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MSFC STREAM MODEL PRELIMINARY RESULTS: MODELING RECENT LEONID AND PERSEID ENCOUNTERS

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Abstract. The cometary meteoroid ejection model of Jones and Brown [*Physics, Chemistry, and Dynamics of Interplanetary Dust, ASP Conference Series* **104** (1996b) 137] was used to simulate ejection from comets 55P/Tempel-Tuttle during the last 12 revolutions, and the last 9 apparitions of 109P/Swift-Tuttle. Using cometary ephemerides generated by the Jet Propulsion Laboratory's (JPL) HORIZONS Solar System Data and Ephemeris Computation Service, two independent ejection schemes were simulated. In the first case, ejection was simulated in 1 h time steps along the comet's orbit while it was within 2.5 AU of the Sun. In the second case, ejection was simulated to occur at the hour the comet reached perihelion. A 4th order variable step-size Runge–Kutta integrator was then used to integrate meteoroid position and velocity forward in time, accounting for the effects of radiation pressure, Poynting–Robertson drag, and the gravitational forces of the planets, which were computed using JPL's DE406 planetary ephemerides. An impact parameter (IP) was computed for each particle approaching the Earth to create a flux profile, and the results compared to observations of the 1998 and 1999 Leonid showers, and the 1993 and 2004 Perseids.

Keywords: Comet, comet ejection, Leonids, meteor, meteor shower, meteoroids, model predictions, numerical integration, Perseids

1. Introduction

The Marshall Space Flight Center (MSFC) meteoroid stream model simulates particle ejection and subsequent evolution from comets in order to provide meteor shower forcasts to spacecraft operators for hazard mitigation and mission planning purposes. This paper is concerned with simulating the evolution of the Leonid and Perseid streams associated with comets 55P/Tempel-Tuttle and 109P/Swift-Tuttle, respectively. The model is in a fairly early phase of development, thus the results reported here are preliminary. The immediate aim was to compare the peak solar longitudes resulting from the model with observations of past Leonid and Perseid encounters.

2. Model

2.1. OVERVIEW

In modeling particle ejection and subsequent evolution from comets Tempel-Tuttle and Swift-Tuttle, the workload is broken into three parts. First the test particles are created, then their positions and velocities are integrated forward in time, and finally the particles are extracted at specific times of interest.

At the first step, the JPL HORIZONS Solar System Data and Ephemeris Computation Service is used to create cometary ephemerides. Particle state vectors are generated for each line in the ephemeris while their physical properties are determined from a uniform, random draw on log β, where β is the ratio of radiation pressure to the Sun's gravitation, and an assumed density. Two separate ejection schemes (two sets of state vectors) are simulated: Timestep and Perihelion. Ejection is simulated in 1 h time steps along the comet's orbit while it is within 2.5 AU of the Sun, hereafter referred to as the Timestep case. Ejection occurring only at the hour of perihelion passage is referred to as the Perihelion case. The model of Jones and Brown (1996b) is used to determine particle ejection velocity. The particle velocity far from the comet is given by

$$V_\infty = 41.7(\sin(\alpha/2))^{0.37}(\cos z)^{0.519}R_c^{1/2}m^{-1/6}\rho^{-1/3}r_h^{-1.038}$$

where α is the semi-angle of the spherical cap of ejection, z is the local solar zenith angle, R_c is the comet radius, m is the particle mass, ρ is the particle density, and r_h is heliocentric distance. Sublimation is taken to occur on the day side of the comet within a constrained cap angle (α); for further description of the cap angle and the other parameters, the reader is referred to Jones and Brown (1996b) and Jones (1995). Other studies (e.g. Brown and Jones, 1998; Göckel and Jehn, 2000; Welch, 2003) have investigated this ejection velocity model.

