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A cometary origin for martian atmospheric methane

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Abstract

Methane has been reported repeatedly in the martian atmosphere but its origin remains an obstinate mystery. Possible sources include aqueous alteration of igneous rocks, release from ancient deposits of methane/water ice clathrates, infall from exogenous sources such as background interplanetary dust, or biological activity. All of these sources are problematic, however. We hypothesise that delivery of cometary material includes meteor outbursts, commonly known as "meteor showers", may explain martian methane plumes. Correlations exist between the appearance of methane and near-approaches between Mars and cometary orbits. Additional correlations are seen between these interactions and the appearance of high-altitude dust clouds on Mars, showing that large amounts of material may be deposited on Mars during these encounters. Methane is released by UV breakdown of delivered cometary material. This hypothesis is testable in future Mars/cometary encounters. A cometary origin for methane would reveal formation of methane through processes that are separate from any geological or biological processes on Mars.

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Introduction

Investigators have reported methane in the martian atmosphere using a variety of analytical techniques, including Earth-based astronomical observations (Krasnopolsky *et al.*, 1997, 2004; Mumma *et al.*, 2009; Krasnopolsky, 2011), the Planetary Fourier Spectrometer on the ESA Mars Express mission (Formisano *et al.*, 2004), and recently by the NASA's Sample Analysis at Mars (SAM) investigation on the Mars Science Laboratory (MSL) mission (Webster *et al.*, 2015). The earliest report of methane to withstand scrutiny was made in June of 1988 (Krasnopolsky *et al.*, 1997), and reports made since that date include several values of ~10 parts per billion by volume (ppbv) over large spatial scales (Krasnopolsky *et al.*, 2004; Formisano *et al.*, 2004; Krasnopolsky, 2011), several non-detections of methane (Villanueva *et al.*, 2013; Webster *et al.*, 2014), and "plumes" ranging up to ~45 (Mumma *et al.*, 2009; Geminale *et al.*, 2011) to 60 ppbv (Fonti and Marzo, 2010). Local plumes of methane have been noted over Syrtis Major (Mumma *et al.*, 2009), the north polar region (Geminale *et al.*, 2011), Valles Marineris (Krasnopolsky *et al.*, 1997) and other localities, but plumes have not been observed to re-occur at the same sites. Similarly, statistical studies of data from Mars-orbiting satellites also show that while methane concentrations vary regionally, those variations are not predictably consistent with latitude, longitude, or seasonal changes on the planet (Geminale *et al.*, 2008, 2011; Webster *et al.*, 2015).

To date, several possible sources for martian methane have been proposed, including: abiological sources such as volcanism (Wong *et al.*, 2003), exogenous sources to include infall of interplanetary dust particles (IDP) and cometary impact material (Schuerger *et al.*, 2012), aqueous alteration of olivine in the presence of carbonaceous material (Oze and Sharma, 2005), release from ancient deposits of methane clathrates (Chastain and Chevrier, 2007), or via biological activity (Krasnopolsky *et al.*, 2004). Methane that was recently reported in martian meteorites (Blarney *et al.*, 2015) may arise from serpentinisation or condensation from a carbon-bearing gas during crystallisation of its parent magma at low oxygen fugacity (Steele *et al.*, 2012). It is not clear at present whether the meteorite-hosted methane reported in Blarney *et al.* (2015) is related to atmospheric methane. Since neither total methane abundance nor mineralogical context are provided by the method used, it is not currently clear whether the methane is a new discovery or a component of the reduced carbon already known to exist at 20 ± 6 ppm concentration in martian meteorites (Steele *et al.*, 2012). Identifying the source(s) of martian methane has potentially far-reaching importance, particularly with biogenesis as one hypothesis. Previous investigations have examined and rejected exogenous material as a source of martian methane, specifically via IDP infall and cometary impacts (Krasnopolsky *et al.*, 2004; Webster *et al.*, 2015).

There is a third type of exogenous source, however, that may satisfy the observed features of martian methane, namely its sudden appearance, regional scale spatial distribution, and total methane mass observed for past martian plumes. We hypothesise that this potential exogenous source of martian methane, including the appearance of plumes, may be explained by infall of carbonaceous material delivered into the martian atmosphere by periodic, cometary-origin meteor outbursts (or "meteor showers"). This mechanism may also explain the recently reported appearance of high-altitude dust plumes on Mars (Sánchez-Lavega *et al.*, 2015).

