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The Daytime Craterids, a radar-detected meteor shower outburst from hyperbolic comet C/2007 W1 (Boattini)

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ABSTRACT

We report a new daytime meteor shower detected with the Canadian Meteor Orbit Radar (CMOR). This shower has a radiant in the southern constellation Crater. The Daytime Craterid shower was observed in 2003 and 2008 but not in any of the other years in the 2002–09 interval. The strength of this shower in the years observed is equivalent to a daily averaged zenithal hourly rate (ZHR) over 30, with a peak ZHR likely much higher at the time of the outburst. The orbital elements of the shower closely match those of Comet C/2007 W1 (Boattini), which passed perihelion in 2007. The orbit of C/2007 W1 is nominally hyperbolic orbit making this the first meteor shower detected from a clearly unbound comet. The 2003 outburst of the Daytime Craterid shower indicates that this comet must have recently been transferred to an unbound orbit from a bound one, likely through a close encounter with a giant planet. As a result we conclude that this shower provides us with one of the few examples of showers originating from the population of nearly isotropic comets. The stream is difficult to model owing to its proximity to the orbits of Jupiter, Saturn and the Earth. However, the intermittent nature of the shower can be largely understood from numerical simulations. No outbursts of similar strength are expected in the next decade, with the possible exception of 2015.

Key words: comets: individual: C/2007 W1 (Boattini) – meteorites, meteors, meteoroids.

1 INTRODUCTION

Meteor showers offer an opportunity to indirectly sample small Solar system bodies which are otherwise inaccessible. In cases where the shower can be linked to a known parent body, examination of the ablation behaviour and spectra of shower meteors provides clues to the chemistry, physical structure and evolutionary history of the parent (Borovicka 2006). Among the population of small bodies most desirable to sample are meteor showers from dynamically new long period comets [new nearly isotropic comets (NICs) in the taxonomy of Levison 1996]. Meteoroids from new NICs may sample the crusts of new Oort cloud comets and provide clues to the processing they have experienced. Furthermore, the NICs as a population are enigmatic as they disappear very quickly for not yet fully understood reasons, a mystery termed the 'fading problem' (cf. Wiegert & Tremaine 1999). One interpretation is that they are more fragile than Jupiter-family comets or Halley-type comets and disintegrate readily; if true this weak physical structure may be expressed in the chemistry or strength of daughter meteoroids.

Unfortunately, meteor streams associated with long-period comets are very rare. Only a handful of showers have confirmed long-period parents, among the best studied linkages are comet Thatcher and the Lyrid shower and comet Kiess and the Aurigids (Jenniskens 2006). The reasons for this lack of showers from long-period parents are several. Long-period streams, due to their larger orbits, are less dense than equivalent mass streams with shorter periods and often are quickly dispersed, such that only one revolution trails produce detectable activity (Lyytinen & Jenniskens 2003). As NICs may make only a few or even just one perihelion passage within the planetary system, it is difficult for a typical NIC to establish complete 'closed-loop' meteoroid streams as the ejected meteoroids move on orbits with very different periods. The large semimajor axis of the parent means that small velocity perturbations at ejection (or differences in radiation pressure among particles) can create an enormous spread in the periods of daughter meteoroids. This further contributes to the apparent weakness of NIC-related streams as seen at the Earth.

Here we report on the discovery of a strong daytime shower peaking near August 31 recorded by the Canadian Meteor Orbit Radar (CMOR, Webster et al. 2004) in 2003 and 2008 and whose orbital elements are close to those of comet C/2007 W1 (Boattini). The shower showed strong activity only in 2003 and 2008 and no detectable activity in other years from 2002 to 2009.

Comet C/2007 W1 was discovered by Andrea Boattini on 2007 November 20 as part of the Mt Lemmon Survey (Boattini et al. 2007). Though not intrinsically bright, C/2007 W1 passed 0.21 au of the Earth on 2008 June 12 and reached naked eye brightness

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Table 1. Orbital elements of the meteor shower based on the wavelet maxima as measured by CMOR on two separate days in 2003 and 2008. The orbital elements of comet C/2007 W1 from different sources are included in the lines below.

	q (au)	e	i (°)	Ω (°)	ω (°)	V_g (km s^{-1})	A_1	A_2	A_3
2003-158.0	0.814	0.769	9.3	338.0	303.7	18.1	–	–	–
2003-159.0	0.809	0.763	9.5	339.0	302.8	18.2	–	–	–
2008-158.0	0.805	0.802	9.7	338.0	303.0	18.9	–	–	–
2008-159.0	0.801	0.790	9.5	339.0	302.3	18.8	–	–	–
C/2007 W1[a]	0.8497	1.000 18	9.889	334.5	306.6	–	–	–	–
C/2007 W1[b]	0.8497	1.000 027	9.889	334.5	306.6	–	+3.85	−0.9414	0
C/2007 W1[c]	0.849 728	1.000 154	9.890 34	334.5313	306.5461	–	–	–	–

[a]Marsden & Williams (2008).
[b]Minor Planet Circular 63599.
[c]JPL Horizons, http://ssd.jpl.nasa.gov, retrieved 2010 February 26.

(Mattiazzo et al. 2008). The orbital elements for the comet are given in Table 1. The absolute nuclear magnitude is estimated at 16.9 (JPL Horizons web site http://ssd.jpl.nasa.gov).

Relative to this nominal orbit of C/2007 W1, the meteor shower has a D parameter (Southworth & Hawkins 1963) of 0.044 as computed using the algorithm of Neslusan, Svoren & Porubcan (1998) using the adjustment of the orbit by variation of the perihelion distance or 0.11 using the adjustment of the orbit by variation of the argument of perihelion. The minimum orbital intersection distance of the nominal comet orbit with the Earth is 0.0177 au at its ascending node. These values are close enough to make a reasonably secure association between the stream and its parent.

