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# On the non-observability of meteors from Comet C/1995 01 Hale–Bopp

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## ABSTRACT

The possibility of observing enhanced meteoric activity, at Earth, from dust associated with C/1995 01 Hale–Bopp is investigated. We consider the nodal distribution of dust ejected from the comet during post-discovery nuclear outbursts, and we consider the hypothetical nodal distribution of meteoroids ejected from the comet during an assumed previous perihelion passage. In each case we find no reason to believe that the Earth will sample any significant numbers of C/1995 01 derived meteoroids.

**Key words:** celestial mechanics, stellar dynamics – comets: individual: C/1995 01 – meteors, meteoroids.

## 1 MOTIVATION AND INTRODUCTION

It has been known for many years that the distribution of meteoroids in space is not just a topic of academic interest (Whipple 1947). Indeed, the numerous large space platforms that presently orbit the Earth are continually at risk from meteoroid collisions, and the high levels of capital investment associated with these objects dictate a new imperative to the understanding of the temporal, as well as the spatial, distribution of meteoroid streams that intersect the Earth's orbit (Beech, Brown & Jones 1995). Under these circumstances there is a predisposition that, for each new cometary discovery in which a close Earth-orbit approach is indicated, an assessment of the accompanying dust distribution be made.

Comet C/1995 01 Hale–Bopp has excited some considerable interest since its discovery on 1995 July 23 (Green 1995). The astonishingly high nuclear brightness of C/1995 01 at the time of its initial detection ($m_1 \approx +10.5$ mag at $r \approx 8$ au) has prompted much speculation about the near-perihelion brightness of the comet (Aguirre 1995), and it has been suggested that Hale–Bopp may become the 'Great Comet' of this century. On its way towards perihelion C/1995 01 will pass within 0.1 au of the Earth's orbit, but will pass no closer than 1.3 au to the Earth itself. The Earth cuts through the orbital plane of C/1995 01 in January and July each year.

Subsequent to its discovery C/1995 01 has undergone at least three nuclear outbursts. Each of these outbursts culminated in the formation of a distinctive spiral jet composed of cometary dust (Sekanina 1995a). Sekanina (1995b) has suggested that the jets are derived from a single active region on the cometary nucleus. Observations obtained by A'Hearn and co-workers with the *IUE* telescope (A'Hearn 1995) also indicate that the near-nucleus environment of C/1995 01 is remarkably dusty.

In this study we attempt to address two questions. First, we ask whether the material ejected during the pre-perihelion outbursts of C/1995 01 will be observable at the Earth's orbit. Secondly, we ask what might the distribution of any meteoroid stream associated with C/1995 01 look like, given that it has passed perihelion at least once before.

## 2 METEOROID EJECTION FROM C/1995 01

The manner in which meteoroids are ejected from cometary nuclei is well understood in principle (see e.g. Jones 1995), and typically the formula derived by Whipple (1951) is used to estimate meteoroid ejection velocities. Whipple's formula is based upon the understanding that meteoroids are transported away from the cometary nucleus by a gas outflow initiated by surface ice sublimation. In the case of C/1995 01, however, we need also to consider meteoroid ejection at the time of cometary outbursts.

Very little is in fact known about the processes responsible for the occurrence of cometary outbursts (Hughes 1991; Matese & Whitman 1994). It is known, however, that at least some of the dust particles ejected during an outburst must have diameters in excess of 0.1 μm – smaller particles, although probably present, will not scatter sunlight efficiently.

An estimate of the mass of the largest meteoroid in any dust stream associated with C/1995 01 can be obtained from the formula given by Sekanina (1972) – the formula being derived upon the balance of the gas drag equation with gravity when the comet is near perihelion. Assuming that the nuclear diameter of C/1995 01 is between 10 and 60 km (A'Hearn, private communication), then the largest meteoroid in the cometary dust stream will have a mass in the range ~1 to ~50 g. The mass of the smallest meteoroid that might exist in any Hale–Bopp stream (assuming at least one previous perihelion passage) is set by the effects of radiation pressure. The condition for hyperbolic ejection at perihelion is determined as $\beta \geq (1-e)/2$, where $\beta$ is the ratio of the solar radiation force to the gravitational force of the Sun and $e$ is the orbital eccentricity. Since C/1995 01 has a highly elliptical orbit ($e \approx 0.995$), the smallest meteoroid ejected at perihelion that might be expected to remain on a bound orbit has a mass of $\sim 10^{-4}$ g.

