Recognition of rayed craters on Mars in THEMIS thermal infrared imagery: Implications for Martian Meteorite source regions.

L. L. Tornabene[1*], H. Y. McSween Jr.[1], J. E. Moersch[1], J. L. Piatek[1], K. A. Milam[1] and P. R. Christensen[2], [1]Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, Tennessee 37996-1410, USA, [2]Department of Geological Sciences, Arizona State University, Tempe, Arizona 85287–6305, USA.

Introduction: Four definitive large (km-sized) rayed craters have been recently identified on Mars bearing the provisional IAU names of Tomini (D=7.4 km), Gratteri (D=6.9 km), Zumba (D=3.3 km) and Dilly (D=2.0 km) [1-2]. These four craters are similar to the martian rayed crater Zunil (D=10.1 km) [3-5] with rays that are most easily recognized by a thermophysical contrast in THEMIS nighttime (nTIR) and daytime (dTIR) thermal infrared images from the Mars Odyssey Thermal Infrared Imaging System (THEMIS)[1-2]. A thermophysical contrast between the rays and their surroundings (Fig. 1) is the distinguishing characteristic of these craters, rather than a contrast in albedo as with well known lunar analogs. The largest crater, Zunil, has an estimated secondary crater field population of ~10^7 [5] suggesting that these craters eject numerous blocks, perhaps even some with sufficient velocities to escape Mars (>5 km/s). With Zunil, these craters are presently thought to be the best candidate source craters for the Martian Meteorites (MMs) [1, 5]. This hypothesis is based on observations, inferences and models with respect to the MMs and our current knowledge of the martian surface.

Oblique-rayed craters as possible MM sources: Oblique impacts may be required to both generate crater rays on Mars, and to effectively eject materials from the martian gravity field. Oblique impacts have previously been suggested as a promising mechanism for the delivery of MM [6-9]. Most recently, it has been suggested that moderately oblique (30-45º) impacts generate the highest spallation volume to impactor volume ratios [6]. Higher volumes mean higher probabilities for MM escape. Four of the five definitive and both "probable" large, martian rayed craters exhibit evidence of a moderate oblique impact event in the form of a "forbidden zone" in their ejecta patterns [2].

The diameters of rayed craters are also consistent with recent MM delivery models. Six of the possible seven falls within or above the minimum diameter range estimated for MM source craters of ~2.5-3 km [6, 10].

In addition to morphological evidence supporting current MM delivery models, rayed craters also provide physical evidence of the spallation mechanism that enables MM delivery: rays. Spallation is the only ejection mechanism that produces high-ejection speeds (>5km/s) while preserving sizable (cm-m) ejecta at low shock pressures [11-12]. Spallation provides both the physical means to launch MMs from Mars as well as account for the low shock metamorphism observed in MM meteorites. The diameters, oblique-impact origin and rays exhibited by these craters appear to be morphologic evidence for being effective producers of high-speed ejecta.

Are most MMs from Elysium Planitia?: Full-resolution and contrast-balanced band 9 nTIR THEMIS brightness temperature mosaics of these five definitive rayed craters have improved on our previous observations [1] and facilitated the discovery of 2 additional "probable" rayed craters with a faint thermophysical signature [2]. These additional "probable" rayed craters suggest that the martian rayed crater population is biased to Elysium Planitia, with 5 out of a possible 7 occurring there (Fig. 2).

This geographic bias of rayed craters on Mars may be related to biases observed in the current MM collection, with respect to the martain surface and other achondrite meteorite collections (Lunar and HEDs). The rayed crater geographic bias appears to favor terrain of a specific composition, age and rheological properties. Therefore, we suggest that the observed and inferred surface properties of Elysium may be related to the composition, age and textural biases seen in the MM collection.

Compositional bias. MMs are compositionally biased. Most of the MMs are shergottites (~70%) [13], which are crystalline igneous rocks with a basaltic composition. This overall basaltic composition is consistent with inferences from remote sensing and modeling of Elysium's composition [5]. According to a TES global compositional survey, small areas not covered by dust in the Cerberus plains are basaltic [14]; modeling also suggests that Elysium is basaltic in composition [15], and therefore, we infer that the composition for Elysium may also be basaltic. Further evidence from TES or THEMIS-derived emissivity will be sought to determine if these small dust-free regions, or the rayed craters themselves have mineral compositions that are more consistent with shergottites or basalts.

Age bias. Crystallization ages for most MMs range from 175 Ma to 1.3 Ga and ejection ages range from 0.7 to 20 Ma [16]. Both suggest these meteorites originate from recent impacts on an Amazonian surface. Elysium is one of the youngest surfaces on Mars [5], consistent with these ages and martian rayed craters are presumably amongst the youngest craters on the surface of Mars for their size class (<10 km) [2-5]. Also, martian rays are presumably younger than lunar rays (~1 Ga [17]), due to faster weathering rates from the atmosphere and active aeolian processes. Estimates of Zunil's age suggest that it may be as young as 4-10 Ma, consistent with MM ejection ages [5]. If the other rayed craters are comparably young, then the 4 new rayed craters are also consistent with the MM ejection ages.

