AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Planets

RESEARCH ARTICLE

10.1002/2016JE005076

Key Point:

- Methane variations in the atmosphere of Mars are not correlated with predicted meteor events

Correspondence to:
S. K. Atreya,
atreya@umich.edu

Citation:
Roos-Serote, M., S. K. Atreya, C. R. Webster, and P. R. Mahaffy (2016), Cometary origin of atmospheric methane variations on Mars unlikely, *J. Geophys. Res. Planets*, *121*, 2108–2119, doi:10.1002/2016JE005076.

Received 16 MAY 2016
Accepted 3 AUG 2016
Accepted article online 6 AUG 2016
Published online 17 OCT 2016

Cometary origin of atmospheric methane variations on Mars unlikely

M. Roos-Serote[1], S. K. Atreya[1], C. R. Webster[2], and P. R. Mahaffy[3]

[1]Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan, USA, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, [3]Goddard Space Flight Center, Greenbelt, Maryland, USA

Abstract The detection of methane in the atmosphere of Mars was first reported in 2004. Since then a number of independent observations of methane have been reported, all showing temporal variability. Up until recently, the origin of methane was attributed to sources either indigenous to Mars or exogenous, where methane is a UV degradation byproduct of organics falling on to the surface. Most recently, a new hypothesis has been proposed that argues that the appearance and variation of methane are correlated with specific meteor events at Mars. Indeed, extraplanetary material can be brought to a planet when it passes through a meteoroid stream left behind by cometary bodies orbiting the Sun. This occurs repeatedly at specific times in a planet's year as streams tend to be fairly stable in space. In this paper, we revisit this latest hypothesis by carrying out a complete analysis of all available data on Mars atmospheric methane, including the very recent data not previously published, together with all published predicted meteor events for Mars. Whether we consider the collection of individual data points and predicted meteor events, whether we apply statistical analysis, or whether we consider different time spans between high methane measurements and the occurrence of meteor events, we find no compelling evidence for any correlation between atmospheric methane and predicted meteor events.

1. Introduction

First reports of methane in the atmosphere of Mars were published from Mars Express orbital observations [*Formisano et al*., 2004] and Earth-based telescopes [*Krasnopolsky et al*., 2004]. A relatively uniform methane background level of 10 ppbv was reported by both, whereas Mars Express also reported hot spots and temporal changes. Other observations from Earth-based telescopes [*Krasnopolsky et al*., 2004; *Krasnopolsky*, 2012; *Mumma et al*., 2009] also reported similar or higher levels of methane and variability. These data are either at the limit of methane detection capability [*Formisano et al*., 2004; *Krasnopolsky et al*., 2004] or controversial due to possible terrestrial contamination [*Zahnle et al*., 2010 on *Mumma et al*., 2009]. Since 2012, measurements have been made in situ from the surface of Mars by the Curiosity Rover [*Webster et al*., 2013, 2015]. These data revealed relatively high levels of methane only over a period of approximately 2 months, while low background methane persisted for the rest of the time. A number of sources for the origin of the Martian methane have been proposed, with hydrogeochemical and methanogenic sources being the leading candidates [*Krasnopolsky*, 2012; *Atreya et al*., 2007; *Mumma et al*., 2009]. However, no realistic physicochemical explanation exists for the large variability of methane reported before the Curiosity measurements [*Atreya et al*., 2011], while the high methane events seen by Curiosity were attributed to a small local source [*Webster et al*., 2015]. In a recent publication *Fries et al*. [2016] compare the times when high atmospheric methane concentrations were measured to when meteor showers are predicted to occur and conclude that there is a clear correlation, i.e., they find that all high methane values fall within a 16 day time period following a predicted meteor event.

This is an interesting hypothesis that we investigate further in this paper. In our analysis we take into account new observations of atmospheric methane, as well as all the predicted meteor shower events as reported in the literature, and we consider both low and high methane measurements. We also consider different time spans between meteor events and methane measurements.

We will first briefly review the predicted meteor events and how methane can be generated from them. We then present a new way of representing the data and our reanalysis of a possible correlation between Martian meteor events and atmospheric methane values.

Table 1. Predicted Meteor Showers for Mars, Adopted From *Christou* [2010]. Different Colors Indicate Different Classes of Meteor Streams as Defined by *Christou* [2010]

	Name	Ls(°)	Class	Reference
1	13P/Olbers	2.9	A	*Christou* [2010]
2	C/1979 Y1, Bradfield	13.1	B	*Christou* [2010]
3	C/1942 X1 Whipple-Fedtke-Tevzadze	13.7	C	
4	P/2006 HR30, Siding Spring	43.8	B	*Christou* [2010]
5	5335 Damocles	47.8	B	*Christou* [2010]
6	275P/Hermann	80.1		*Fries et al.* [2016]
7	C/1854 L1 Klinkerfues	84.8	A	*Christou* [2010]
8	C/2007 D2 Spacewatch	86.6	C	*Christou* [2010]
9	C/2007 H2 Skiff	119.2	C	*Christou* [2010]
10	C/1932 G1 Houghton-Ensor	128.3	B	*Christou* [2010]
11	MG (Marsden Group)	179.9	JFC / Encke	*Christou* [2010]
12	ARI (Areitids)	180.1	JFC / Encke	*Christou* [2010]
13	177P/Barnard	186.4	C	*Christou* [2010]
14	ZPE (ζ Perseid)	194.0	JFC / Encke	*Christou* [2010]
15	BTA (β Taurid)	210.3	Encke group	*Christou* [2010]
16	C/1952 H1 Mrkos	216.6	C	*Christou* [2010]
17	C/2013 A1 Siding Spring	216.8		*Fries et al.* [2016]
18	SDA (Southern δ Aquarids)	222.1	Machholtz group	*Christou* [2010]
19	C/1940 O1 Whipple-Paraskevopoulos	230.8	C	*Christou* [2010]
20	C/1974 O1 Cesco	250.1	C	*Christou* [2010]
21	C/1769 P1 Messier	275.8	C	*Christou* [2010]
22	161P/Hartley-IRAS	276.4	A	*Christou* [2010]
23	DSX (Daytime Sextantid)	291.2	Phaeton-Geminid	*Christou* [2010]
24	2005 UD	295.9	JFC / Encke	*Christou* [2010]
25	STA (Southern Taurids)	297.3	Encke group	*Christou* [2010]
26	2004 TG10	303.8	JFC / Encke	*Christou* [2010]
27	NTA (Northern Taurids)	305.2	JFC / Encke	*Christou* [2010]
28	C/1984 U2 Shoemaker	318.9	C	*Christou* [2010]
29	1P/Halley	321 - 329	A	*Christou* [2010]
30	C/1998 U5 Linear	341.1	C	*Christou* [2010]
31	GEM (Geminid)	345.6	Phaeton-Geminid	*Christou* [2010]
32	3200	345.8	JFC / Encke	*Christou* [2010]
33	GEM (Geminid)	349.6 - 351	Phaeton-Geminid	*Christou* [2010]

2. Meteor Showers on Mars

Comets and other minor bodies eject dust while orbiting the Sun. As discussed by *Christou* [2010], this dust forms a tube-like structure encompassing the orbit. We refer to this as a meteoroid stream or simply stream. If the orbit of a planet crosses the stream, then when this planet meets the stream once in its year, dust particles collide with the atmosphere resulting in a meteor shower. *Christou* [2010, and references therein] presents a list of 31 known meteoroid streams that are possible candidates for producing significant meteor shower activity in the atmospheres of Mars and Venus. The selection is based on properties of known comets from the Catalogue of Cometary Orbits 2008 [*Marsden and Williams*, 2008]. *Christou* [2010, Table 2] defines three classes of streams, A, B, and C, with decreasing likelihood of producing significant showers on Mars. Class A has a high probability of producing strong showers, class B a 50% probability, and class C a less than 50% probability. In Table 1 we reproduce all the predicted streams relevant to Mars and list them as a function of increasing Solar Longitude, L_s, at which Mars is predicted to encounter the stream. *Christou* [2010, Table 3] also lists a number of Encke-type comets that are considered to be potential candidates for producing meteor showers on Mars. Encke-type streams are likely to be not as homogeneously supplied as those of other comets due to random nucleus fragmentation and subsequent release of material from fragments. This is why no class has been attributed to these streams. They do however present serious candidates for meteor showers, and hence, we include them in our Table 1. Finally, we include two more candidates as reported by *Fries et al*. [2016]: comet 275P/Hermann at $L_s = 80.1°$ and C/2013 A1 Siding Spring at $L_s = 216.8°$.