## 3 THE DISTRIBUTION OF OUTBURST METEOROIDS

Since we do not know the physical details of the outburst process, we simply assume that all of the outburst-ejected material, irrespective of mass, acquires the same velocity at infinity. The outburst jet features observed from C/1995 01 indicate ejection velocities of at least 25 to 50 m s$^{-1}$. It is worth noting, however, that the observed ejection velocities apply to micron-sized dust grains, and it is entirely possible that the larger meteoroids will have lower velocities at infinity. We also note that the observed ejection velocities from other comets during outbursts have ranged as high as several hundred metres per second (Hughes 1991). The ejection velocities observed for C/1995 01 are about twice that predicted by Whipple's formula, at 8 au, for ~$10^{-4}$-g meteoroids, and some 20 times larger than that predicted for 1-g meteoroids. There is no reason to believe, however, that the normal water-ice sublimation process is active at 8 au from the Sun. In the analysis that follows, we treat the outburst ejection velocity as an free parameter, and ask what is the descending node distribution of material ejected from C/1995 01, given that an outburst takes place at a time 2 years before perihelion passage. The time constraint is chosen to model that of the observed outbursts. The orbital parameters for C/1995 01 are taken from Marsden (1995).

Our modelling is straightforward. The initial orbital distribution of outburst material is determined by combining the orbital velocity of C/1995 01 with that of 2000 hypothetical meteoroids ejected in random directions at an assumed ejection velocity. While it is clear that material is not ejected uniformly during an outburst, the assumption of isotropic ejection does allow for a complete coverage of all possible meteoroid distributions.

Fig. 1 shows the nodal distribution for material ejected from C/1995 01 at a pre-perihelion passage time of $\Delta t = -2$ yr, assuming ejection velocities of 50 and 200 m s$^{-1}$. Since the orbital inclination of C/1995 01 is nearly perpendicular to the ecliptic plane, the cloud of outburst meteoroids has a near-circular cross-section. Fig. 2 shows the solar distance versus nodal crossing time. Since we have allowed for material to be ejected isotropically, the outburst material passes through the descending node 3 to 5 d ahead of and 3 to 5 d behind C/1995 01. Table 1 is a summary of the hypothetical outburst conditions.

We find that if the outburst ejection velocity exceeds ~250 m s$^{-1}$ (at $\Delta t = -2$ yr) then a small fraction of the outburst cloud material will cross the Earth's orbit. This material moves through the descending node, however, well before the Earth is actually in a position to encounter any meteoroids.

Therefore, in relation to the outburst material ejected 2 yr before perihelion (i.e. the observed situation), our conclusion is straightforward: we do not expect to see any enhanced meteoric activity when the Earth cuts through the orbital plane of C/1995 01 Hale–Bopp on 1997 July 4.38.