Remarkably, C/2007 W1 is in a nominally hyperbolic orbit and hence classified as a new NIC; however, based on the association with the new shower, it would appear it is a returning NIC with a very long orbital period. As shown in the next section, the theoretical shower radiant location, velocity and timing are in good agreement with these observed values under the assumption that they were produced by the perihelion passage of the comet immediately preceding that of 2007, using the method of Lyytinen & Jenniskens (2003). Theoretical analysis of this shower is complicated by the absence of a closed parent orbit and the proximity of the stream to the orbits of both Jupiter and Saturn; nonetheless, a largely satisfactory explanation of the stream's activity levels can be obtained.

In Section 2 we discuss the radar observations of this shower; in Section 3 we discuss how a hyperbolic comet can be associated with recurring meteor shower; Section 4 presents the results of our simulations of the shower's activity, both past and future, and conclusions are drawn in Section 5.

2 RADAR OBSERVATIONS

The CMOR has been running continuously since 2002 recording 2000–3000 individual meteoroid orbits per day. Details of the radar operations, data reduction techniques and hardware can be found in Webster et al. (2004), Jones et al. (2005), Brown et al. (2008, 2010). CMOR operates simultaneously at three frequencies (17.45, 29.85 and 38.15 MHz) and each system uses a five-element interferometer to determine echo direction as seen from the main radar site. Additionally, the 29.85-MHz system has two outlying stations which permit time-of-flight speed measurements. This information, combined with interferometry from the main site, allows the computation of individual orbits. Meteor echoes strong enough to be detected at all three stations are typically from meteors of radio magnitude +7, corresponding roughly to meteoroids of mass 10^{-7} kg at 30 km s^{-1}.

Beginning in 2006, a long-term analysis programme of shower detection and monitoring has been undertaken with CMOR. Detection of the Daytime Craterid shower outbursts was originally made automatically as part of expanded automated processing based upon application of 3D wavelet transforms to the CMOR data set focusing on short duration (1–2 d) shower enhancements. Details of the underlying detection methodology are given in Brown et al. (2010).

Table 2 shows the output from the 3D wavelet processing algorithm which isolated the Daytime Craterid radiant maximum, shown over a 2-d period in each of 2003 and 2008. The Daytime Craterid outbursts in 2003 and 2008 were the strongest outbursts detected by CMOR in the interval 2002–09, exceeding even the 2005 Draconid outburst (Campbell-Brown et al. 2006). Here the wavelet search was done in radiant Sun-centred ecliptic coordinates with a spatial probe size of 4°, a velocity probe size of 10 per cent

Table 2. Measured radiant maxima for the Daytime Craterid shower based on a 3D wavelet transform (cf. Brown et al. 2010). The solar longitude is λ_0, λ and β are the ecliptic longitude and latitude of the radiant, V_g is the geocentric velocity, W_c is the (dimensionless) wavelet coefficient, $N\sigma$ is the signal-to-noise ratio of the shower above the background, σ is the background rate (units of W_c) and n is the number of meteor orbits used in the computation of the wavelet value. All angular elements are J2000.0 and in degrees.

	λ_0	$\lambda - \lambda_0$	β	α	δ	V_g (km s^{-1})	W_c	$N\sigma$	σ	n
2003										
	158.0	18.5	−18.5	169.3	−15.5	18.1	203.1	39.9	5.1	91
	159.0	17.8	−18.5	169.5	−15.7	18.2	204.2	39.4	5.2	96
2008										
	158.0	18.0	−18.4	168.8	−15.3	18.9	227.6	40.3	5.6	113
	159.0	17.4	−18.1	169.4	−15.2	18.8	196.1	38.5	5.1	90

of the geocentric velocity value and with angular step sizes of 0°.1. Maxima were identified if: (1) they exceeded the background by more than 3σ, where both the statistical fluctuations appropriate to the wavelet probe and the standard deviation of the measured annual background radiant activity at the same probe position were used to compute σ and (2) if more than 60 meteors were used to compute the wavelet coefficient. The Daytime Craterid outburst is nearly 40σ above the background and is extremely obvious in the raw data. The peak solar longitudes of 158–159 corresponds to UT dates of August 31–September 1 in 2003 and 2008.

Fig. 1 shows the combined radiant activity measured using CMOR data at 29.85 MHz and the radiant mapping technique of Jones & Jones (2006). Here we have combined the daily radiant maps (in equatorial coordinates) for the one week centred around August 31–September 1 in each year from 2002 to 2009. Consistent activity is visible near the origin each year (from the Taurid/Aquariid