2.1. Making Methane From Meteoric Chondritic Material

When a dust particle collides with the atmosphere of a planet at a typical speed of several tens of km/s, it ablates, creating a light trail, a shooting star. If the particle is a carbonaceous chondrite, a pristine stony particle containing a few percent of organic material, then methane may be released as a product of the ablation. *Court and Sephton* [2009] present a study of the amount of methane produced by ablation and pyrolysis of micrometeorites during entry in the Martian atmosphere. They find that released quantities are extremely low and do not contribute to any detectable level of atmospheric methane. Once at the surface, methane can be produced from the interaction of organic material with the solar UV radiation [*Keppler et al*., 2012; *Schuerger et al*., 2012]. *Flynn and McKay* [1990] estimate that micrometeorites of 60–1200 μm in size should survive and reach the surface of Mars unmelted and that this deposited material can comprise up to 29% by mass of the top Martian surface layer composition. It might therefore become a source for methane. *Flynn* [1996] estimates a total carbon deposition rate on Mars on the order of 2.4×10^5 kg per year from micrometeoric material. *Keppler et al*. [2012] carried out a laboratory study in which they irradiated samples of the Murchison meteorite, a carbonaceous chondrite, under Mars-like surface conditions of pressure, temperature, and UV flux. They found that methane is formed instantaneously by the UV at temperatures as low as −80°C. *Schuerger et al*. [2012] obtained similar results for methane from UV radiation of the same carbonaceous chondrite meteorite. Using the above annual deposition rate of carbonaceous material at the surface of Mars from *Flynn et al*. [1996], they conclude that global methane levels of 2.2–11 ppbv can be produced from such a source. They also conclude that direct surface impacts, airbursts of bolides, and cascading airbursts of low-density rubble-pile comets are unlikely sources of large variations in the atmospheric methane concentration. The recent observation of the interaction of comet C/2013 A1 Siding Spring ($L_s = 43.8°$, Table 1) with Mars by the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft has shown that meteoric materials are detected as high as 185 km altitude in the atmosphere [*Benna et al*., 2015]. The instruments on MAVEN measured a large number of metallic ions, but organic compounds that were likely present were below the sensitivity limit of the mass spectrometer. In a paper published before the Siding Spring comet encounter, which occurred on 19 October 2014, *Moores et al*. [2014] estimated a total of 4.3×10^5 kg of material from this comet would survive atmospheric entry and deposit $1.9–4.6 \times 10^3$ kg of organic material at the surface. The amount of methane produced from this would be negligibly small. By way of comparison, *Mumma et al*. [2009] deduce a total amount of methane of 19,000 t (1.9×10^7 kg) in a single regional methane plume they observed in 2003, which corresponds to 2 ppbv when spread over the whole planet [*Mumma et al*., 2009]. The dust activity of Siding Spring was monitored between November 2013 and November 2014 [*Opitom et al*., 2016] from the ground. It shows that the comet became less and less active during 2014 and that at the time of the Mars encounter had reached a minimum. At the time of this writing no published estimates exist as to the actual amount of dust deposited into the Martian atmosphere by comet Siding Spring, but it seems to have been small and comparable to sporadic fluxes [*Benna et al*., 2015].

Passing through a stream can take a few hours to several days. Hence, a large part or all of the atmosphere of Mars will be exposed to meteoric infall, because the planet rotates on its axis in approximately 24 h. As described above meteoric material interacts with Mars and could create methane instantaneously both on its way down and once at the surface. Circulation in the atmosphere will distribute methane vertically in less than a few days and globally in a few months. As Mars moves on its orbit at an average rate of about 0.5°of L_s per day, this timescale corresponds to a range of L_s of a few degrees up to several tens of degrees. An instrument such as the Sample Analysis at Mars (SAM) [*Mahaffy et al*., 2012] on the Curiosity Rover of the Mars Science Laboratory (MSL) at Gale Crater located just south of the equator should see the effect of an increase in methane due to meteorite infall on this timescale.

3. Representing the Information

In order to evaluate the possible correlation between predicted meteor events and the methane concentration in the Martian atmosphere and to represent the seasonality of the occurrence of meteor showers, we have created the series of circular graphs as shown in Figures 1–5 (see figure captions for detailed explanation).

In Figure 1 we present the same methane measurements and meteoroid streams as taken into account by *Fries et al*. [2016]. In Figure 2 we show the same streams, but now including the six new methane observations that have become available recently (Table 2).

In Figure 3 we show all of the 33 predicted meteoroid streams (Table 1) and compare them to the selection of methane observations from Figure 1. In Figure 4 we consider all the available methane measurements and predicted meteoroid streams.

Finally, in Figure 5 we present all the methane measurements from the SAM instrument only (Table 2) and all the meteoroid streams (Table 1).

We will now present our analysis with the help of these figures.

4. Methane and Meteor Stream Data, the Full Picture

We will first consider only that subset of methane data and the meteor events was the basis of the cometary origin of atmospheric methane on Mars as proposed by *Fries et al*. [2016, their Table 1]. All these high methane measurements are within 16 days of a meteor event from which it was concluded that the influx of meteoric material during these events is a plausible explanation for all high methane observations [*Fries et al*., 2016]. We represent the same data in our Figure 1. Note that the methane concentrations reported by *Krasnopolsky et al*. [1997] and *Mumma et al*. [2009] are off the scale in the figure and are represented more toward the center of the circle. Inspection of Figure 1 and the data used by *Fries et al*. [2016] in their Table 1 makes the conclusion of a correlation look plausible. We note that in the rest of this section we compare in terms of L_s, keeping in mind that a 16 day time span is about 7° L_s at aphelion ($L_s = 251°$), and 10° L_s at perihelion ($L_s = 71°$).

It should be noted, however, that it is incorrect to take an upper limit value of 7.2 ppbv, reported by *Villanueva et al*. [2013] of 28 April 2010 at $L_s = 83°$, to mean zero methane as did *Fries et al*. [2016]. It is also incorrect to omit the stream from comet 275P/Hermann, which interacts with Mars at $L_s = 80.1°$, only 7 days before this methane measurement. In addition, one Mars Science Laboratory SAM data point published by *Webster et al*. [2015a] is missing from the *Fries et al*. [2016] analysis. It is the data point from 1 June 2013 at $L_s = 328.6°$ (Table 2). Low methane was measured on that day, and it coincides with the predicted A class meteor shower from comet 1P/Halley that occurs from $L_s = 321°$ to 329° (Table 1 and Figure 4). So, there are at least two low methane measurements associated with the meteor streams selected by *Fries et al*. [2016].

In the meantime, six new methane measurements have been made by the SAM-TLS, some of them to coincide deliberately with the high methane observed by the same instrument in the previous Mars year at the same epoch. These are five new measurements done between April and November 2015 in L_s range 331°–69.7° [*Webster et al*., 2015b] and one new measurement done in January 2016 at $L_s = 94.2°$, which is being presented here for the first time. In Figure 2 we show the same information as in Figure 1, but with these new data now included.

