THE VENUS AND MARS PILOTED INTERPLANETARY ROUNDTRIP EXPEDITIONS: SCIENCE OPPORTUNITIES OF THE NEXT HUMAN SPACEFLIGHT AGE.

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Introduction: Venus science missions are detailed in the current NASA Decadal Survey [1] and ESA's Cosmic Vision [2]. NASA's Discovery and New Frontiers programs, and the ESA's M-class solicitations regularly include small and medium-size Venus mission proposals on multi-year year cycles. The Venera D mission – a joint effort between NASA, Russia, and others [3], is being explored as well. However, opportunities for Venus exploration, especially for large, high-capability missions are few and far between. A class of opportunities for multiple significant Venus planetary science missions exists on the human pathway to Mars over the next decades.

Age of EMPIRE: Venus flybys and even orbital missions have been part of plans for human space exploration since the early days of space flight. The earliest documented Venus human flyby proposal dates back to 1956, with a launch opportunity in 1971 [4] (Fig 1). In the ensuing decades, multiple NASA studies explored in detail various multiple piloted planetary mission scenarios, some of which included Venus flybys, or dual-planet missions [5-7, others]. The series of studies was included EMPIRE (Early Manned Planetary-Interplanetary Roundtrip Expeditions), and meant to leverage nuclear rockets and Apollo-era hardware into ever more ambitious human space endeavors.

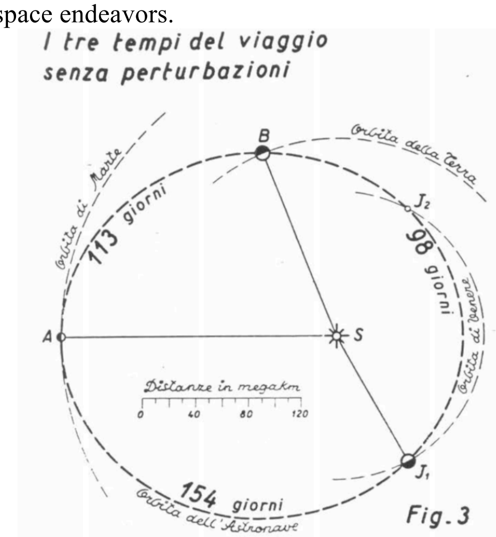

Fig. 1. First proposed piloted Venus-Mars flyby trajectory [4].

Early proposals proved to be technically, economically, and/or politically unfeasible or unworkable over time. For example, in addition to basic long-term human life support, long-term radiation exposure and inner solar system heat hazards could not be addressed in detail 50 years ago. Nevertheless, a number of human piloted Venus flyby and rendezvous mission studies were undertaken and completed through the 1960's and early 1970's and Venus flyby components of Mars missions have persisted through the decades.

Venus to Mars Today: In the current NASA plan for human exploration of Mars, as expressed in the amended Design Reference Architecture (DRA) 5.0 [8-10], Venus flybys remain as valid choices in the latest documented plans for the human path to Mars using current and imminent technological capability such as the Space Launch System (SLS) [11].

Venus flyby scenarios currently under consideration are for "opposition" type missions to Mars (Fig. 2) in which the spacecraft swings by Venus on the outward or return leg to Mars, and mission durations at Mars are from 20 to 100 days in length [10]. These shorter Mars-stay missions, as opposed to 550 to 730-day stay-at Mars "conjunction" class missions occupy an enticing sweet-spot among candidate Mars rendezvous missions, combining weeks to months at Mars with shorter total mission duration and lower total mission ΔV (Fig. 2).

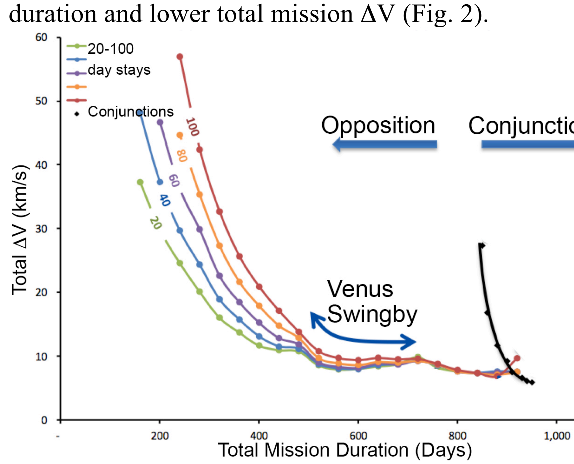

Figure 2. Example round trip ΔV as a function of total mission duration. See [10] for bounding assimptions. The "Venus Swingby" region delineates a subset of mission types that minimize both total duration and ΔV.

