The Running of the Bulls: A review of Taurid fireball activity since 1962

Martin Beech [1,2], Megan Hargrove[2], and Peter Brown[3]

[1] Campion College and [2] Department of Physics, The University of Regina, Regina, SK, Canada S4S 0A2
[3] Department of Physics and Astronomy, The University of Western Ontario, London, ON, Canada N6A 3K7

Model predictions based upon the existence of a 7:2 mean motion resonance with Jupiter suggest that in about 20% of Taurid meteoroid stream encounters enhanced numbers of meteors and fireballs should be seen. Here we examine the veracity of the predictions against a set of six temporally overlapping fireball surveys. It is found that in the time interval from1962 to 2002 enhanced, or at least conspicuous, numbers of Taurid fireballs were recorded on all eight occasions predicted by the resonance-controlled, swarm-encounter model. We find evidence for elevated Taurid activity in 1974 and possibly in 1985 as well, indicative, perhaps, of additional stream structure.

Introduction

The Taurid meteoroid stream is part of the Taurid Complex (TC); an extensive system of dynamically related objects that vary in size from several kilometers across down to dimensions of just a few microns[1, 2, 3]. Visual and photographic studies have revealed that the Taurid meteor shower is active each year from early October to late November[4], with meteors being derived from a double (north and south) radiant structure. The, so-called, Southern Taurids peak on November 6th, while the Northern Taurids reach their maximum ten days later on November 16th. In this paper we make no specific distinction between the two radiant components, and hereafter refer to the shower simply as the Taurids. The annual Taurid activity is typically low, amounting to perhaps ten visual meteors per hour, under good observing conditions, at the times of maximum activity. The shower is well known, however, for delivering bright fireballs[5, 6], and was apparently one of the most conspicuous fireball generating showers of the 11th century[7, 8]. In general we use the term fireball to mean any bright and conspicuous meteor, and, indeed, the survey data sets to be discussed below relate specifically to those meteors that have negative visual magnitudes at peak brightness.

Whipple[9] long ago identified Comet 2P/Encke as the parent comet to the Taurid meteoroid stream, and Jones[10] has more recently argued that the shower's double radiant structure can develop through Jovian gravitational perturbations on a time scale of order 10^4 to 10^5 years. The orbital period of Comet 2P/Encke is some 3.30 years, which is close to the 7:2 Jovian mean motion resonance ($P_{7:2}$ = 3.39 years), and this similarity has apparently proven to be of great significance with respect to the orbital evolution of TC

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meteoroids. Indeed, Asher and Clube[11] have shown that the 7:2 mean motion resonance with Jupiter has restricted the orbital dispersion of a dense swarm of meteoroids within the Taurid stream. The Earth at the present epoch passes through this resonance-produced swarm of meteoroids at intervals corresponding to 3, 4 or 7 years, and at these times enhanced Taurid activity is predicted to occur. Asher and Izumi[12] find that in the time interval from 1972 to 1995, those years in which enhanced Taurid fireball activity is reported (specifically to the Nippon Meteor Society) are in good agreement with the swarm encounter predictions. In this review have we set out to extend the temporal test domain of the model predictions, and to look for features similar to those seen in the Nippon Meteor Society data in other fireball surveys.

In addition to its association with the nighttime Taurid shower, Comet 2P/Encke is also dynamically related to the daytime β-Taurid and ζ-Perseid meteor showers[1, 2] that occur in June of each year. We do not intend to review the yearly activity of these two showers here, but we note that Asher and Clube[11] have also predicted times of elevated activity for the June swarm encounters. Given the daytime nature of these two showers, however, next to no data on their extended temporal activity exists.

A survey of fireball surveys

A total of six temporally overlapping surveys have been examined with respect to gauging annual Taurid activity over the time period from 1962 to 2002. No stringent selection criteria have been applied against the surveys studied; they are mostly published in the readily available astronomical literature, and they simply represent examples of fireball occurrence data gathered through a variety of observational techniques over an extended period of time. Given the diverse collection and analysis methods that apply to the surveys under review, our approach to interpreting the data is qualitative rather than quantitative, and we do not aim to extract a definitive, forty-year history of the Taurid shower from the data.

