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The P/Halley Stream: Meteor Showers on Earth, Venus and Mars

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Abstract We have simulated the formation and evolution of comet 1P/Halley's meteoroid stream by ejecting particles from the nucleus 5000 years ago and propagating them forward to the present. Our aim is to determine the existence and characteristics of associated meteor showers at Mars and Venus and compare them with 1P/Halley's two known showers at the Earth. We find that one shower should be present at Venus and two at Mars. The number of meteors in those atmospheres would, in general, be less than that at the Earth. The descending node branch of the Halley stream at Mars exhibits a clumpy structure. We identified at least one of these clumps as particles trapped in the 7:1 mean motion resonance with Jupiter, potentially capable of producing meteor ourbursts of ZHR $\sim$ 1000 roughly once per century.

Keywords 1P/Halley · Mars · Venus · Meteors · Meteor outbursts · Meteor showers

1 Introduction

1P/Halley, the archetype for the Halley-type comet class, is one of the most extensively studied cometary bodies. It has been observed at 30 perihelion returns since 239 BC. This, and the relative regularity of its orbital evolution, have allowed the reconstruction of its

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orbital motion back to 1404 BC, over a millenium before the first observations (Yeomans and Kiang 1981). The comet's nucleus was recently investigated in situ by a flotilla of Russian and European spacecraft at its return to perihelion in 1986. Because the nodes of its orbit are near 1 AU, Halley meteoroids intercept the Earth both before and after perihelion, resulting in two distinct meteor showers, the October Orionids and the May η Aquariids. The comet's orbit also approaches the orbits of Venus and Mars, raising the possibility that meteors can occur at those planets when the latter pass through the Halley meteoroid stream. To investigate this point we have simulated the evolution of the Halley stream and characterised its planet-intercepting component at Earth, Mars and Venus.

2 Method

Our method is that of Vaubaillon et al. (2005a; b). An ensemble of test particles is ejected from the cometary nucleus and propagated forwards in time under planetary perturbations and size-dependent non-gravitational forces until a planet intercept occurs. Values of those cometary parameters required to translate our model particle fluxes into actual meteoroid fluxes were assumed as follows: $[Af\rho] = 17378$ cm (a measure of the dust production rate) at perihelion (Feldman et al. 1987; A'Hearn et al. 1995), nuclear radius $r_N = 7.5$ km, fraction of active area $f = 0.3$ (van Nes 1986), differential size distribution index s $= 3.25$. It is important to note that this s is related to the differential mass distribution index s_m (cf. Eq. C4 in Vaubaillon et al. (2005a)) but it is *not* s_m.

The simulation of the generation and evolution of the meteoroid stream was run on 5–50 parallel processors at CINES (France). We ejected 5×10^4 test particles distributed over five size bins (100 μm–10 cm) during a single perihelion passage. The starting state vector of the comet, from which the test particles are ejected, was derived by taking the reference orbit of comet Halley at the 239BC perihelion passage from JPL HORIZONS (small body code: 900001; Giorgini et al. 1996) and integrating it backwards to a perihelion state vector at 2924 BC. At this point we expect the location of the comet in its orbit to be significantly randomized with the true comet position differing by several decades in mean anomaly from our starting position. However, previous works have shown the structure of the stream's projection on the ecliptic to be insensitive to the position of the comet itself (McIntosh and Jones 1988; Ryabova 2003). It is rather dependent on the orbit evolution which is regular over this timescale and dominated by precession of the lines of apses and nodes (McIntosh and Hajduk 1983).

Several provisos should apply to interpreting our results. Firstly, our estimated ZHR is strictly applicable only to the case of the Earth (Koschack and Rendtel 1990a, b) but should be representative of observable meteor activity in the Martian atmosphere for such fast meteoroids (Adolfsson et al. 1996). At Venus, it should be treated as a lower limit due to the intrinsic capacity of that atmosphere to produce brighter meteors than the Earth's (Christou 2004; McAuliffe and Christou 2006). Our ZHR estimate also depends on the size of the sampling area, on the planetary orbital plane, over which the particles are counted to estimate the flux (the ΔT quantity in Vaubaillon et al. (2005a) multiplied by the planet's orbital velocity). Here we adopted $\Delta T = 20$ h as it yields the best agreement with the observed relative activity between the two Halley branches at the Earth. Results for all three planets are summarised in Table 1.