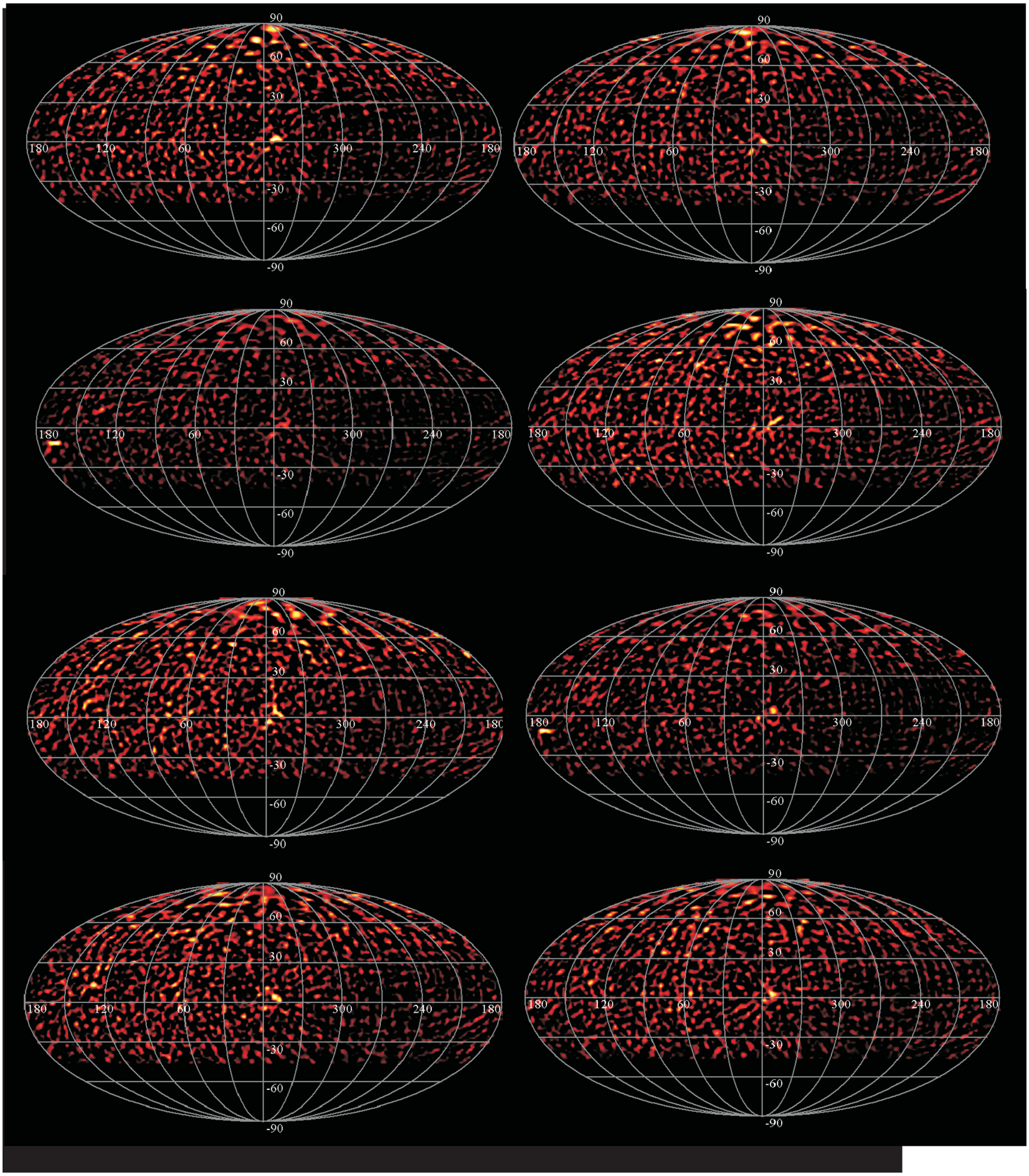

Figure 1. CMOR 29.85-MHz radiant activity mapped with the technique of Jones & Jones (2006) in equatorial coordinates. The daily radiant maps are for the 1 week centred around August 31–September 1 in each year from 2002–09. The data for 2002 are in the upper left corner with 2003, 2004 and 2005 below it in that order. The plots on the right hand side are ordered similarly, with 2006 in the upper right and 2009 in the lower right. The signature of strong Craterid activity is visible in 2003 and 2008 (under the 180° RA label) near an apparent radiant of (+170°, −15°).

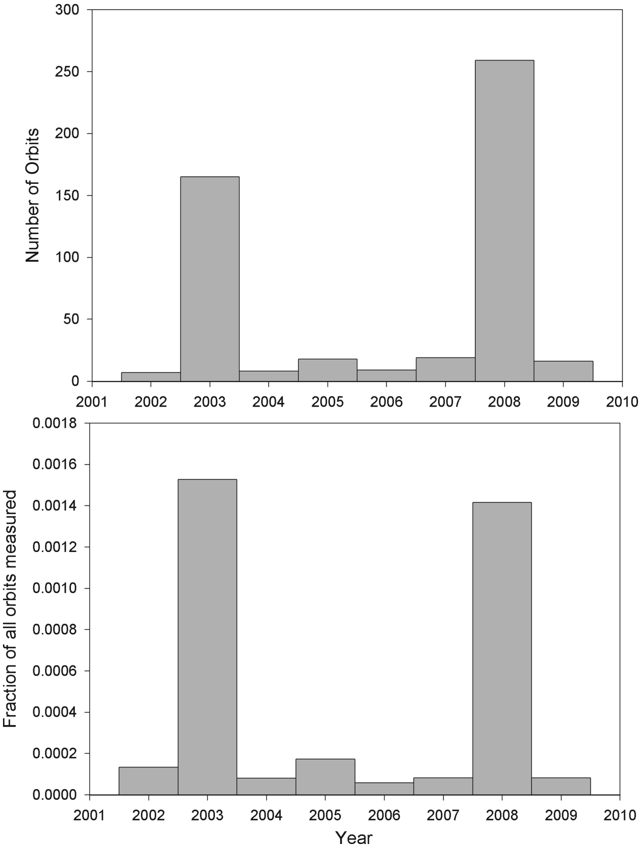

Figure 2. Number of CMOR-recorded meteors observed from August 20 to September 10 each year which are within 6° of the radiant position at maximum and within 20 per cent of the geocentric velocity (top panel); the fraction of these Daytime Craterid orbits seen relative to the total number of meteors recorded in the same time interval (bottom panel).