When considering these new measurements, a correlation between methane and meteor events is less evident. A low methane value is observed just 4 days after the encounter with the class A 1P/Halley comet stream at $L_s = 321–329°$. This is in addition to the observation 1 Martian year earlier mentioned in the previous paragraph. Another new measurement was timed to coincide with the Damocles stream at $L_s = 47.8°$. This measurement on 4 October 2015 at $L_s = 50°$ (Table 2) yielded a low methane abundance. Three more low methane values were measured on 20 October 2015, 18 November 2015, and 13 January 2016 at $L_s = 57°$, $L_s = 69.7°$, and $L_s = 94.2°$, respectively. These four observations of low methane are during the same time period as the high methane concentrations observed by SAM in the previous Mars year during December 2013 to January 2014 [*Webster et al*., 2015a]. These new data 1 Mars year later do not show evidence of high methane related to the Damocles meteor event. *Fries et al*. [2016, Table 1] used the Damocles event as evidence for the first of the series of high methane abundance observations in the previous Mars year [*Webster et al*., 2015a].

As mentioned earlier *Christou* [2010] listed a total of 31 possible streams that can produce meteor showers on Mars, and two additional streams are noted by *Fries et al*. [2016]. All streams are listed in Table 1. *Fries et al*.

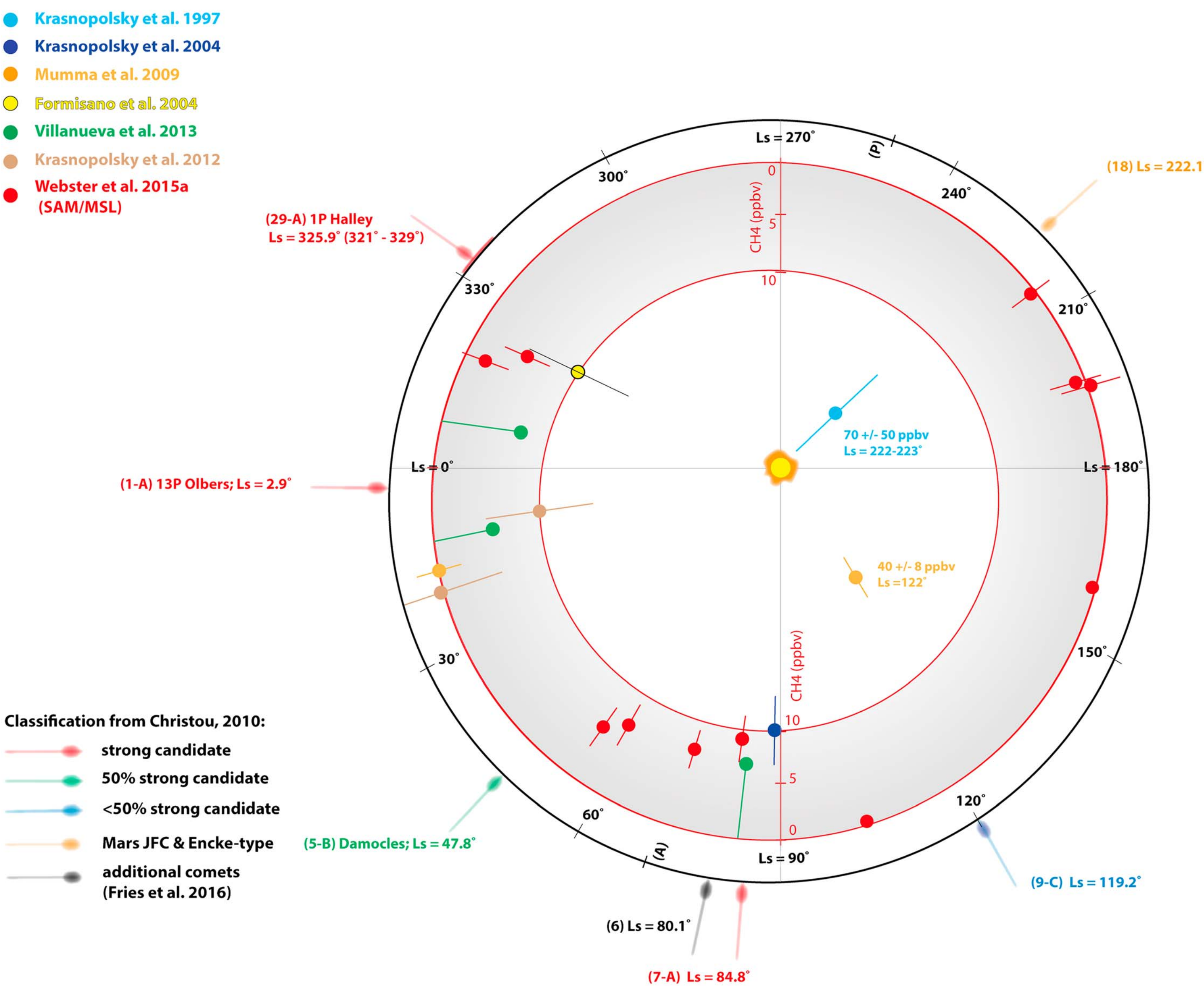

Figure 1. Methane and meteor stream data selection as presented by *Fries et al*. [2016]. The orbit of Mars is represented as a function of L_S with the correct eccentricity and orientation. Mars moves on its orbit in counterclockwise direction. The points (P) and (A) are the perihelion and aphelion, respectively. On the inner part of the circle we present the methane data. For $L_S = 158.8°$, we use the more precise of the two values listed in Table 2 (0.9 ± 0.16), i.e., the one from a SAM enrichment run. Most of the methane mixing ratios are between 0 and 10 ppbv, so that we have adopted this scale. Two of the methane measurements [*Krasnopolsky et al*., 1997 and *Mumma et al*., 2009] fall outside the scale, and we have approximately placed them higher (more toward the center) and indicated the measured values for the methane mixing ratio. Color coding refers to the source of the data (Table 2). On the outside of the orbit we have represented the positions of the predicted meteor showers. The color coding is related to the classification of the stream as by *Christou* [2010]: (red) A class stream with more than 50% chance of producing a strong meteor shower, (green) B class stream with 50% chance, (blue) C class stream with less than 50% chance, (brown) Encke-type stream, and (black) two additional streams added reported in *Fries et al*. [2016]. We have numbered them streams in Table 1 with increasing L_S and used the same numbering in the figure, leaving out the names of most to improve readability.

[2016] consider those streams that correlate with high methane. Without considering the other (low) methane data, this has the danger of being a false positive, even without taking into account the new data sets. Moreover, from *Christou* [2010] we see no particular reason as to why one should discard any of the predicted streams.

Hence, in Figure 3 we present all the streams and compare them with all the methane measurements considered by *Fries et al*. [2016]. The emerging picture now changes rather dramatically. Even when not including

