et al.* (1985) and more recently by Divine (1993). The impact probability, $I_{sp}$, expressed as a percentage, can be calculated trivially from $N_{sp}$ as:

$$I_{sp} = 100 N_{sp}. \tag{4}$$

The number of stream meteoroids, $N_{sh}$, that might impact upon a space platform, is given in the same manner as $N_{sp}$ above. The main difficulty in calculating $N_{sh}$, however, is the lack of any detailed data on the flux of shower meteoroids, $\Phi(m, sh)$. Rather than using the flux of stream meteoroids, we use the stream number density to calculate space platform impact probabilities. Accordingly, we find that $I_{sh}$, the impact probability, expressed as a percentage, from a shower meteoroid is given by:

$$I_{sh} = 10^{-13} n_9\, VAt \tag{5}$$

where $n_9$ is the number density of stream meteoroids capable of producing a meteor of absolute visual magnitude greater than $+6{\cdot}5$ per $10^9$ km$^3$, and $V$ (km sec$^{-1}$) is the velocity of the stream meteoroids. The number density of stream meteoroids can be derived from the observed ZHRs (Koschack & Rëndtel 1990), but only a few streams have been observed visually with sufficient reliability for such calculations to have been made. Koschack & Roggemans (1991b) find, however, that for the Orionid stream $n_9 \approx 2{\cdot}5$ ZHR, while Koschack & Roggemans (1991a) find that $n_9 \approx 1{\cdot}8$ ZHR for the Perseid meteoroid stream. During a meteor storm or outburst we assume that the spatial number density of stream meteoroids will increase in proportion to the observed ZHR. That is, during a storm or an outburst $n_9$ will scale by the ZHR enhancement factor $F$. This critical assumption assumes implicitly that the mass index is the same during a storm as during the regular shower return. If the mass index increases during a storm, as suggested by past observations summarized in Section 5, then the value of $n_9$ will be much larger than that derived by linear scaling the ZHR of the quiet-time value of $n_9$. Thus, the analysis which follows presents the *minimum* increase in $n_9$ which would result.

Figure 1 indicates the spatial number density required of stream meteoroids for an impact probability of 0·1 per cent to result for a space platform of area 100 m$^2$, given an impact velocity $V$ (km sec$^{-1}$), and exposure times $t = 500$, 1000 and 2000 sec. Larger impact probabilities and smaller exposure areas will shift each curve in Fig. 1 linearly upwards in $n_9$. Figure 1 illustrates, for example, that the critical number density for the Orionid meteoroid stream ($V = 66$ km sec$^{-1}$) to produce an impact probability of 0·1 % per cent with a space platform of surface area 100 m$^2$ in a time interval of 500 sec is $n_9 > 3 \times 10^5$. This corresponds to a ZHR of order $10^5$, and implies an enhancement factor $F \approx 5000$.

