N87-17761

ASTRONOMY ON A MANNED MARS MISSION

Jack O. Burns
Institute For Astrophysics
Department of Physics and Astronomy
University of New Mexico
Albuquerque, NM 87131

ABSTRACT

Three extra-solar-system astronomical experiments aboard a manned Mars mission are proposed. First, a modest, 50-cm aperture optical-uv-IR telescope (or pair used as an interferometer) coupled with the Mars-Sun baseline would increase the number (by a factor of 3.4) and a volume of stars with accurately measured distances via stellar parallax and, therefore, greatly improve upon the cosmic distance scale; the darker sky at Mars would also provide nearly a full astronomical magnitude deeper images of distant and low brightness objects (limited by zodiacal light). Second, a gamma-ray burst detector coupled with similar detectors in other parts of the solar system will be used to reduce the position error boxes and to study the nature of these energetic sources. Third, the long baselines on a Mars mission radio interferometer will provide a view of the radio universe at unprecedented resolution, 4×10^{-9} arcsec at 1-mm wavelength, which can potentially resolve the "engine" in nearby active galaxies. Each of these experiments is relatively inexpensive, taking advantage of the human presence for operation and maintainance, and the long Earth to Mars baselines.

INTRODUCTION

The duration of a manned mission to Mars may be anywhere from one to three years. The majority of this time will be spend in transit, going to and returning from the planet. What scientific activities will occupy the attentions of the crew during the long voyage? One can envision several useful and possibly unique astronomical experiments that could be performed during the flight with minimal additional cost to the mission.

The trip to Mars should not be viewed simply as a long wait before the commencement of productive scientific endeavors. To the contrary, a manned Mars mission could present us with an unprecedented opportunity to study the cosmos, free of the confinement of the Earth-Moon system. The spacecraft could serve as an interplanetary platform to house important scientific experiments not currently possible in our local environment. These experiments could provide data for scientists back on Earth as well as challenge the scientists and engineers aboard the spacecraft.

We propose three criteria for selecting astronomical experiments. First, they must be in some sense superior to what could be performed on the Earth, in Earth orbit, or on a future lunar base. Therefore, the Mars mission scientific station could genuinely add to our knowledge of the Universe. Second, the experiments should represent a minimal additional cost to the mission. A significant cost savings can be realized over that of completely automated space probes by using the crew to operate and maintain the telescope instrumentation. Third, where possible, they should allow (or even require) human judgement and possible human intervention to maximize the available science and to take advantage of unexpected research opportunities in flight. The experiments could be more complex and ambitious than those on an unmanned probe since human beings will be present to operate and adapt the equipment to the environment or unanticipated changes in the experimental goals.

OPTICAL-UV-IR OBSERVATIONS

The Hubble Space Telescope is the first major optical-uv-near-IR spaceborne observatory. The primary mirror has a diameter of 2.4-meters and the principle imaging detector (wide-field camera) operates over the wavelength range of 1155 nm to 1100 nm. Such a wavelength range is unprecendented because of the previous atmospheric constraints of ground-based optical telescopes. This facility is the first major optical astronomical telescope that will reach the diffraction limit of resolution. The wide-field camera and the faint object camera will have point response functions for as little as 0.04 arcseconds (FWHM) in the middle of the optical band in the longest focal ratio mode; the faint object camera can achieve a resolution of 0.007 arcsec in very narrow fields.

One might envision a more modest aperture telescope, say 50-cm in diameter, operating over about the same wavelength range, for astronomical observations on the Mars mission. At a wavelength of 200 nm, this telescope has an impressive diffraction-limited resolution of 0.08 arcsec. Astrometric centroid positions of stellar objects can be measured nearly a factor of ten more accurately. A pair of such telescopes, operating as an interferometer, could achieve astrometric position accuracy similar to that of the star tracking telescopes on the Space Telescope (ST), namely 0.002 arcsec. The cost of this telescope (or pair) would be quite small in comparison to ST. Once again, the vast majority of the $\$10^9$ cost of ST is due to the required unmanned automation and great weight of this free-flying observatory. On the other hand, a 50-cm telescope is cheap to manufacture and very inexpensive to operate on a manned mission since astronauts will point the telescope, change and maintain detectors, record the data, and provide in-flight calibration of this data. With the new lightweight mirror designs, launch costs will also be minimal.