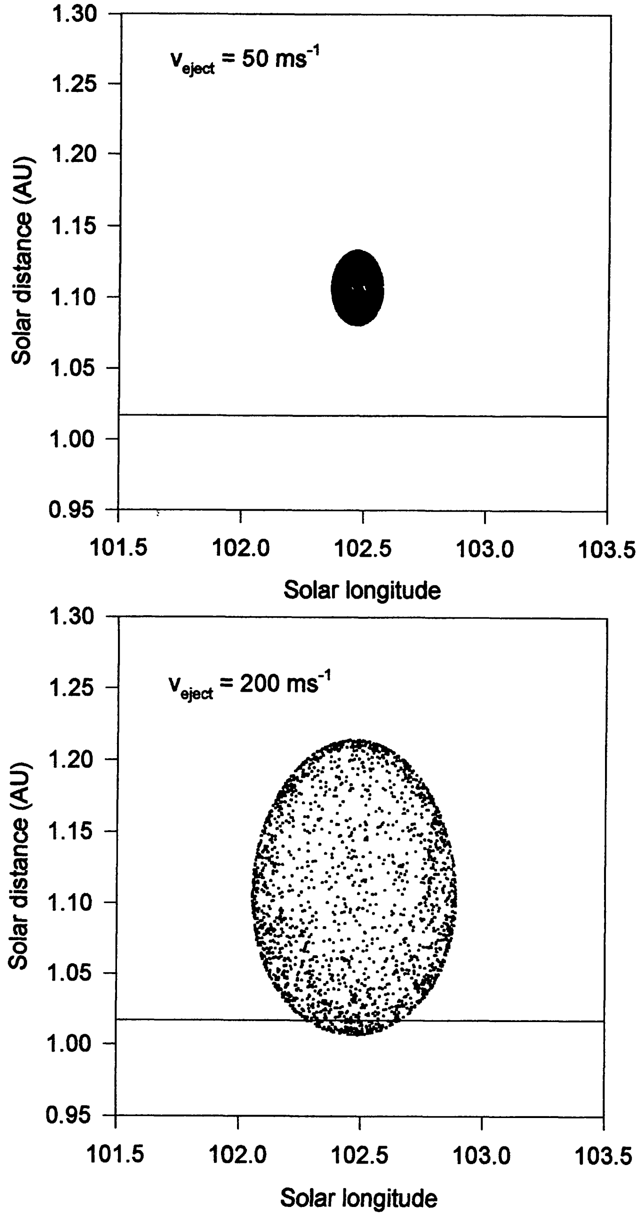

**Figure 1.** Nodal distribution of meteoroids ejected from Comet Hale–Bopp for an outburst event 2 yr before perihelion passage. The solid line corresponds to the radius of the Earth's orbit at a solar longitude of 102°.5 (epoch 2000).

## 4 THE DISTRIBUTION OF STREAM METEOROIDS

It is not at all clear that C/1995 01 is on its first sojourn to the inner Solar system. Marsden (1995) has found that the Comet was last at perihelion some 4200 yr ago, and that its present orbital period is ~3400 yr. It appears, therefore, that the comet has made at least one and perhaps several previous perihelion passages, and may consequently have an accompanying meteoroid stream. We can assess the possible distribution of meteoroids ejected from Comet Hale–Bopp, at a previous perihelion passage, by following the orbital evolution of hypothetical meteoroids ejected from the comet during its present perihelion passage. This method pre-supposes that the orbit of C/1995 01 has not changed significantly over the past 2500 yr. Given the near-90° orbital inclination of Hale–Bopp's orbit, this is probably a good assumption.

To model the meteoroid stream associated with C/1995 01 we have numerically followed the orbital evolution of 30 000 hypothetical test particles. For each particle the ejection velocity is determined via Whipple's (1951) formula. The particle ejection is allowed to take place provided that $2.3 \geq R_{ej} \geq q$, where $R_{ej}$ is the heliocentric distance in au where ejection occurs, $q$ is the perihelion distance and the ejection takes place according to a random distribution of true anomalies over the arc constrained by $R_{ej}$. The orbital evolution of 5000 meteoroids, in five mass categories (1, $10^{-1}$, $10^{-2}$,

