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Short communication

Lander rocket exhaust effects on Europa regolith nitrogen assays

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ABSTRACT

Soft-landings on large worlds such as Europa or our Moon require near-surface retropropulsion, which leads to impingement of the rocket plume on the surface. Surface modification by such plumes was documented on Apollo and Surveyor, and on Mars by Viking, Curiosity and especially Phoenix. The low temperatures of the Europan regolith may lead to efficient trapping of ammonia, a principal component of the exhaust from monopropellant hydrazine thrusters. Deposited ammonia may react with any trace organics, and may overwhelm the chemical and isotopic signatures of any endogenous nitrogen compounds, which are likely rare on Europa. An empirical correlation of the photometrically-altered regions ('blast zones') around prior lunar and Mars landings is made, indicating $A=0.02T^{1.5}$, where A is the area in m^2 and W is the lander weight (thus, ~thrust) at landing in N: this suggests surface alteration will occur out to a distance of ~9 m from a 200 kg lander on Europa.

1. Introduction

Europa has attracted much interest as a target of astrobiological exploration (e.g. Hand et al., 2009; Hand, 2015). While long of scientific interest, the claimed prospect of habitable conditions or even life in Europa's ice-covered water ocean has attracted the attention of politicians and the public. The United States Congressional budget language (Consolidated Appropriations Act, 2016) for FY2016 mandates " an orbiter with a lander." Thus renewed efforts are underway to evaluate landing concepts to explore Europa's habitability and search for extant life.

Living things contain substantial amounts of nitrogen (the Redfield ratio of Carbon:Nitrogen is 106:16).Nitrogen is an essential element for life: obvious examples include the amino acids that form proteins to execute living functions, and the purine and pyrimidine bases that encode information in DNA and RNA. However, Europa may be nitrogen-starved, as it formed in the warm protoJovian nebula in conditions which did not favor the accumulation of materials more volatile than water (Lunine and Stevenson, 1982). This formation scenario was unlike Titan whose abundant nitrogen (e.g. Lorenz and Mitton, 2008) accreted as ammonia and whose methane presumably accreted as clathrate. Like Europa's meager carbon inventory, the only supply of nitrogen to Europa's surface may be the small sporadic delivery of cometary material.

Understanding the amount and form of any nitrogen in the Europan regolith (and by implication, its ocean) is a key goal of future exploration, and a lander in particular. However, since Europa is an airless body with a substantial gravitational field, soft landing will likely require rocket propulsion which may deposit nitrogen-bearing compounds from thruster exhaust around the landing site. In this paper I briefly explore quantification of this concern, drawing on observations of landing site disturbances on previous lander missions and with a simple thruster plume deposition and chemistry model.

To set some historical context, this problem received considerable attention during preparation of the Viking lander missions, whose focus was similarly on astrobiology. Studies of thruster plume impingement (e.g. Clark, 1970) led to a clustered-nozzle design to attempt to minimize mechanical disturbance, and some laboratory work was performed (Holzer and Oro, 1977) to assess how thruster exhaust compounds might perturb chemical analyses of the regolith. The Phoenix lander demonstrated quite strong excavation underneath its thrusters, with the fortuitous effect (Plemmons et al., 2008; Mehta et al., 2011) of exposing subsurface ice deposits. This effect seems to be a result of the pulsed thrust modulation (Mehta et al., 2013) which causes transient flow in the regolith (Scott and Ko, 1968; Metzger et al., 2009, 2011 and Morris et al. (2015) also discuss recirculation vortices in rocket exhaust and pit formation in regolith. However, astrobiology was not a focus of this mission, so deleterious effects of exhaust were not a concern. The Mars Science Laboratory (MSL), Curiosity, however would have confronted issues with site modification, even though its sky-crane landing and throttleable rather than pulsed thrusters (e.g. Sengupta et al., 2009; Dawson et al.,

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2007; Vizcaino and Mehta, 2015) would be less damaging for a given lander weight. While this mission does have astrobiology as a focus, it is a rover and thus chemical concerns at the landing site could be addressed simply by driving out of the blast zone. It may be noted that in part because the lander weight and thrust was high, there was appreciable site modification, and indeed grit blasted up from the landing damaged one of the meteorology instruments.

2. Empirical observations of soft-lander disturbances

Although the topographic excavation has been documented in small regions directly beneath various planetary landers by imaging from those platforms themselves (e.g. Hutton et al., 1980; Mehta et al., 2011; Arvidson et al., 2014) or from walking around nearby (Scott, 1969), the much wider areas that are altered more subtly, by chemical and/or microstructural changes, are most easily observed from orbit. Photometric disturbances of the lunar regolith were detected in Clementine data by Kreslavsky and Shkuratov (2003), and more recently in Lunar Reconnaissance Orbiter imaging data by Kaydash et al. (2011), Clegg et al. (2014) and Clegg-Watkins et al. (in press). The latter paper gives a compilation of the measured disturbance areas for five Apollo landers, four Lunas, four Surveyor landers and the recent Chang-E 3 landing. Here we have plotted those areas against the landed mass multiplied by lunar gravity (i.e. using weight as a proxy for the thrust at landing – since descent at constant velocity is a common control law for landing guidance, vertical force balance requires equivalence of thrust and weight and this estimate will in general be accurate to better than 10%) – see Fig. 1.