The normalized annual Taurid activity for each of the surveys selected for study is shown in figure 1. Before attempting to interpret the figure, however, we briefly discuss below the characteristics and *modus operandi* of the various surveys. This being said, we should also, at the very outset, make clear what it is that the survey data shown in figure1 can not reveal. Specifically, the data do not allow for the direct measurement of Taurid fireball fluxes. The various surveys that we consider employ a wide range of detection and analysis techniques and consequently any inter-comparisons between survey results must carry a complex 'baggage' of selection effect difficulties. We must also bear in mind that the surveys themselves suffer from non-completeness in both observing coverage (due, for example, to cloudy conditions) and in data analysis. Indeed, no great significance, other than an indication of the times at which activity peaks apparently occur, can be attached to the data shown in figure 1. Our aim has been to arrange the data from each survey in such a fashion that the relative annual Taurid fireball activity is revealed, and from there to see if any possible correlation between the apparent variation in Taurid activity and the predictions of Asher and Clube[11] is discernible.

The Millman Fireball Archive (MFA)

The MFA contains data on some 2129 visually observed fireballs witnessed from across Canada in the time interval from January 1962 to September 1989. The fireball data was gathered through reports made by a combination of dedicated observers and via serendipitous observations reported by the general public[13]. The MFA curve in figure 1 shows the normalized annual variation in the relative number of fireballs reported between October 1st and November 30th. The fireballs recorded in this time interval will be a combination of Taurid fireballs and sporadic background fireballs. We have removed, whenever the observational details allow for it, the Leonid fireballs from the interval count in each year. The removal of Leonid fireballs was only significant in 1965, when a well attested Leonid outburst occurred[14]. For 1965 we removed a total of 11 fireballs, all deemed to be Leonids, that were observed on the nights of November 16th and 17th. Dividing our Taurid plus sporadic fireball count by the total number of fireballs recorded in each year we arrive at an approximate measure of the relative 'strength' of the Taurid shower from one year to the next. In this evaluation we also assume that the sporadic fireball count is essentially constant in the time window each year. The data in figure 1 has been normalized according to the 1985 observations when out of a total of 63 fireballs reported during the year, some 27 were observed between October 1st and November 30th.

We present relative annual activity for the MFA survey (and where possible for the other surveys) since it provides some measure of the observational efficiency for the year. Not just the MFA, but all of the surveys consider in this review had 'good' and 'bad' years with respect to weather conditions, equipment function, operational funding and staffing levels to perform data analysis. Certainly, the relative annual activity is not an ideal measure, but given the tenet of this review it does, we would argue, provide some indication as to the overall 'observational impact' of the Taurid display from one year to the next.

The Nippon Meteor Society (NMS)

Two fireball survey data sets have been gathered from the NMS. The first data set is taken from column 3 of table 1in ref. (12), and these correspond to the total number of Taurid fireballs reported to the NMS between October 1st to November 30th in each year from 1972 to 1995. Since we do not have annual activity information, the curve in figure 1 (solid line and dots) shows the normalized annual counts. The data being normalized to the 1988 observations when 16 Taurid fireballs were reported in the specified time window. Further, Yasuo Shiba has kindly provided us with an additional set of fireball reports from the NMS archives. This second data set covers the reported fireball activity in the time span from 1994 to 2002. We have extracted and counted those fireballs that are identified as being probable Taurids and the normalized annual activity (dashed line and squares) is shown in figure 1. The data are normalized to the 1998 observations when 76 Taurid fireballs were reported to the NMS. We treat this latter data set as being independent of the Asher and Izumi[12] list, and although there is a 2-year overlap in the data sets we have normalize them separately.

The Prairie Network (PN)

The PN was comprised of 16 wide-angle camera stations distributed throughout the central planes of the United States of America. Operational from 1964 to the close of 1974 the PN cameras monitored fireball activity over a sky area of 1.14 x 10^6 km^2. In total, the PN cameras recorded some 2700 multiply imaged fireballs, and McCrosky, Shao and Posen[15] published a summary of the orbital characteristics deduced for 334 of them. The orbital data relates to the brightest (typically brighter than magnitude –8) and 'best observed' fireball events and while Perseid, Leonid and Gemind fireballs were specifically excluded from their analysis, the Taurids were singled out for special attention. We have determined the ratio of the annual Taurid fireball counts to the yearly totals, and these are shown in a normalized form in figure 1. The data are normalized to the 1965 observations when, out of a total of 37 fireball orbits reduced, 5 were deemed to belong to the Taurid stream.

Meteorite Observation and Recovery Program (MORP)

The MORP was a network of 12 camera stations distributed across the Prairie Provinces of Canada[16] that monitored fireball activity over a sky area of some 8.3 x 10^5 km^2. Halliday, Griffin and Blackwell[17] present a detailed analysis of 213 MORP recorded fireball events observed in the time interval from 1971 to 1985. Orbital characteristics were derived for each of the 213 fireballs and 23 were deemed to be from the Taurid stream [see table 3 of ref. (17)]. The normalized variation in the ratio of the annual Taurid fireball count to the yearly total of fireballs is shown in figure 1. The data are normalized to the 1981 observations when, out of a total of 31 fireball orbits reduced, 9 were found to be Taurid stream members.