At the second step, a 4th order variable step-size Runge–Kutta integrator is used to integrate meteoroid position and velocity forward in time, accounting for the effects of radiation pressure, Poynting–Robertson drag, and the gravitational influences of 7 planets, Venus through Neptune. JPL's DE406 is used to compute the positions of the planets; interpolation is done via cubic spline. Integration of the particle ensemble is performed on 9 dedicated AMD Athlon[TM] 64-bit FX processors. The CPU time for each case, as discussed in Section 2.2, is approximately 5 days for the Leonids and 2 weeks for the Perseids.

In the last step, particles are extracted within 0.01 AU of Earth within 1 week before and after the expected shower peak. The node-Earth distance

for each particle is computed, along with an impact parameter (IP) for each meteoroid approaching Earth. The IP is defined as follows

$$\mathrm{IP} = (R_{\mathrm{E}} + h_{\mathrm{atmos}})/D$$

where R_{E} is the radius of the earth, h_{atmos} is the height of the atmosphere, and D is the Earth-particle distance at nodal crossing; it is scaled to 1 at the top of the atmosphere. It is known that D is not the closest a particle will approach Earth, especially in the case of streams associated with low inclination comets. In the case of streams associated with high inclination comets, however, the difference between D and the actual closest approach distance is inconsequential. Thus the IP is valid for streams with large orbital inclinations, as is the case for the Leonids and the Perseids.

2.2. INPUTS

In modeling the Leonids it was necessary to simulate ejection from comet Tempel-Tuttle during the last 12 revolutions, epochs 1600–1965. Three hundred thousand particles were ejected during each epoch, in both ejection schemes, for a total of 3.6 million particles for each case, Timestep and Perihelion. The meteoroid production rate was varied with the heliocentric distance as r_{h}^{-5}, based on previous simulations, and β ranged from ~10^{-5} to 10^{-2}, resulting in a mass range between approximately 1 μg and 1 kg, as the density was assumed to be 1000 kg m^{-3}. A cap angle of $\alpha = 30°$ was chosen. The radius of the comet was assumed to be 2.0 km (Hainaut et al., 1998).

For each ejection case and two different cap angles, comet Swift-Tuttle was modeled with 900,000 particles ejected over each of its last 9 revolutions dating from 826 to 1862. This resulted in 4 total Perseid cases with 8.1 million particles each. Particle production depended on r_{h}^{-6} (Fomenkova et al., 1995). Again, β ranged from ~10^{-5} to 10^{-2}, the corresponding masses from 1 kg down to 1 μg, assuming density was 1000 kg m^{-3}. Cap angles of 25° and 60° were chosen based on the literature, respectively Jones (1995), and Jones and Brown (1996a) and Brown and Jones (1998). The radius of the comet was assumed to be 11.0 km, based on Boehnhardt et al. (1996).

2.3. MODEL COMPARISON

Per Welch (2003), numerical simulations of meteor showers tend to conform to one of two types whereby: (1) large numbers of meteoroids are ejected from a parent comet and the subsequent evolution of these particles is followed until the period of interest, or (2) the meteoroid orbit with the

correct change of period necessary to pass through the relevant node at the time of the shower in a given year is determined for a given ejection epoch. The MSFC model is of the first type. It is similar to models seen in Brown (1999), Brown and Arlt (2000), Göckel and Jehn (2000), and Vaubaillon and Colas (2002) in that respect. The models in Kondrat'eva and Reznikov (1985), Wu and Williams (1996), Asher (1999), and McNaught and Asher (1999) are of the second type. Welch (2003) is a combination of these types. It is unknown at this time under which type category the work of Lyytinen (1999) and Lyytinen and Van Flandern (2004) falls.