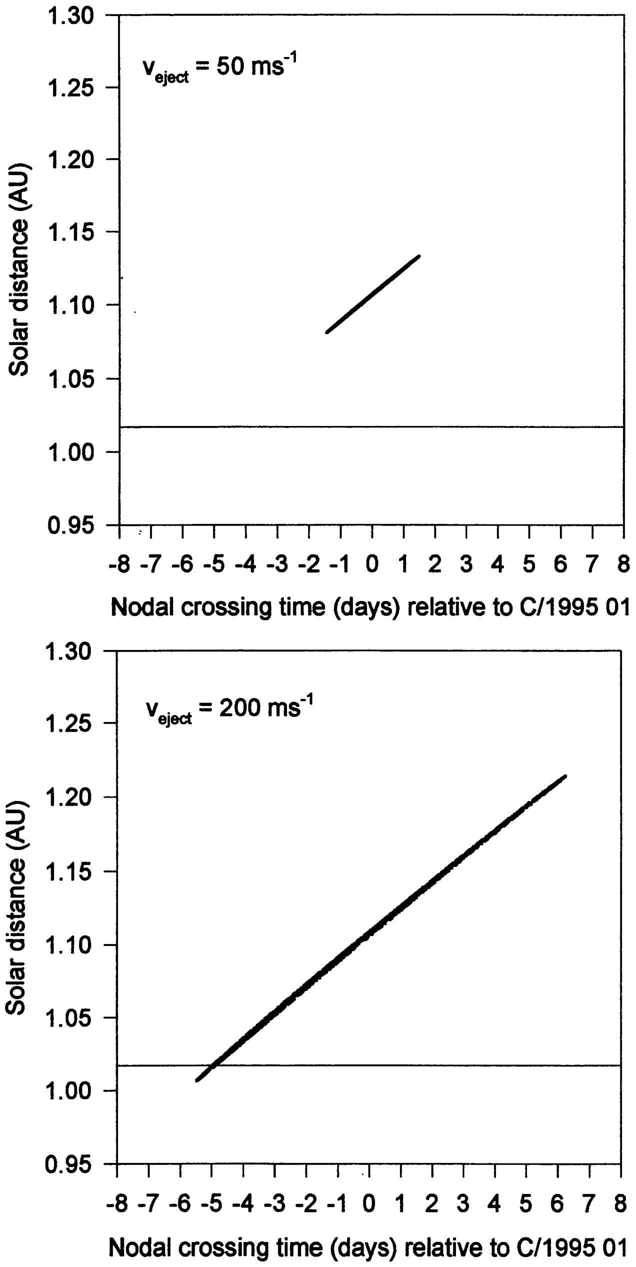

**Figure 2.** Nodal distance versus nodal crossing time for hypothetical meteoroids ejected from Comet Hale–Bopp for an outburst event 2 yr before perihelion passage. The solid line corresponds to the radius of the Earth's orbit at a solar longitude of 102°.5 (epoch 2000).

$10^{-3}$ and $10^{-4}$ g), has been followed. We have also considered a $10^{-6}$-g mass category. The motivation for considering the orbital evolution of very low-mass meteoroids was prompted by discussions with Bruce Burlton of Telesat Canada, who suggested to us that, given high enough spatial number densities, even low-mass meteoroid impacts can cause noticeable effects on spacecraft attitude control systems. A meteoroid density of 0.8 g cm$^{-3}$ was assumed and a nuclear diameter of 40 km was adopted. The orbital evolution of each particle was followed to its descending node or until it evolved on to a hyperbolic orbit (at which point the orbital evolution of the particle was no longer followed). Details of the numerical scheme and the input physics are given in Jones (1985).

**Table 1.** Summary of nodal crossing conditions for material ejected from C/1995 01 at a pre-perihelion passage time of $\Delta t = -2$ yr. $V_{ej}$ is the ejection velocity while $R$ is the mean heliocentric distance of the outburst-ejected meteoroid cloud at the descending node (see Fig. 1). $R_{min}$ is the smallest heliocentric distance at the descending node. $\lambda_\odot$ is the mean solar longitude of the outburst-ejected meteoroid cloud at the descending node, while $\delta\lambda$ is the extent of the meteoroid cloud in degrees. $\delta t$ is the overall spread in time with which the meteoroids in the outburst cloud reach their respective nodes relative to the nodal crossing time of C/1995 01 (see Fig. 2).

| $V_{ej}$ | $<R$(au)$>$ | $R_{min}$(au) | $\lambda_\odot$(deg) | $\delta\lambda$ (deg) | $\delta t$ (days) |
|---|---|---|---|---|---|
| 25 | 1.107 | 1.094 | 102°.47 | 0°.104 | 1.46 |
| 50 | 1.107 | 1.081 | 102°.46 | 0°.209 | 2.92 |
| 100 | 1.109 | 1.056 | 102°.47 | 0°.416 | 5.84 |
| 250 | 1.104 | 1.006 | 102°.47 | 0°.835 | 11.71 |