In order to estimate the meteoroid flux density required for the ZHR calculation we binned together planet-approaching meteoroids between two consecutive perihelion passages of the comet (e.g. between 1910 and 1986) and averaged the result over the

Table 1 Characteristics of the Halley meteor showers both at the ascending (HAN) and descending (HDN) nodes on Venus, Earth and Mars as derived from our simulations

Branch	Planet	Max (°)	Activity arc (°)	v (km sec^{-1})	ZHR
HDN (EAQ)	E	41	38–48	67	20
HAN (ORI)	E	211	208–213	67	13
HDN	M	26	26–29	55	62
HAN	M	220	216–224	55	2
HDN	V	65	61–73	80	4

Column 2 identifies the relevant planetary body as Earth (E), Venus (V) or Mars (M). Columns 3 and 4 give the activity maximum and duration in terms of the solar longitude (λ_s). Column 5 provides the velocity of the meteoroids at atmospheric entry. Column 6 gives the estimated ZHR

number of planetary years in that period. This method should be valid when the structure of the shower remains unaltered from year to year over this timescale but breaks down when outburst activity dominates the flux.

3 Results

3.1 Earth

The structure of the Halley stream at the Earth's orbit has been modelled extensively in previous works (McIntosh and Hajduk 1983; McIntosh and Jones 1988; Wu and Williams 1993; Ryabova 2003). Here we have used more particles and let them evolve longer than previously attempted but our purpose is different: a realistic end result at the Earth, as gauged by the level of agreement with those works, will bolster the validity of our findings at Venus and Mars. The structure we find is shown in Fig. 1. The "lopsided tadpole" form of the Halley descending node (HDN) branch, responsible for the η Aquariid shower, is

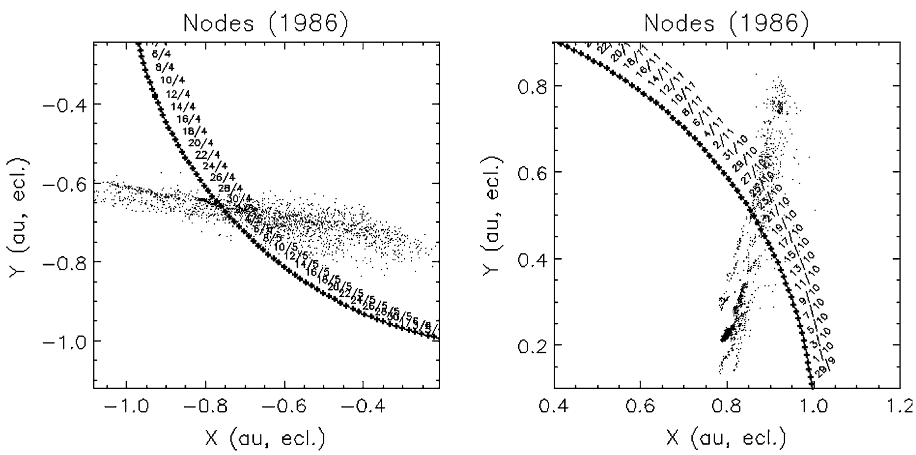

Fig. 1 Ecliptic nodes of particles ejected in 2924 BC that approached the Earth between 1910 and 1986. Left panel: Descending nodes related to the η Aquariids. Right panel: Ascending nodes related to the Orionids

reminiscent of Fig. 4 of McIntosh and Jones (1988) and Fig. 8 of Ryabova (2003). The head of the tadpole is thought to be rich in larger particles mimicking the dynamical evolution of the comet. The tail is composed of smaller particles lagging behind the main body of the stream, their orbits having suffered significant differential precession due to non-gravitational forces. We also see filamentary structure, also reported in those works. The width of the stream at the Earth's orbit as given in Table 1 is contained within the observed duration of the shower (37°–51°; Hajduk et al. 2002; Dubietis 2003). Our model maximum occurs $\sim$4 days earlier than observed (Rendtel 1997; Hajduk et al. 2002), possibly due to the stream having suffered more differential precession than recently-ejected material. Taking this result at face value implies that this shower, as presently observed, contains meteoroids ejected 5000 years ago, probably a small fraction compared to the accumulated population from previous and subsequent perihelion passages. The model results for the Halley Ascending Node (HAN) branch, responsible for the October Orionids, are generally quite similar with those of McIntosh and Jones and Ryabova but there are also differences. The main body of our model HAN meteoroids clearly intersects the orbit of the Earth, in agreement with the conclusion by those authors that the Orionid meteoroids we currently observe were ejected from the nucleus of P/Halley before 1404 BC. As found for the η Aquariids, our model gives a shorter duration than the observations. The stream model maximum is at 211°, 3 days later than observed. Combined with the earlier than observed η Aquariid maximum, this indicates some precession in ω between the observed and the model shower. Several dense concentrations or clumps of Earth-intercepting material are also evident. These may be associated with the trapping of Halley particles in mean motion resonances with Jupiter as recently reported (Trigo-Rodriguez et al. 2007; Sato and Watanabe 2007; Rendtel 2007). A global analysis of the Halley resonant meteoroid complex will be the subject of a future paper; we do, however, mention one particular case in some detail in the section discussing our results at Mars.