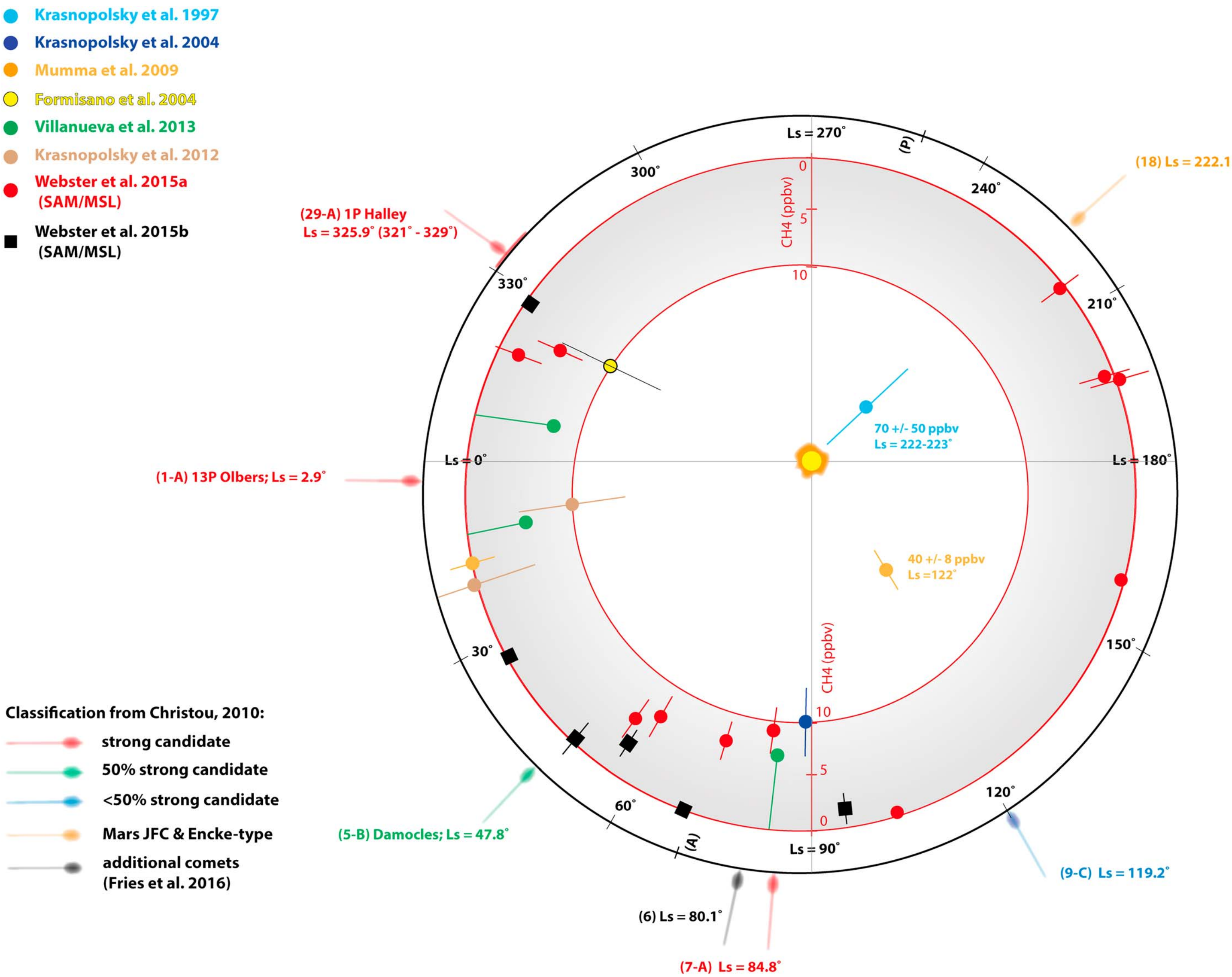

Figure 2. Same as Figure 1 with the six new methane observations (black squares) that have become available since *Fries et al*. [2016] added (Table 2). Five of them were presented by *Webster et al*. [2015]. The last one from 13 January 2016 at $L_s = 94.2°$ is presented here for the first time. For $L_s = 158.8°$ and 69.7° we use the more precise of the two values listed in Table 2 (0.9 ± 0.16 and 0.25 ± 0.08, respectively), i.e., the one obtained from a SAM enrichment run.

the low SAM measurement at $L_s = 328.6°$, there are seven low methane values preceded by one or several meteor streams within a 16 day time span. This is the same number as there are high methane values—meteor shower pairs within that same time span.

1. The low values reported by *Mumma et al*. [2009] at $L_s = 17°$ and by *Krasnopolsky et al*. [2012] at $L_s = 20°$ are preceded by two meteor streams at $L_s = 13.1°$ (comet Bradfield) and $L_s = 13.7°$ (comet Whipple-Fedtke-Tevzadze).
2. The upper limit on 28 April 2010 at $L_s = 83°$, as reported by *Villanueva et al*. [2013], is preceded by comet 275P/Hermann at $L_s = 80.1°$.
3. The two low methane SAM measurements at $L_s = 195°$ and $L_s = 196.2°$ are preceded by the Encke-type stream ZPE at $L_s = 194°$.
4. The low methane SAM value measured at $L_s = 214.9°$ is preceded by Encke-type stream BTA at $L_s = 210.3°$.
5. The upper limit reported by *Villanueva et al*. [2013] at $L_s = 352°$ is preceded by three Encke-type streams, GEM and 3200 at $L_s = 345.7°$ and GEM active at $L_s = 349.6°–351°$.

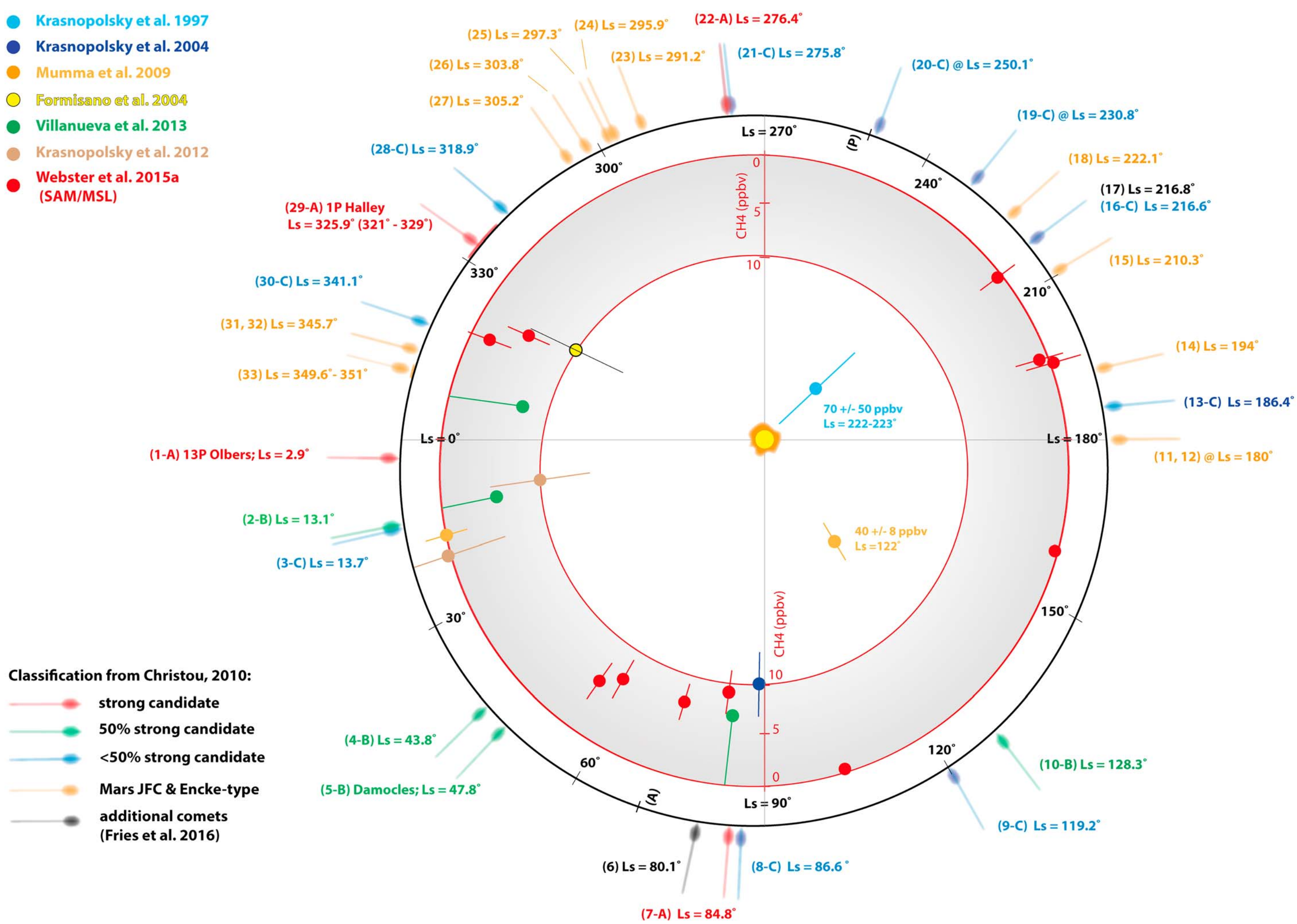

Figure 3. Same as Figure 1 with all the 33 predicted meteoroid streams included (Table 1).