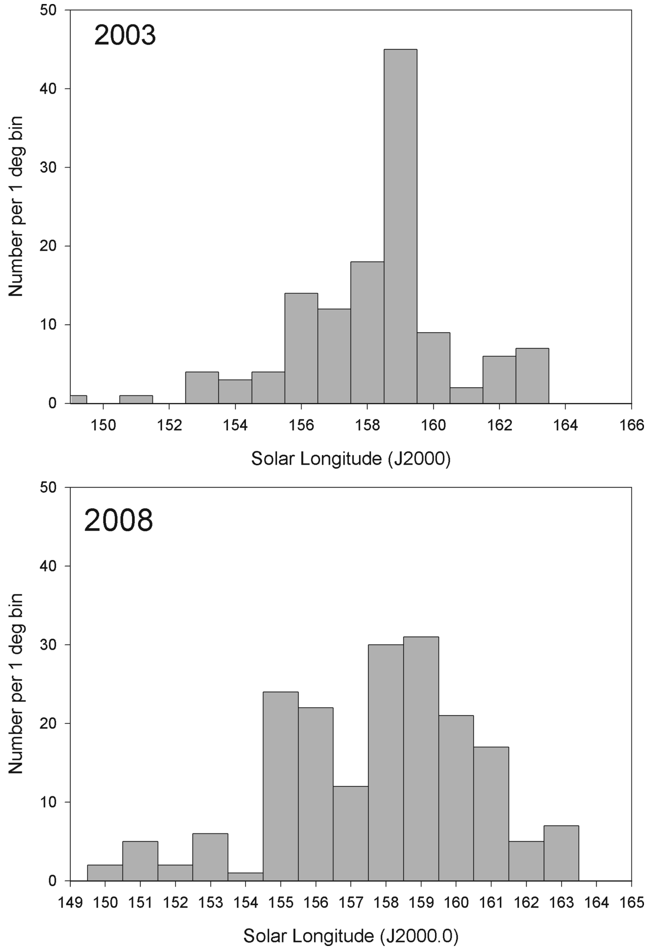

Figure 3. The number of orbits recorded in 2003 and 2008 by CMOR over the solar longitude interval 150–165.

complex), but a horizontal line of strong activity is visible in 2003 and 2008 (under the 180° RA label) near an apparent radiant of (+170°, −15°). The outbursts in 2003 and 2008 are also visible in similar plots from 38.15-MHz data. Further confirmation of the strength of the shower is evident when individual radiants are selected. In Fig. 2 we have plotted the relative number of meteors from August 20 to September 10 each year which are within 6° of the radiant position at maximum (as given in Table 2) and within 20 per cent of the geocentric velocity. The figure shows the actual number of orbits selected (top plot) and the relative number of orbits compared to the total number of meteors recorded by CMOR in the interval from August 20 to September 10 each year. This total number varies from as few as 52 000 orbits in 2002 to as many as 230 000 in 2007, the difference largely attributable to variability in the UHF propagation conditions between the main site and remote sites (cf. Brown et al. 2010 for a more detailed discussion). The low number of background orbits reflects the relatively large elongation of the radiant from the apex and its location just outside the helion sporadic source. Furthermore, at this elongation and velocity only nearly parabolic orbits can produce radiants in this region.

Fig. 3 shows the number of orbits recorded in 2003 and 2008 over the solar longitude interval 150–165. The peak in 2003 centred at 159 is apparent; the numbers of recorded orbits should not be interpreted rigorously as changes in the flux of the shower as the number is a sensitive function of the link propagation strength between the remote stations and the main site. In 2008, in particular, from 153 to 157 there was significant disruption of the links. These values should be interpreted to indicate the range in detectable activity of the shower and an indication of the peak time, but only qualitatively as to the change in activity with time. To compute fluxes, the echoes within 5° of the radar echo-line corresponding to the shower radiant were selected in single station data on 29.85 MHz and this rate was used together with the radar collecting area formalism described in Brown & Jones (1995) and Campbell-Brown & Jones (2006) to compute an equivalent flux. This rate was corrected for sporadic background contamination by subtracting equivalent rates from the same radiant direction (in Sun-centred ecliptic coordinates) outside the activity interval of the shower. A mass index of $s = 2.0$ was assumed in all calculations. The peak flux in 2003 was found to occur near 158–159 and have a value of $\Phi = 1.7 \times 10^{-2}$ meteoroids km^{-2} h^{-1} with mass $>10^{-6}$ kg, while in 2008 the peak flux was $\Phi = 1.5 \times 10^{-2}$ meteoroids km^{-2} h^{-1} with mass $> 10^{-6}$ kg near 158. Using the conversion methodology given in Brown & Rendtel (1996) and a mass index of $s = 2.0$ these fluxes correspond to equivalent average visual zenithal hourly rates (ZHRs) of ≈30. We note that the these represent daily averages; actual hourly ZHRs were likely much higher at the peak.

We sought to confirm the Craterid outbursts by querying the operators of other radar systems as to whether or not they had detected them as well. However, we were unable to obtain much data. We were fortunate enough to gain access to the CLOVAR windprofiler radar (Hocking 1993) data base, which confirmed the outbursts in 2003 and 2008. The absence of an outbursts in other years, up to and including 2002 was also confirmed. Unfortunately no earlier observations at the correct time of year were available, so the presence or absence of earlier outbursts could not be checked from the CLOVAR data.

We do note that CMOR has both 29.85- and 38.15-MHz systems which are largely independent and thus provides what are effectively two separate measurements of Craterid activity. Even in the case of the non-detections of activity in 2000 and 2001, the sensitivity of the CMOR systems as they were at the time is such that we believe that they constitute independent measurements of non-activity in these years.

From these radar data we want to measure the variation in orbital elements as the Earth crosses the stream and also determine the 'best' orbit of the stream meteoroids. The best estimate for the stream orbit is uncertain due to need for correction of the velocity for the deceleration of meteoroids in the atmosphere – for our nominal orbits we have used a mean atmospheric deceleration correction as described in Brown et al. (2004). The uncertainty arises because we observe the meteor echoes at essentially only one point (randomly distributed) along the trail. Depending on what height this specular reflection occurs, the measured velocity will be somewhat below the true out-of-atmosphere meteoroid velocity. For all orbits in this analysis each echo was manually examined, time inflection picks verified, bad echoes discarded and Fresnel velocity as measured at the main site directly computed from observed amplitude oscillations (cf. Ceplecha et al. 1998 for a description of Fresnel amplitude oscillations). To verify that our time-of-flight velocities are robust (and also the quality of our radiant measurement which depends on the same time picks) in Fig. 4 we plot all selected Daytime Craterid orbits time-of-flight speed values minus the Fresnel speed measurement. The standard deviation of the difference is less than 1 km s^{-1}, giving an indication of the error ($\sim$5 per cent) in our speed measurements.

