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Meteor showers on Earth from sungrazing comets

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ABSTRACT
Sungrazing comets have always captured a lot of interest and curiosity among the general public as well as scientists since ancient times. The perihelion passage of comet C/2012 S1 (ISON) at the end of this year (on 2013 November 28) is an eagerly awaited event. In this work, we do a mathematical study to check whether meteoroids ejected from this comet during its journey around the sun can produce spectacular meteor phenomena on Earth. Our calculations show that although the orbital elements of this comet are much more favourable than for most sungrazers to have its descending node near the Earth's orbit, even ejection velocities as high as 1 km s^{-1} do not induce sufficient nodal dispersion to bring meteoroids to Earth intersection during present times. A similar result applies to Newton's comet C/1680 V1 which has surprisingly similar orbital elements, although it is known to be a distinct comet from C/2012 S1. Our analysis also shows that for meteoroids ejected from all known sungrazing groups during recent epochs, only the Marsden family (with required ejection velocities of some hundreds of m s^{-1}) can produce meteor phenomena during present times. In a broader sense, we indicate why we do not observe visually brilliant meteor showers from frequently observed sungrazers.

Key words: celestial mechanics; meteoroids, meteors, meteorites; comets: general; comets: individual: C/2012 S1 (ISON), C/1680 V1 (Newton's comet)

1 INTRODUCTION

There have been various interesting observational records (Marsden 1967, 1989, 2005; Strom 2002; Sekanina & Chodas 2012) of extremely bright and spectacular sungrazing comets since historical times. Intuitively one would expect some of these to produce spectacular meteor showers (like those from many Jupiter family and Halley type comets). In case of such a shower when sungrazers are involved, there are two factors in favour of producing intense meteor phenomena. Firstly these comets pass very close to the sun ($q \sim 0.004 - 0.06$ au) which would enable more ices to sublime according to conventional understanding (Whipple 1950) and thereby eject more dust particles into similar orbits. Secondly some sungrazers are dynamically new comets (Bailey, Chambers & Hahn 1992), coming from the Oort-Öpik cloud into the inner solar system for the first time, suggesting a strong possibility for more volatiles in their composition (enhancing chances for strong outgassing).

Nevertheless we hardly observe any spectacular meteor activity on Earth due to these frequently observed sungrazing comets. This work presents a mathematical formalism of demonstrating the absence of any strong meteor shower from comet C/2012 S1 (ISON). During this analysis some parallels are drawn with the famous Newton's comet C/1680 V1 due to the surprisingly similar orbital elements. The same technique is then applied to all the known sungrazing families.

2 EFFECT OF EJECTION VELOCITY ON METEOROIDS' NODAL DISTANCES

We use the notation:
a (semi-major axis), e (eccentricity), q (perihelion distance), i (inclination), ω (argument of pericentre), Ω (longitude of ascending node), ϖ (longitude of pericentre), E (eccentric anomaly), f (true anomaly), S, dv_r (radial component of meteoroid ejection acceleration/velocity), T, dv_t (transverse component = in-plane, orthogonal to radial), W, dv_n (normal component), n (mean motion), G (universal gravitational constant), M (mass of sun), t (time), r (heliocentric distance), r_a, r_d (heliocentric distance of ascending/descending node)

2.1 Conditions to favour meteor phenomena on Earth

Among the most critical parameters determining the feasibility of meteor showers on Earth are the ascending and descending nodal distances of meteoroid particles:

$$r_a = \frac{a(1-e^2)}{(1+e\cos\omega)} = \frac{q(1+e)}{(1+e\cos\omega)} \quad (1)$$

$$r_d = \frac{a(1-e^2)}{(1-e\cos\omega)} = \frac{q(1+e)}{(1-e\cos\omega)} \quad (2)$$

The necessary condition (but not sufficient) for meteor activity on Earth is: $r_a \sim 1$ au or $r_d \sim 1$ au. This implies

$$\omega = \cos^{-1}[(q(1+e)-1)/e] \quad (3)$$

$$\omega = \cos^{-1}[(1-q(1+e))/e] \quad (4)$$

From the compiled observations of sungrazers (Marsden & Williams 2008) one can constrain the range of e and q. The condition $e \sim 1$ simplifies equations (3) and (4) to

$$\omega = \cos^{-1}[2q-1] \quad (5)$$

$$\omega = \cos^{-1}[1-2q] \quad (6)$$

For the range $q \sim$ [0.004 au, 0.06 au] which comes from observations of various sungrazing families: equation (5) shows $r_a \sim 1$ au only if $\omega \sim$ [152,173], [187,208]; equation (6) shows $r_d \sim 1$ au only if $\omega \sim$ [7,28], [332,353]. Each interval spans $\sim 21^\circ$, and ω in one of these four ranges is a necessary (but not sufficient) condition for high e sungrazers to undergo meteoroid intersection with Earth.