3.2 Venus

At Venus we find that only the HDN branch is active, the HAN branch passing well outside the Venusian orbit (Fig. 2). The duration of the resulting meteor shower would be 12° in orbital longitude or 7 days (e.g. 24/06/2007–05/07/2007). Looking at the evolution of this part of the stream over time, we find that the meteoroids started to intercept the Venusian orbit only recently, around 500 AD, their nodes moving progressively inwards and counterclockwise on the Venusian orbital plane.

3.3 Mars

Both branches of the Halley stream appear to be active at the Martian orbit. The distribution of nodes of Mars-intercepting meteoroids (Fig. 3) indicates that the two Martian showers may have different activity profiles, even taking into account the overlap with meteoroid trails from other perihelion returns of the comet.

The particle flux profile of the HAN branch appears symmetric with a maximum at $\lambda_s = 220°$ and an overall duration of $\sim$8° (15 days) in solar longitude. The equivalent period in the Martian Calendar adopted by the atmospheric science community (Clancy et al. 2000) is $L_s = 321°–329°$ (e.g. 29 Sep–5 Oct, 2007) and repeats every Martian year. Extrapolating from our earlier comparison between the predicted and

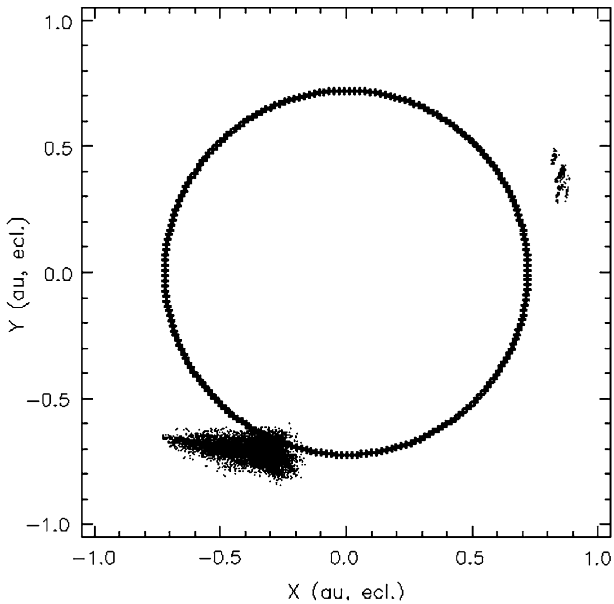

Fig. 2 As Fig. 1 but for Venus. Particle nodes are plotted for the Venusian orbital plane. At the heliocentric distance of Venus, Halley particles intercept the planet at the descending node only