A plot of height versus measured velocity provides an additional constraint on the initial velocity of the shower. Our earlier estimate for the out-of-atmosphere velocity of the shower (see Table 2) is based on an interpolation of the average height deceleration profile for a selection of reference showers observed by CMOR (see Brown et al. 2004 for a description). We have no a priori reason to expect this broad global fit to apply to the Daytime Craterid shower. To independently estimate the robustness of our initial velocity estimate for the stream we apply the entry model of Campbell-Brown & Koschny (2004) to try to reproduce our observed echo characteristics. In addition to the height versus velocity we also compute the instantaneous electron line density (q) associated with each echo, using the observed amplitude, a calibration of this amplitude to power received at the antenna, our gain pattern and the known range to the echo together with single-body meteor radar theory (cf. Ceplecha et al. 1998). For our orbit measurements, the radar detection algorithm excludes overdense echoes, so we expect the upper mass limit (at the specular point) to be $\approx 10^{-6}$ kg to perhaps a few times this value at the approximate speed of the Daytime Craterids. We choose a range of initial masses from 10^{-5} to 5×10^{-7} kg, in half decadal mass increments. We also use the average entry angle from our observed sample (30°), and values for the entry model appropriate to cometary meteoroids (such as an assumed particle density of 1000 kg m^{-3} etc.) as given by Campbell-Brown & Koschny (2004). Finally, we assume single-body ablation (no fragmentation). The results of these simulations together with the observations are shown in Fig. 5.

We performed forward modelling of the simulation between entry velocities from 21.2 to 25.7 km s^{-1}, (the latter being the parabolic velocity for the shower given its radiant location), in 0.5 km s^{-1}

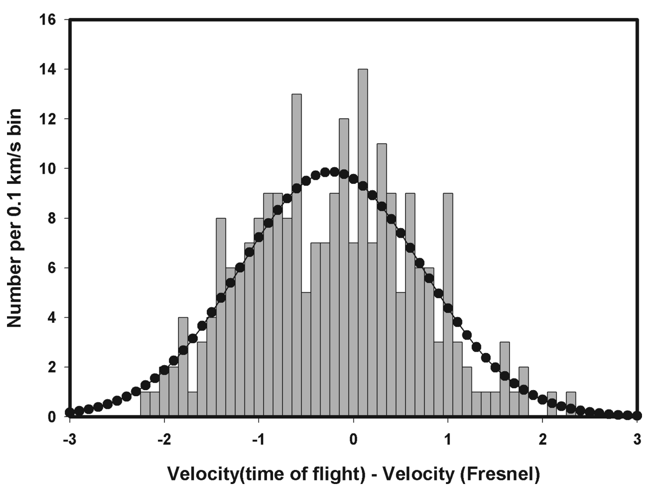

Figure 4. Time-of-flight speeds minus the Fresnel speed measurement for Daytime Craterid meteors. The solid black line is a Gaussian fit to these values.

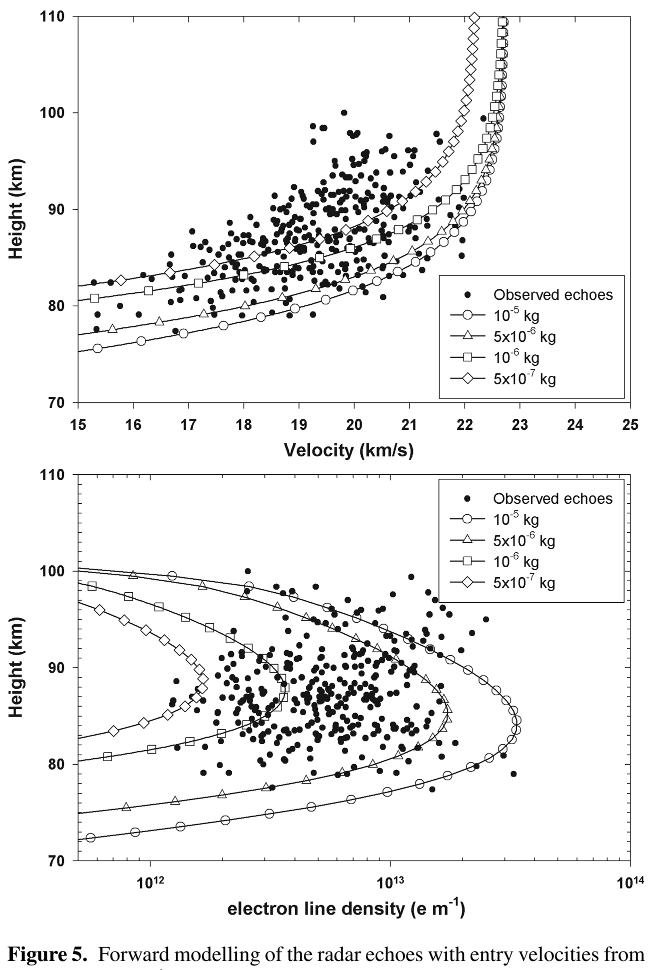

Figure 5. Forward modelling of the radar echoes with entry velocities from 21.2–25.7 km s^{-1} and a range of masses. The lines on the upper graph indicate modelled meteor speeds and heights for different mass particles, while the filled circles indicate the measured values of the radar-observed echoes. The lower plot is similar except that it plots the modelled electron line density. See text for more details.

Table 3. Mean orbital elements of the meteor shower based on the best fit to the observed shower parameters derived from entry modelling at a solar longitude of 158°.

a (au)	q (au)	e	i (°)	Ω (°)	ω (°)	V_g (km s^{-1})	α_g	δ_g
5.5 ± 1.3	0.804 ± 0.008	0.853 ± 0.034	8.0 ± 0.6	338.0	304.0 ± 1.4	19.4 ± 0.6	171°.4	−12°.7

increments for four different masses of particles from 5×10^{-7} to 10^{-5} kg (Fig. 5). We find that our best fit for three of the four masses is 22.7 km s^{-1} but the overall best fit to the sample is for the fourth mass, 5×10^{-7} kg at $v = 22.2 \pm 0.5$ km s^{-1}. Velocities $\gtrsim$23 km s^{-1} produce an excess of higher velocities than is observed at the highest heights as compared to our model. Indeed, from the figure it is apparent that the largest observed velocities are 22–22.3 km s^{-1}, consistent with our fit. Similarly, velocities $\lesssim$21.5 km s^{-1} predict too few low-speed meteors compared to our errors at the highest heights. Our maximum in electron line density does correspond to the observed maximum, but the model predictions are shifted downward almost 10 km in height. This is exactly the expected behaviour presuming fragmentation is common. A similar effect will tend to shift the simulation curves in the top plots upward and to the left. In a qualitative sense (having no hard constraints on the nature of the fragmentation) our simulation can self-consistently explain the observations using an initial entry velocity of $v = 22.2 \pm 0.5$ km s^{-1} and initial meteoroid masses of $<10^{-5}$ kg.