A brief summary comparing the Leonid MSFC model to the Leonid models of other authors is given in Table I. The main categories of comparison involve how the cometary ephemerides are created, the ejection velocity law used, the particle production dependence on heliocentric distance, the ejection scheme – particles ejected along the comet's orbit or only at perihelion, and the integrator used to integrate the position of the comets back in time and/or evolve the particles forward in time. The MSFC model uses JPL Horizons to calculate the cometary ephemerides, instead of introducing the additional complexity of integrating the comets, whose dynamics are significantly influenced by jetting, reflected in the A1 and A2 terms. Ejection velocity is based on Jones and Brown (1996b) and Jones (1995). Type 1 models, with the exception of Vaubaillon and Colas (2002), and Welch (2003) have explored this ejection velocity model, among others, with a set cap angle of 60°. Vaubaillon and Colas (2002) and Welch (2003) have investigated the ejection velocity model of Crifo and Rodionov (1997). The MSFC model's particle production dependence on heliocentric distance is not fixed at r_h^{-2} but is instead based on observational evidence found in the literature or determined based on previous simulations. Two different ejection schemes are compared in this model: particle ejection along the comet's orbit within 2.5 AU and also ejection just at the hour of perihelion, like models of Types 1 *and* 2. In the MSFC model a 4th order variable step-size Runge–Kutta integrator is used to evolve the particle orbits, like Brown (1999), and Brown and Arlt (2000). Various other numerical integrators have been used, including Runge–Kutta–Nystrom 12 (10) 17 (e.g. Welch, 2003), Radau 15 (e.g. Vaubaillon and Colas, 2002), and Stumpff-Weiss (e.g. Göckel and Jehn, 2000).

3. Results and Discussion

A subset of the total number of particles propagated, those extracted within 0.01 AU of Earth within 1 week before and after the expected shower peaks of interest, is now examined. As stated previously, an IP is computed for each particle of this set approaching the Earth. In effect, this is the scaled

probability that the particle will hit Earth. (It must be noted that a stream that approaches Earth, but does not appear to cross its path, still has a nonzero probability of striking the Earth.)

The particle IPs are summed in 0.01° solar longitude bins (this corresponds to a time interval of 14.6 min), thereby representing cumulative probabilities. Ideally, the IPs would be summed in 0.005° bins, corresponding to the Earth moving approximately 1 Earth diameter plus the height of the atmosphere. There were not enough particles in the subset, however, for this binning scheme, so 0.01° solar longitude bins were used.

A Lorentzian is fit to the binned IP versus solar longitude – essentially the flux profile – in order to determine the time of the shower peak. The results are compared to observations of the 1998 and 1999 Leonid showers, and the 1993 and 2004 Perseids. In this way, the goal – to compare the solar longitudes of the main shower peak resulting from the model with observations of past Leonid and Perseid encounters, thereby validating the MSFC meteoroid stream model's timing – is achieved.

In the following sections the results of this validation are described. Cross-section plots showing the composition of the showers by stream are included and appear as parts (a) of Figures 1–4. Each of the particles in parts (a) has an associated IP. These IPs are summed in solar longitude bins and, for comparison purposes the amplitudes are scaled, thus creating a flux profile, shown in parts (b) of Figures 1–4. The model results are simply scaled to the peak ZHR observed so that the *time* of the observed peak and that of the peak predicted by the model can be easily compared. The observational data is also shown in parts (b). Finally, predictions from other modelers, where possible, are given in tabular form.

3.1. Leonids

Figure 1 shows the modeling results of the 1998 Leonids. The shower had two main peaks. The first peak, thought to be characterized by old ejecta according to Arlt and Brown (1999), was not modeled. The second peak (the nodal peak), however, is clearly prominent at solar longitude 235.311° ± 0.007° (ibid). It is made up of particles ejected from recent passages of Tempel-Tuttle, namely 1965, 1932, and 1899. The MSFC model predicted a peak time at 235.27° ± 0.01°, a difference of about 1 h. Table II summarizes the results of the 1998 Leonid encounter alongside predictions from other authors.

