Chapter 7: Conclusions, Summary and Future Work

7.1 Summary and Conclusions

In this thesis I have developed and applied a numerical model for the formation and subsequent evolution of two meteoroid streams, the Perseids and Leonids. The numerical results have been compared to available observations of the streams and the best physical representations of the cometary decay processes involved derived as a result.

The two streams, while periodic in nature, are very different. Two key reasons for these differences may be identified. First, the parent comet of the Perseids (Swift-Tuttle) is larger, probably older and is certainly more active than Tempel-Tuttle; with the relative mass difference of the comets being more than two orders of magnitude. Secondly, the encounter distance/geometries of the two comets with the Earth and their orbital energies are very different. Swift-Tuttle has a nodal point which has always been outside the Earth's orbit in the recent past and almost an order of magnitude further than Tempel-Tuttle's nodal point, while at the same time having less than 1/2 the specific energy of Tempel-Tuttle's orbit.

One manifestation of the first difference is in the best fit ejection velocities from each comet which are most able to reproduce observed stream activity at Earth: for Swift-Tuttle this yields best-fit ejection velocities of order 10 - 100 m/s for visual class ($<10^{-3}$ g) meteoroids, while for Tempel-Tuttle the fits are most consistent with average ejection velocities of a few m/s and certainly <20 m/s. The age of the Perseids, of order ~25 000 years for the core component of the stream, is an order of magnitude greater than for the Leonids, implying a far greater distribution of material perpendicular to the Perseid orbit and thus a much longer period of activity (as is observed).

The difference in encounter geometries is critical. From our simulations, we find the delivery of Perseid meteoroids to Earth is tightly correlated with the distance to the comet at the time of ejection; no similarly strong correlation exists for the Leonids. The greater distance for Perseids implies that we only skirt the outer portions of the densest portions of the stream; this effect is further enhanced by radiation pressure which is slightly more significant for the larger orbit of the Perseids than for the Leonids. The youngest Leonids may have nodal points so close to the Earth as to be accessible to it after only one or a few revolutions; as a result Earth may access the very densest portions of the Leonid stream and strong storms may result. No similar geometry exists for the Perseids and this effect, combined with higher Perseid ejection velocities, greater relative radiation pressure effects and lower orbital energy (and longer period) for the stream implies much faster diffusion of the densest portions of that stream, relative to the Leonids. Such distinctions provide a probable explanation for the difference in magnitude between the observed relative strengths of the periodic and annual components of the two streams. It also suggests that storms comparable to the Leonids from the Perseid stream are unlikely.

Similarities, however, do exist between the two showers. Planetary perturbations, most notably from Jupiter, dominate the evolution of both streams. These planetary perturbations also move nodal points into Earth-crossing orbits and directly result in the "periodic" component of the showers. For the Perseids, it is pre-perihelion perturbations from Jupiter and Saturn which move meteoroid nodal distances in the present epoch inward enough to intersect the Earth; for the Leonids, more distant direct perturbations cause much smaller but systematic differential perturbations which move the nodal distances outward. The effects of terrestrial perturbations are small to negligible for both showers, despite Earth being the planet, which passes closest to the mean stream orbits.

As well, the time-scale (in terms of stream revolution periods) over which various evolutionary forces rule is similar. For the Perseids, the initial ejection velocities are important over the first ~5 revolutions post-ejection after which radiation pressure and planetary perturbations control subsequent evolution. The ejection velocities and radiation pressure effects for the Leonids are the key mechanisms in stream development for the first three or four revolutions after which planetary perturbations take over. The makeup of the "outbursts" and (for the Leonids) "storms" are also comparable in age for the two streams - typically less than five or six revolutions old. The systematic shifts in the positions of maximum from year to year for both streams are clearly linked to the differing age of the primary meteoroid populations represented in both cases.

For the first time, we have investigated through simulation, a number of characteristics associated with both the Perseids and Leonids. The probable age for the various outbursts of the Perseid stream observed over the last decade and the location of these outburst maxima have been identified and correctly predicted (and post-dicted). Using observed radiant dispersion and average location as well as shower duration and width we have also estimated the age for the core population of the Perseids (~25 000 years), its ultimate age (>100 000 years) and shown that the outbursts we are currently experiencing from the stream are young (typically less than five revolutions of the comet in age). We have also identified the most probable ejection origin(s) for each outburst and their physical cause (impulsive perturbations from Jupiter and Saturn). As well, we have also directly associated sungrazing and hyperbolic ejection of test meteoroids from the Perseids as probable sinks for the stream over periods comparable to the age of the core and diffuse population as well as clarifying the role of the Earth in the evolution of the Perseid stream as minor.