Finally, we add the six new SAM-TLS data points. The result is shown in Figure 4. Three additional low methane values are preceded by meteor streams within a 16 day time span.

1. The low methane measurement at $L_s = 50°$ is preceded by the Siding Spring stream at $L_s = 43.8°$ and the Damocles stream at $L_s = 47.8°$.
2. The new low methane SAM measurement at $L_s = 94.2°$ is preceded by cometary stream D2 Spacewatch at $L_s = 86.6°$.
3. The low methane value seen at $L_s = 331°$ is preceded by the 1P/Halley stream that is active between L_s of 321° and 329°, and a similar low methane value measured the previous Martian at L_s of 328.6°.

At this point there are more low methane values preceded by predicted meteor streams than there are high methane values. From looking at this data set, there is clearly no obvious correlation between high methane concentrations and the occurrence of meteor events.

Next, we will apply a simple statistical analysis to numerically study the relationship between methane detections and meteor shower events. This was not done by *Fries et al*. [2016] since a predicted encounter of Mars with a meteoroid stream does not guarantee a significant infall of material, because the distribution of meteoroids along the comet's orbit is subject to multiple stochastic processes and likely to be irregular. However, we believe that a simple counting exercise combined with a basic statistical dependency test can provide valuable insight, exactly for the same reason that we have no information on the distribution and evolution of the streams, so that significant and insignificant infall of material are both equally likely. In the absence of any information on the dust content of the streams, we treat all streams equal.

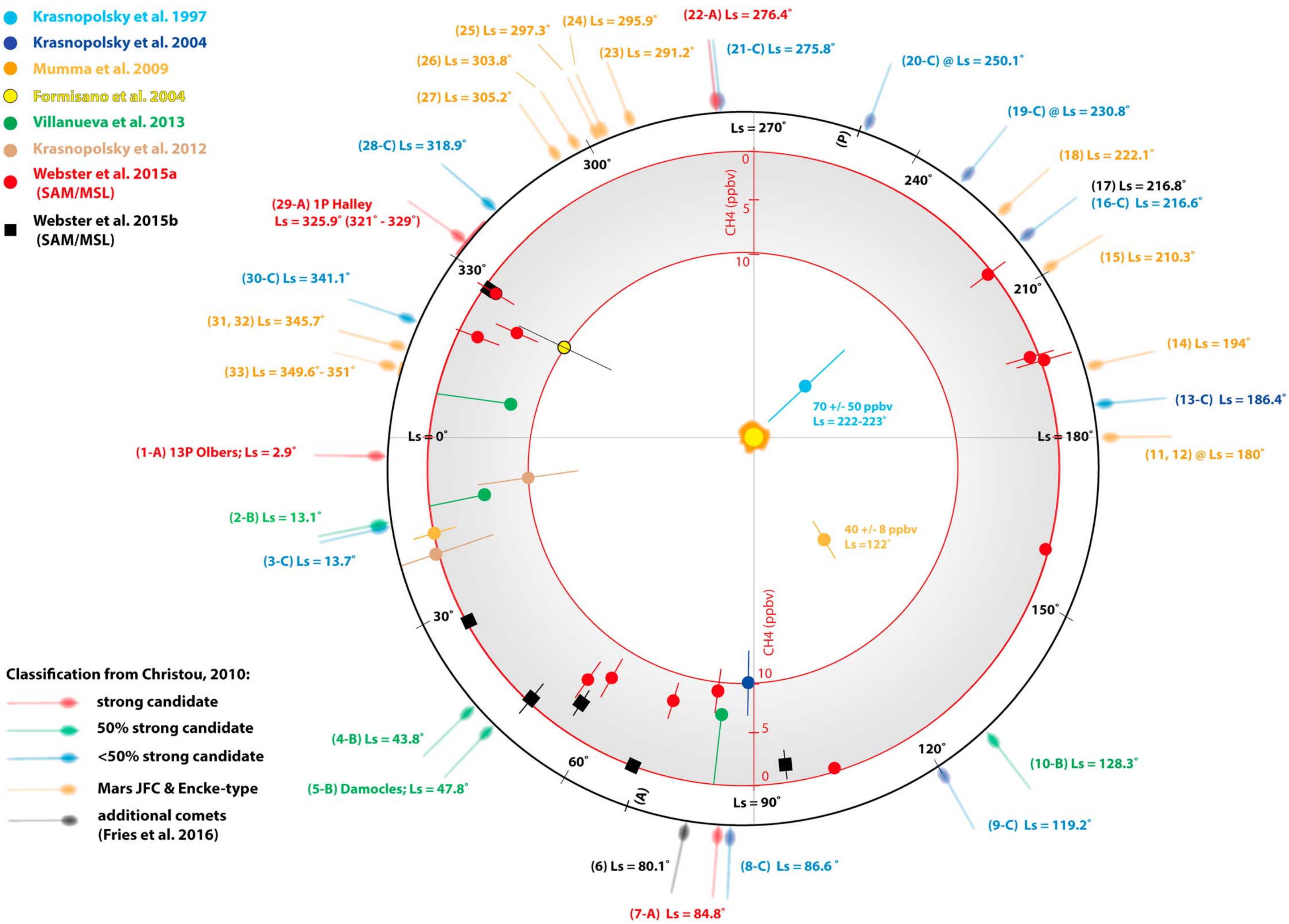

Figure 4. Same as Figure 3 with the complete SAM methane data set.

5. A New Analysis

In order to obtain a numerical evaluation of the likelihood of a correlation between predicted meteor events and high methane concentrations, we perform a simple counting exercise in combination with a basic statistical dependency test.

For a given combination of methane measurements and predicted meteoroid streams ("case"), as presented in Figures 1–5 and explained in the previous section, we take the individual methane measurements and count the number of meteoroid streams found in the range of 8°, 15°, 30°, and 60° L_s preceding each measurement. We call these counts $\mathbf{N}_{\mathbf{Ls,j}}$, where L_s indicates the L_s range and j the methane measurement in the sample. The range selection corresponds to approximately 16, 30, 60, and 120 days on average in the orbit of Mars. We chose these ranges to exclude any possible effect the time choice might have. Since no real information about the streams' activities exists, we consider all streams to be equal.

For each L_s range we divide the counts $\mathbf{N}_{\mathbf{Ls,j}}$ into low counts and high counts. As the boundary between low and high counts we take the minimum value of $\mathbf{N}_{\mathbf{Ls,j}}$ in the series for a given L_s: low counts are those instances where $\mathbf{N}_{\mathbf{Ls,j}}$ is less than or equal to the minimum, high counts are those instances where $\mathbf{N}_{\mathbf{Ls,j}}$ is greater than the minimum. In all cases the minimum corresponds to $\mathbf{N}_{\mathbf{Ls,j}}$ of zero, except for $L_s = 60°$, where the minimum is 1, 2, or 3.

