Exploring Mars from a Wagon Train. M. H. Hecht,[1] J. Blandino[2], and T. Roy[2], [1]Jet Propulsion Laboratory, California Institute of Technology, M/S 306-431, Pasadena, CA 91109 (email: mhecht@jpl.nasa.gov), [2]Worcester Polytechnic Institute, Worcester, MA,

The concept: We suggest a mission architecture that will enable broad participation in Mars missions without imposing burdensome costs on NASA.

Constrained by enormous infrastructure requirements, Mars exploration (and deep-space exploration in general) is coordinated by major space agencies and follows roadmaps that represent broad scientific consensus. In contrast, orbital space is sufficiently accessible that it has become a scientific playground for universities, private institutions, numerous government agencies, nonprofit societies, and nations large and small around the globe. From a scientific perspective, orbital space hosts a healthy and democratized mix of science – big and small, mainstream and blue-sky. The difference between the two cases is that small payloads can readily "piggy-back" to Earth orbit on larger missions without incurring a large resource penalty.

Here we propose a radical break with the traditional deep space paradigm, with the goal of opening up Mars exploration to a similar mix of participants. Recent breakthroughs in miniaturized propulsion systems, particularly electric propulsion, can provide an inexpensive, Class II microspacecraft (1 – 5 kg) [1] with sufficient ΔV capability to journey to Mars. *What is lacking to enable such missions is the equivalent capability in navigation and communication.* We propose, therefore, a mission architecture that would provide that support to a flotilla of small craft, whose individual mission objectives could be unrelated. The proposed architecture would leverage regularly scheduled missions to Mars, much as Deep Space 2 (DS-2) leveraged the Mars Polar Lander opportunity, but without the accommodation constraints that drove the complexity of DS-2 and ultimately probably caused its failure.

Approach: Three critical subsystems currently block deployment of CubeSats and other miniature spacecraft to deep space: Propulsion, navigation, and communication. The proposal here is to bypass two of those subsystems, communication and navigation, substituting instead the support of a mother-ship. This choice is driven by the state of the art of the three subsystems, as well as bottlenecks such as Deep Space Network availability. A deep space mission from Earth to Mars with zero excess hyperbolic velocity (C3 = 0), typically requires a ΔV of a few km/s [2]. In the near-future, developments in miniaturized electric propulsion systems are expected to meet these requirements for nanosats. Busek Co. Inc., in particular, has developed a TRL 5 CubeSat Electrospray Propulsion System (**Error! Reference source not found.**) that is characterized by 1mN thrust at 800 s ISP and a capability of throttling both thrust and ISP to suit mission needs. The core technology was developed as part of the JPL Lisa Pathfinder program, which resulted in Busek's delivery of the first flight electrospray system.

Thus, rather than imposing a common fleet architectural to accommodate coordinated missions, it is suggested instead that a fleet of *unrelated* miniature spacecraft join up at a pre-arranged Geostationary Transfer Orbit (GTO) as a means to reach a common destination. Delivery of a CubeSat to GEO, for example, could be accomplished through the use of conventional Poly-PicoSatellite Orbital Deployers (P-POD) on GEO bound satellites. The P-POD system has extensive heritage in low earth orbit.

From GTO, the assembled small craft depart on the deep-space expedition, wagon train style, behind a NASA "mother-ship," which provides navigational and communications support in the course of its own navigation to Mars. The mother-ship uses conventional star-tracking, radar navigation, and direct-to-Earth communication, adding relay services as its only additional requirement to support the fleet. This might be accomplished with the same Electra systems that are routinely taken to Mars to support surface relays.

Ideally, the mother-ship would use solar-electric (SEP) or other low-thrust propulsion to more readily allow the satellites in the "train" to follow in loose formation, but this isn't strictly necessary. Other than the ability to keep pace with the lead ship, the participating satellite subsystem design would be unconstrained except for link-up, communication, and collision avoidance protocols to ensure safety of the fleet. The short-range capability required to communicate with the mother-ship would be similar to the methodol-

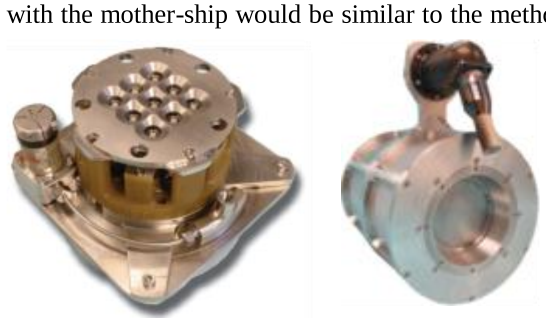

Fig. 1: Commercial propulsion systems approaching the capability needed for interplanetary flight of miniature spacecraft. Left, electrospray thruster from Busek with Isp=1300 s. Right, ion thruster from Busek with Isp=3800 s.

ogy that is used currently by CubeSats and other small satellites to communicate with the ground.

Potential applications are limited only by the imagination and by trade studies that have yet to be performed. Fly-bys or Phobos impactors are the simplest parasitic payloads, but orbital observatories and even small DS-2 style probes to the surface could conceivably be dispatched. These miniature landers might relay meteorological information or place corner-cube reflectors as beacons and calibration targets.

First steps: The a key technology barrier to implementing a demonstration "wagon train" mission is the lack of protocols and analyses for link-up, break-up, communication, and contact-avoidance. A roadmap to flight would entail system and mission studies (e.g. Team-X), identification of an orbital surrogate for a mother-craft capable of providing communications support, and a demonstration orbital (or lunar) CubeSat mission to validate the approach of link-up and relay-only communications and navigation.

The design concept seeks to achieve breakthrough capability through a novel architecture while relying on existing, mature technologies. Risk reduction will largely occur through studies of the link-up, break-up, and tracking protocols, with emphasis on crash avoidance among the fleet. A demonstration mission with minimal payload development (e.g. a camera) could likely be mounted for a cost comparable to DS-2, on the order of $25M, which would largely be to retire non-recurrent engineering challenges.

Finally, we emphasize that the motivation for this architecture is *not* a trade study of the cost efficiency of a fleet of individual spacecraft vs. one large spacecraft. Instead, we follow the logic that drives the CubeSat popularity: The ability to obtain diverse sponsorship, to customize the mission profile, to attempt high-risk endeavors, and to train students.

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References: 1] Micci, M. & Ketsdever, A. (2000) *AIAA Progress in Aeronautics and Astronautics Series*, *187*, 52. [2] Brophy, J. R. & Rodgers, D.H. (2000) *AIAA-2000-3412*, http://trs-new.jpl.nasa.gov/dspace/ *bitstream/2014/15789/1/00-1530.pdf*