The age and origin of the storms from the Leonids observed over the last 200 years have been established and found to be in general agreement with previous determinations made by Kondra’teva and Reznikov (1985), Kondra’teva et al., (1997) and Asher (1999). The distances from each of the dense cometary “trails” causing these storms was found to agree well with the independent determinations of Asher (1999). We have found that material evolving outside the orbit of comet Tempel-Tuttle does so primarily through previous distant direct perturbations from Jupiter, often on the outbound leg of the Leonid orbit. Radiation pressure does not directly increase noticeably the nodal distances for the masses examined, though it does cause meteoroids to lag the comet. It is these differential perturbations, due to distant, direct, often outbound Jovian effects, which cause stream meteoroids to move significantly outward relative to the cometary nodal position; a similar effect has been mentioned by Asher (1999). We have compared the observed widths of several Leonid storms with those suggested through modelling and determined that the most probable normal component of ejection velocities for Leonids for the largest storms is 1-5 m/s, in agreement with previous investigators using other methods (eg. Kresak 1993). The overall ejection velocities are of order ~10 m/s for the population causing storms. The density diffusion has been quantitatively examined and found to decrease by two to three orders of magnitude in approximately 100 years for the densest portion of the stream; the temporal regimes in which various forces likely dominate evolution have also been identified. The possible role of several mean motion resonances and Tempel-Tuttle has been examined as has the effect these resonances may have on the distribution of semi-major axes within the Leonid stream.

7.2 Future Work

Numerical modelling of meteor streams has developed in concert with the availability of fast computers. Only in the last decade have computers fast enough to efficiently follow the orbital evolution of significant numbers of test particles been available.

Interestingly, though the speed of computers has increased significantly, most workers have not exploted this to investigate the effects changes in the many free parameters have on the final distribution of meteoroids through computation of many additional test particles. For example, Wu and Williams (1996) recently studied the Leonids, but they used only a few hundred test particles to investigate it. The reason has become apparent in undertaking this work: with 10^7 or more test particles to follow, the limiting factor is not the computation time, but rather the daunting task of analyzing and interpreting (as well as storing) this amount of information. Yet many of the results in this thesis would not have been apparent had only a few hundred (or even a few thousand) test particles been examined. For many of the tasks in interpretation it is only the very small sub-population near the Earth at the time of past (or future) shower apparitions which are important; from this perspective most of the particles are a “waste” of integration time (though not in the case of macro-features of the streams such as diffusion). Wu and Williams (1996), for example, have attempted to overcome this by recognizing that only specific values of mean anomaly at a single point of ejection will produce near intersection with Earth at some future date. However, even modestly small ejection speeds, (in many directions, at varying positions along the orbital arc of the comet and covering differing values of radiation pressure) quickly complicate this simple situation and make its applicability limited.

In its ideal form, the simulation of the evolution of the stream could be entirely divorced from the need to adopt any physical model for the stream formation. Instead a grid of ejection velocity and radiation pressure combinations could be formulated at each step along the orbital arc for each past apparition of the comet and then the evolution of each particle followed to Earth-intersection. In this way the most “efficient” ejection conditions could be established and then compared to physical models.

The other limiting factor in our understanding of meteor stream evolution is a paucity of observations. While activity curves for showers are regularly produced from observations each year, many more precise radiant determinations would provide a more complete testbed for studying the evolution of streams.

Perhaps the most promising technique, however, for studying the ejection conditions and evolution of (young) meteoroid streams is hyperprecise velocity/trajectory information. The backward integration of very precise individual meteor observations offers the greatest hope of unlocking the secret of the magnitude/direction of meteoroid ejection as well as location. Gustafson (1989) has attempted such a technique for some precisely observed Geminids with modest success. Potentially the most powerful technique in this regard is down-the-beam radar observations of head-echoes (Taylor et al. 1995) which would permit velocity determinations to of order a few m/s as well as trajectory information comparable in precision to photographic observations.

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