PART II

COMETS AND METEOR STREAMS

PHYSICAL PROCESSES AFFECTING THE MOTION OF SMALL BODIES IN THE SOLAR SYSTEM AND THEIR APPLICATION TO THE EVOLUTION OF METEOR STREAMS

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ABSTRACT

In addition to planetary perturbations, the small particles which make up a meteor stream are subject to outward radiation pressure and the Poynting-Robertson effect. New particles can also be generated in a stream through being released from the nucleus of a comet. We summarise the main physical effects, discuss models for meteor stream evolution and give a brief account of the observational data available.

1. INTRODUCTION

One of the advantages (or disadvantages) of producing theoretical models for the dynamical evolution of meteor streams is the existence of a large body of observational evidence gathered in some cases over many centuries. There are in fact nearly twenty meteor streams which can currently be observed from Earth as the meteoroids from which they are composed burn up in the Earth's atmosphere. In some of these streams, the number of meteors seen per hour is very low, perhaps not exceeding 10 even at maximum. However streams such as the Quadrantids, Geminids and Perseids can give very impressive displays with upwards of 100 meteors per hour being observed. The Quadrantids and the Geminids streams appear to have become visible only fairly recently, the first recognition of the Quadrantids being in 1835 [Wartmann, 1841] while the Geminids were first mentioned with any certainty in 1862 [King, 1926]. On the other hand, the Perseids stream appears to be much older, dating back to 36 A.D., with at least a dozen recorded appearances between this date and 1451. Two other "old" streams are the Eta Aquarids (405 A.D.) and the Orionids (585 A.D.). These two streams are of considerable current interest since they are thought to be associated with Halley's comet.

Since a stream, in order to be detected, must interact with the Earth's atmosphere, it is safe to assume that the true population of meteor streams must be in excess of the twenty or so known streams. Meteors interacting with the atmosphere can in fact be detected in two ways, visually and be means of radar. Hughes (1978) deduced that the

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radio meteors could have a mean mass of the order of 10^{-4}g and a mean density of 0.8 gcm^{-3} while the visual meteors have a mass of 10^{-1}g and a density of 0.3 gcm^{-3}. Their radii are thus around one third mm and a few millimeters respectively. They are thus small particles and it is worthwhile first considering the forces acting on such particles and the effect of such forces.

2. FORCES ACTING ON METEORITES

It is not our intention to give an exhaustive review of forces acting on small particles, but rather concentrates only on those parts which are relevant to meteroid motions. Clearly the dominant force must be the solar gravitational field, which at heliocentric distance r has magnitude $GM_{\odot}/r^2$, for if this were not the case, then the meteoroids would not move on even approximately regular orbits and no stream could develop. Donnison and Williams (1977) have shown that the effect of a solar wind is similar to that of the Poynting-Robertson effect and radiation pressure. We need not here therefore consider both phenomena.

Radiation pressure produces a force which opposes gravity on a body of radius a, of magnitude

$$\frac{a^2 Q L_{\odot}}{4r^2 c} ,$$

where $L_{\odot}$ is the solar luminosity, c the speed of light and Q is called the efficiency factor for radiation pressure. In general, Q is a factor of meteoroid radius, composition and wavelength of the incident light and a general discussion is given for example by Wickramasinghe (1967). For meteoroids of the dimensions under consideration it will be satisfactory to regard Q as a constant with a value close to unity. As can be seen, both the radiation pressure and gravity have the inverse square dependence on heliocentric distance and it is therefore convenient to write the radial force as

$$\frac{GM_{\odot}m}{r^2} (1 - \beta) ,$$

where $\beta = 3QL_{\odot}/16\pi cGa\sigma M_{\odot}$,
σ being the density of a meteoroid. β is a nondimensional constant for a given meteoroid, but as can be seen, is smaller for large bodies than for small ones. For object of 1 km radius like a cometary nucleus, β is effectively zero, while it increases to near unity for micron sized particles. Of course once $\beta \sim 1$ there is no attractive force and so we would expect sub-micron sized particles to be lost from a stream very quickly. One important consequence of the above, pointed out by Kresak (1974), is that small meteoroids on being released from a comet will start pursuing an orbit of larger seminajor axis than the comet because of the β factor.