The scope of this study includes statement of a new hypothesis for formation of martian atmospheric methane via meteor outbursts, and a re-analysis of existing methane and high-altitude dust detections on Mars as a test of the hypothesis. The meteor-outburst hypothesis is inherently testable and so a strategy is presented for doing so, using currently available techniques that have been successfully employed in the past, such as Earth-based observations of methane, detection of cometary infall by orbital assets (Jakosky *et al.*, 2015), and methane detection by the Mars Science Laboratory rover (Webster *et al.*, 2015).

Background

All prior hypotheses for the origin of methane in the martian atmosphere present significant challenges (Lefevre and Forget, 2009; Zahnle *et al.*, 2011), and thus no consensus has yet emerged on methane origin. While volcanic activity (Wong *et al.*, 2003) could potentially release methane in episodic outbursts, multiple studies have rejected that model because the martian atmosphere lacks SO_2 of volcanic origin (Wong *et al.*, 2003; Krasnopolsky, 2011), indicating that substantial volcanic activity has not occurred recently. Conversely, both serpentinisation and biological activity can produce methane but neither is conducive to sudden production of massive methane plumes such as one reported (Mumma *et al.*, 2009) to involve the sudden release of 19,000 tonnes (19 x 10^5 kg) of CH_4.

Exogenous delivery of methane by infall of IDPs or by large impacts has also been proposed. Delivery of interplanetary dust was recently confirmed by the MAVEN mission team, who detected dust at very high altitudes in the martian atmosphere (Andersson *et al.*, 2015). An IDP origin for Mars' methane has been considered and rejected by previous authors (Formisano *et al.*, 2004; Krasnopolsky *et al.*, 2004; Schuerger *et al.*, 2012; Webster *et al.*, 2015) because the steady flux of IDPs cannot explain episodic and transient methane plumes. Cometary impacts (Kress *et al.*, 2004) have also been ruled out due to the lack of young impact craters of suitable size, both on the planetary scale (Krasnopolsky *et al.*, 2004) and near the MSL rover at the time the rover detected methane (Webster *et al.*, 2015).

Cometary debris streams (Fig. S-1) also produce infall of exogenous material into the martian atmosphere. This material arises from low-velocity emissions of large particles, forming trails spanning portions of a comet's orbit (Sykes *et al.*, 1986; Christou and Beurle, 1999; Treiman and Treiman, 2000; Christou, 2004, 2010). While generally associated with short-period comets, a debris trail has also been identified in association with the long-period Halley's comet (Jenniskens, 1995). As a consequence of planetary perturbations, trails subsequently evolve into filaments and elongated streams in a larger "tube" about the comet orbit.

When Earth, Mars and other bodies pass through such structures on an annual basis, meteor outbursts, or "meteor showers" may be observed (Christou, 2004; Fig. S-1). On Earth, these streams are well known and are actually targeted for collection of cometary material using high-altitude aircraft. Here we examine the temporal, spatial, and mass distributions of "meteor outburst" infall to Mars, and show that it is a plausible candidate as a source of atmospheric methane.

Meteor Showers and Methane Detection

As a first test of the meteor shower hypothesis, we have compared the dates of previous methane detections on Mars with Mars' currently known cometary debris stream interactions (Sykes and Walker, 1992; Treiman and Treiman, 2000; Christou, 2010). Table 1 shows the dates of methane observations along with the names and dates of correlating cometary orbital interactions. All of the methane observations are taken as single observations with the exception of Mars Express data, which are retrieved from the Planetary Fourier Spectrometer (PFS) instrument via a statistical technique over the course of two months. Figure S-2 illustrates the L_S dates of methane detections by the MSL rover versus interactions between Mars and the orbits of 5335 Damocles and 1P/Halley, indicating that methane detections occurred shortly after Mars interacted with the orbits of those bodies. Values for orbital interaction minimum distances come from Christou (2010) and Treiman and Treiman (2000). Results show that all of the methane observations occur within 16 days of the near-intersection of Mars' orbit with that of a known cometary meteor stream (Table 1). Some are especially striking, such as the exact correlation between a potentially strong, 70 ± 50 ppbv CH_4 observation reported in (Krasnopolsky *et al.*, 1997), which occurred on the day of an encounter between Mars and debris from the Marsden group of cometary fragments. Similarly, the strong plume noted by Mumma *et al.* (2009) occurred only four days after the nominal closest encounter between Mars and the orbit of comet C/2007 H2 Skiff (SI-3). That comet's orbit passes only ~150,000 km from Mars, less than half the distance from the Earth to the Moon and similar to the very close ~137,000 km pass distance between Mars and comet C/2013 A1 Siding Spring in October of 2014 (SI-1).