Although confirming the presence of a meteor shower on Earth would depend on other parameters like time of nodal crossing, Earth's precise position in its own orbit at that time and width of the dust trail, confirming the absence of significant meteor activity can be done using this necessary condition concerning the geometry of nodes.

2.2 Separating the effects due to three components of ejection velocity

Even if parent bodies' nodal distances are quite far from Earth's orbit, meteoroid ejection in different directions can change the nodal distances into $r_a \pm dr_a$ and $r_d \pm dr_d$ depending on the ejection velocity components. Therefore checking these parameters for realistic values of cometary ejection velocities can verify whether the meteoroid stream's nodal distances can approach 1 au.

The mathematical technique underlying our analysis uses Lagrange's planetary equations:

$$\frac{da}{dt} = \frac{2}{n\sqrt{1-e^2}}(Se\sin f + \frac{a(1-e^2)T}{r}) \quad (7)$$

$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na}(S\sin f + T(\cos E + \cos f)) \quad (8)$$

$$\frac{d\varpi}{dt} = \frac{\sqrt{1-e^2}}{nae}[-S\cos f + T(1+\frac{r}{a(1-e^2)})\sin f] + 2\frac{d\Omega}{dt}\sin^2(\frac{i}{2}) \quad (9)$$

$$\frac{d\Omega}{dt} = \frac{Wr\sin(\omega+f)}{(na^2\sqrt{1-e^2}\sin i)} \quad (10)$$

Equations (7) to (10) are taken from page 184, Roy (1978). Using the definition $\varpi \equiv \Omega + \omega$ we have:

$$\frac{d\omega}{dt} = [-\cos f\frac{\sqrt{1-e^2}}{nae}]\,S + [\sin f(1+\frac{r}{a(1-e^2)})\frac{\sqrt{1-e^2}}{nae}]\,T + [(2\sin^2(\frac{i}{2})-1)(\frac{r\sin(\omega+f)}{na^2\sqrt{1-e^2}\,\sin i})]W \quad (11)$$

Equation (11) can be shown to be equivalent to the expression on page 57, Murray & Dermott (1999):

$$\frac{d\omega}{dt} = e^{-1}\sqrt{a\mu^{-1}(1-e^2)}[-S\cos f + T\sin f(\frac{2+e\cos f}{1+e\cos f})] - (\frac{d\Omega}{dt})\cos i \quad (12)$$

(where $\mu = GM$), which confirms that our substitutions from the fundamental equations given by Roy (1978) yield the right result.

Taking the differential of equation (1) and finding the expressions for the partial derivatives gives

$$dr_a = [\frac{(1-e^2)}{1+e\cos\omega}]da + [\frac{-2ae(1+e\cos\omega) - a\cos\omega(1-e^2)}{(1+e\cos\omega)^2}]de + [\frac{ae(1-e^2)\sin\omega}{(1+e\cos\omega)^2}]d\omega \quad (13)$$

Similarly equation (2) leads to

$$dr_d = [\frac{(1-e^2)}{1-e\cos\omega}]da + [\frac{-2ae(1-e\cos\omega) + a\cos\omega(1-e^2)}{(1-e\cos\omega)^2}]de + [\frac{-ae(1-e^2)\sin\omega}{(1-e\cos\omega)^2}]d\omega \quad (14)$$

Equations (13) and (14) require expressions for da, de and $d\omega$. These orbital element changes can be related to the separate velocity components using (7), (8) and (11):

$$da = [\frac{2}{n\sqrt{1-e^2}}e\sin f]dv_r + [\frac{2a\sqrt{(1-e^2)}}{nr}]dv_t + [0]dv_n \quad (15)$$

$$de = [\frac{\sqrt{1-e^2}}{na}\sin f]dv_r + [\frac{\sqrt{1-e^2}}{na}(\cos E + \cos f)]dv_t + [0]dv_n \quad (16)$$

$$d\omega = [-\cos f\frac{\sqrt{1-e^2}}{nae}]\,dv_r + [\sin f(1+\frac{r}{a(1-e^2)})\frac{\sqrt{1-e^2}}{nae}]\,dv_t + [(2\sin^2(\frac{i}{2})-1)(\frac{r\sin(\omega+f)}{na^2\sqrt{1-e^2}\sin i})]dv_n \quad (17)$$