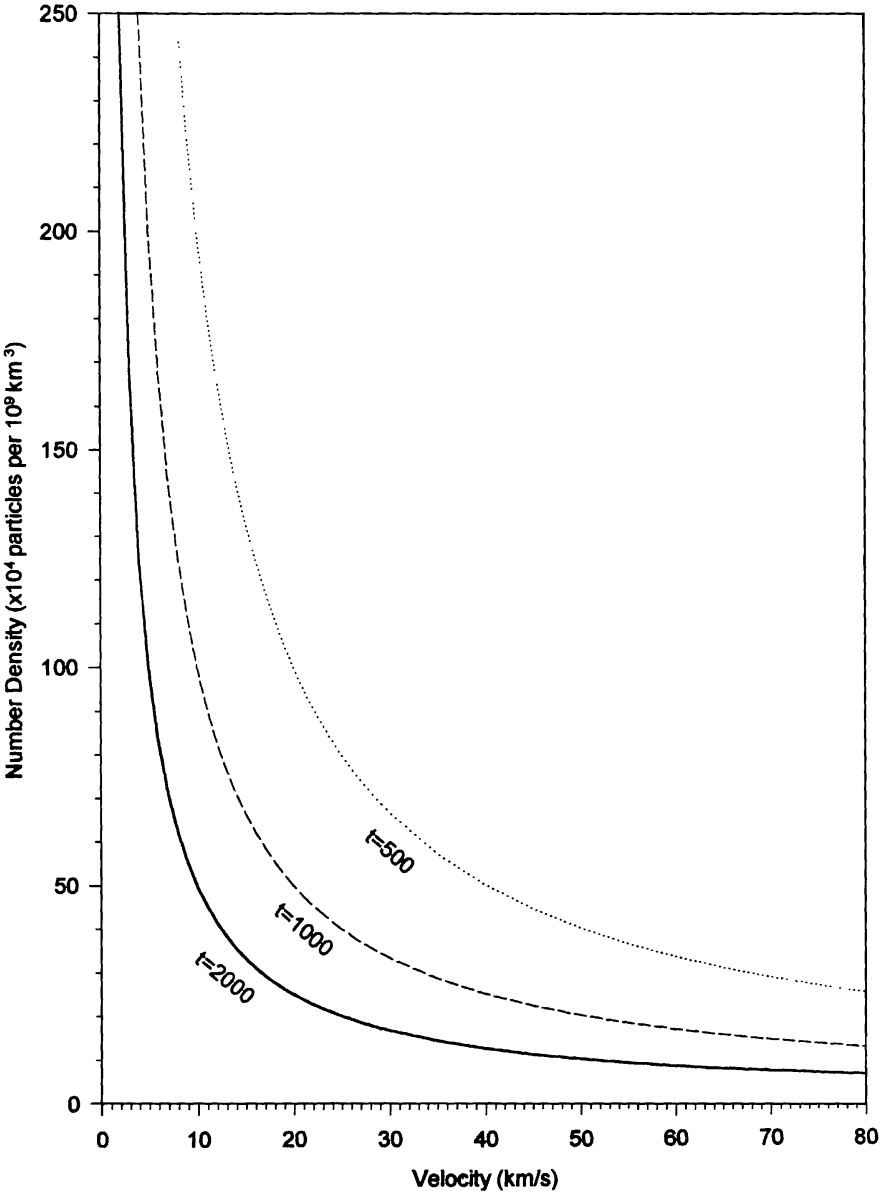

FIG. 1. Critical number density for Ip = 0·1 per cent and $A$ = 100 $m^2$.

The only storm/outburst 'candidate' stream listed in Table IV to have a detailed and directly observed spatial number density is the Perseids (Koschack & Roggemans 1991a). For this stream we can determine the impact probability given a target area, a ZHR enhancement factor, and a storm/outburst time interval. Figure 2 shows the variation of the impact probability with target area given two time intervals of 500 and 2000 sec, and ZHR enhancement factors of $F$ = 10, 100 and 1000. We see from Fig. 2 that if the enhancement factor is 1000, and the target area is 100 m², then a storm of duration 500 sec will produce a Perseid impact probability of 0·06 per cent. The Perseid impact probability can be interpolated in Fig. 2 for a given target area, time interval (2000 > $t$ > 500) and enhancement factor (1000 > $F$ > 10).

