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Mars encounters cause fresh surfaces on some near-Earth asteroids

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ABSTRACT

All airless bodies are subject to the space environment, and spectral differences between asteroids and meteorites suggest many asteroids become weathered on very short (<1 Myr) timescales. The spectra of some asteroids, particularly Q-types, indicate surfaces that appear young and fresh, implying they have been recently been exposed. Previous work found that Earth encounters were the dominant freshening mechanism and could be responsible for all near-Earth object (NEO) Q-types. In this work we increase the known NEO Q-type sample of by a factor of three. We present the orbital distributions of 64 Q-type near-Earth asteroids, and seek to determine the dominant mechanisms for refreshing their surfaces. Our sample reveals two important results: (i) the relatively steady fraction of Q-types with increasing semi-major axis and (ii) the existence of Q-type near-Earth asteroids with Minimum Orbit Intersection Distances (MOID) that do not have orbit solutions that cross Earth. Both of these are evidence that Earth-crossing is not the only scenario by which NEO Q-types are freshened. The high Earth-MOID asteroids represent 10% of the Q-type population and all are in Amor orbits. While surface refreshing could also be caused by Main Belt collisions or mass shedding from YORP spinup, all high Earth-MOID Q-types have the possibility of encounters with Mars indicating Mars could be responsible for a significant fraction of NEOs with fresh surfaces.

1. Introduction

Space weathering is a term used to broadly describe the effects of the space environment, such as impacts by high energy particles and micrometeorites, on the surface of airless bodies. The space environment produces a variety of effects on an observed spectrum such as changes in albedo, band depth, and spectral slope, but these effects are not consistent among all bodies. Lunar-style space weathering increases spectral slope and decreases band depth and albedo (Hapke, 2001; Noble et al., 2001; Pieters et al., 2000; Taylor et al., 2001). While many laboratory experiments on ordinary chondrites or their mineral constituents reveal space weathering effects similar to lunar-style such as increased spectral slope reddening and decreased albedos (Sasaki et al., 2001; Clark et al., 2002; Chapman, 2004; Brunetto and Strazzulla, 2005; Brunetto et al., 2006a,b; Brunetto, 2009), space weathering on S-complex asteroids as seen by spacecraft missions do not follow lunar-style trends nor do they display weathering trends consistent with each other (e.g., Veverka et al., 1996; Helfenstein et al., 1996; Clark et al., 2001; Murchie et al., 2002; Bell et al., 2002; Gaffey, 2010). This might not be surprising, however, given that the S-complex encompasses a diverse set of compositions (e.g., Gaffey et al., 1993; Dunn et al., 2013).

A more specific class of asteroids, the Q-type, is currently found primarily (though not exclusively) among near-Earth objects (NEOs) that are the best spectroscopic matches to LL ordinary chondrites over visible to near-infrared wavelengths (McFadden et al., 1985; Binzel et al., 1996). Because they are a direct meteorite match, they are expected to have undergone processes that disturb their weathered surface regolith, overturning the space weathered grains and revealing fresh, unweathered grains (Binzel et al., 2010; Nesvorný et al., 2010) on recent timescales (<1 Myr, Vernazza et al., 2009). The link between asteroid Itokawa and LL ordinary chondrites from the Hayabusa mission as well as the spectral gradient seen from Q-type to S-complex among asteroids, particularly as a function of size, have been considered evidence that increased space weathering changes a spectrum from Q to S (Binzel et al., 1996, 2004, 2001; Nakamura et al., 2011; Thomas et al., 2012), however, considering the compositional diversity of the S-complex, the variety of space weathering spectral trends, and recent evidence that some S-complex asteroids are unweathered (Mothé-Diniz et al., 2010), caution should be taken before generalizing this taxonomic trend to the entire S-complex (Gaffey, 2010). In this work we focus on the example of Q-types as markers of unweathered surfaces because there is less compositional variation and thus less ambiguity among that sample, though we note we

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Table 1
Observation table.