Figs 3 and 4 show the distribution of the 1- and $10^{-4}$-g particles at their respective descending nodes. The figures indicate the solar distance versus nodal crossing time for each particle that has remained on a bound orbit (the nodal distributions for the other mass categories considered are similar to the ones shown in Figs 3 and 4). As one might expect the 'spread' in solar distance is much greater for the $10^{-4}$-g particles than for the 1-g particles. This is partly a consequence of the smaller mass particles having higher ejection velocities, and partly due to the effects of differential radiation pressure. Fig. 5 shows the descending node distribution of the $10^{-6}$-g particles. Only about 35 per cent of the test particles initially ejected in this low-mass range survived to return to perihelion. This is as we would expect since we have already argued

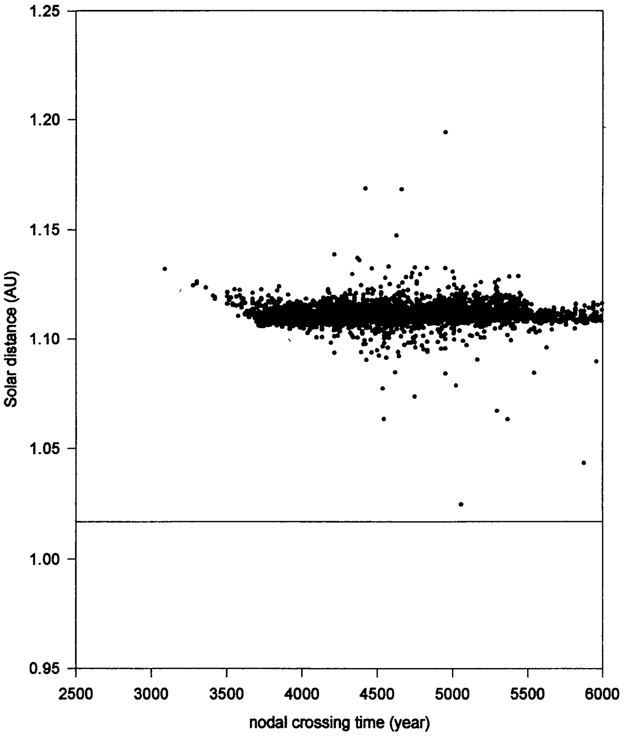

**Figure 3.** Nodal distance versus year of nodal crossing for 1-g meteoroids ejected from Hale–Bopp at an assumed previous perihelion passage. The solid line corresponds to the radius of the Earth's orbit at a solar longitude of 102°.5 (epoch 2000).