Equations (15), (16), (17) followed by (13) or (14) express the changes in ascending and descending nodal distances as linear combinations of the separate radial, transverse and normal ejection velocity components at any given point in the orbit. Numerical checks confirmed these differential approximations to be good for the ranges in dv_r, dv_t, dv_n up to ± 1 km s^{-1} where we apply them.

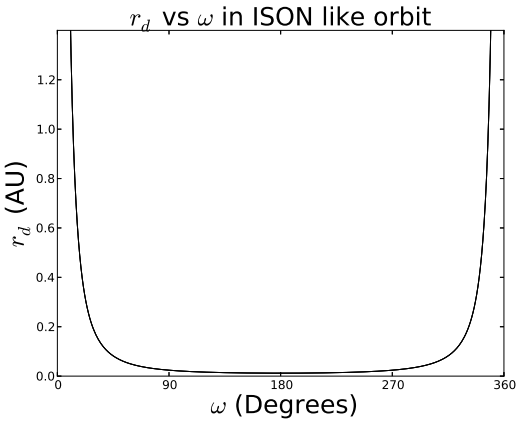

Figure 1. Heliocentric distances of descending node versus argument of pericentre for an ISON like ($q \sim 0.012$ au, $e \sim 1$) orbit: $r_d \sim 1$ au when $\omega \sim 12$ or 348°. The real comet ISON's $\omega \sim 346°$ is close to this value.

Table 1. Orbital elements taken from JPL Horizons (Giorgini et al. 1996), IAU Minor Planet Center, and computed nodal distances, for a few well known sungrazers namely ISON, Lovejoy, Ikeya-Seki & Newton's comet respectively; $e \sim 1$ for all of them.

Comet	q (au)	i (Degrees)	ω (Degrees)	r_a (au)	r_d (au)
C/2012 S1	0.012	61.8	345.536	0.012	0.755
C/2011 W3	0.006	134.3	53.877	0.007	0.029
C/1965 S1-A	0.008	141.9	69.049	0.012	0.025
C/1680 V1	0.006	60.5	350.613	0.006	0.881

3 C/2012 S1 (ISON) AND C/1680 V1 (NEWTON'S COMET)

Comet C/2012 S1 (ISON) is predicted to pass very close ($q \sim 0.012$ au) to the sun on 2013 November 28 (Samarasinha & Mueller 2013; Knight & Walsh 2013) and hence expected to be a spectacular sungrazer this year. ISON's $\omega \sim 346° \in [332,353]$ lies in the favourable range (Section 2.1) for which the descending node can be close to Earth's orbit, i.e. the perihelion direction is quite favourably oriented for potential meteor showers. Specifically, for an ISON like orbit (q=0.012 au and $e \sim 1$), equations (5) and (6) imply $r_a \sim 1$ au when $\omega \sim 168$ or 192° and $r_d \sim 1$ au when $\omega \sim 12$ or 348° (Fig. 1), and equation (2) shows comet ISON itself has $r_d \sim 0.76$ au (see Table 1).

Calculations outlined in Section 2.2 were done to find the nodal dispersion of meteoroids ejected over the entire range of true anomaly from 0–360°. In reality, for water ice sublimation one needs to check only $r \sim 0.012 - 3.4$ au (cf. Fitzsimmons & Williams 1994) which corresponds to $f \in [-174, 174]$ here. Previous work on comet C/1995 O1 (Hale-Bopp) has shown that CO outgassing could even occur around 7 au (Enzian 1999) which corresponds to $f \in [-176, 176]$ in the case of ISON. Fig. 2(a) shows the change to r_d at all f for a fixed value (1 km s^{-1}) of each velocity component. For small enough changes as considered here, dr_d is proportional to ejection velocity, and the nodal displacements simply alternate signs depending on whether the velocity is positive or negative. Table 2 shows the maximum absolute change in r_d (also in r_a, not plotted in Fig. 2) over all f when the magnitude of the ejection velocity component is ± 1 km s^{-1}.