Using this speed estimate (and its error) together with our measured radiant (and an estimated error of 1° from Brown et al. (2010)) we provide our best estimate for the mean stream orbit in Table 3.

3 THE COMET/STREAM ASSOCIATION

As mentioned in the introduction, the meteor shower has a D parameter (Southworth & Hawkins 1963) of 0.044–0.11 relative to the nominal orbit of C/2007 W1 (Boattini), a low value which suggests a connection between the two. However, orbital determinations of C/2007 W1 indicate that it entered the planetary system on an unbound orbit relative to the Solar system barycentre. Table 1 lists cometary orbital elements derived from three different sources. Backwards integrations of each of these elements, some of which include non-gravitational forces, all produce qualitatively the same result, that the comet entered the Solar system on a slightly unbound orbit. The comet catalogue of Marsden & Williams (2008) also provides a value for the inverse semimajor axis of C/2007 W1 prior to entering the planetary system (the ‘original 1/a’) of −0.000 010 au^{-1}, a mildly hyperbolic approach orbit. If the comet was truly making its first return from the Oort cloud (or even if it were arriving on a true hyperbolic path), it could not have already deposited a meteoroid stream and thus cannot be the parent of the Daytime Craterid meteor shower, at least not of the outburst seen in 2003.

However, it is difficult to determine high-precision orbital energies for comets. The coma produced during the comet’s brightest phases makes a precise determination of the much-smaller cometary nucleus problematic. Comet Boattini was noted to have an asymmetric coma during its discovery report (Boattini et al. 2007) which may have contributed to this problem. In fact, the comet catalogue of Marsden & Williams (2008) lists many comets with orbits whose arrival energies with respect to the Solar system barycentre indicate that they are unbound. These are widely interpreted to be in reality arriving on very weakly bound orbits from the Oort cloud.

Adding to the difficulty in determining the true orbit of C/2007 W1 is the fact that it passed 1.2 au (less than three Hill radii) from Saturn on 2006 April 26, just prior to its most recent perihelion passage. Such close approaches are notorious for increasing the uncertainty of orbit integrations for bodies passing through such encounters.

Thus it may well be that measurement uncertainty masks the true nature of the orbit of this comet. We investigated this; however, the Horizons web site (http://ssd.jpl.nasa.gov) is the only one that provides the orbit uncertainties needed to do a more careful analysis. We took a set of 1000 clones with orbits chosen randomly within the 1σ orbital element error bars provided by Horizons and integrated them backwards. Upon doing so the nominal orbit of C/2007 W1 was found to be hyperbolic as was reported by the sources mentioned earlier, but 434 of the clones were found to originate on orbits which were not hyperbolic but bound to the Solar system barycentre. Thus while the best single interpretation of the observational data points to a non-periodic nature for C/2007 W1 (Boattini), the data actually allow that there is almost one chance in two that C/2007 W1 is actually a returning periodic comet.

Bolstering the case for the periodic nature of C/2007 W1 is the radar-detected meteor shower observed in 2003, pointing to a stream of meteoroids released from this comet during a previous perihelion passage. Though it is difficult to exclude the possibility that this stream was actually produced by distinct separate comet, the orbital similarity of the stream and comet, the clear-cut dynamical explanation of the stream’s behaviour this provides (presented in Section 4) and the unlikelihood of an orbital coincidence leads us to conclude that C/2007 W1 has made at least one perihelion passage through the inner Solar system before.

On the basis of the arguments above, we conclude that C/2007 W1 (Boattini) was until recently on a periodic orbit around the Sun. This is an important conclusion as it puts this meteor shower among a rare class of showers associated with NICs.

4 THE SIMULATIONS

Dynamical simulations of the Daytime Craterid meteor shower were performed using a Wisdom & Holman (1991) type symplectic integrator with the Chambers (1999) method for handling close approaches between particles and the planets. The RADAU integrator of Everhart (1985) was used to check some simulations. The RADAU integrator is much slower, necessitating smaller numbers of particles, but the results were similar to those of the symplectic methods. The speed of the symplectic method allows an order of magnitude more particles to be examined and thus better statistics, and so those are the results reported here. Our simulated Solar system includes the Sun and all eight major planets, with masses, positions and velocities derived from the JPL DE406 ephemeris (Standish 1998). Poynting–Robertson drag and radiation forces were included. A time-step of 1 d was used.

The observational data reveals Daytime Craterid activity in 2003 and 2008, and one is naturally led to ask whether there were any unusual occurrences in those years that would lead to the outbursts.

In fact, there was a passage of the planet Jupiter near the meteor stream orbit in 2003, and 2008 was the year following the most recent perihelion passage of the comet. This leads one to suspect that these events are the causes of the observed activity; however, a closer examination reveals that neither of these events can be neatly connected to the shower outbursts.