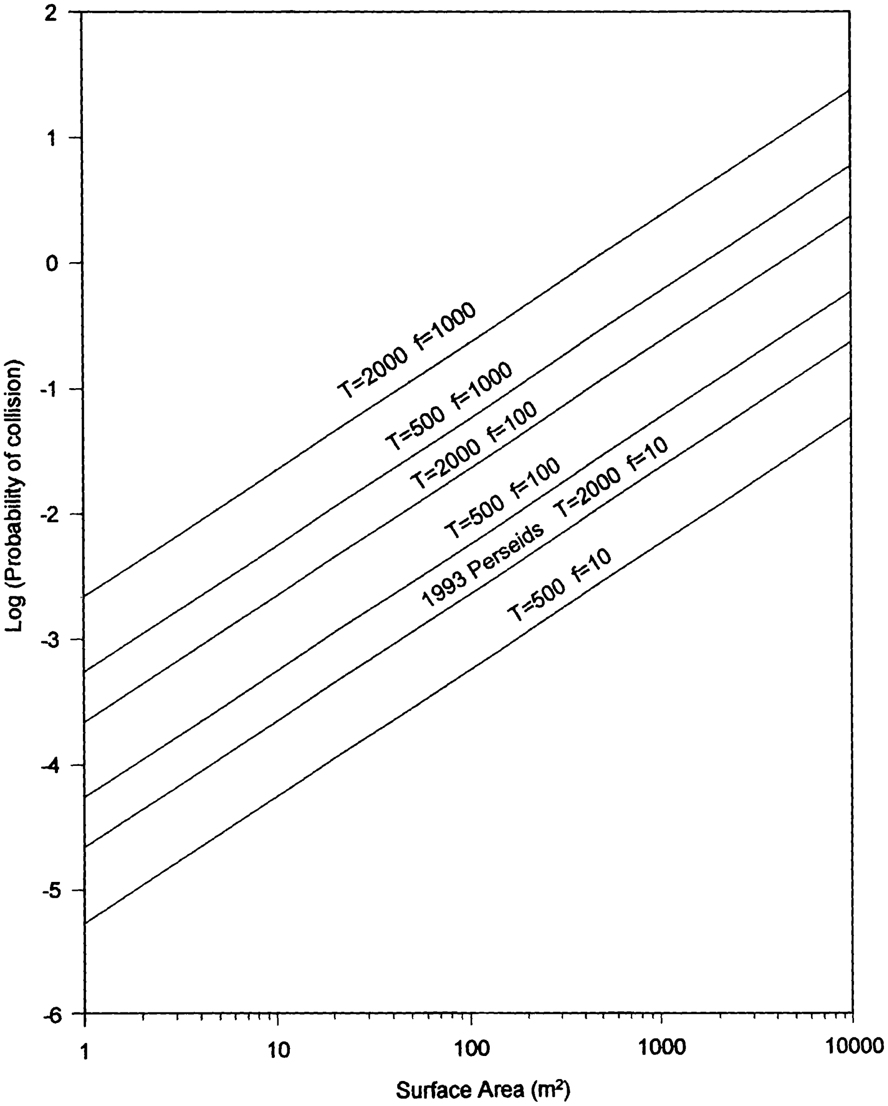

FIG. 2. Collisional probability for the Perseid meteoroid stream.

The derivation of space platform impact probabilities is greatly hampered by our having only a few reliable and direct estimates of meteoroid stream fluxes, spatial number densities and mass indices. It would seem prudent that studies be initiated to determine these parameters. In the short term it would be particularly useful to evaluate the spatial number density for the Leonid meteoroid stream. The frequent storm cycle of this shower (see Table IV), and the very high meteoroid encounter velocity (see Table V), both suggest that this stream poses the greatest near term threat to space platform integrity.

The damage that impacting meteoroids might cause a space platform can be gauged from the study of impact craters displayed by spacecraft retrieved from Earth orbit. Laurance & Brownlee (1986) have found that the diameter, $D$ (cm), of an impact crater scales with the impact velocity, $V$ (km sec$^{-1}$), and mass, $m$ (g), as:

$$D = 1{\cdot}081\ m^{0{\cdot}4}\ V^{0{\cdot}88}. \qquad (6)$$

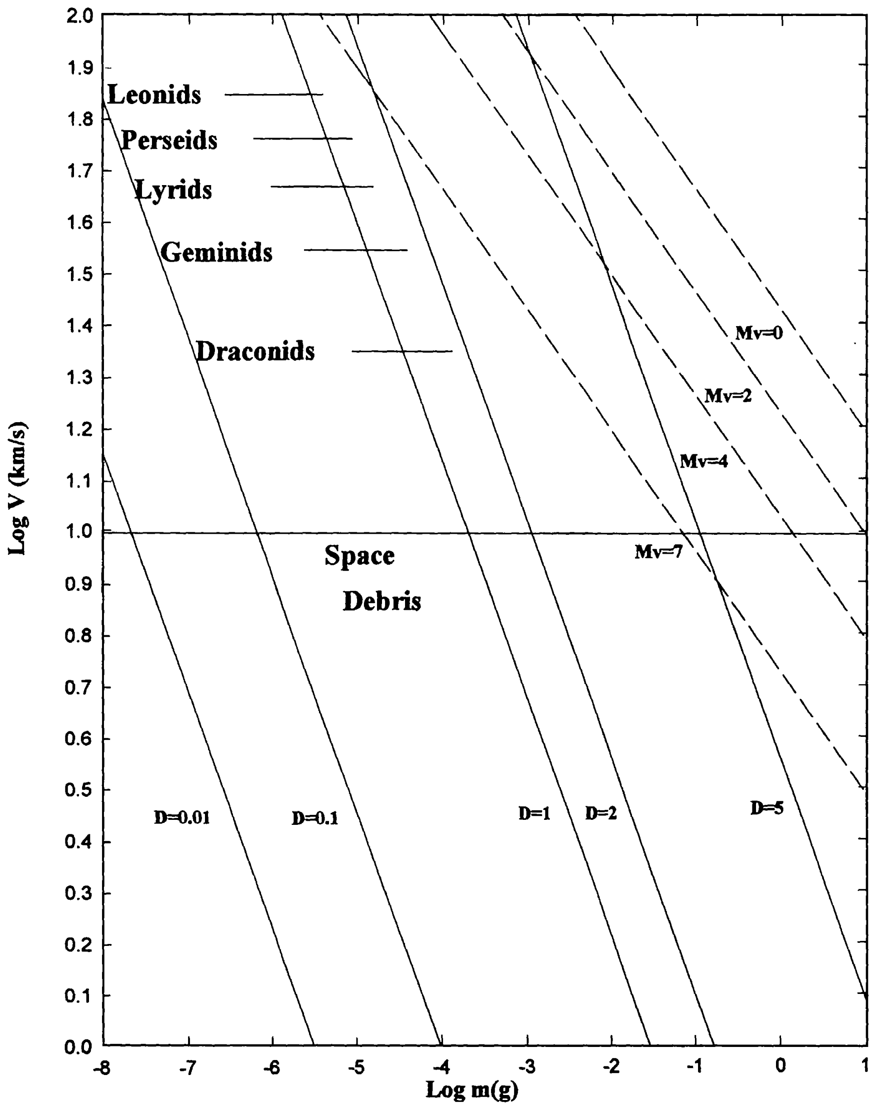

FIG. 3. Loci of constant crater diameter in cm (——), and constant visual magnitude (– – – –).

In deriving this relation a meteoroid density of 1 g $\mathrm{cm}^{-3}$, and an aluminium target have been assumed. The available observations further suggest that the crater depth, $T$, is related to the crater diameter by a relation of the form:

$$T \approx 0{\cdot}62D. \tag{7}$$

Loci of constant crater diameter are shown in the meteoroid velocity–meteoroid mass plane in Fig. 3. Also shown in the figure are loci of constant apparent visual magnitude. The apparent visual magnitude, $M_v$, is calculated according to the formula of Verniani (1973). Many formulae have been published relating impact crater diameter to collisional parameters (see, for example, the review by Kysar 1990). The relation derived by Laurance & Brownlee (1986) is representative of the crater diameter formulae, and admirably serves our purpose of illustration.

The impact velocities associated with stream meteoroids are between two and seven times higher than those associated with space debris (Kessler 1991). On an equivalent mass basis, therefore, meteoroid impacts will cause greater structural damage than that from space debris. Even low mass, microgram meteoroids (see Fig. 3) can be expected to produce craters of several centimetres in diameter in an aluminium target. Craters of this magnitude will almost certainly result in substantial satellite damage.

## 7 POSSIBLE DAMAGE TO SPACE PLATFORMS AND MITIGATION SCENARIOS

The space debris and meteoroid impact bumpers to be flown on the proposed Space Station are being designed according to the concept of a critical mass impact. It has been proposed that Space Station shielding be able to withstand a direct impact from a 1 cm diameter aluminium sphere travelling at 10 km $\sec^{-1}$ (Potter *et al.* 1991, Lambert 1993, Christiansen *et al.* 1993). We call this the critical space debris sphere (CSDS). This lower size limit has been set with the understanding that collision avoidance manoeuvres can be performed for larger pieces of space debris (Christiansen *et al.* 1993). We note in passing that while it is possible in principle to manoeuvre around large pieces of artificial space debris, no such manoeuvres could be performed to avoid large meteoroid collisions. Reasons for this impasse are the non-circular, non-repetitive orbits of meteoroids in the near-Earth environment, and the very short lead time that would presage a direct meteoroid impact on a space platform.

A CSDS has a mass of order 0·5 g, and can impart $2{\cdot}5 \times 10^{11}$ ergs of kinetic energy upon impact. The impact energy of the CSDS can be used to determine a critical stream meteoroid mass (CSMM). Any stream meteoroid with a mass in excess of the CSMM will have sufficient kinetic energy to exceed the shielding limit set for the Space Station. We have plotted in Fig. 4 the kinetic energy versus meteoroid mass for the streams listed in Table V. The CSMMs can be determined from this figure according to the CSDS limit. The CSMMs and their equivalent visual magnitudes are given in Table VI. The CSMMs for the Perseid and Leonid streams, which have very high encounter velocities, are found to be roughly 10 mg.

To ascertain the impact probability of CSMMs with space platforms, an assessment of the meteoroid mass distribution has to be made. The mass distribution index, $s$, is defined so that the number of meteoroids, $dN$, in the mass range $M$ to $M + dM$ is given by the relation $dN = kM^{-s}\, dM$, where $K$ is a constant. The mass distribution index can be derived from the observed magnitude distribution of stream meteors. The observations suggest that typically $2{\cdot}5 > s > 1{\cdot}5$ for meteoroid streams (McKinley 1961). We define the minimum meteoroid mass, $M_{\min}$, to be the mass of a stream meteoroid that will produce a meteor of absolute visual magnitude $+6{\cdot}5$. With this definition, the minimum meteoroid mass is consistent with the lower luminosity limit used to derive $n_9$, the stream's spatial number density. The upper mass limit, $M_{\max}$, discussed in Section 5, is defined according to the limit set by the gas-drag equation. If $N_{\text{tot}}$ is the total number of stream meteoroids with masses between $M_{\min}$ and $M_{\max}$, $N(M)$ is the number of stream meteoroids with