The next step is to divide the methane measurements for each case into two groups: low and high values. The SAM measurements dominate the sample of methane data. Most of the SAM measurements are so-called

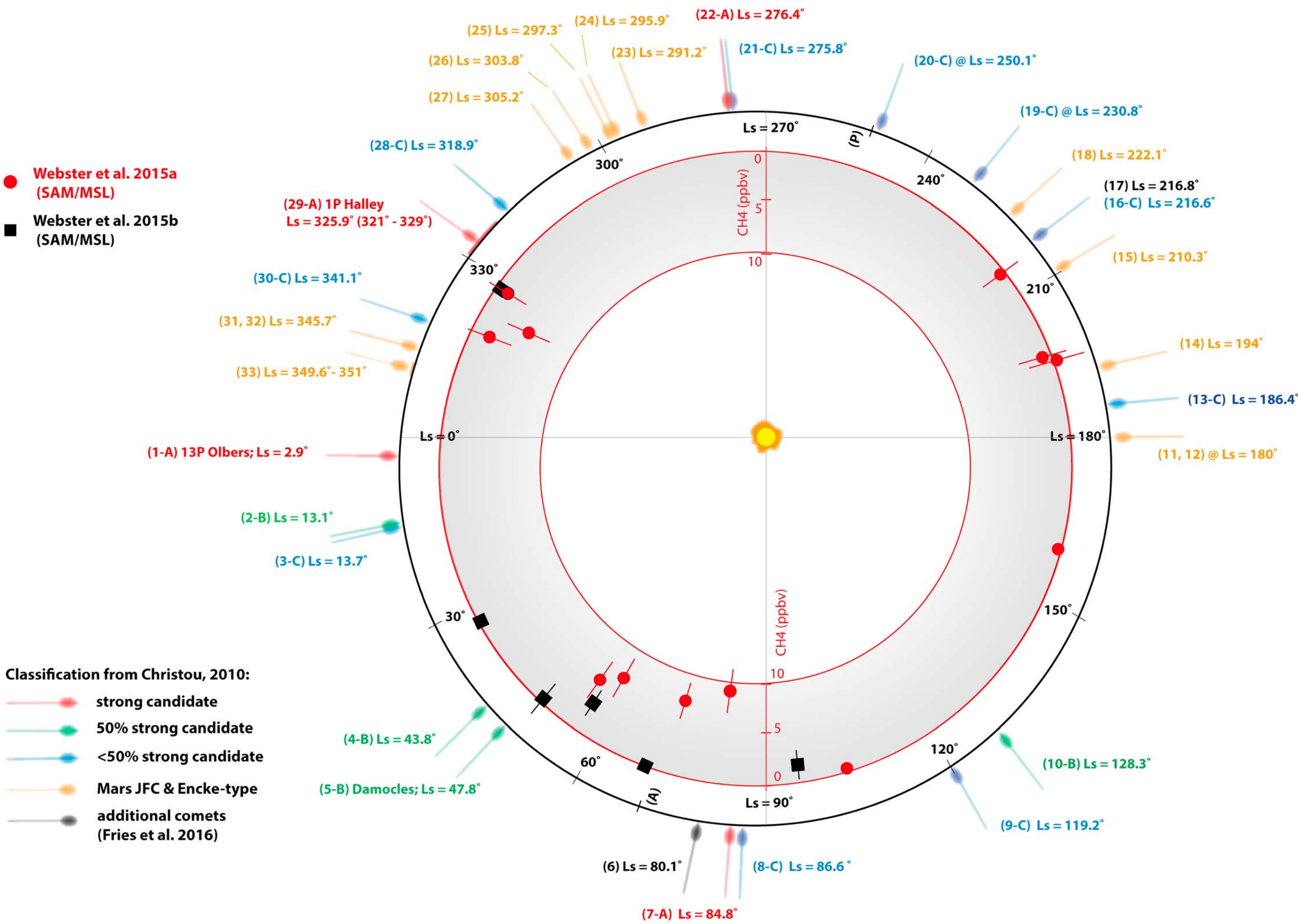

Figure 5. All the methane measurements from the SAM instrument only (Table 2) compared to all the predicted meteoroid streams (Table 1).

regular runs [*Webster et al*., 2015a, 2015b] and have an uncertainty on the order of ±2 ppbv (1 sigma, Table 2). Therefore, we take a bin of twice this uncertainty, i.e., 0 to 4 ppbv, and consider methane concentrations within this bin as low values. Anything larger than 4 ppbv we consider a high methane concentration.

These two parameters, low/high methane and low/high meteoroid stream count, can now be combined so as to evaluate the likelihood whether there is, or not, any dependency between them. We apply the Pearson's chi-square test, which is a standard test for this type of problem. The null hypothesis (H_0) is that there is no correlation between the two parameters. The test requires drawing up a 2 × 2 matrix containing the observed number of counts for the combinations of (1) low methane and low $\mathbf{N}_{\mathbf{Ls,j}}$, (2) low methane and high $\mathbf{N}_{\mathbf{Ls,j}}$, (3) high methane and low $\mathbf{N}_{\mathbf{Ls,j}}$, and (4) high methane and high $\mathbf{N}_{\mathbf{Ls,j}}$. We divide the matrix elements by the total number of methane measurements in the sample for the case under consideration. From the resulting fractions the expected number of counts for each matrix element is calculated, and then the sum of the squared differences between the observed and expected counts, normalized to the expected counts, is taken. The resulting number, chi^2, relates to a probability that the null hypothesis is true: a small value for chi^2 corresponds to a large probability.

We also want to get an idea of the uncertainties in the probability due to the uncertainties in the methane measurements in the sample. To address this, for each case, we add or subtract a random number to each methane measurement, based on a normal distribution with the quoted uncertainly for that measurement as the standard deviation. In this "new" sample of methane values some methane measurements swap from

Table 2. Mars Atmospheric Methane Measurements as a Function of L_s, Earth-Based Observations (Green), Mars Express (White) and at the SAM/MSL (Orange)

Date of observation	L_s (°)(Martian Year)	CH_4 mixing ratio(ppbv)	Comment	Reference
28-30-JUN-1988	222-223 (18)	**70 ± 50**	FTS at Kitt Peak Observatory	*Krasnopolsky et al.* [1997]
24-JAN-1999	88 (24)	**10 ± 3**	FTS/CFHT	*Krasnopolsky et al.* [2004]
27-JAN-1999	89 (24)	**10 ± 3**	FTS/CFHT	*Krasnopolsky et al.* [2004]
11-JAN-2003	122 (26)	**40 ± 8**	CHSELL/IRTF & NIRSPEC Keck2	*Mumma et al.* [2009]
JAN/FEB-2004	330-40 (26-27)	**10 ± 5**	MEX / PFS	*Formisano et al.* [2004]
06-JAN-2006	352 (27)	**<7.8**	CHSELL/IRTF & NIRSPEC (Keck 1 & 2)	*Villanueva et al.* [2013]
10-FEB-2006	10 (28)	**10 ± 5**	CSHELL/IRTF	*Krasnopolsky* [2012]
26-FEB-2006	17 (28)	**1 ± 2**	CHSELL/IRTF & NIRSPEC Keck2	*Mumma et al.* [2009]
20-NOV-2009	12 (30)	**<6.6**	CRIRES	*Villanueva et al.* [2013]
07-DEC-2009	20 (30)	**-1.6 ± 5.6**	CSHELL/IRTF	*Krasnopolsky* [2012]
28-APR-2010	83 (30)	**<7.2**	NIRSPEC (Keck 2)	*Villanueva et al.* [2013]
25-OCT-2012	195.0 (31)	**-0.51 ± 2.38**	MSL / SAM	*Webster et al.* [2015a]
27-OCT-2012	196.2 (31)	**1.43 ± 2.47**	MSL / SAM	*Webster et al.* [2015a]
27-NOV-2012	214.9 (31)	**0.68 ± 2.15**	MSL / SAM	*Webster et al.* [2015a]
01-JUN-2013	328.6 (31)	**0.56 ± 2.13**	MSL / SAM	*Webster et al.* [2015a]
16-JUN-2013	336.5 (31)	**5.78 ± 2.27**	MSL / SAM	*Webster et al.* [2015a]
23-JUN-2013	340.5 (31)	**2.13 ± 2.02**	MSL / SAM	*Webster et al.* [2015a]
29-NOV-2013	55.7 (32)	**5.48 ± 2.19**	MSL / SAM	*Webster et al.* [2015a]
06-DEC-2013	59.2 (32)	**6.88 ± 2.11**	MSL / SAM	*Webster et al.* [2015a]
06-JAN-2014	72.7 (32)	**6.91 ± 1.84**	MSL / SAM	*Webster et al.* [2015a]
28-JAN-2014	81.7 (32)	**9.34 ± 2.16**	MSL / SAM	*Webster et al.* [2015a]
17-MAR-2014	103.4 (32)	**0.47 ± 0.11**	MSL / SAM	*Webster et al.* [2015a]
09-JUL-2014	158.8 (32)	**0.90 ± 0.16**	MSL / SAM	*Webster et al.* [2015a]
09-JUL-2014	158.8 (32)	**0.99 ± 2.08**	MSL / SAM	*Webster et al.* [2015a]
24-APR-2015	331.0 (32)	**0.66 ± 0.095**	MSL / SAM	*Webster et al.* [2015b]
26-AUG-2015	32.9 (33)	**0.25 ± 0.055**	MSL / SAM	*Webster et al.* [2015b]
04-OCT-2015	50 (33)	**0.85 ± 1.44**	MSL / SAM	*Webster et al.* [2015b]
20-OCT-2015	57 (33)	**2.5 ± 1.5**	MSL / SAM	*Webster et al.* [2015b]
18-NOV-2015	69.7 (33)	**0.25 ± 0.08**	MSL / SAM	*Webster et al.* [2015b]
18-NOV-2015	69.7 (33)	**-0.16 ± 1.53**	MSL / SAM	*Webster et al.* [2015b]
13-JAN-2016	94.2 (33)	**2.01 ± 1.83**	MSL / SAM	