From the beginning, Venus flyby missions were not viewed merely as an opportunity for getting to Mars more easily, or with lower cost and risk, but also as a science opportunity. Venus flyby plans have included language for "dropping off" of science payloads and science observations during the flyby. The same would be true in the modern conception of a piloted Venus flyby, and for unpiloted support or infrastructure missions en route to Mars. Both the planetary and human space flight communities would benefit from consideration specific science opportunities of the different options.

A New EMPIRE: Most current concepts of SLS-launched missions to Mars include 4-10 rocket launches, and each SLS launch has the capability of bringing up secondary payloads (of as yet unconstrained mass and other specifications). Even human Mars missions that do not include a Venus flyby component still provide orbital staging opportunities for planetary missions. The DRA describes SLS secondary accommodations for multiple comsat or equivalent secondary payloads per SLS launch. These payloads present opportunities for solar system targets, including Venus. However, on Earth-Venus-Mars-Earth (EVME) or Earth-Mars-Venus-Earth (EMVE), Venus probes in particular would be logical secondary payload choices. Venus flyby orbits would create enabling opportunities for one or more significant probes to be dropped for insertion to Venus orbit or descent into the atmosphere and/or to the surface. The EVME mission might be most practical for larger Venus-destined payloads carried with the crew, since the jettisoning of Venus-bound payloads would reduce total mass for spacecraft maneuvers for the rest of the mission.

What kind of missions might be enabled by a piloted flyby of Venus? Having a crew en route, during, and after flyby enables several mission architectures, including, but not limited to:

- "Very Large Venus Probes": This concept would include large, potentially modular probes or constellations launched in pieces and assembled or otherwise enabled by crew en route to Venus. Mission concepts could include cubesat, smallsat, or larger multiple satellite constellations [12], or large probes brought into space in pieces in multiple SLS launches with final assembly en route to Venus.
- "Human-In-The-Loop Probes". These missions would capitalize on the minimization of light-speed delay in communication between a crew flying by Venus and a payload inserted into Venus's atmosphere or surface to enable real-time decision-making and reaction to events [13]. Crew may actively guide human-in-the-loop probes in the Venus environment during the days or weeks around closest approach using real-time telemetry. These mission concepts include guide-able aerial platforms [14,15] to surface rovers [16]. Human decision-making could assist in terminal guidance for pinpoint landing selection, fast evaluation and sample selection, initial roving destination and guidance for mobile platforms, and possibly other functions.
- "Grab and Go Sample Return" Fast sample-grab-and-return from the Venus atmosphere, rendezvousing with the departing spacecraft instead of transiting to Earth [17].

The Opportunity: While Venus flyby opportunities on the path of human exploration of Mars are currently in the books, they do not have high mind-share in the human spaceflight community. Issues, technical challenges, and risks of temperature and radiation exposure in the <1 AU environment, and protection of crew and equipment are examined in the current DRA and its supplements, but Venus flybys are not at the forefront of thinking or plans.

Another concern about any pathway to Mars is the repeatability of the architecture. Risk and cost are reduced if a mission profile can be repeated multiple times. EVME and EMVE present two similar Mars mission profiles that are still different from each other as well as from direct-to-Mars trajectories. The question remains whether the potential costs and benefits to human spaceflight and scientific exploration balance out in favor of a Venus component. Venus flybys en route do, however, create multiple additional opportunities for Mars flyby and Mars rendezvous missions. Analysis of opportunities for the current decade (2015-2025) [18], find five Mars flyby and six Mars short-stay (weeks to months) opportunities with Venus flybys either outbound or inbound, all with reasonable total mission durations and ΔV. In addition, Earth-Venus-Earth (EVE) flyby missions were identified. Low ΔV EVE launch opportunities are more frequent than are Earth-to-Mars (19-month cadence vs. 26 month) [19], and could be utilized as early, reduced-risk, long-duration piloted missions on the path to Mars, i.e., a "shakedown" dress-rehearsal mission prior to the longer-duration first human expedition to Mars.

Repeating Venus planetary science opportunities presented by EVE, EVME and EMVE missions are significant and, in an era of renewed interest in and ambition for going to Mars, a timely opportunity that could span decades.

Looking to 2050, the Venus science community has the opportunity at this time to voice active support not just for human-crewed missions, but human exploration of Mars in particular (*and* Venus) in the next several decades, for the additional payload opportunities it creates. Furthermore, the Venus community has a stake in advocating for *how* we get to Mars as well. Making the case that the best path may include both planets is an idea whose time has come around again.

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