The 1999 Leonid result can be seen in Figure 2. A storm of activity was observed at 235.285° ± 0.001° (Arlt et al., 1999). The MSFC model predicted the storm peak, consisting mainly of particles from 1899 to 1932 but

TABLE I
A brief summary comparing the Leonid MSFC model to the Leonid models of other authors

Authors (Leonids)	Cometary elements/ Ephemerides source	Ejection velocity	Particle production dependence	Ejection scheme	Integrator
MSFC	JPL Horizons	Jones ejection (Jones, 1995; Jones and Brown, 1996b)	r_h^{-5}	Timestep, within 2.5 AU; Perihelion	Runge–Kutta 4
Brown (1999), Brown and Arlt (2000)	Yeomans et al. (1996)	Jones ejection (Jones, 1995), modified Jones and parabolic Jones (Brown and Jones, 1998), Crifo (1995)	r_h^{-2}	Timestep, within 4 AU	Runge–Kutta 4
Göckel and Jehn (2000)	–	Jones ejection (Jones, 1995), modified Jones and parabolic Jones (Brown and Jones, 1998), Crifo (1995)	r^0	Timestep, within 4 AU	Stumpff-Weiss
Vaubaillon and Colas (2002)	Rocher (2002)	Crifo and Rodionov (1997)	r^0, weighted later by r_h^{-2}	Timestep, within 3 AU	Radau 15
Kondrat'eva and Reznikov (1985)	independent	set at 1 value at perihelion – 0 km/s – then iteratively determined	n/a	Perihelion	algorithm of Kulikov (1960)
Wu & Williams (1996)	n/a	set at 1 value at perihelion – a mean ejection velocity less than 0.6 km/s	n/a	Perihelion	Runge–Kutta–Nystrom

Asher (1999), McNaught and Asher (1999)	Nakano (1998), Yeomans et al. (1996)	n/a	n/a	Perihelion	Radau 15
Welch (2003)	Nakano (1998)	Jones ejection (Jones, 1995), modified Jones (Browm and Jones, 1998), Crifo and Rodionov (1997)	r_h^{-2}	Timestep, within 3.5 AU	Runge–Kutta–Nystrom

The main categories of comparison involve how the cometary ephemerides are created (most modelers take cometary elements from various sources and integrate backwards), the ejection velocity law used, the particle production dependence on heliocentric distance, the ejection scheme – particles ejected along the comet's orbit or only at perihelion, and the integrator used to integrate the position of the comets back in time and/or evolve the particles forward in time. The top section of the table shows models of Type 1, the middle section shows models of Type 2, and the bottom section shows the hybrid. It is unknown at this time under which type category the work of Lyytinen (1999) and Lyytinen and Van Flandern (2004) falls; these works are not included in this table.
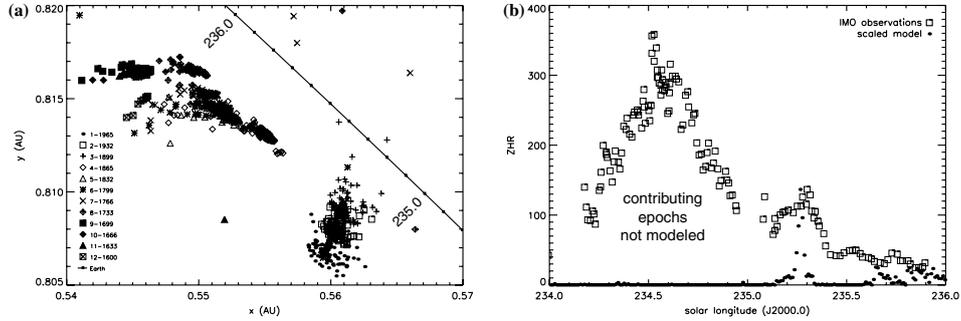
Figure 1. Results of the 1998 Leonids, Timestep case. (a) Cross-section in $x - y$ ecliptic coordinates showing the composition of the shower by stream. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. Ejecta from 1899, 1932, and 1965 played the greatest role in the nodal peak. (b) Comparing the scaled model with observations. Observational data was collected by the International Meteor Organization (IMO) and published in Arlt and Brown (1999). The model is scaled to the maximum ZHR of the nodal peak.
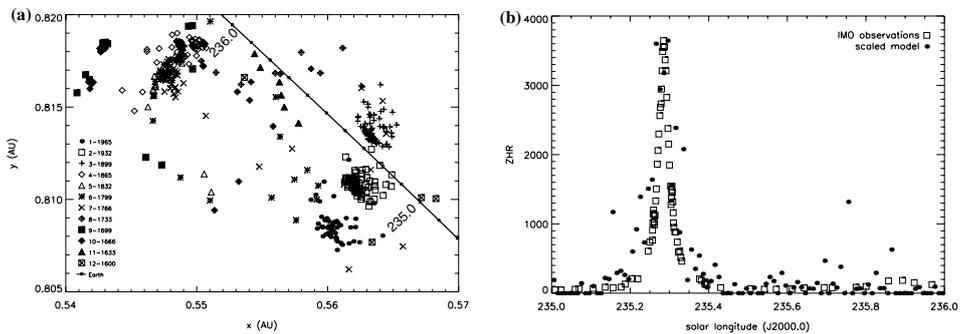
Figure 2. Results of the 1999 Leonids, Timestep case. (a) $X - Y$ cross-section plot showing the composition of the shower by stream. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. Revs 2 (1932) and 3 (1899) played the greatest role in the storm peak, as well as particles from 1965. (b) Comparing the scaled model with observations. Observational data was collected by the IMO and published in Arlt et al. (1999).