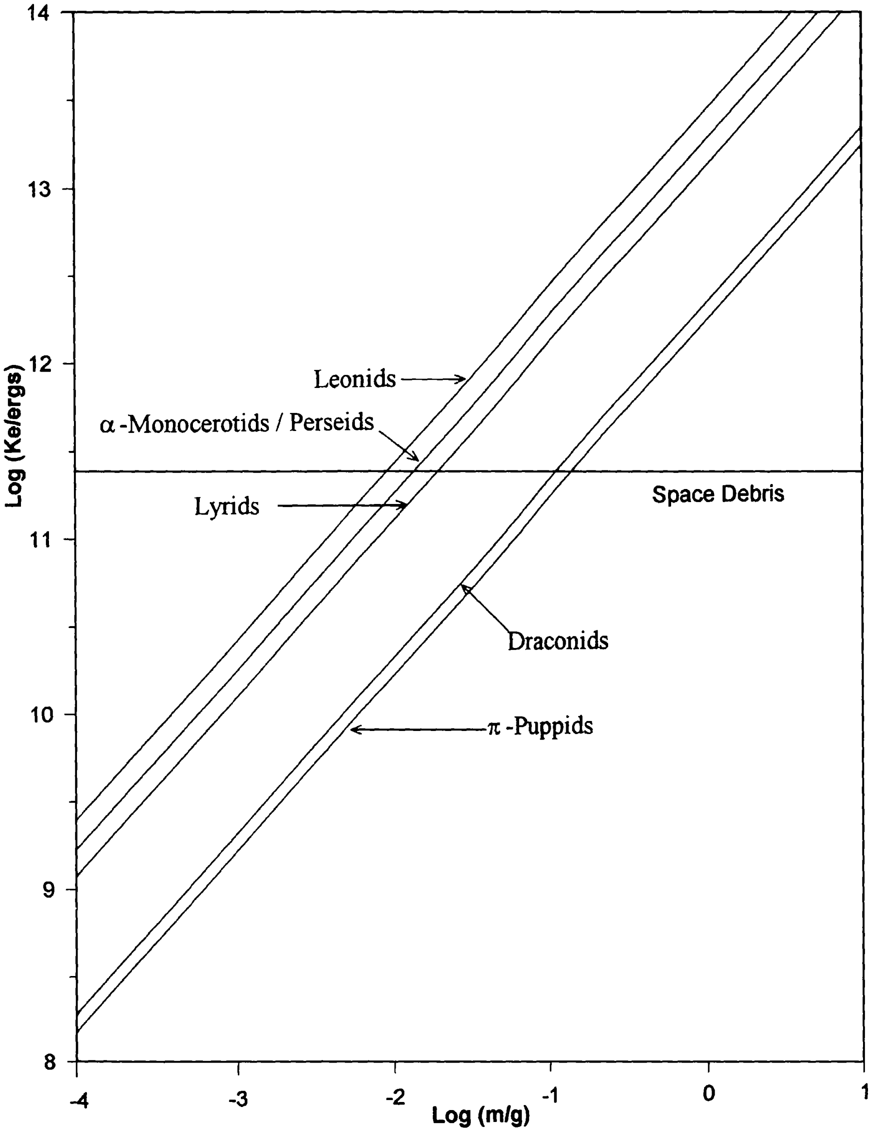

FIG. 4. Kinetic energy content of stream meteoroids. The line labelled space debris corresponds to the CSDS.

TABLE VI

*Masses and corresponding visual magnitude of CSMM meteoroids*

| Stream | Critical mass (gm) | $M_{\mathrm{v,crit}}$ |
|---|---|---|
| Lyrids | $1{\cdot}9 \times 10^{-2}$ | 1·5 |
| π-Puppids | 0·2 | 3·0 |
| Perseids | $1{\cdot}4 \times 10^{-2}$ | 1·0 |
| Draconids | 0·1 | 3·5 |
| α-Monocerotids | $1{\cdot}4 \times 10^{-2}$ | 1·0 |
| Leonids | $1{\cdot}1 \times 10^{-2}$ | 1·0 |