Some methane detections can be correlated with the same comet. One example is Comet 1P/Halley, whose orbit had close approaches to Mars at the times of methane detections in 2004 (Formisano *et al.*, 2004), and 2013 (Webster *et al.*, 2015). In total, all methane detections on Mars to date could be ascribed to close encounters with only seven cometary debris streams (Table 1, Column 5).

Cometary meteor showers could also be responsible for the two high-altitude dust plumes observed over Mars (Sánchez-Lavega *et al.*, 2015). These two optically visible dust plumes occurred at elevations >200 km above the martian surface, well above martian weather or dust storm phenomena (<60 km altitude). The first dust plume, on 17 May 1997, appeared on the same day as the closest approach between Mars and the orbit of comet C/2007 H2 Skiff, whose orbit passes only about 19 Mars diameters from the planet (Fig. 1). It is worth noting that in 2003, the closest approach between the orbit of C/2007 H2 Skiff and Mars was only four days before the large methane plume noted by Mumma *et al.* (2009), consistent with infall from a massive dust stream shed from Skiff (Fig. 2). The second dust plume (Sánchez-Lavega *et al.*, 2015) was noticed on 12 March 2012, three days after the closest approach between Mars and the orbit of comet 275P/Hermann.

Table 1 Reported detections on Mars and potential correlations with cometary dust streams.

	Date	Mixing ratio (ppbv)	Days between cometary encounter and detection	Encountered cometary orbit	Mars/comet orbit distance (10^-3 AU)
Martian methane: Earth-based telescopic observations					
Krasnopolsky *et al.*, 1997	28-Jun-88	70 +/- 50	0	(SDA Meteor Shower) Marsden Group Comets	16.139*
Krasnopolsky *et al.*, 2004	24-Jan-99	10 +/- 3	6	C/1854 L1 Klinkerfues	4.778*
"	27-Jan-99	10 +/- 3	9	C/1854 L1 Klinkerfues	4.778*
Mumma *et al.*, 2009	11-Jan-03	max. ~40 +/- 6	4	C/2007 H2 Skiff	0.845*
Krasnopolsky, 2011	10-Feb-06	~10	15	13P/Olbers	26.580*
Martian methane: ESA *Mars Express* orbiter observations					
Formisano *et al.*, 2004	Jan-Feb 2004	10 +/- 5	3	1P/Halley	66.965*
Methane: Mars science laboratory rover					
Webster *et al.*, 2014	16-Jun-13	5.78 +/- 2.27	16	1P/Halley	66.965*
"	23-Jun-13	2.13 +/- 2.02			
"	29-Nov-13	5.48 +/- 2.19	16	5335 Damocles	53.630*
"	6-Dec-13	6.88 +/- 2.11			
"	6-Jan-14	6.91 +/- 1.84			
"	28-Jan-14	9.34 +/- 2.16	4	275P/Hermann	8.600**
"	17-Mar-14	0.47 +/- 0.11			
"	9-Jul-14	0.9 +/- 0.16			
Visible dust: Earth-based/Hubble telescopic observations					
Sanchez-Lavega *et al.*, 2015	17-May-97		0	C/2007 H2 Skiff	0.845*
"	12-Mar-12		3	275P/Hermann	8.600**
Non-detections					
Villanueva *et al.*, 2013	6-Jan-06	0	–	–	–
	19-Aug-09	0	–	–	–
	20-Nov-09	0	–	–	–
	28-Apr-10	0	–	–	–
Mumma *et al.*, 2009	26-Feb-06	0	–	–	–
Webster *et al.*, 2014	25-Oct-12	-0.51 +/- 2.83	–	–	–
	27-Oct-12	1.43 +/1 2.47	–	–	–
	27-Nov-12	0.6 +/- 2.15	–	–	–
"	9-Jul-14	0.99 +/- 2.08			
Krasnopolsky, 2011	7-Dec-09	0	–	–	–