also including those from 1965, at 235.282° ± 0.002°. This is a difference of just over 4 min. The MSFC results for the 1999 Leonids, and the results of other authors, are presented in Table III.
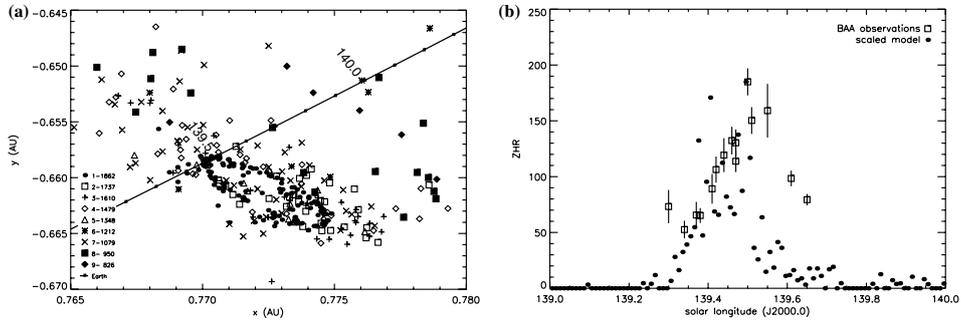
Figure 3. Results of the 1993 Perseids, Timestep case, 60° cap angle. (a) Cross-section in $x - y$ ecliptic coordinates showing the composition of the shower by stream. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. Ejecta from years 1862, 1479, and 1610 made up the bulk of the peak, with 1862 being most prominent. (b) Comparing the scaled model with observations. Observational data was collected by the British Astronomical Association (BAA) and published in Bone and Evans (1996).
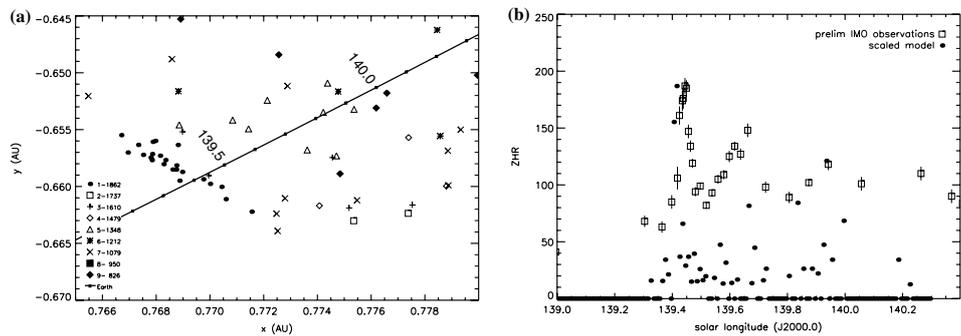
Figure 4. Results of the 2004 Perseids, Timestep case, 60° cap angle. (a) $X - Y$ cross-section plot showing the composition of the shower by stream. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. The maximum was made up from the 1862 stream. (b) Comparing the scaled model with observations. Observational data was collected by the IMO, and is not yet published (Arlt, unpublished observations).