Photographic survey by S. J. Evans (SJE)

Evans[18] has discussed the variation of Taurid fireball activity over the time interval from 1982 to 1991. Using a battery of cameras aligned so as to monitor a band stretching around the entire sky at elevations between 30 and 70 degrees, fireballs typically brighter than magnitude –1 were recorded. In figure 1 we show the normalized variation in the ratio of the Taurid count to the total number of fireballs recorded by the system per year. The data are normalized to the 1988 observations in which year, out of a total of 10 fireballs photographed, 8 were deemed to be Taurids.

Space Based Sensors (SBS)

Since the early 1970's the United States Department of Defense and Department of Energy have used space-based optical and infrared sensors, placed into geostationary orbit, to monitor the Earth's atmosphere for the signatures of nuclear explosions[19, 20, 21]. The exact properties and operation of the detectors used onboard the satellite systems is classified information, but the limiting brightness for fireball detection is reported to be of order magnitude –17. The actual fireball detection rate by the satellite systems is also classified, but we have been able to ascertain that in the period from 1973 to 2001 at least 40 fireball events have been recorded at times and locations where the Taurid radiant would have been above the local horizon. We note here two important points with respect to the satellite data: firstly, since we do not have any orbital information at our disposal the imposed radiant selection condition only allows us to assign a provisional Taurid candidacy to the events observed. Secondly, since the reporting and detection rate history for the satellite systems is not accessible to us, we can not place any great trust in the reality of the deduced annual variations. The normalized, provisional Taurid fireball count for each year is shown in figure 1. The data are normalized to the 1996 and 1998 observations when, in both years, 7 provisional Taurid fireballs were observed.

Discussion of survey findings

The survey results shown in figure 1 are based upon a wide variety of observing techniques and upon various conditions for identifying Taurid stream candidacy. The MFA data is based purely upon the time of fireball detection (i.e., occurring between October 1st and November 30th) with a correction being made for Leonid fireball candidates only. While the PN and MORP Taurid data sets are derived according to measured orbital parameters they suffer from being based upon a small subset of the total number of fireballs recorded. In addition, while approximately the same total number of fireballs are analyzed per year (of order 20) in the MORP data set, the PN annual totals vary significantly (from as low as 7 per year too as high as 83). The NMS and JSE data are derived according to the time of detection and from an estimated association with the Taurid radiant. The SBS data have a time of arrival and radiant height condition applied to them, but suffer from an incomplete knowledge of the orbital parameters and reporting efficiency. In addition to the variant Taurid candidacy conditions that apply to the surveys, there is also the issue of what Taurid meteoroid population is being sampled. The SBS data relates to Taurids brighter than peak magnitude –17, while the MFA, NMS and JSE data relate to Taurids brighter than a peak magnitude of approximately –1. The MORP and PN Taurids are all brighter than magnitude –5. Suffice it to say that the satellite-detected fireballs will be much larger, and hence more massive, than the fireballs reported in the other surveys.

With all of the above being said, only a very broad and non-specific activity variation can be deduced from the combined data shown in figure 1. Asher and Clube[11] predict that 8 Taurid outbursts (that is, swarm encounters) should occur in the time interval between 1962 and 2002 (see the vertical dashed lines in figure 1). It is the accuracy of this prediction that we wish to test against the collected survey data. While there is no formal, or even agreed upon definition of the term outburst, we use it here (admittedly rather loosely) to identify those years in which distinct and perhaps exceptional Taurid fireball activity has been observed. Ostensibly this means identifying those years in which activity peaks are seen in figure 1 in preferably more than one survey data set. In addition, we note that Asher and Clube[11] provide swarm encounter predictions, they do not, as such, predict what level of Taurid activity might be produced. Indeed, we should bear in mind that the TC swarm is not considered to be specifically large meteoroid (and hence fireball producing) rich. Rather, the proportion of fireball producing meteoroids is essentially constant within the stream[6] from one year to the next. It is, however, the detection of heightened fireball activity (they are, after all, more conspicuous and easier to observe that ordinary meteors) that betrays the fact that the overall Taurid rates are elevated.