Textural bias. When compared to lunar (>85%) and HED (>95%) meteorite collections, the MMs (0-3%) are notably lacking in breccias [2]. Therefore, MMs are likely sourced from young, competent and relatively regolith-free surfaces. This is consistent with the young crystallization ages of these meteorites, because, aside from aeolian veneers, younger surfaces on Mars should have a relatively thin to negligible regolith layer from less impact gardening over a shorter period of time [10].

Other MMs: Based on the terrain ages, two definitive rayed craters (Gratteri and Zumba - Fig 2.), are candidate source craters for the nakhlites, chassigny, and ALH84001. Zumba (Amazonian-Hesperian) [18] may be the source of the nakhlites and chassigny, which are comparatively older than the shergottites [2, 16]. Gratteri occurs in Noachian-aged terrain [18] and may be the source for ALH84001.

Conclusions: We suggest here that the Elysium region is presently the best candidate source region for the majority of the MM (shergottites) and that the nakhlites, chassigny and ALH84001 may be sourced from the rayed craters outside of Elysium. These suggestions are based on the following connections between rayed craters and MMs: 1) evidence for a moderately oblique impact origin of all 5 definitive rayed craters, which is required by the current models of secondary spallation and MM ejection, 2) sufficient size requirements for rayed craters, 3) geographical bias and the link between the inferred composition of Elysium from TES and models (basaltic) with shergottites (basaltic), 4) inferred ages (surface and rayed craters ages) and measured (MM crystallization and ejection ages), and 5) inferred rheological properties of the source terrains (regolith-poor) with respect to textural biases in the MM collection (lack of breccias) compared to lunar and HED meteorite collections.

If rayed craters are indeed the launch sites of MMs, both rayed craters and most MMs appear to be restricted to competent, relatively uncratered and youthful surface like Elysium. The fact that Martian rayed craters and the MM appear to be restricted in such a way, whereas lunar rayed craters and HED meteorites are not, may be a consequence of the stronger Martian gravity field and the presence of an atmosphere. These factors may critically limit spalls on Mars – and consequently, rays - from less competent (regolith-rich, older) surfaces [2, 6, 10].

Other rayed craters may be present but difficult to detect by THEMIS TIR [2]. Low thermal inertias in Tharsis, for example, would yield poor contrast between rays and the surrounding terrain. Areas poleward of 45 have not yet been surveyed due to the difficulty in deriving thermal inertias at high latitudes. Tharsis may also be a viable locale for MM source craters. However, of the areas that would best preserve THEMIS-detectable evidence, Elysium is the best candidate source region for most MMs.

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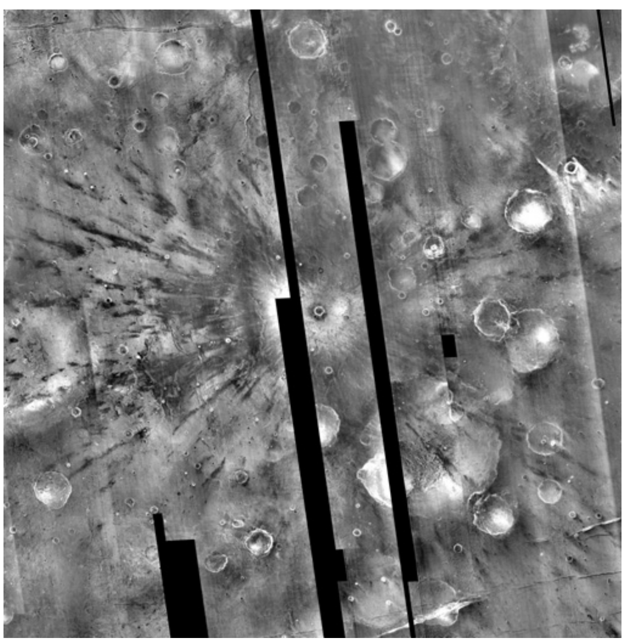

Figure 1. THEMIS nTIR mosaic (on strip is ~ 30 km wide) of Gratteri crater, an excellent example of a martian rayed crater with a very distinctive thermophysical contrast. Crater diameter: 6.9 km; Max ray length measurable in THEMIS nTIR mosaic: ~595 km.

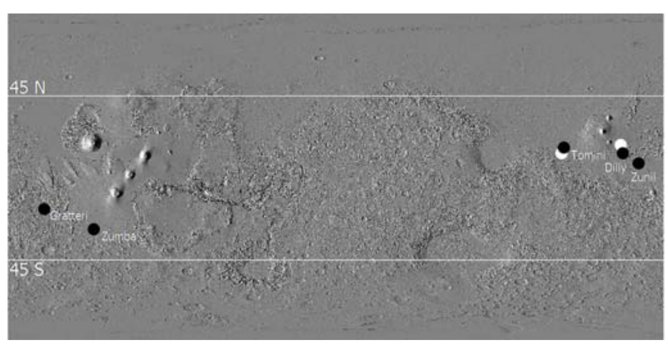

Figure 2. Location map of definitive (black circles) and "probable" (white circles) martian rayed craters. Gratteri is located in the Memmonia Fossae region while Zumba is in the Daedalia Planum region (left). The other rayed craters, Zunil, Tomini and Dilly, as well as the two "probable" ones are all within the Elysium region (right).