the low value bin to the high value bin or the other way around, thus slightly changing the test matrix' elements. We next run the test and obtain a corresponding chi^2 and probability. We do this 10,000 times and take the average and standard deviation over these runs to be the final answer. In Table 3 we present the results for all the cases and ranges of L_s.

Not surprisingly, as we already saw from a visual analysis of the Figures 1–4, we conclude that in the case as presented by *Fries et al*. [2016] there seems to be a clear correlation between high methane and predicted meteor events. *Fries et al*. [2016] mention all high methane measurements fall within 16 days (difference in L_s of about 8°) of a predicted meteor event. From our statistical test, the probability that there is no correlation between methane and meteoroid events (the null hypothesis, H_0) is only 5%, so that H_0 is rejected. With their selection of meteor streams there seems to be a correlation for all our considered ranges of L_s, but decreasing in strength as the range extends. At the L_s range of 60° we find a 61% probability that H_0 is true. This is expected, because as the range extends to the extreme of 360° all the streams are counted for each methane measurement, so that all we see is the methane data.

Adding the new SAM data to the analysis (Figure 2), the correlation is less evident for the range of $L_s \geq 30°$.

Table 3. Correlation Between Measured Methane and Predicted Meteor Streams. The Null Hypothesis H_0 is that There is no Correlation Between Observed Methane and the Occurrence of Meteoroid Streams. The Value of p(H0) is the Probability that H_0 is Correct

	L_s range 8°	L_s range 15°	L_s range 30°	L_s range 60°
Fries et al. [2016] methane & stream selection (Figure 1)				
chi^2	5.7 ± 2.8	3.7 ± 2.2	2.8 ± 1.5	0.56 ± 0.81
p(H_0)	0.05 ± 0.09	0.12 ± 0.15	0.15 ± 0.17	0.61 ± 0.28
All methane & *Fries et al.* [2016] streams selection (Figure 2)				
chi^2	5.3 ± 2.5	3.0 ± 1.8	1.5 ± 0.85	0.68 ± 0.86
p(H_0)	0.06 ± 0.09	0.15 ± 0.16	0.30 ± 0.23	0.55 ± 0.27
Fries et al. [2016] methane selection & all streams (Figure 3)				
chi^2	0.15 ± 0.34	0.18 ± 0.40	0.028 ± 0.042	0.091 ± 0.14
p(H_0)	0.79 ± 0.19	0.78 ± 0.20	0.90 ± 0.083	0.82 ± 0.14
All methane & all streams (Figure 4)				
chi^2	0.23 ± 0.43	0.67 ± 0.61	0.03 ± 0.037	0.03 ± 0.037
p(H_0)	0.74 ± 0.21	0.48 ± 0.18	0.89 ± 0.078	0.89 ± 0.078
SAM methane & all streams (Figure 5)				
chi^2	0.12 ± 0.28	0.04 ± 0.099	0.28 ± 0.20	0.28 ± 0.20
p(H_0)	0.88 ± 0.21	0.88 ± 0.099	0.62 ± 0.12	0.62 ± 0.12

Considering all the 33 predicted meteor streams and the selection of methane measurements by *Fries et al*. [2016], we see that there is no correlation (Figure 3), with a probability that H_0 is true of more than 78% for all ranges of L_s.

When adding the six new data points to the mix (Figure 4), the same conclusion is drawn with a probability of more than 74% for all ranges, except for L_s of 15° which shows a probability of 48%. We are not certain why this value is lower than all the surrounding high values, but it does not affect the overall conclusions.

Finally, we present a similar exercise taking into account all the 33 predicted meteor shower events from Table 2 combined with just all the SAM measurements to date. The SAM measurement series presents the largest and most consistent data set collected in situ by the highest spectral resolution instrument at Mars to date, applying a standard calibration procedure. We present the results in the Figure 5.

From visual inspection of Figure 5 no obvious correlation between high methane measurements, and the occurrence of meteor showers jumps out. Meteor streams occur close to low values as they do to some high values of methane. We already highlighted some features in the previous section. In addition, we want to emphasize the following:

1. The stream from comet 1P/Halley, an A class stream that occurs over a 2 week period between $L_s = 321°$ and 329°, is followed by two low methane values in two subsequent Martian years at 328.6° and 331° and one high value at 336.5°. There are also five additional Encke-type streams some 2 months before between $L_s = 291.2°$ and 305.2°.
2. A new low methane value on 26 August 2015 at $L_s = 32.9°$ is preceded by an A class, a B class, and a C class stream, at $L_s = 2.9°$, 13.1°, and 13.7°, respectively.
3. Three new measurements were performed between $L_s = 50°$ and 70° in the fall of 2015, and all show low methane concentrations. This is the same season where in the previous Mars year a cluster of four high values was observed [*Webster et al*., 2015a]. It is preceded by two B class streams at $L_s = 43.8°$ and 47.8°.

The probabilities that H_0 is true for this case are over 62% for all ranges of L_s (Table 3).

6. Conclusions

Several observations of Martian methane to date report temporal variability in concentration. According to a new idea, the variability in methane is correlated with meteor events at Mars [*Fries et al*., 2016]. Here we have reanalyzed such possible correlation by considering the full set of methane abundance measurements at Mars, including six new data points obtained by the SAM instrument, in combination with all predicted meteor shower events at Mars. Whether by examining individual methane measurements or using a simple statistical analysis, we reach the same conclusion: there is no correlation between high atmospheric methane abundance and the occurrence of meteor showers on Mars. It does not mean that no methane will be formed from infalling organic material. From laboratory experiments it seems likely that methane can easily be formed under Martian conditions [*Keppler et al*., 2012; *Schuerger et al*., 2012]. However, estimates of the quantities of infalling material in combination with the efficiency to produce methane from such material do not seem to match the amounts needed to explain the high methane events. The low background levels of ~0.5 ppbv methane observed by the SAM-TLS on the Curiosity rover since 2012 could result from the UV degradation of surface organics delivered by interplanetary dust particles or any combination of surface organics, methanogens, and geology, whereas the higher methane levels do not appear to be due to surface organics [*Webster et al*., 2015]. Continued observations of the variations in atmospheric methane will be important, and measurements of the actual quantities of infall of meteoric material will be crucial to get a better understanding of its role on Mars.