Enhanced Taurid numbers are evident in the MFA data for 1964, while the PN data indicates enhanced fireball numbers for 1965. The PN Taurid count for 1964 is actually zero, but we note that only 7 fireball orbits were reduced for the entire year. In contrast, 37 meteor orbits were reduced for 1965, of which 5 were found to be Taurids. We would suggest, therefore, that the total PN sample for 1964 was simply too small to reveal any distinctive Taurid outburst activity – alternatively, perhaps no truly bright and distinctive Taurid fireballs were produced in that year (the threshold for PN registration was brighter than magnitude –8). The Taurid outburst predicted for 1971 is evident in the MFA data, but entirely absent in the PN data. We note, however, that only 16 PN recorded fireball orbits were reduced for all of 1971. The Taurid outburst for 1978 is evident in the MFA, NMS and MORP data. The outburst for 1981 is strongly evident in the MFA and MORP data, weakly evident in the NMS data, and entirely absent in the SBS data. The 1988 outburst is clearly evident in the MFA, NMS, SBS and JSE data sets. The 1991 outburst is evident in the NMS, SBS data sets, and possible evident in the JSE data set. The 1995 Taurid outburst is evident in the NMS data, but it is not evident in the SBS data. We note with respect to the 1995 observations, however, that some 10 exceptionally bright Taurid fireballs (all being brighter than magnitude –5, and 5 being brighter than magnitude –9) were photographed by the European Network (EN) of cameras[22] in a time interval of just 16 days. The 1998 Taurid outburst is apparently evident in the SBS data, and is strongly evident in the NMS data (a total of 76 probable Taurid fireballs being reported in that year). McBeath[23, 24] further notes that an increased number of minor (magnitude –3 to –5) Taurid fireballs were reported to the International Meteor Organization in 1998.

The PN, NMS and MORP data sets indicate elevated Taurid activity in 1974, although no swarm encounter was predicted for that year. Slightly enhanced Taurid numbers are also evident in the MFA data for 1974. In contrast, a strong activity peak is evident in the MFA data for 1985. We note, however that in this particular year the annual fireball count for the MFA was fairly small (some 63 fireballs as opposed to the more typical 100); an effect which tends to push the relative Taurid activity term upwards. This being said, the MFA fireball count for October and November in 1985 was definitely elevated compared to surrounding years, there being 27 fireballs reported in 1985 compared to 9 in 1984 and 13 in 1986. The NMS and JSE data sets also indicate slightly elevated Taurid numbers for 1985. While it is not our intention to 'explain away' apparent Taurid activity peaks that do not correspond to predicted swarm encounter years, we do note that comet 2P/Encke was at perihelion in April of 1974 and March of 1984. It may be, therefore, that we are seeing elevated Taurid numbers due to the perihelion return of the comet. Indeed, Asher and Izumi[12] note that Taurid activity is often elevated in the year following the return of 2P/Encke to perihelion. In addition, Asher and Clube[11] predicted elevated activity for the daytime β-Taurid and ζ-Perseid showers in June of 1975 and 1985. In which case the apparently elevated activity levels in the October and November Taurids for 1975 and 1985 may indicate that the spatial distribution of the TC meteoroid swarm is more complex than the model envisioned by Asher and Clube presently allows for.

There are apparent activity 'spikes' in the SBS data set in the years 1980, 1984, 1994, and 1996. There are, however, no corresponding activity peaks in the other contemporaneous surveys, and consequently these 'peaks' are most likely attributable to the intermittent reporting history of the SBS program. Within the context of a study relating to annual fireball activity, it is regrettable that no great reliance can be placed in the SBS survey data since, in principle, it is the one survey that actually monitors fireball (that is, superbolide) activity on a global scale.

In summary, we tentatively suggest that the survey data shown in figure 1 is consistent with there being elevated Taurid activity in all of those years (e.g., 1964, 1971, 1978, 1981, 1988, 1991, 1995 and 1998) predicted by the swarm encounter model of Asher and Clube[11]. In addition, however, a distinct peak of activity is evident in 1974, corresponding to an apparently 'missed' prediction. Likewise, there may have been enhanced levels of Taurid activity in 1985, corresponding, if true, to a second 'missed' prediction.

Discussion

The relatively low visual meteor rates and the relatively long duration of the Taurid shower have made it a very difficult display to quantify[4, 6, 24, 25]. There is some evidence, we would suggest, however, that a number of distinct Taurid fireball outbursts have occurred during the past 42 years, with the enhanced fireball activity indicating by proxy that the Taurid meteor rates as a whole were elevated. Further, it appears that the years in which elevated fireball activity is apparently seen correspond nicely with those years in which Asher and Clube[11] have predicted that TC swarm encounters will take place – the swarm corresponding to meteoroids 'trapped' in a 7:2 mean motion resonance with Jupiter. Indeed, the veracity of the predictions by Asher and Clube is seemingly well established by the available fireball data, and as such they afford us a good opportunity for advanced observational planning given that the next predicted swarm encounter is in November of 2005.