In mid-2003, Jupiter passed through the Daytime Craterid meteoroid stream, which has a node near Jupiter's orbit. This resulted in a strong perturbation of the stream. However, simulations reveal that the affected meteoroids do not arrive at the Earth until 2004, and in any case, they are dispersed and do not produce concentrated activity. As well, though C/2007 W1 passed perihelion in 2007, simulations of the meteoroids released during this passage reveal that they do not hit the Earth in 2008. Rather they remain largely in the vicinity of the comet, missing the Earth by a substantial margin (as does their parent). In addition, these freshly produced meteoroids travel on orbits with longitudes of the ascending node Ω near the value of their parent ($\Omega \approx 335°$) not that of the observed stream ($\Omega \approx 339°$). Thus a straightforward explanation of the shower outburst as resulting from either of these two events is not possible, and we must proceed to a more general simulation of the meteoroid stream.

The largest difficulty to stream modelling is posed by the need to select a semimajor axis for the stream, a quantity which is not at all well known. This quantity is not easily measured by radar to the accuracy needed. The nominal shower orbit has $a = 5.5$ au, while the putative parent is nominally unbound. The difficulty is alleviated somewhat by the fact that the comet's orbit is certainly quite large, and thus the trajectory of the meteoroid stream through the *inner* Solar system is largely unaffected by the precise nature of its orbit. The radiant direction and velocity of meteors in the Earth's atmosphere will be quite similar for our simulated stream, whether their orbits be weakly bound or weakly unbound.

Here we will use a variation on the approach of Lyytinen & Jenniskens (2003). They developed a clever technique for investigating the behaviour of meteoroid streams associated with long-period comets in the case where the parent comet orbit is not or only poorly known. Here the orbital elements of the meteor shower in 2003 will be taken to be those of the parent, and integrated backwards to the previous perihelion passage, where the release of the meteoroids is assumed to have taken place.[1] This method is somewhat ad hoc but should capture some of the most important dynamical effects on the meteor stream, and has been used with good results in the past. We note that the meteors of the Daytime Craterid shower were observed by CMOR a few days after their perihelion passage, and so we actually need to integrate back to the preceding perihelion passage in order to arrive at our presumed parent orbit. An assumed semimajor axis a is needed, and here we used the value of $a =$ 50 au. The simulations were also run with semimajor axes of 100 au, and these produced very similar results.

Once integrated backwards to the previous perihelion, the orbit is integrated forwards once again. This orbit now acts as the nominal parent orbit, from which meteoroids are ejected to form the meteoroid stream. Here our approach differs slightly from that of Lyytinen & Jenniskens (2003) in that we do not specify the orbital elements of the meteoroids so that they return to the Earth over a specific range of time. Rather we use the meteoroid ejection models of Brown & Jones (1998) (Models 1 and 2), Crifo (1995) and Crifo & Rodionov (1997) to populate the streams. This presents us finally with eight separate simulations of the meteoroid stream, for two initial assumed a values, and four different ejection models. Each simulation released particles with radii of 100 μm to 10 cm (density 1000 kg m^3) corresponding to $0 \lesssim \beta \lesssim 10^{-1}$, with a size distribution that was flat in log space.

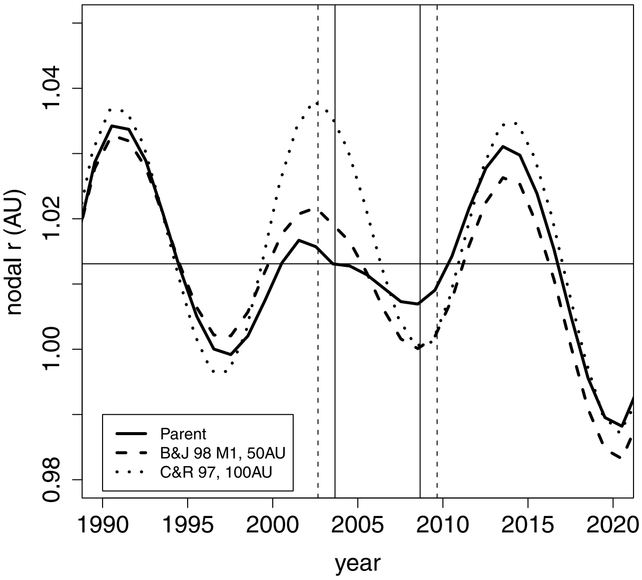

Figure 6. The mean osculating heliocentric distances of the ascending node of the stream meteoroids are shown, for the Brown & Jones (1998) model 1 with a parent semimajor axis of 50 au, and the Crifo & Rodionov (1997) model with a parent semimajor axis of 100 au. The other six models show similar patterns. The thick solid line marks the osculating nodal location of the parent orbit. The solid horizontal line marks the heliocentric distance of the Earth during the Daytime Craterid shower. The solid vertical lines mark the years 2003 and 2008 which saw shower activity. The dashed vertical lines indicate the time interval 2002–09 during which CMOR orbital data exist.

The instantaneous mean locations of the nodes of the streams are shown in Fig. 6, for two sample simulations (the other six show similar characteristics) Also shown in the location of the node of the parent orbit for the $a = 50$ au case (again, the 100 au case is very similar). The location of the parent's osculating node coincides with the Earth in 2003. However, this occurs by construction since we have taken the 2003 shower as our nominal parent orbit and provides no particular insight into the behaviour of the stream.

The mean locations of the stream nodes themselves are actually farthest from the Earth in the years 2003 and 2008 when activity is observed at Earth, contrary to what one would expect if the meteoroid stream was very old and thoroughly populated. This leads us to conclude that the activity seen in 2003 and 2008 represent meteoroids near the edges of the notional meteoroid torus, and indicate the existence of substantial inhomogeneity in the density of material along the stream orbit.

Despite the substantial distance between the Earth and the mean node of the stream during the years 2003 and 2008, the simulations do reproduce the activity observed during the interval in question when one considers whether or not meteoroids were actually near Earth during the observed showers. The intersection of the osculating meteoroid orbit with the Earth's is not sufficient for an outburst to occur; the particles on these orbits must actually be near the Earth in order for a shower to occur.

[1] We performed a similar analysis with the meteor shower elements of 2008. However, this orbit, when integrated backwards, was found to have an immediate close approach with Saturn which eliminated its usefulness as a nominal parent orbit.