Acknowledgments
Gloria Kim helped with literature search and preparation of table entries. We thank F. Pijpers for help with the best choice of statistical methods. We are grateful to the two referees for their constructive comments. This research was supported by the NASA MSL/SAM project. Part of the research described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). All the data used in this analysis can be found in Tables 1–3.

References

Atreya, S. K., P. R. Mahaffy, and A. S. Wong (2007), Methane and related trace species on Mars: Origin, loss, implications for life, and habitability, S. K. Atreya, P. R. Mahaffy and A. S. Wong, *Planet. Space Sci.*, *55*, 358–369.

Atreya, S. K., O. Witasse, V. F. Chevrier, F. Forget, P. R. Mahaffy, P. B. Price, C. R. Webster, and R. W. Zurek (2011), Methane on Mars: Current observations, interpretation, and future plans, *Planet. Space Sci.*, *59*, 133–136, doi:10.1016/j.pss.2010.10.008.

Benna, M., P. R. Mahaffy, J. M. Grebowsky, J. M. C. Plane, R. V. Yelle, and B. M. Jakosky (2015), Metallic ions in the upper atmosphere of Mars from the passage of comet C/2013 A1 (Siding Spring), *Geoph. Res. Lett.*, *42*, 4670–4675, doi:10.1002/2015GL064159.

Christou, A. A. (2010), Annual meteor showers at Venus and Mars: Lessons from the Earth, *Mon. Not. R. Astron. Soc.*, *402*(4), 2759–2770, doi:10.1111/j.1365-2966.2009.16097.x.

Court, R. W., and M. A. Sephton (2009), Investigating the contribution of methane produced by ablating micrometeorites to the atmosphere of Mars, *Earth Planet. Sci. Lett.*, *288*(3-4), 382–385, doi:10.1016/j.epsl.2009.09.041.

Flynn, G. J. (1996), The delivery of organic matter from asteroids and comets to the early surface of Mars, *Earth Moon Planets*, *72*(1), 469–474, doi:10.1007/BF00117551.

Flynn, G. J., and D. S. McKay (1990), An assessment of the meteoritic contribution to the Martian soil, *J. Geophys. Res.*, *95*, 14,497–14,509, doi:10.1029/JB095iB09p14497.

Formisano, V., S. Atreya, T. Encrenaz, N. Ignatiev, and M. Giuranna (2004), Detection of methane in the atmosphere of Mars, *Science*, *306*(5702), 1758–1761, doi:10.1126/science.1101732.

Fries, M., et al. (2016), A cometary origin for Martian atmospheric methane, *Geochem. Perspect. Lett.*, *2*, 10–23, doi:10.7185/geochemlet.1602.

Geminale, A., V. Formisano, and M. Giuranna (2008), Methane in Martian atmosphere: Average spatial, diurnal, and seasonal behaviour, *Planet. Space Sci.*, *56*(9), 1194–1203, doi:10.1016/j.pss.2008.03.004.

Geminale, A., V. Formisano, and G. Sidoni (2011), Mapping methane in Martian atmosphere with PFS-MEX data, *Planet. Space Sci.*, *59*(2-3), 137–148, doi:10.1016/j.pss.2010.07.011.

Keppler, F., I. Vigano, A. McLeod, U. Ott, M. Früchtl, and T. Röckmann (2012), Ultraviolet-radiation-induced methane emissions from meteorites and the Martian atmosphere, *Nature*, *486*(7401), 66–93, doi:10.1038/nature11203.

Krasnopolsky, V. A. (2012), Search for methane and upper limits to ethane and SO_2 on Mars, *Icarus*, *217*(1), 144–152, doi:10.1016/j.icarus.2011.10.019.

Krasnopolsky, V. A., G. L. Bjoraker, M. J. Mumma, and D. E. Jennings (1997), High-resolution spectroscopy of Mars at 3.7 and 8 μm: A sensitive search for H_2O_2, H_2CO, HCl, and CH_4, and detection of HDO, *J. Geophys. Res.*, *102*, 6525–6534, doi:10.1029/96JE03766.

Krasnopolsky, V. A., J. P. Maillard, and T. C. Owen (2004), Detection of methane in the Martian atmosphere: Evidence for life?, *Icarus*, *172*(2), 537–547, doi:10.1016/j.icarus.2004.07.004.

Maguire, W. C. (1977), Martian isotope ratios and upper limits for possible minor constituents as derived from Mariner 9 infrared spectrometer data, *Icarus*, *32*(1), 85–97, doi:10.1016/0019-1035(77)90051-3.

Mahaffy, P. R. (2012), The sample analysis at Mars investigation and instrument suite, *Space Sci. Rev.*, *170*(1), 401–487, doi:10.1007/s11214-012-9879-z.

Marsden, B. G., and G. V. Williams (2008), *Catalogue of Cometary Orbits 2008*, 17th ed., Minor Planet Cent./Cent. Bur. for Astron. Telegrams, Cambridge, Mass.

Moores, J. E., T. H. McConnochie, D. W. Ming, P. D. Archer Jr., and A. C. Schuerger (2014), The Siding Spring cometary encounter with Mars: A natural experiment for the Martian atmosphere?, *Geophys. Res. Lett.*, *41*, 4109–4117, doi:10.1002/2014GL060610.

Mumma, M. J., G. L. Villanueva, R. E. Novak, T. Hewagama, B. P. Bonev, M. A. DiSanti, A. M. Mandell, and M. D. Smith (2009), Strong release of methane on Mars in northern summer 2003, *Science*, *323*, 1041–1044, doi:10.1126/science.1165243.

Opitom, C., A. Guilbert-Lepoutre, E. Jehin, J. Manfroid, D. Hutsemékers, M. Gillon, P. Magain, G. Robert-Borsani, and O. Witasse (2016), Long-term activity and outburst of comet C/2013A1 (Siding Spring) from narrow band photometry and long-slit spectroscopy, *Astron. Astrophys.*, *589*, A8, doi:10.1051/0004-6361/201527628.

Schuerger, A. C., J. E. Moores, C. A. Clausen, N. G. Barlow, and D. T. Britt (2012), Methane from UV-irradiated carbonaceous chondrites under simulated Martian conditions, *J. Geophys. Res.*, *117*, E08007, doi:10.1029/2011JE004023.

Villanueva, G. L., M. J. Mumma, R. E. Novak, Y. L. Radeva, H. U. Käufl, A. Smette, A. Tokunaga, A. Khayat, T. Encrenaz, and P. Hartogh (2013), A sensitive search for organics (CH_4, CH_3OH, H_2CO, C_2H_6, C_2H2, $C2H_4$), hydroperoxyl (HO_2), nitrogen compounds (N_2O, NH_3, HCN) and chlorine species (HCl, CH_3Cl) on Mars using ground-based high-resolution infrared spectroscopy, *Icarus*, *223*(1), 11–27, doi:10.1016/j.icarus.2012.11.013.

Webster, C. R., et al. (2015a), Mars methane detection and variability at Gale crater, *Science*, *347*, 415–417, doi:10.1126/science.1261713.

Webster, C. R., P. R. Mahaffy, S. K. Atreya, G. Flesch, and the SAM Science Team of Curiosity Rover (2015b), Mars methane detection and variability at Gale Crater measured by the TLS instrument in SAM on the Curiosity rover, Abstract P43B-2110 presented at Fall Meeting, AGU.

Zahnle, K., F. S. Freedman, and D. C. Catling (2010), Is there Methane on Mars?, *Icarus*, *212*, 493–503, doi:10.1016/j.icarus.2010.11.027.