3.2. PERSEIDS

Figure 3 illustrates the modeling results of the 1993 Perseids. The main peak occurred at 139.53° ± 0.01° (Bone and Evans, 1996; Rendtel and Brown, 1997). A time of 139.491° ± 0.002° was determined from the MSFC model, a

TABLE II

This table shows the modeling results of various authors alongside the results of the MSFC model and the observations for the 1998 Leonids

Year	Peak	McNaught and Asher (1999)	Brown and Arlt (2000)	MSFC result	Observations	MSFC difference
1998	Nodal	–	–	235.265	235.311	~1.1 h
	1965	235.26	235.34	235.262	*n/a*	*n/a*
	1932	235.27	235.22	235.263	*n/a*	*n/a*
	1899	–	–	235.270	*n/a*	*n/a*

The activity peak near the passage of the descending node of Tempel-Tuttle is referred to as the nodal peak; the fireball peak made up of older ejecta was not modeled. Modeling by McNaught and Asher (1999) and Brown and Arlt (2000) found that the 1965 and 1932 streams contributed to the nodal peak and calculated separate solar longitudes for each. Binning the IPs of ejecta from different epochs separately and fitting a curve to the data, the solar longitudes of the maxima for 1965 and 1932 ejecta from the MSFC model are shown for comparison purposes. Material from 1899 was also found to be a contributor and shown accordingly. Observations showed a peak at solar longitude 235.311 (Arlt and Brown, 1999). An analysis of the subset described in the text, combining ejecta from each perihelion passage (1965, 1932, and 1899 included) gives a peak at 235.265, a difference of about an hour. Errors are omitted for convenience.

TABLE III

This table shows the modeling results of various authors alongside the results of the MSFC model and the observations for the 1999 Leonids

Year	Peak	Kondrat'eva and Reznikov (1985)	McNaught and Asher (1999)	Brown (1999)	Lyytinen (1999)	MSFC result	Observations	MSFC difference
1999	Storm	–	See 1899	See 1899	See 1899	235.282	235.285	~4 min
	1965	–	235.279	–	–	235.272	*n/a*	*n/a*
	1932	–	235.273	–	235.270	235.275	*n/a*	*n/a*
	1899	235.29	235.29	235.3	235.291	235.295	*n/a*	*n/a*

A storm of activity was observed at solar longitude 235.285 (Arlt et al., 1999). In the models of Kondrat'eva and Reznikov (1985), McNaught and Asher (1999), Brown (1999), and Lyytinen (1999), as well as the MSFC model, the major (or only) contribution to the storm peak came from particles ejected in 1899. Solar longitudes of the maxima for material ejected in 1899, 1932, and 1965 are given separately. Binning the IPs of ejecta from different epochs individually and fitting a curve to the data, the solar longitudes of the maxima for the 1899–1965 streams from the MSFC model are shown for comparison purposes. An analysis of the subset described in the text, combining ejecta from each perihelion passage (1965, 1932, and 1899 included) gives a storm peak at 235.282, a difference of about 4 min. Errors are omitted for convenience.

difference of 57 min. Particles ejected from Swift-Tuttle's passages in 1862, 1479, and 1610 were the main contributors. This breakdown is somewhat different from Brown (1999). The 1862 stream contributed the most significantly.

TABLE IV

This table shows the modeling results the MSFC model, alongside the results of Lyytinen and Van Flandern (2004) where possible, and the observations for the 1993 and 2004 Perseids

Year	Lyytinen and Van Flandern (2004)	MSFC result	Observations	MSFC difference	Main contributors
1993	–	139.491	139.53	~57 min	1862, 1479, 1610
2004	139.441	139.42	139.443	~34 min	1862

The main peak of the 1993 Leonids was at 139.53 (Bone and Evans, 1996; Rendtel and Brown, 1997). The MSFC model showed a peak at 139.491, a difference of about 57 min. Particles ejected from Swift-Tuttle's passages in 1862, 1479, and 1610 were the main contributors. In 2004, material from 1862 was the main contributor to the peak. The prediction of Lyytinen and Van Flandern (2004) was very close to what was observed. The result of the MSFC model, with a peak at 139.42, was about 34 min premature. Errors are again omitted for convenience.