TABLE VII

*The percentage distribution of stream meteoroids of mass greater than the CSMM for the selected values of the stream mass index (s)*

| Stream | N(M)/NT [%]<br>$s =$ 1·50 | 1·75 | 2·00 | 2·25 | 2·50 |
|---|---|---|---|---|---|
| π-Puppids | 21·0 | 9·7 | 4·4 | 2·0 | 0·9 |
| Perseids | 6·3 | 1·6 | 0·4 | 0·1 | 0·03 |
| Draconids | 23·8 | 11·6 | 5·7 | 2·8 | 1·3 |
| Leonids | 6·8 | 1·8 | 0·5 | 0·1 | 0·03 |

masses between the CSMM and $M_{\max}$, and assuming that the mass index is constant in the mass range $M_{\min}$ to $M_{\max}$, then we have:

$$N(M)/N_{\text{tot}} = (M^{1-s} - M_{\max}{}^{1-s})/(M_{\min}{}^{1-s} - M_{\max}{}^{1-s}). \tag{8}$$

Table VII shows the percentage of stream meteoroids with masses between the CSMM and $M_{\max}$ for selected values of the mass index. It can be seen from Table VII that the number of meteoroids in the critical mass range decreases as the mass index increases as expected. Table VII also indicates, for example, that for the Perseid meteoroid stream, which has a mass index of about 2, something like 1 per cent of the stream meteoroids which produce meteors in the visual magnitude range have a mass in excess of the CSMM.

The probability of no penetrating impacts, PNPI, is determined through the exponential distribution and is given by:

$$\text{PNPI} = \text{e}^{-N_c A t}, \tag{9}$$

where $N_c$ is the flux of stream meteoroids with a mass in excess of the CSMM. $N_c$ can be evaluated from the stream meteoroid number density, $n_9$, the velocity of the stream meteoroids, $V$, and a factor, $f_s$, accounting for the percentage of meteoroids with masses greater than the CSMM. This latter factor can be gauged from Table VII according to an assumed mass index.

As a case study we shall consider the PNPI for the Perseid meteoroid stream. Since the number density, and velocity of Perseid meteoroids are well known, the flux of penetrating Perseid meteoroids is:

$$N_c = 1{\cdot}06 \times 10^{-11} f_s F, \tag{10}$$

where $F$ is the storm/outburst enhancement factor. Given that the Perseid mass index during normal returns is about 2 (Kaiser, Poole & Webster 1966) $f_s$ will be 0·005. Note that this represents an effective upper limit for $f_s$ as the best documented meteor storms show lower than normal mass indices (cf. Porubčan & Štohl 1992). With the very small flux of meteoroids with masses in excess of the Perseid CSMM, the PNPI will be entirely negligible for all but the largest of space platforms, with the largest exposure times, and the greatest of enhancement factors. Table VIII shows the PNPI for what might be considered a worst case Perseid meteor storm scenario ($F = 1000$). The best odds for a critical impact occurring during a Perseid meteor storm lasting 1 h, upon a space platform with a surface area of 1000 m$^2$ are about 1 in 5000. This result suggests that while some impacts are highly likely during a strong Perseid storm, the chances of a critical impact occurring are small.

TABLE VIII

*Probability of no penetrative impacts (PNPI) for Perseid meteoroids of mass greater than the CSMM. An enhancement factor of 1000 has been assumed in the worst case scenario. The Space Shuttle, HST and the Long-Duration Exposure Facility are examples of space platforms with exposure areas of about 100 m$^2$. The MIR-1 Space Station has an exposure area of about 500 m$^2$*

| Duration (sec) | | PNPI [%] | | |
|---|---|---|---|---|
| | Area (m$^2$) = | 100 | 500 | 1000 |
| 1000 | | 99·9995 | 99·9973 | 99·9947 |
| 2000 | | 99·9989 | 99·9947 | 99·9894 |
| 3000 | | 99·9984 | 99·9920 | 99·9841 |
| 4000 | | 99·9979 | 99·9894 | 99·9788 |

The shielding requirements of space platforms in general are not as stringent as those stipulated for the proposed Space Station. Consequently the critical impact threshold for the vast majority of space platforms will be exceeded at meteoroid masses much lower than the CSMMs listed in Table V.

Meteoroid-space platform collisions fall under the category of hypervelocity impacts. In this regime the impact generated pressure will greatly exceed the material strength of the meteoroid and the target. Both impact components will therefore behave as fluids rather than solids during the collisional encounter (Kysar 1990). Upon impact, the catastrophically fragmented meteoroid, and the crater spall form a rapidly expanding debris cloud. For habitable space structures it is the collisional ejecta, rather than the puncturing of a small hole that present the greatest threat to life. Very early on it was realized that the most efficient way to protect a space platform from collisional damage was to place a thin 'bumper' shield around the main structural bulkheads. Such 'bumpers' are commonly called 'Whipple Shields', after the astronomer Fred Whipple who first suggested their use in 1946 (Whipple 1947).