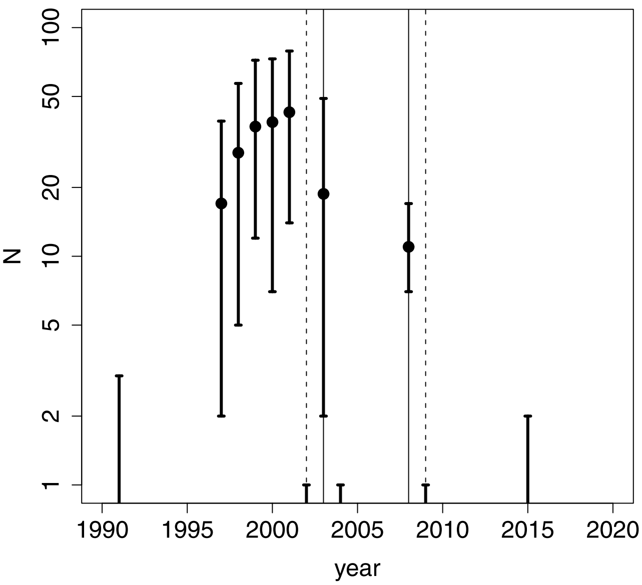

Figure 7. The mean number of meteoroids passing within 0.001 au of the Earth's orbit during a particular year for all eight simulations, along with error bars spanning the minimum and maximum values. Mean values below one are not plotted, though any maximum values extending above this limit are shown. The solid vertical lines mark the years 2003 and 2008 which saw shower activity. The dashed vertical lines indicate the time interval 2002–09 during which CMOR orbital data exist.

The dynamical simulations show that the meteoroids do return the Earth in 2003, and thus predict meteor activity in this year. The activity in this particular year is again the result of our choice of parent orbit. Of much more interest is whether or not activity is predicted in other years. The number of simulated meteoroids (out of 5000 ejected) that pass within 0.001 au of the Earth's orbit during the year in question for the time range 1990–2020 are shown in Fig. 7. The results are consistent regardless of the ejection model chosen and of the initial semimajor axis chosen for the nominal parent. Fig. 7 plots the average number over the eight simulations, with error bars extending from the minimum and maximum number among the simulations.

Though only a small number of meteoroids from our simulations actually intercept the Earth (a result of the large semimajor axis of the parent orbits, which disperse the meteoroids widely), the results are very encouraging. The simulations reproduce the shower activity in 2003 and 2008, and at about equal strength, while showing little or no activity throughout the remainder of 2002–09. Both 2003 and 2008 have mean values above 10, while all other years in the 2002–09 interval have mean values below one. This in itself is quite good agreement, and gives us some confidence in the results.

We can do a rough analysis to determine the likelihood that the activity pattern in 2002–09 is matched simply by chance. If we take the shower to be active when the mean N from the simulations is above 1, and inactive otherwise, there are 7 yr of activity during the 31 yr plotted in Fig. 7. Assuming from this a random 7/31 chance per year that a shower is active, there is only a $(7/31)^2(24/31)^6 \approx 0.011$ or 1 per cent chance that activity would be seen in 2003 and 2008 and not in any other years of CMOR orbital data. Thus the chance of the pattern of activity being matched by simple coincidence is very low.

The average location of the simulated shower is consistent from year to year with a mean RA of 173°, a mean Dec. of $-15°$ and a mean geocentric velocity far from the Earth of V_g of 23 km s^{-1}. These values differ slightly from the observed values, given in Tables 2 and 3 but this is to be expected. The zenithal attraction is very large for meteors with such low geocentric velocities, and so very small differences in velocity make large differences in the geocentric radiant.

The beta values of particles that constituted the 2003 and 2008 outbursts in the simulated showers were small, typically $\beta < 10^{-4}$; large β particles tend to travel on larger orbits that delay their arrival at the Earth.

We note that the simulations predict that there was considerable activity, comparable or stronger than that observed in 2003 and 2008, in the years 2001 and earlier. This activity was not seen by CMOR. The radar was not operating in orbital mode at this point, but was making single station measurements. However, there are no signs of strong radiants at the locations of this shower in 2000 and 2001, the two-year CMOR would have been expected to see them. This is the largest discrepancy between the simulations and the observations. The daytime nature of the shower also means that we cannot look to visual or optical observations to provide the answer. Though it is possible that the shower was missed in 2000 and 2001 by the radar, there is no obvious reason from the simulations why this might have occurred. The spread in solar longitudes of the simulated meteors is comparable in all years, as are their β values and other orbital parameters. Our considered opinion is that the simulations are likely at fault here. The simulations face considerable difficulties: we have no precise parent orbit to start from and so we must assume one; we consider only one previous perihelion passage; and the parent and stream are subject to frequent close encounters with Jupiter, Saturn and the Earth. Given these constraints, the results of the dynamical simulations are perhaps as good as can be hoped for, and are used here mainly to underscore the veracity of the association between the Daytime Craterid shower and C/2007 W1.

5 DISCUSSION

Comet C/2007 W1 (Boattini) is argued to be the parent of the Daytime Craterid meteor shower observed by the CMOR meteor radar in 2003 and 2008. This makes the Daytime Craterid shower one of the few showers linked to long-period or near-isotropic comets, and the only one linked to a hyperbolic parent comet. The Daytime Craterid shower itself is unusual, being a strong intermittent daytime shower that approaches the Earth from nearly the antapex direction.

Dynamical simulations of the meteoroid stream show a good match to the radar observations where the radar data is of the highest quality. Simulations predict outbursts of roughly equal strength in 2003 and 2008, with no activity for other years in the 2002–09 range. A question mark remains over the years 2000 and 2001, when a less calibrated and a poorer sensitivity radar data set shows no activity but the simulations do predict outbursts. Activity is also expected in 1997–99 but CMOR was not operational during the Daytime Craterid showers of these years. The simulations do not predict any Daytime Craterid activity for the upcoming decade, though the year 2015 is the most likely candidate as some of the simulations show minor activity in this year.

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