Number	Name	Run	Observing date	Phase angle	V mag	Type[a]
1566	Icarus	Sp42	2005 06 05	49	16.9	Q
1862	Apollo	Sp48	2005 11 22	24	13.7	Q
2212	Hephaistos	Sp57	2006 12 22	14	15.7	Q:
3361	Orpheus	Sp45	2005 10 08	6	17.3	Q
3753	Cruithne	Sp45	2005 10 08	57	16.6	Q
4183	Cuno	Sp103	2011 10 24	10	16.9	Q
4688	1980WF	Sp03	2001 01 29	43	17.9	Q
5143	Heracles	Sp55	2006 10 25	16	15.3	Q
5660	1974MA	Sp43	2005 07 09	37	15.9	Q
7336	Saunders	Sp93	2010 09 06	12	16.6	Q
7341	1991VK	Sp103	2011 10 24	25	16.3	Q
11054	1991FA	Sp09	2002 01 12	43	15.8	Q:
19764	2000NF5	Sp93	2010 09 06	19	16.2	Q:
23183	2000OY21	Sp49	2006 01 30	33	15.5	Q:
23187	2000PN9	Sp05	2001 03 28	51	16.6	Q:
39572	1993DQ1	Sp73	2008 09 02	65	15.6	Q:
66146	1998TU3	Sp74	2008 10 02	70	15.5	Q
85236	1993KH	Sp76	2008 12 03	61	16.4	Q:
85839	1998YO4	Sp89	2010 03 16	22	16.3	Q:
88254	2001FM129	Sp89	2010 03 17	81	15.7	Q
89958	2002LY45	Sp98	2011 04 05	10	16.3	Q
136923	1998JH2	Sp102	2011 09 25	45	17.0	Q:
137032	1998UO1	Sp74	2008 10 02	54	13.8	Q
138883	2000YL29	Sp84	2009 09 20	36	15.4	Q
139622	2001QQ142	Sp58	2007 01 21	55	16.9	Q
143487	2003CR20	Sp84	2009 09 20	51	16.5	Q
143651	2003QO104	Sp79	2009 03 30	41	16.0	Q
152931	2000EA107	Sp89	2010 03 16	50	16.7	Q
154244	2002KL6	Sp81	2009 06 21	48	15.5	Q:
154715	2004LB6	sp96	2011 01 06	51	17.7	Q:
162058	1997AE12	Sp26	2003 10 16	59	17.0	Q
162117	1998SD15	Sp64	2007 10 02	32	16.8	Q:
162483	2000PJ5	Sp82	2009 08 08	53	17.3	Q
163081	2002AG29	Sp102	2011 09 25	49	17.2	Q
163697	2003EF54	Sp83	2009 08 24	48	16.1	Q
164400	2005GN59	Sp73	2008 09 02	27	15.7	Q:
184266	2004VW14	Sp69	2008 04 13	53	16.3	Q:
206910	2004NL8	Sp78	2009 03 02	16	16.9	Q
218863	2006WO127	Sp89	2010 03 17	66	16.0	Q
219071	1997US9	Sp104	2011 10 31	23	16.9	Q
274138	2008FU6	Sp99	2011 04 30	52	16.5	Q
	1998SJ70	Sp74	2008 10 02	7	16.6	Q
	2002NY40	Sp16	2002 08 17	20	11.1	Q
	2003FH	Sp104	2011 10 31	65	16.6	Q
	2003MJ4	Sp92	2010 07 11	35	17.3	Q
	2003UV11	Sp94	2010 10 13	23	18.1	Q
	2004QJ7	Sp103	2011 10 24	45	17.5	Q
	2005ED318	Sp40	2005 05 11	59	16.4	Q
	2006VB14	Sp76	2008 12 03	52	16.4	Q
	2007LL	Sp71	2008 06 11	19	17.3	Q
	2007RU17	Sp94	2010 10 14	4	16.1	Q
	2008CL1	Sp68	2008 03 10	26	16.1	Q
	2008HS3	Sp70	2008 05 10	50	17.5	Q
	2011OV4	Sp101	2011 08 22	15	17.2	Q
	2011PS	dm03	2011 09 03	39	16.9	Q
	2000QW7	Sp01	2000 09 04	29	13.7	Q:
	2002GO5	Sp12	2002 04 14	11	14.6	Q:
	2006HQ30	Sp51	2006 06 11	32	15.7	Q:
	2006VQ13	Sp56	2006 11 21	31	16.5	Q:
	2007DT103	Sp62	2007 07 31	86	14.3	Q:
	2008FU6	Sp98	2011 04 05	4	16.6	Q:
	2008UE7	Sp76	2008 12 03	24	16.1	Q:
	2010CM44	Sp90	2010 04 16	8	16.7	Q:
	2010LY63	Sp93	2010 09 07	38	15.5	Q:

[a] Q is for Q-type, Q: indicates uncertainty between Q- and Sq-type.

work under the assumption that all the Q-types are young and fresh.

Multiple mechanisms have been postulated to cause this surface freshening, such as tidal effects from close planetary encounters, YORP spinup, asteroid collisions, and electrostatic levitation of grains from passing through Earth's magnetosphere (e.g. Nesvorný et al., 2005; Marchi et al., 2006; Binzel et al., 2010; Nesvorný et al., 2010; Thomas et al., 2011; Rivkin et al., 2011). Orbital trends have shown that for the near-Earth asteroid population, planetary encounters play an important role (Marchi et al., 2006). Based on a dataset of 95 objects, Binzel et al. (2010) find that all 20 spectral Q-types in their dataset have an extremely low Minimum Orbit Intersection Distance (MOID) to the Earth. They propose that Earth tidal forces due to close Earth encounters, as suggested by