The 2004 Perseid result is shown in Figure 4. The maximum occurred at $139.443° \pm 0.003°$ (Arlt, unpublished observations). The MSFC model predicted a peak time of $139.42° \pm 0.01°$, a difference of 34 min. Particles from 1862 made up the peak.

Table IV summarizes the results of the Perseid encounters.

3.3. MODEL VARIABLES

Two different ejection cases, Timestep and Perihelion, were simulated for both the Leonids and the Perseids. In general, the Perihelion case produces narrower particle distributions, as is to be expected. An example of this can be seen for the 2000 Leonids in Figure 5(a). These two cases yield similar peak times at this preliminary analysis stage. It is the Timestep case, however, that is felt to be more physically realistic.

The Leonids were only simulated with one cap angle value. For the Perseids, two different cap angles, $\alpha = 25°$ and $\alpha = 60°$, were tested. The smaller of the two values simulates an exit cone of about 60°; the 60° cap angle corresponds to a hemispherical exit cone (Jones and Brown, 1996b). Of the two values, the 60° cap angle model generally predicts a solar longitude closer to that of the observed maximum ZHR. The 1998 Perseids, shown in Figure 5(b), is a good example of this. With scaling, the maximum is clearly distinguishable despite the scatter. The observed peak ZHR occurred at solar longitude $139.75° \pm 0.03°$ (Arlt, 1999). The 60° and 25° cap angle models have peaks at $139.72° \pm 0.01°$ and $139.83° \pm 0.01°$, respectively.
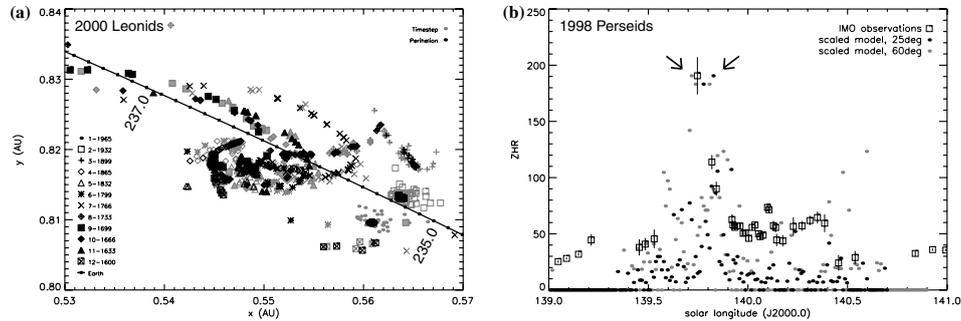
Figure 5. (a) $X - Y$ cross-section plot showing the composition of the shower by stream for the 2000 Leonids. As shown in the legend, the different symbols represent various streams by year, and the solid black line represents the Earth's path. The Perihelion ejection case (in black) is shown superimposed on the Timestep case (in gray). Note especially how focused the 1965 and 1932 streams of the Perihelion case are, as compared to the Timestep case. (b) Comparing two scaled models with observations for the 1998 Perseids. The 60° cap angle model (in gray) matches the time of the observed maximum better than the 25° model (in black). Observational data was collected by the IMO and published in Arlt (1999).

4. Summary

The MSFC stream model predicts, within about an hour or better, the peak times of several Leonid and Perseid encounters. Further refinement is necessary in analyzing the results, especially concerning ZHR calculations. Work exploring the effects of ejection schemes, the Timestep case and the Perihelion case, and cap angles is underway. Additionally, the inclusion of observational data, such as population indices, is underway in order to better constrain parameters associated with particle ejection from comets. Future work addressing the effects of different cometary ephemerides is planned; these effects are expected to be significant.

Acknowledgements

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