The essential idea behind the Whipple Shield is to fragment a meteoroid before it can impact directly upon a critical space platform component. Many variants of the original Whipple Shield have been developed. The main design variables are the number of thin, pre-bulkhead shields, the spacing of the shields and the composition of the shield material. It has also been found that considerable mass savings can be made by using specialized materials such as Kevlar, Nextel and Spectra fabrics (Kysar 1990, Christiansen *et al.* 1993, Lambert 1993). Reynolds & Emmons (1964) have further shown that injecting low density foam between the shield plate and the bulkhead offers a considerable improvement in penetrative protection.

There are no compelling reasons to suggest that stronger impact shields be added to all new space platforms on the off-chance that a meteor storm might occur during their operational life time. Rather, it seems more prudent to establish a series of Risk Curtailment Scenarios (RCS). The simplest RCS minimizes the surface area that a space platform exposes to the stream radiant, and is the one employed by the HST Mission Controllers during the 1993 and 1994 outbursts of the Perseid meteoroid stream. No noticeable impacts were recorded on the HST during the Perseid outburst, and this minimal RCS can easily be employed again. If it is not possible to perform minimizing surface area manoeuvres, as, for example, with the MIR-1 Space Station, a more direct RCS will be required. Under extreme conditions it may be desirable to deploy an umbrella-like foil-shield in the direction of the stream radiant to serve as an extra meteoroid 'bumper', thereby providing some measure of extra space platform protection. The foil-shield could either be built into the substructure of the space platform, along the lines proposed by Redmon *et al.* (1991), or deployed as a temporary structure during an EVA. Since the foil-shield should ideally protect as much of the space platform as possible, it might be desirable to develop a rotating foil system, similar to the rotating mirror flown onboard the MIR-1 Space Station in 1992. A rotation stabilized foil would require fewer structural supports per unit area than a foil blanket, and would be more easily deployed, and retrieved.

The application of a deployable shield RCS will not only protect a space platform against direct impacts, it will also reduce the inevitable impact erosion that would occur during a meteoroid storm. Indeed, the very friable meteoroids associated with a meteor storm may be prone to electrostatic disruption in the neighbourhood of Earth (cf. Rhee 1976). This disruption would create a wide cloud of smaller debris, a sort of 'Cosmic Buckshot'-effect which could make even small outbursts highly erosive to space platforms. The deployable shield RCS will not protect a space platform from large (masses greater than the stream CSMM) meteoroid impacts. Indeed, very little can be done to protect a space platform from such impacts. Provided the storm or outburst is of a short duration it may be possible to position the space platform on the opposite side of the Earth to the stream radiant. This Earth-shielding RCS certainly offers the greatest protection from meteoroid impacts, but will be impractical under many circumstances.

## 8 CONCLUDING REMARKS

When they occur, meteor storms must surely rank among the most spectacular of heavenly displays. They are also one of the most poorly understood phenomena in our Solar System both observationally and theoretically. In this paper we have attempted to review and assess the near term prospects for the occurrence of meteor storms and outbursts. Of these two, meteor storms are deemed to be the most dangerous to Earth-orbiting satellites. The historical record suggests that on average a few meteor storms can be expected to occur per century. The meteor storm rate during the past two centuries, however, has been especially high. We do not necessarily believe that the near-term meteor storm rate will rival that of the 19th century, although our assessment does reveal (see Table III) that several meteor storms and/or outbursts are likely to occur before the end of this century.

The most likely meteoroid stream to produce a meteor storm in the next decade is the Leonid meteoroid stream. The probability that this stream will yield at least one meteor storm between 1998 November and 2000 November appears to be quite high according to recent studies and we suggest that space agencies should begin the development of RCSs immediately.

The last great meteor storm occurred 28 years ago and at that time the exploration of the near-Earth environment had hardly begun. When the next storm occurs the likelihood of some space platforms being damaged is, we believe, high. Indeed, it is our general belief that one of the greatest threats to the ability of space platforms to survive over time scales of order decades is the occurrence of meteor storms.

## ACKNOWLEDGEMENTS

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## APPENDIX

Brief notes on the individual meteoroid streams listed in Table III.