* Christou, 2010
** Treiman and Treiman, 2000

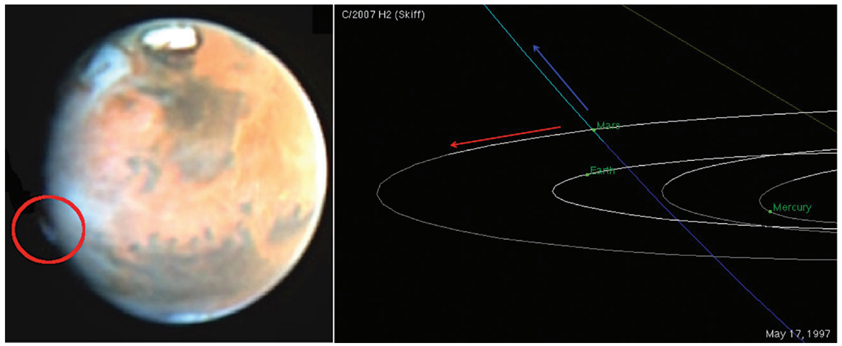

Figure 1 **(left)** Image adapted from Sánchez-Lavega et al. (2015) showing a high-altitude dust plume that was seen to appear suddenly on Mars. **(right)** The locations of Mars and the orbit of comet C/2007 H2 Skiff on 17 May 1997, the same day the dust plume appeared. The motion of Mars is shown by the red arrow and the motion of debris along the orbit of comet Skiff is shown by the blue arrow. Image: JPL Small Bodies Database.

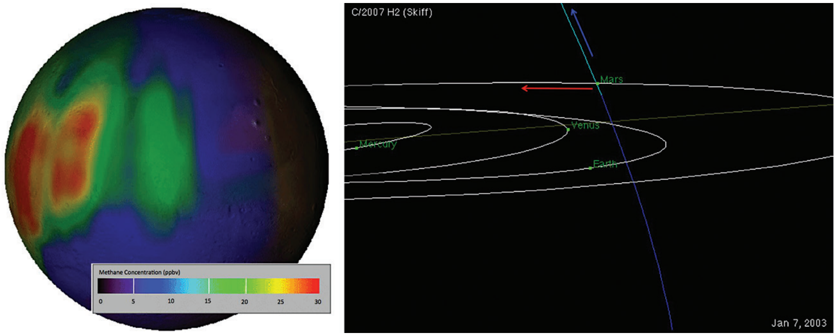

Figure 2 **(left)** Methane plume reported by Mumma *et al.* (2009) showing methane detected in the martian atmosphere on 11 Jan 2003. Image originally from NASA. **(right)** The locations of Mars and the orbit of comet C/2007 H2 Skiff four days before the methane detection, approximately as seen from Earth. The red arrow shows Mars' direction and the blue arrow shows the movement of debris along Skiff's orbit. Image: JPL Small Bodies Database.

The areal extent of meteor showers is in agreement with the areal extent observed for martian methane plumes. Meteor showers typically peak over a course of hours, depositing material onto an area that can be sub-hemispherical in extent (Jenniskens, 1995), which is in agreement with the size of the Mumma *et al.* (2009) plume.

At first glance it may appear straightforward to test this hypothesis via a statistical comparison between methane detection events and the known frequency of interactions between Mars and cometary orbits. Unfortunately this approach is ambiguous because the occurrence of a Mars/comet orbit interaction does not guarantee the infall of a sizable amount of material into Mars' atmosphere (*e.g.*, Jenniskens, 2006). The distribution of cometary debris along a comet's orbit is subject to multiple stochastic processes, including the ejection of material from the parent body and dynamical perturbations of debris. Attempts to correlate orbital interactions with methane detection will result in a large number of false negative results.