In addition to providing an outward push, radiation also removes angular momentum from a meteoroid. If h is the specific angular momentum, then

$$\frac{dh}{d\theta} = -\frac{GM_{\odot}\beta}{c} .$$

If, in addition, it is assumed that the meteoroid is on or near eliptic orbit, then this equation can be converted into an equation which gives the time taken for orbital decay as

$$\frac{dl}{dt} = -\frac{8GM_{\odot}}{lc}(1-e^2)^{3/2} .$$

e and l being the eccentricity and semi-latus rectum of the orbit. Similarly the eccentricity changes are given by

$$\frac{de}{dt} = \frac{10GM_{\odot}e(1-e^2)^{3/2}}{l^2c} .$$

Of more interest perhaps is the rate of change of aphelion, Q. By combining the two above equations, we have

$$\frac{dQ}{dt} \simeq \frac{1.5\times 10^{-7}}{a\,\sigma}\ AUy^{-1}$$

for a meteoroid on an orbit similar to the Quadrantid stream [See Burns *et al* 1979].

Thus the duration in the stream of particles less than about .01 mm is getting rather short and they may well not exist in streams.

In addition to the above forces, meteor streams are also perturbed by the gravitational field of the planets. Because of the general dimensions and eccentricity of their orbits, meteor streams are in fact more susceptible than most other solar system bodies to such perturbations as they can pass close to more than one planet. It is possible to include planetary perturbations, either by calculating the secular changes in an orbit, as for example Babadzhanov and Obrubov (1979) do, or alternatively by going into a full numerical treatment which we shall mention later.

3. OTHER POSSIBLE EFFECTS

Collisions do not in fact play an important role in the general evolution of the stream. Though they do of course play a role in causing meteoroids to be lost from the stream and become sporadic meteors. For an average meteor shower, the number density of meteoroids, n, can be calculated in two ways. Either we can proceed from the mean hourly rate of observation of meteors during a shower E_n say, and assuming the relative speed of stream and Earth is of the order of the Earth's orbital velocity V_E we have roughly

$$\pi R_E^2 V_E n = E_N ,$$

R_E being the earth's radius.

Secondly, one estimate could be obtained on the assumption that a stream represents the break-up of a significant fraction of a cometary nucleus and so estimating the volume of a stream and the mean meteorite mass, again allows a determination of n. Both these approximations yield similar values of about 10^{-25} cm^{-3} for n. With such a number density, any specific meteoroid could expect to be involved in a collision every 10^{12} orbits, thus the majority of a stream is in essence collision-free. However there are some 10^{17} meteoroids in a stream and so 10^5 of them can expect a collision on an orbit. This is a very significant number in terms of populating the sporadic family, but is insignificant in the context of stream evolution.

A final effect which warrants mention is the possibility that a cometary nucleus is feeding particles into the stream. Particles may be expected to be fed in with small velocities in random directions relative to the nucleus. Once released these new meteoroids become subject to all the effect mentioned above and must be included in any calculation. A recent model incorporating this effect is given by Fox *et al* (1982).

The above describes the main forces and effects that operate on meteor streams. I shall now briefly describe our model for meteor stream evolution and summarize our results.

4. A COMPUTER MODEL

In all the models we have produced, the meteor stream is represented by a set of independent particles, each moving on a given initial orbit (not necessarily the same orbit for all particles) and having a given position on the orbit at $t = 0$. Each particle is then subject to the forces mentioned above. The positions of the planets, required to evaluate planetary perturbations, are obtained by integrating their motion backwards in time from the most convenient ephemeris point. The first models were concerned with the Quadrantid meteor stream and Hughes *et al* (1979) showed that the variations in mean orbital parameters between A.D. 1830 and the present agreed well with observations while Murray *et al* (1980) showed that the influx of meteoroids into Earth crossing orbits from the model was consistent with the first sighting of the stream in the 1830's. In these early models, numerical integration was carried out using the fourth order Runge-Kutta technique with self-adjusting step length. It was later found that the Gauss-Jackson method was more convenient [See Herrick 1971, Fox 1982].

The apparent different behaviour of the radio and visual meteors in the Quadrantid stream was explained in terms of the effect mentioned earlier (Radiation-pressure and the Poynting-Robertson effect) placing the smaller set in the vicinity of the 2:1 resonance with Jupiter by Hughes *et al* (1981).

Fox *et al* (1982) have included the effect of insertion of particles from a cometary nucleus into the model and produce a pictorial representation of the cross section of the stream as it crosses the ecliptic, thus giving a visual representation of its evolution. This was applied to the Geminid meteor stream and helped to explain the anomaly where the stream appears to have no retrogression of the ascending node despite all calculations suggesting that it should.

More recent work using the same model will be described by Fox (1983).

5. CONCLUSIONS

The evolution of meteor streams can be studied be means of computer models. These models give results which are in excellent agreement with the observed results from meteor streams which indicates that the physics inserted into the models could also be used beneficially to study areas such as the Trojan asteroid family and ring systems around planets.

6. REFERENCES

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