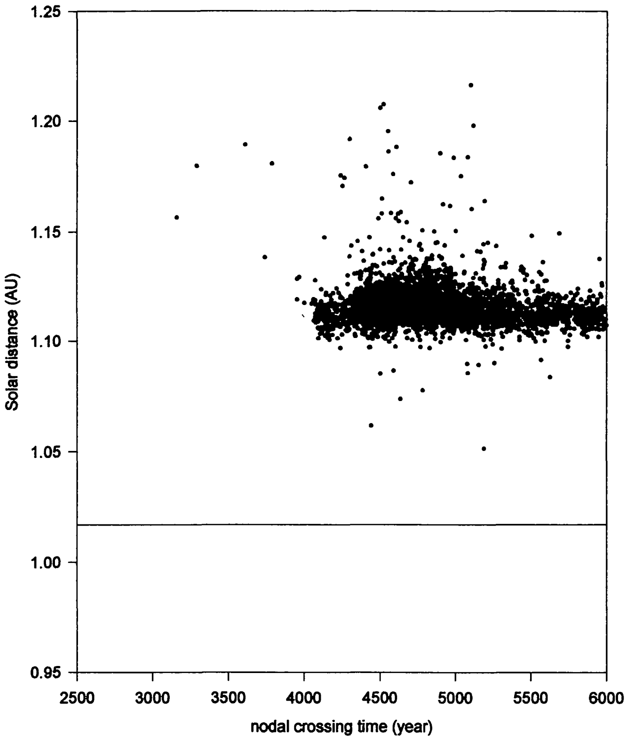

**Figure 4.** As Fig. 3 but for $10^{-4}$-g meteoroids.

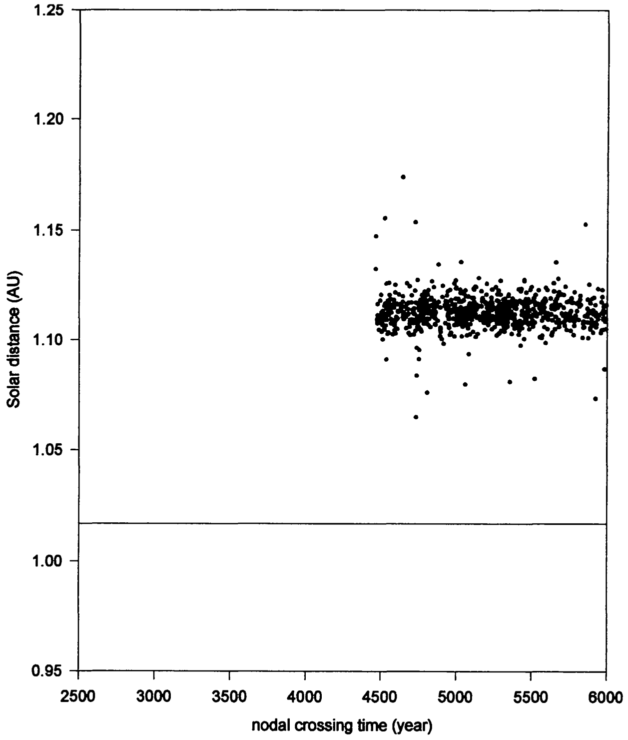

**Figure 5.** As Fig. 3 but for $10^{-6}$-g meteoroids.

that radiation pressure effects will become increasingly significant for masses smaller than $10^{-4}$ g. Also, the ejection velocities for $10^{-6}$-g particles are $\approx 400\,\mathrm{m\,s^{-1}}$ at 1 au, according to Whipple's formula, which further weakens the condition for remaining on a bound orbit after ejection. The $10^{-6}$-g particles that remain on bound orbits are essentially those ejected far from perihelion, and Fig. 5 indicates that the 'spread' of these particles away from the orbit of C/1995 01 is small. Consequently we do not expect the Earth (or for that matter Earth-orbiting satellites) to encounter any significant numbers of low-mass meteoroids from Comet Hale–Bopp.

It is clear from Figs 3 to 5 that there is very little chance of any of the meteoroids ejected from C/1995 01 reaching Earth orbit. Consequently, on the suppositions that our modelling assumptions are correct, that C/1995 01 has made at least one previous perihelion passage and that its orbital elements have not dramatically changed in the last several thousand years, we do not expect to see any enhanced meteoric activity when the Earth cuts through the orbital plane of C/1995 01 Hale–Bopp in 1997 July. Also, we can add the somewhat far-sighted corollary to the foregoing argument that we do not expect to see any enhanced meteoric activity from C/1995 01 when it next returns to perihelion some 3400 yr hence.

## 5 DISCUSSION

In this work we have considered the distribution of hypothetical meteoroids ejected from C/1995 01 Hale–Bopp at their descending nodes only. The ascending node of C/1995 01 Hale–Bopp is situated some 5 au from the Sun and well away from the Earth. Steel (1995) has recently argued, and we agree with his comments, that contrary to speculative debate there is no physical reason to believe that Comet C/1995 01 Hale–Bopp is the parent comet of the Quadrantid meteoroid stream. The fact that the Earth cuts through the orbital plane of the comet on the night during which the Quadrantids reach their peak (January 3) is entirely coincidental.

The forthcoming perihelion passage of Comet C/1995 01 Hale–Bopp promises to be a spectacular visual event. It appears, however, from the modelling described above that it will not be accompanied by any enhanced meteoric activity.

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