Fig. 2 and Table 2 show that changes in nodal distance due

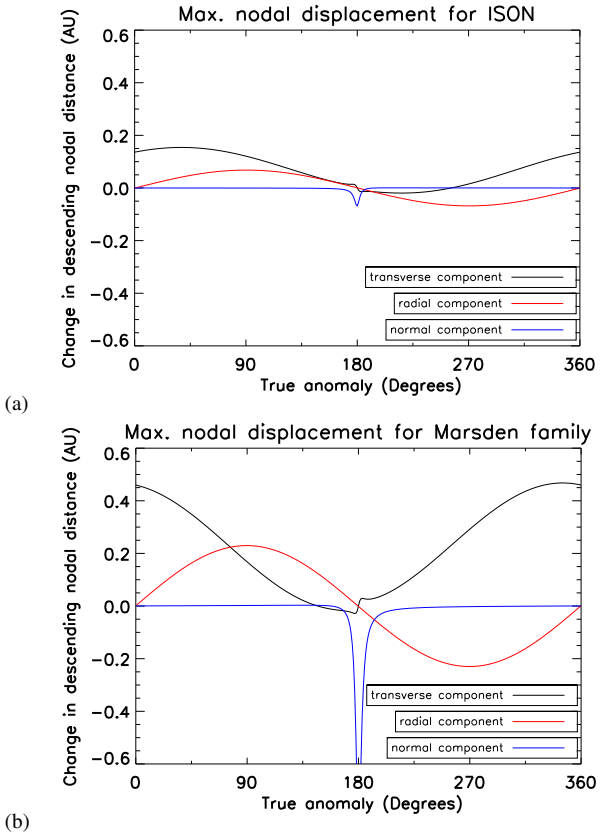

Figure 2. Effect of each component of ejection velocity on descending nodal distance, as a function of true anomaly when transverse (black line); radial (red line); normal component (blue line) = 1 km s^{-1} for (a) C/2012 S1 ISON (b) Marsden family comets.

to radial and normal ejection velocity components are much less effective than those due to the transverse part in bringing the node close to Earth's orbit. However, a value of dv_t = 1 km s^{-1}, even at the most suitable f, still fails to bring the orbit to Earth intersection ($r_d + dr_d \sim 0.91$ au).

Ejection velocities well above 1 km s^{-1} could bring the node close to Earth. Most well known meteor showers (from Jupiter family and Halley type comets) show prominent activity due to meteoroids with ejection velocities of the order of 10 m s^{-1}. This has been confirmed from numerous earlier works comparing the prediction and accurate observation of meteor outbursts (Asher, Bailey & Emel'yanenko 1999; Brown & Arlt 2000; Ma & Williams 2001; Rendtel 2007; Sekhar & Asher 2013). Because q is much less for sungrazers compared to other types of comet, meteoroid ejection with higher speeds than a few tens of m s^{-1} is definitely feasible, e.g. ejection speeds approximately proportional to r^{-1} for small r (cf. Whipple 1951; Jones 1995; Ma, Williams & Chen 2002). However according to Whipple's model, ejection velocities in the range of a few km s^{-1} are unrealistic even for low q sungrazers.

Moreover the number of particles with diameters $\gtrsim$ 1 mm, which produce visually spectacular showers, would be small and hence they will not lead to any intense activity. Also the evolution of particles of diameter significantly less than 1 mm with such high ejection velocities will be dominated by other forces (Nesvorný et al. 2011) such as radiation pressure and Poynting-Robertson (Burns, Lamy & Soter 1979). Hence studying the geom-

Table 2. Maximum nodal displacement of meteoroids due to individual components of ejection velocity

Comet	dv_r (km s^{-1})	dv_t (km s^{-1})	dv_n (km s^{-1})	$\mid dr_a \mid$ $\times 10^{-3}$(au)	$\mid dr_d \mid$ $\times 10^{-1}$(au)
C/2012 S1	0	0	± 1	3.167	0.677
	0	± 1	0	4.274	1.503
	± 1	0	0	3.166	0.668
C/1680 V1	0	0	± 1	1.022	0.569
	0	± 1	0	1.524	1.589
	± 1	0	0	1.137	0.569

etry of nodal dispersion due to ejection velocities would not work efficiently to verify such rare (and almost visually unobservable) processes.

