Geochemical Perspectives Letters

Reply to Comment on "A cometary origin for martian atmospheric methane" by Crismani *et al.*, 2017

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Reply to Comment

doi: 10.7185/geochemlet.1716

Received 5 September 2016 | Accepted 8 February 2017 | Published 18 February 2017

First, I would like to extend thanks to Crismani *et al*. for their commentary, which highlights an important uncertainty acknowledged in Fries *et al.* (2016), namely whether the total mass of infall material required to produce the observed methane is on par with that available from meteor showers. I would like to disagree on two points presented in the letter, and then discuss the implications of their findings.

There are two points to discuss from the logical argument presented in the Crismani *et al.* (2017) letter. The first involves the assertion that meteor shower mass does not add appreciably to the overall meteor flux on Earth. The second involves direct comparison between comet Siding Spring's encounter with Mars and encounters with the debris trails of dynamically mature comets.

First, the Crismani *et al.* (2017) letter asserts that meteor showers add a negligible mass to the overall IDP flux. This is based on a reference to Grebowsky *et al.* (1998), which is based on a total of ~40 data points collected from sounding rockets, of which only 5 occurred "during or near the peak times of a meteor shower" (ibid.). The Grebowsky *et al.* (1998) paper constitutes a minority view on the subject of meteor shower input mass. Using far more voluminous data from eleven separate radar and optical studies, Ceplecha *et al.* (1998) (Table XXIII) reviewed the available literature and show that meteor-shower infall flux varies between 15 to 65 % of the Earth's meteor flux. This variation arises from changes in meteor shower activity, and in minor part to variations in the steady interplanetary dust particle (IDP) flux. Meteor shower infall accounts for a significant amount of Earth's infall flux, and the same can be expected for Mars.

Second, the Crismani *et al.* (2017) letter directly compares Mars' interaction with comet C/2014 A1 Siding Spring with more typical, annual meteor shower activity. Siding Spring was not discussed in detail in Fries *et al.* (2016) for two reasons. For one, this encounter was a strongly atypical event, and it is not certain that it compares well with a typical meteor shower. Mars directly interacted with the comet's coma, and infall material was composed largely of fine dust and gas as noted in Schneider *et al.* (2015); material that tends to be dynamically removed from comet debris streams. This resulted in deposition of mass higher in the atmosphere than typical (ibid.), while the only asset capable of searching for methane at the time was the Mars Science Laboratory (MSL) rover, which is located on the planet's surface a full ~100 km below the maximum mass deposition altitude (ibid.), and—unfortunately—almost perfectly antipodal to the site of maximum mass input (Moores *et al*., 2014). As such, it is not surprising that MSL has not reported an increase in methane even if the Siding Spring encounter produced the gas. This is the second, and more important, reason why Siding Spring did not feature in Fries *et al.* (2016)—without a robust measurement for methane to test whether the gas is produced, the encounter is interesting as a study of an anomalous encounter, but of very limited utility in testing the hypothesis of a meteor shower origin for martian methane plumes (hereafter "the hypothesis").

Aside from these two items, the Crismani *et al.* (2017) letter makes an important point about the total infall mass of meteor showers versus the calculated mass necessary to account for the larger methane plumes. The letter states that meteor flux onto Earth lies in the 10^3–10^5 kg/day range, and this is in agreement with other sources that estimate a ~10^4 kg/day flux (Mathews *et al*., 2001). Thus, a meteor shower flux onto Mars of the order of 10^8 kg required to generate the Mumma *et al.* (2009) methane plume would have to be an extraordinary event. Even if the Mumma *et al.* (2009) is in error by an order of magnitude as proposed by Zahnle (2011), other measurements in the 10s of ppbv of methane exist (see Table 1 of Fries *et al*., 2016). Therefore, a meteor shower delivering three or four orders of mass more than the typical flux is needed to generate methane in the tens of ppbv as Crismani *et al.* (2017) state. One interpretation of this is that the 10^8 kg infall mass is unlikely to the point that it disproves the hypothesis. However, while meteor showers of this magnitude are uncommon, they are not out of the question. Strong outbursts of meteor activity, called "meteor storms", can achieve flux in excess of four orders of magnitude greater than the typical background (Beech *et al*., 1995). In fact, the Mariner IV spacecraft was damaged in the vicinity of Mars by meteoroid strikes after it had completed its primary mission. Mariner IV's carried a dust detector which measured a flux four orders of magnitude greater than the background at the time, damaging the thermal protection for the spacecraft and imparting an attitude change in the spacecraft.

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On Earth, storms of this magnitude are estimated to occur about once per century (Beech *et al*., 1995), which would seem to degrade this rationale as a source of martian methane plumes, given that the literature includes four methane plumes of ~10 ppbv and two in the tens of ppbv range since 1988 (see Table 1, Fries *et al*., 2016). However, many more comets interact with Mars than with Earth. Treiman and Treiman (2000) find that four times more short-period comets, and about twice as many long-period comets interact with Mars than interact with Earth. Therefore, the number of methane plumes in the ≥10 ppbv range may compare favorably with the relative number of cometary interactions. Since no direct measurements of meteor flux exist for Mars, we are left with this statistical analysis which does not provide a clear answer to the problem. Few spacecraft sent to Mars have included a capability to detect meteor activity, such as Mariner IV in 1967 and an attempt to count meteors with a MER rover (Domokos *et al*., 2007). The high meteor flux problem noted in the Crismani *et al.* (2017) letter is important as a test of the hypothesis, but there is sufficient uncertainty in the available data on martian meteor flux and historical meteor shower intensity that we cannot currently prove or disprove the hypothesis on this issue.

The most definitive test of the hypothesis is a direct test for methane evolution correlated with the time and location of a statistically significant suite of proven, significant meteor showers. This can be done with existing instrumentation and expertise, and within the science operations plans of current missions. NASA's MAVEN mission can detect martian meteor showers via observation of Mg+ in the high martian atmosphere (Benna *et al*., 2015). ESA's Trace Gas Orbiter can perform very sensitive methane detection that is resolved in time, area, and altitude. And the interaction dates for Mars and the debris streams of a large number of comets is known. These spacecraft are capable of verifying the occurrence of meteor showers and then watching for a correlated appearance of methane, offering a solid test of the hypothesis.

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Cite this reply as: Fries, M. (2017) Reply to Comment on "A cometary origin for martian atmospheric methane" by Crismani *et al*., 2017. *Geochem. Persp. Letters* 3, doi: 10.7185/geochemlet.1716.

Editor: Eric Oelkers

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