The Methane Source

Having shown that methane 'plumes' on Mars are consistent in space and time with meteor shower infall, it remains to be shown that methane can be generated from that infall, and that the mass of methane generated is consistent with the observed baseline and transient abundances. Methane from meteor outbursts is not delivered directly to Mars, but is generated by UV photolysis of macromolecular carbon (MMC) solids under Mars ambient conditions (Keppler *et al.*, 2012; Schuerger *et al.*, 2012). The amount of methane that can be generated through a combination of IDP flux and meteor showers is generally consistent with historical methane observations on Mars. The abundance of methane in the martian atmosphere is not simply a global average, as seen in Figure S-1. Instead, periods of non-detection are punctuated by occasional observations that are usually around 10 ppbv with episodic plumes featuring local concentrations of up to ~45 and 60 ppbv as explained above. This is broadly consistent with a steady background IDP flux that is punctuated by periodic meteor showers that vary widely in delivered mass (Fig. S-1). Geminale *et al.* (2008) found that 2.7 x 10^5 kg of CH_4 yr^{-1} are necessary to sustain 10 ppbv methane on Mars. Previous investigations have noted that IDP flux is sufficient to provide this amount (Geminale *et al.*, 2008; Keppler *et al.*, 2012) via UV photolysis of methane from IDPs under Mars-ambient conditions (Keppler *et al.*, 2012; Schuerger *et al.*, 2012). However, Schuerger *et al.* (2012) dispute the 10 ppbv finding and calculates that IDP flux provides a global average of 2.2 ppbv CH_4. The MSL rover data thus far show a background methane abundance of ~0.7 ppbv (Webster *et al.*, 2015), for which Schuerger's 2.2 ppbv is excessive if MSL's measurements are representative of the full thickness of the martian atmosphere. Overall, martian methane is at very low abundances at ground level with both non-detections and higher values noted in measurements made through the full height of the martian atmosphere. Also, IDP flux may account for all or some of the steady-state background but cannot account for methane plumes.

Martian methane plumes may be attributable to periodic meteor showers. The appearance of methane plumes correlates with Mars' interactions with known cometary orbits as seen in Table 1, but meteor showers must produce enough mass to account for observed methane abundance. To produce a 1.9 x 10^7 kg CH_4 plume like that in Mumma *et al.* (2009) requires 7.9 x 10^8 kg of infalling material, assuming 20 % UV photolysis yield (Schuerger *et al.*, 2012) of 12 wt. % carbon (Thomas *et al.*, 1993; Flynn, 1996). This amount is equal to ~100x the annual IDP flux in a single event. Cometary debris streams can include billions of kg of material in total (Jenniskens, 2006) spread out into debris streams and Mars would have to interact with a local concentration to generate a meteor shower with a high local methane concentration. Mitigating factors include the fact that the 1.9 x 10^7 kg value has been challenged (Zahnle *et al.*, 2011) as an artifact of terrestrial ^{13}C-bearing methane and probably indicates an upper limit for the plume, and that the comet implicated in the 19 x 10^5 kg methane detection, C/2007 H2 Skiff, may simply be capable of meteor showers of this magnitude. Material ejected from long period comets such as C/2007 H2 Skiff are known to generate episodic meteor outbursts at the Earth (Flynn and McKay, 1990), and the passage of Skiff's orbit near Mars in 1997 correlates exactly with the appearance of a dust plume that was dense enough to be visible to amateur astronomers on Earth (Sánchez-Lavega *et al.*, 2015). Additionally, while Flynn and McKay (1990) found that about 3x more cometary material survives unmelted on Mars than on Earth, that paper disregarded material that melts during infall because that carbon does not "survive" the process. This is a valid assumption on Earth where the atmosphere contains ~21 % oxygen and melting a particle will combust the carbonaceous fraction. On Mars, however, the ~95 % CO_2 atmosphere should restrict combustion, driving direct devolatilisation of light species to include methane. The melted mass disregarded in Flynn (1996) amounts to 29.1 % of the total IDP carbon delivered to Mars annually, constituting significant additional methane from infall sources. The portion of particles experiencing greater than 50 % melting is composed of particles greater than 10^{-4} g in mass (Flynn, 1996), and this larger mass fraction is important because lunar impact monitoring programs indicate that meteor streams contain a higher flux of large (>30 g) meteoroids than the IDP population (Oberst and Nakamura, 1991; Lyytinen and Jenniskens, 2003; Suggs *et al.*, 2014), which is dominated by particles of 10^{-6}-10^{-4} g (Gruen *et al.*, 1985). In fact, larger particles are preferentially concentrated in the vicinity of comet orbits (Asher and Izumi, 1998; Dubietis and Arlt, 2007), as observed directly in dust trails (Sykes *et al.*, 1986). Finally, larger masses tend to generate significant amounts of micrometre-sized "smoke" particles upon infall (Klekociuk *et al.*, 2005) that may be particularly conducive to generation of methane via UV photolysis due to their large amount of freshly-exposed surface area. These considerations collectively suggest that the total mass of carbon delivered to the martian atmosphere by meteor streams may exceed prior estimates.