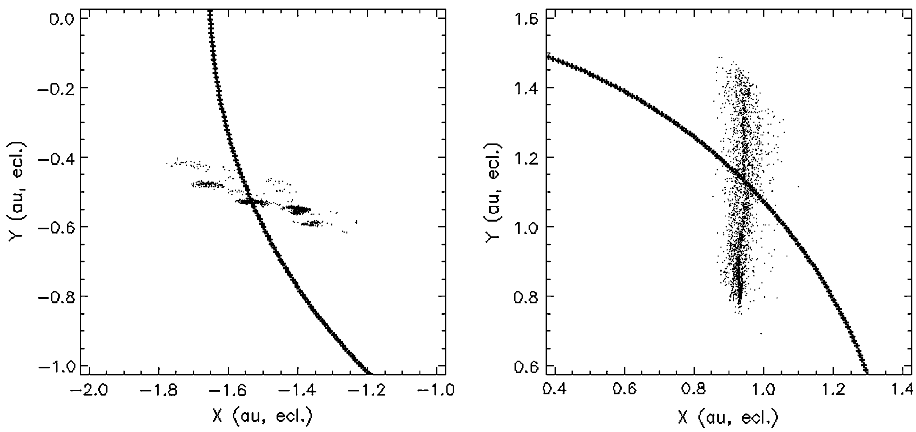

Fig. 3 As Fig. 1 but for Mars. Particle nodes are plotted for the Martian orbital plane. These intercept the planet both before and after perihelion, resulting in two distinct showers. Note the clumpy nature of the outbound branch compared to that of the inbound one

observed properties of the two branches at the Earth, we expect the actual shower to be longer in duration and its maximum several degrees of longitude in advance of our estimated value.

The HDN branch, on the other hand, exhibits a clumpy structure. Over the 40 Martian orbital periods that elapsed from 1910 to 1986, only 4 contained Mars-approaching material. Moreover, the ZHR of $\sim$60 reported in Table 1 comes from a single encounter between Mars and a dense clump of <1 cm meteoroids in 1972 when

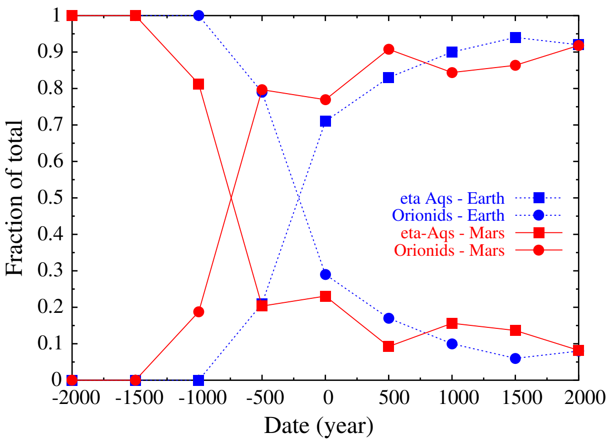

Fig. 4 Model variation in activity of the HAN and HDN branches at the Earth and Mars over the past four millenia. At the Earth, the two showers switch in activity during the latter half of the first millenium BC. After this time, HDN becomes the dominating branch. For Mars, a similar switch occurs during the first half of the first millenium BC but in the opposite sense so that the HAN branch becomes predominant

the ZHR reached 1200. A more careful inspection revealed that such encounters occur at $L_s = 113°–116°$ and follow a pattern, that is, they occur in 83-year intervals and only when Jupiter is in a particular segment of its orbit ($\lambda = 275°–323°$). This lead us to suspect that the origin of these outbursts were Halley meteoroids trapped in the 7:1 mean motion resonance with Jupiter. This was confirmed by verifying that the angle $7\lambda_{\text{Halley}} - \lambda_{\text{Jupiter}} - 6\varpi_{\text{Halley}}$ librates for many of these particles. It is important to emphasise that, since (a) we do not, in fact, know that the nucleus of comet Halley reached perihelion in 2924 BC and (b) the position-sensitive nature of the resonant trapping and confinement of cometary particle trails (Asher et al. 1999), we cannot issue any forecasts on Martian meteor storms. Our work does show, however, that the existence of dense resonant structures in the Halley stream is dynamically possible over long periods of time, in this case $\sim$5000 years. This is especially relevant given recent observations of Orionid outbursts at the Earth attributed to resonant structures (Trigo-Rodriguez et al. 2007; Sato and Watanabe 2007; Rendtel 2007). It suggests that Mars may be a prime observing location for studying the Halley resonant complex. Observations of such outbursts at Mars may also be used to infer the position of the comet several thousand years before its present observational arc.

Finally, we investigated how the level of activity from the two branches varies, according to our model, over the past several thousand years at Mars and the Earth. Counting the fraction of planetary years, between two successive perihelion returns of the comet, in which planet-intercepting meteoroids were detected, we found a duality between the two branches (Fig. 4). The HAN branch at the Earth and HDN branch at Mars appear to be the only active branches before 1500 BC. After that time, the other two branches begin to pick up in activity and a switch occurs, during the first and second halves of the first millenium BC for Mars and the Earth respectively. This leads to the present situation with HDN being the dominant branch at the Earth and HAN at Mars.

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