Surprisingly the orbital elements of this new comet ISON in 2013 and the famous Newton's comet of 1680 have similar orbital elements (Table 1). This has even led to speculations that both might have a common ancestor, although ISON's original period of millions of yr (given on IAU Minor Planet Center website) is accurate enough to exclude their actually being the same comet. The value of $\omega \sim 351^\circ$ (for C/1680 V1) is also favourable (Section 2.1), and $r_d \sim 0.88$ au. Similar calculations were done (Section 2.2) to check the nodal dispersion of ejected meteoroids. As with ISON, radial and normal components are less effective (Table 2) in pushing the nodes towards Earth. In principle, the transverse component of ejection velocity can bring the descending node ($r_d + dr_d \sim 1$ au) very close to Earth's orbit at very high ejection velocities ($dv_t \sim 800$ m s^{-1}). The absence of any known predictions or observations by Newton or other scientists at that time or later about possibly related spectacular meteor phenomena prevents any further conclusions here. (If there had been any such credible observations, it could be evidence for high ejection speeds ~ 1 km s^{-1}, provided other conditions were satisfied such as meteoroids and Earth reaching their mutual node at the same time).

For comparison, the well known sungrazers C/2011 W3 (Lovejoy) and C/1965 S1-A (Ikeya-Seki) do not have ω in the favourable range discussed in Section 2.1. As expected their nodes are far away (see Table 1) from Earth's orbit. A similar analysis in terms of the ejection velocity components showed the nodes of meteoroids remain well below 1 au even at very high ejection velocities ($dv_t, dv_r, dv_n \sim 1$ km s^{-1}). Hence meteor activity on Earth from particles ejected from these comets in present times can also be completely ruled out.

4 MARSDEN FAMILY VERSUS OTHER SUNGRAZING FAMILIES

A search among 1440 compiled orbits of sungrazers belonging to various known sungrazing families (Marsden & Williams 2008) showed that only 27 of these orbits have ω in the favourable ranges mentioned in Section 2.1 (Table 3). It is reasonable to assume that out of this small number of favourable parent bodies, a few of them might have fallen into the sun or got tidally fragmented (like the Kreutz family discussed in Biesecker et al. 2002) which thereby makes the number of possible candidates even smaller. Many of these sungrazers have very small sizes (Iseli at al. 2002).

Our calculations (using equations 1 and 2) confirm that r_a and r_d are significantly less than 1 au for all other sungrazing families. Thus only Marsden family comets have conditions favourable to produce meteoroids that can encounter Earth in present times

Table 3. Distribution of sungrazing families from Catalogue of Cometary Orbits 2008 (50 of 1490 sungrazing comets listed have not been linked to any specific families).

Family	Number of comets	Bodies favouring the range in ω so that $r_a \sim 1$ au or $r_d \sim 1$ au
Kreutz	1277	0
Meyer	89	0
Marsden	32	27
Kracht 1	31	0
Kracht 2	4	0
Kracht 3	2	0
Anon 1	3	0
Anon 2	2	0

(although comets from other families could have favourable conditions, in terms of the right combination of ω and q, to produce meteor phenomena during their distant past or future).

Marsden family members have $r_d \in [0.16, 4.76]$ au. The range for the 27 most favourable members (cf. Table 3) is $r_d \in [0.81, 4.63]$ au. Fig. 2(b) shows the change to r_d at all f due to each ejection velocity component; these plots are virtually identical for all Marsden family members. Fig. 2(b) shows that the transverse component dv_t is most effective in changing the nodal distance so that it can come near 1 au. For values of f where dv_t is ineffective, both dv_r and dv_n can be significant (Fig. 2(b)), although dv_n is most effective near aphelion where normal meteoroid ejection is not expected.

Earlier works (Seargent 2002; Ohtsuka, Nakano & Yoshikawa 2003; Sekanina & Chodas 2005; Jenniskens 2006; Jenniskens, Duckworth & Grigsby 2012) have proposed that the Marsden family could be linked to the daytime Arietids (171 ARI, IAU-MDC). Our calculations show that Marsden family members typically need ejection velocities of at least a few hundred m s^{-1} so that $r_d \pm dr_d \sim 1$ au. The number of large meteoroids (diameters $\gtrsim 1$ mm) having high ejection velocities of several hundred m s^{-1} (required to bring their nodes close to Earth's orbit in this case) will be quite small (cf. discussion in section 3). This could be an explanation if the Zenithal Hourly Rate of visually observed Arietids is indeed low, at about 1–2 meteors/hour (Jenniskens et al. 2012).