### (1) *The Lyrids*

The Lyrid meteor shower is active at present from April 16 to April 25, with a short-lived, 1–2 h, shower maximum on April 22. The peak ZHR is variable from year to year, but is typically of order 10 $h^{-1}$. Activity from the Lyrid meteoroid stream has been noted as far back as 687 BC (Hasegawa 1993), making the Lyrids the oldest known meteor shower. Lyrid outbursts were recorded in 1982, 1946, 1934 and 1922, suggesting that outbursts are likely to occur in a 12-year cycle (Guth 1947). The material responsible for the Lyrid outbursts is apparently not directly associated with the stream's parent comet, Comet P/Thatcher, which has a period of 415 years. Porubčan & Štohl (1992) suggest that the meteoroids encountered during the outbursts are associated with the decay of a fragment which broke off from the parent comet some $10^4$ years ago. Activity amounting to storm level was recorded for the Lyrids in 1803 (Table I), and a storm is inferred from the historic record (Table II) to have occurred in 1122 (Hasegawa 1993). Enhanced Lyrid rates were reported by several observers in 1994 (Lunsford 1994). It is not presently clear if a true outburst occurred because of a lack of observer coverage.

### (2) *The Perseids*

In the current epoch the Perseid meteor shower is active between July 17 and August 24 and presently displays two maxima. In 1993 the first maximum associated with the high-activity 'spike' occurred at August 12, 03:20 UT (Brown & Rëndtel 1994). The second maximum occurred at August 12, 15 h UT. The 1993 first 'outburst' maxima had an $F$ value of about 3. In 1994 the outburst took place on August 12 at 11:00 UT with an $F$ value of 2·5. It has been suggested that the meteoroids associated with the recent Perseid outbursts were ejected during comet P/Swift-Tuttle's 1862 perihelion passage (Wu & Williams 1993), though it is possible that some of the material is substantially older than this. Outbursts can be expected from the Perseid stream until at least the end of this century, with the chance of a meteor storm being slight in any of these years. Jones *et al.* (1995) also suggest that outbursts can be expected for the Perseids in the first decade of the next century with peak activity above what is currently being experienced.

### (3) *The Monocerotids*

The November-, or α-Monocerotids are believed to be active from November 15–25, with a short-lived, of the order of 15 min maximum on the night of November 20. There is some, as yet inconclusive evidence to support the idea that the shower undergoes a 10-year outburst cycle (Kronk 1988). Kresák (1958) has suggested that the stream is derived from Comet van Gent-Peltier-Daimaca (1944 I).

### (4) *The Leonids*

Activity from the Leonid meteor shower can be detected in the present epoch from November 14–21. The shower maximum presently occurs on November 17, with a typical ZHR of about 15 (Brown 1992). Historically, the Leonid meteoroid stream has dominated the meteor storm record. Of the 25 storms, and storm candidate events listed in Table II, 11 relate to the Leonids. The Leonid stream is associated with Comet P/Tempel-Tuttle and has historically displayed a 33-year storm/outburst cycle (Yeomans 1981). Comet P/Tempel-Tuttle is due to pass perihelion in 1998 February. Leonid storm activity is highly likely in the time-window several years either side of P/Tempel-Tuttle's next perihelion date (Brown & Jones 1993, Beech & Brown 1994).

### (5) *The π-Puppids*

Meteors from this stream were first observed in 1972 (Kronk 1988). The meteoroids are associated with Comet P/Grigg-Skjellerup which was discovered in 1902. π-Puppid meteors are observed from April 15–28, with a maximum occurring on April 23. The peak ZHR is apparently variable, but rates of the order of 40 $\mathrm{h}^{-1}$ have been recorded. High meteor rates were detected from this stream in 1977, 1982 and 1987 (Hughes 1992). These years correspond to the times at which the parent comet was at perihelion. P/Grigg-Skjellerup next passes perihelion in 1997.

### (6) *The Draconids*

The Draconids are normally active between October 6 and 10 each year. The shower reaches a short-lived maximum of a few hours on October 10. The peak rate is highly variable. Noticeable numbers of meteors are recorded from this stream only when the parent comet, Comet P/Giacobini-Zinner, is near perihelion, with the best displays occurring when the Earth is inside and behind the comet. Meteors from the Draconid stream were first observed by W.F.Denning in 1926 (Denning 1926). Comet P/Giacobini-Zinner belongs to the Jupiter family of comets, and has undergone considerable orbital evolution. The Draconid meteoroid stream has likewise shown great variation. In spite of high anticipation, the perihelion passages of

P/Giacobini-Zinner in 1959 and 1972 did not produce any enhanced meteor activity. A Draconid outburst ($F \approx 40$) occurred in 1985 (Koseki 1990). Comet P/Giacobini-Zinner next passes perihelion in 1998.

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