To those lunar data, we have added the two most recent Mars landings (i.e. those that have occurred since the arrival of the Mars Reconnaissance Orbiter with its high-resolution imaging capability), namely Phoenix and Curiosity. The disturbed region for Phoenix (350 kg at landing) was outlined by eye on HiRISE public release image PSP 008591-2485 (Fig. 2) using the polygon tool in ImageJ: an area of 1020 m^2 was derived. The disturbed region for Curiosity (~2000 kg rover plus descent stage) was reported by Arvidson et al. (2014) to extend 50–100 m from the landing site: adopting 75 m gives an area of 17,000 m^2. Although the presence of the martian atmosphere influences the expansion of the rocket plume and the characteristics of the martian and lunar regoliths are different, on a log-log plot at least, it is seen that these two Mars data points are entirely consistent with the lunar landings of corresponding thrust.

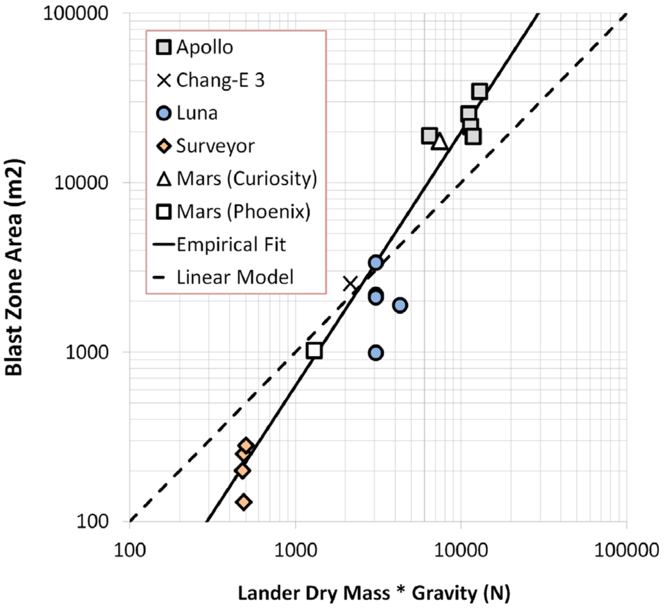

Fig. 1. Correlation of photometrically-disturbed areas for lunar and mars landers with weight at landing (i.e. ~thrust). It is seen that an empirical correlation is rather steeper (~weight$^{1.5}$, solid line) than a simple linear dependence (dashed line). No systematic difference between Mars landers and lunar landers is apparent.

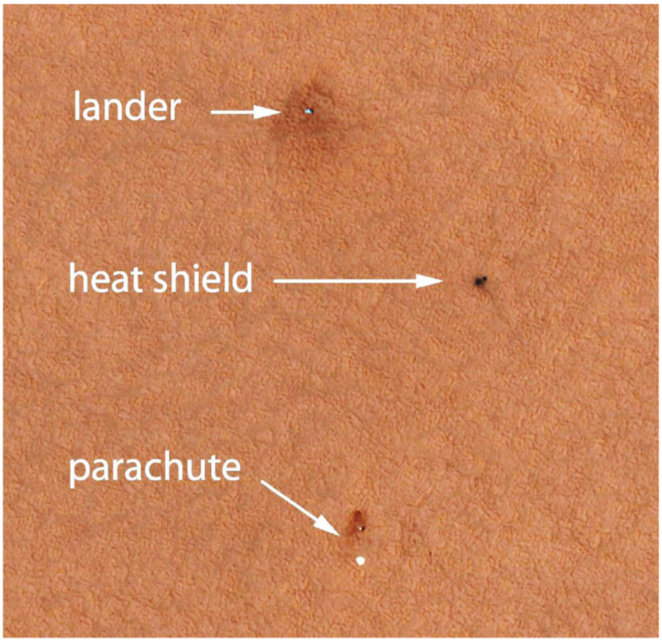

Fig. 2. HiRISE image PSP 008591-2485 showing the northern plains of Mars with a large discolored region around the Phoenix lander, disturbed by its retrorocket exhaust. For scale the heat shield is 150 m away: the much smaller disturbed patches associated with it and the parachute/backshell are due to the direct impact of those passive elements.

All else being equal, if a photometrically disturbed region corresponds to that where some threshold of pressure loading (for example) is exceeded, then one might expect the region to be proportional to the landing thrust (dashed line in Fig. 1). This does not quite seem to be what is observed: the aggregate dataset is rather better described by steeper dependence. Clegg-Watkins et al. (in press) offer a combined linear+quadratic+constant fit to a smaller dataset, without theoretical justification (e.g. their constant term is unphysical). We suggest a simple power law dependence: although the scatter in the data might allow a reasonable linear fit, or an exponent as high as ~2, the best fit appears to be a function of the form $A=0.02\,T^{1.5}$, where A is the disturbed area in m^2, and T the thrust (=weight) at landing. A range of engineering factors (e.g. nozzles higher off the ground on larger vehicles, use of clustered nozzles as on Viking rather than single large motors) and physical processes (aerodynamic and pseudo-ballistic transport of sand and dust, gas flow through the regolith, heating, chemical deposition etc.) may be at work, and it is beyond the scope of the present paper to attempt to explain this dependence.

A small (~200 kg) lander requires a thrust for soft-landing of ~260 N in Europa's gravity, and thus if the correlation above that succeeds for Mars and lunar landings (the latter similar to Europa, both in terms of negligible atmospheric pressure and in surface gravity), it follows that a region about 80 m^2 should be disturbed. In other words, regolith ~9 m from the lander will have been perturbed to a degree comparable with photometrically-disturbed regions on the Moon. 9 m is larger than the reach of practical robotic arm designs, so sampling undisturbed surface material would demand some kind of deployable sampler, or mobility of