Our analysis specifically shows that ejection speeds of some hundreds of m s^{-1} from most Marsden family sungrazers can produce meteoroids whose descending node is at 1 au. This accords with the proposed association with 171 ARI which has $\omega \sim 20$–30°, similar to the Marsden family (cf. equation 6). Long term evolution to induce a substantial ω separation is not required. Various Marsden family members in the dataset we used had perihelion passages during 1996–2008, a range that can easily arise in the short term (even a single revolution). In the short term, the nodal distances r_d remain in the range resulting from the ejection velocities.

However orbital changes due e.g. to planetary perturbations would be substantial during long term evolution, over which different points in the ω precession cycle may be reached. Previous works (Ohtsuka et al. 2003; Sekanina & Chodas 2005) have found that the Kracht group ($\omega \sim 50^\circ$) could be linked to the Marsden family and 171 ARI during their long term evolution. Sekanina & Chodas (2005) identified a possible connection between the Southern δ Aquariids (005 SDA) which have $\omega \sim 150^\circ$ (meteor shower at ascending node; equation 5) and the Marsden and Kracht groups.

The nominal orbital periods of most Marsden sungrazers are very high ($\sim 10^3 - 10^6$ yr) because $e \sim 1$. Hence we have not

checked the orbital evolution of meteoroids for subsequent revolutions. At the upper end of this period range, long term future predictions for meteor showers from this family would even require a completely independent analysis including other effects due to perturbations from galactic tides or passing stars. The same limitation applies for the long term evolution of meteoroids from ISON where original $1/a \sim 9 \times 10^{-6}$ au^{-1} (IAU-MPC) and Newton's comet where $a \sim 444$ au (JPL Horizons) as well. The accuracy of conventional long term predictions (usually applied to Jupiter family and Halley type comets) of meteor showers without considering these additional effects will be questionable when orbital periods are very high (which applies to most sungrazers).

A similar analysis (as for ISON and Marsden family) was done on the orbits of other sungrazing families (mentioned in Table 3). Our calculations clearly show that no realistic ejection velocities in any direction can bring the nodes of meteoroids close to Earth's orbit, $r_a \pm dr_a$ and $r_d \pm dr_d$ for all these cases (during present times) remaining small compared to 1 au.

5 CONCLUSION

The necessary (but not sufficient) condition to create meteor showers on Earth as an immediate result of particles ejected from high e sungrazers is that their orbits lie in a favourable range in ω thereby enabling the ascending or descending node to closely approach Earth's orbit. The forthcoming sungrazing comet C/2012 S1 (ISON) has $\omega \sim 346^\circ$. Although this is unusually (for sungrazers) very close to the ideal condition of $r_d \sim 1$ au, which would occur if $\omega \sim 348^\circ$, the descending node nevertheless does not extend to the Earth's orbit ($r_d \sim 0.76$ au when $\omega \sim 346^\circ$). Even quite high ejection velocities do not bring meteoroids to intersect the Earth's orbit ($r_d + dr_d \sim 0.91$ au for 1 km s^{-1} ejection). This implies the absence of strong meteor activity from this comet.

Compiled observational records of sungrazers (Marsden & Williams 2008) reveal only Marsden family comets with ω lying in this favourable range. The other sungrazing families have ω far from this small range during present epochs and their nodes cannot reach near Earth. This explains why we hardly see any prominent meteor activity from the frequently observed sungrazers of different groups.

Surprisingly out of all observed sungrazing family members, none of them have their orbital elements such that small meteoroid ejection velocities ($\sim 1 - 100$ m s^{-1}) lead to meteor phenomena on Earth (even the Marsden family typically requiring some hundreds of m s^{-1}). It would be interesting to repeat these calculations for the sungrazers which are going to visit us in future and check whether any of them have an apt combination of orbital elements so as to become an exception from this general trend so far.

Furthermore, calculations along these lines can help for forecasting potential meteor showers on Venus especially because Venus is closer to the sun compared to Earth (see small nodal distances in Table 1, particularly C/2012 S1 having r_d close to the venusian semi-major axis of 0.72 au). Hence much smaller ejection velocities could induce sufficient nodal dispersion in meteoroids to reach near the orbit of Venus. This idea gives much scope for future work using similar techniques.

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