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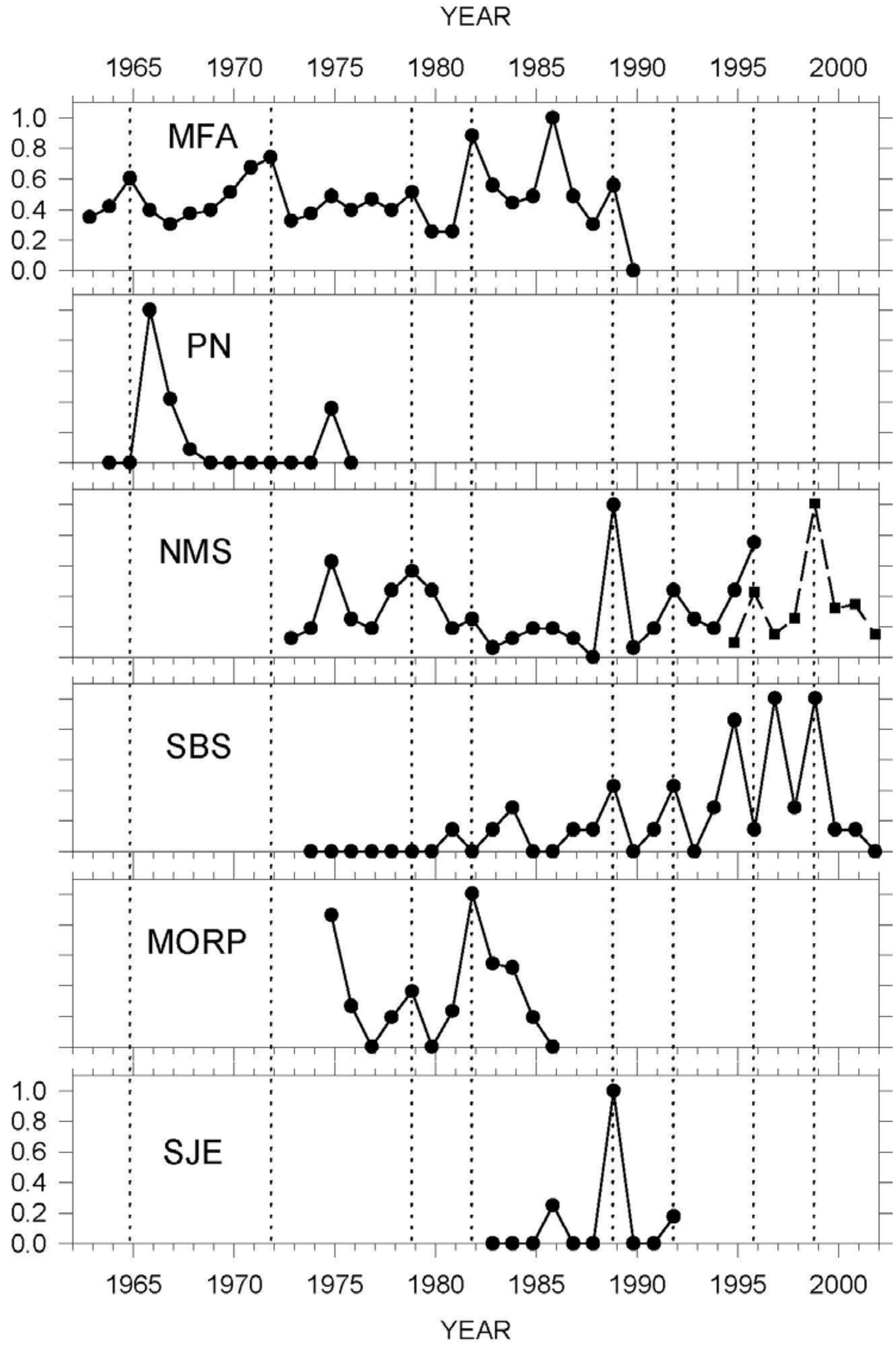
Figure 1:
Normalized annual Taurid activity variations for six independent fireball surveys - see text for survey details and acronyms. The vertical dotted lines correspond to those years in which Asher and Clube[11] predict that TC swarm encounters should take place. Note, on each x-axis the data points are plotted according to the fractional part of the year for November 1st (i.e., November 1st, 1962 ≡ 1962.84).



YEAR
1965
1970
1975
1980
1985
1990
1995
2000
1.0
0.8
0.6
0.4
0.2
0.0
MFA
PN
NMS
SBS
MORP
SJE