Also, two of the methane plumes reported on Mars (Fonti and Marzo, 2010; Geminale *et al.*, 2011) were recognised only through statistical treatment of orbital imagery data, and so are of uncertain spatial extent. Only the plume reported by Mumma *et al.* (2009) is resolved well enough in area to permit a credible estimate of its total methane mass, and even this has been challenged (Zahnle *et al.*, 2011). It is possible that the other two plumes are strong local concentrations of a significantly lower total mass of methane.

The Methane Sink

A cometary debris origin for martian methane may also assist in explaining the observed methane loss rate, which other authors have noted to be inconsistent with currently understood martian atmospheric and surface chemistry (Krasnopolsky *et al.*, 2004; Geminale *et al.*, 2008; Lefevre and Forget, 2009; Zahnle *et al.*, 2011; Webster *et al.*, 2015). Webster *et al.* (2015) noted that some mechanism must be responsible for methane destruction that is "a factor of ≥100" more efficient at destroying methane than surface-level UV photolysis (Fig. S-3). However, with the exception of the MSL rover detection, all detections of methane on Mars have been obtained through the full column of the martian atmosphere and the methane has been assumed to originate from, at or near the surface. Furthermore the MSL report is a point measurement for which the areal and altitudinal extent of the methane is unknown. If, instead, methane is generated at high altitude via cometary debris origin, then the destruction kinetics of martian methane must be revisited. Wong *et al.* (2003) found that UV photolysis at altitudes greater than 80 km above Mars' surface can dominate the methane destruction rate, which may explain the observed destruction rate of methane on Mars noted by Webster *et al.* (2015). The correlation between observed methane depletion rates and the high-altitude methane loss rate is consistent with a cometary debris origin for Mars' methane. We also considered dust storms as a methane sink but did not find a correlation with methane non-detection (SI-2).

Discussion

If the hypothesis of a cometary meteor outburst source for martian methane is proven true, then a long-standing mystery in Mars science will be resolved. Moreover, a new mechanism will be shown that is entirely atmospheric and cometary in origin, with a source that is entirely uninvolved with either martian geology or potential biology. The hypothesis is innately testable with presently deployed assets including investigations at Mars: MSL's SAM investigation and the instrument suite on the MAVEN mission. The upcoming ESA Trace Gas Orbiter will also serve a valuable role, and of course Earth-based astronomical observations remain a valuable asset. Together, these assets should undergo an extended investigation of martian atmospheric methane that includes long-term monitoring to identify when plumes occur, how long they persist, their extent and total methane mass, and the vertical distribution of methane through the full height of the martian atmosphere. Methods used specifically to test the hypothesis of a cometary origin include observations of martian meteor showers (Adolfsson *et al.*, 1996; McAuliffe and Christou, 2006; Domokos *et al.*, 2007) and corresponding detection of magnesium in the martian atmosphere from meteoritic input (Jakosky *et al.*, 2015) at the time of predicted interactions between Mars and cometary orbits, coupled with both areal and vertical distribution of atmospheric methane and high-altitude dust. Upcoming Mars/cometary interactions are listed for this purpose in Table 2. Although meteor shower-origin methane may account for observations of methane seen to date, we stress that it does not necessarily exclude the possibility of methane contributions from other sources. Our hypothesis is not only testable going forward, but presently offers a very promising set of observed correlations that may provide an explanation for previous methane detections on Mars.

Table 2 Approximate upcoming Mars / cometary orbit encounters.

Comet	Date
275P/Hermann	12-Dec-15
C/2007 H2 Skiff	8-Mar-16
(SDA Meteor Shower)	12-Sep-16
1P/Halley	8-Mar-17
13P Olbers	10-May-17
5335 Damocles	16-Aug-17

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Additional Information

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