What purposes will be served by having a moderate-sized optical telescope aboard the spacecraft? First, it represents the only astronomical experiment that we will propose which allows astronauts to visually inspect the fields at which they are pointing. The astronaut-observers will be able to visually roam across a magnificently dark sky. In the vicinity of Mars, the flux of energy from the Sun is decreased by a factor of about 2.3, which corresponds to nearly one astronomical magnitude, in comparison to that near the Earth. Currently, the Space Telescope is projected to have a sensitivity of about 28^m in the visual band for point sources, which corresponds to a flux of 2.2×10^{-19} Watts m^{-2}. This limit is due primarily to the readout noise of the charge-coupled device detector in the wide-field camera. If the detector technology continues to improve at the rapid pace of the past decade, then we will quickly become limited by the sky brightness in space (zodiacal light). Even the modest aperture Mars telescope offers an advance in terms of reduced sky background over the terrestrial environment. In addition, the on-board scientists will have some degree of freedom to select their own observations such as monitoring galaxies for supernova explosions or accurately tracking stellar positions and/or velocities for signs of perturbations by other planetary systems.

Second, such a telescope will be needed to monitor the Sun for potentially lethal solar flare activity. This will be one of the most important safety features of the mission (see Hathaway in this volume).

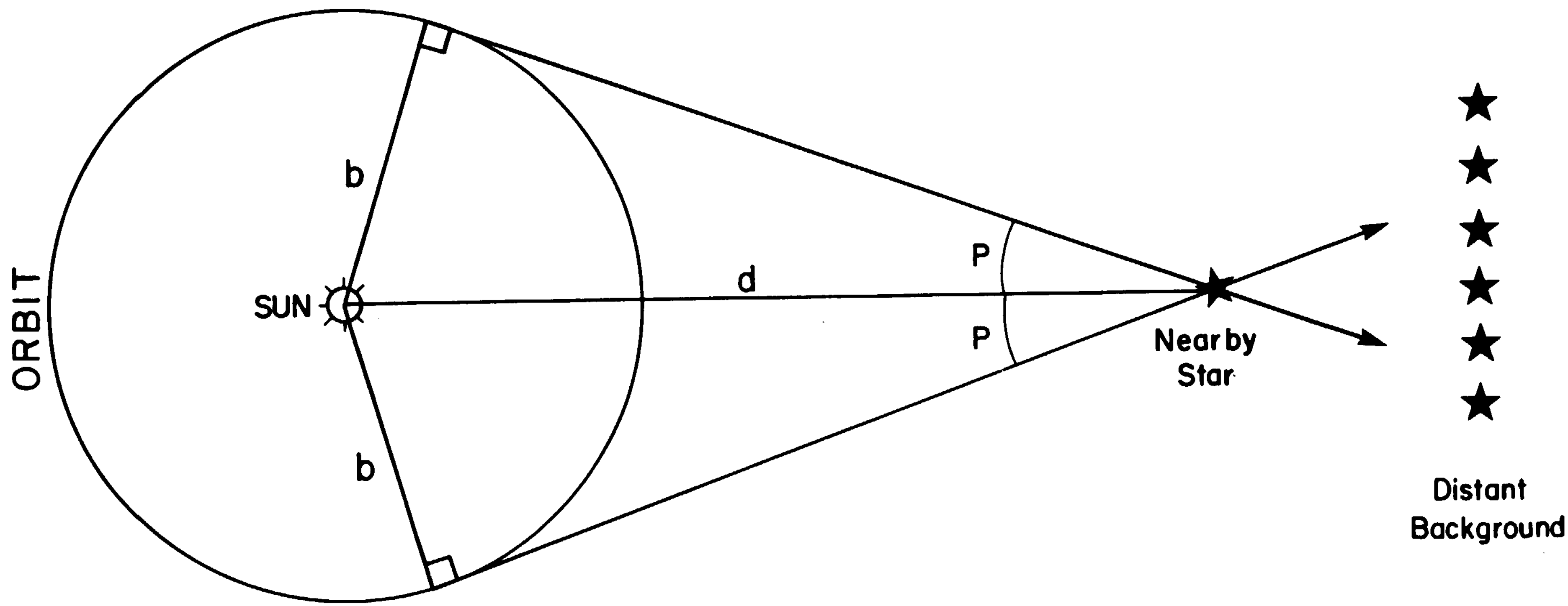
Third, important observations utilizing the longer Earth-Mars or Mars-Sun baselines could also be performed. One of the most important involves stellar parallax studies of more distant stars. Our knowledge of the size and future evolution of the Universe hinges strongly on how accurately we know the distance to the stars in our local neighborhood of the Milky Way Galaxy. This provides the foundation upon which the cosmic distance ladder is constructed. The classical technique used to determine distances to nearby stars, stellar parallax, is illustrated in Figure 1. The longer the baseline and the smaller the seeing disk for stars, the further away one can directly measure the distance. The smallest parallax angle, p, which can be measured from the ground is about 0.05 arcsec. This corresponds to a maximum distance of about 65 lightyears. This situation has remained nearly constant since the middle of the 19th century. The first major advance will come with the launch of Hipparchus satellite by the European Space Agency. This telescope will be capable of measuring stellar parallaxes to ± 0.002 arcsec, similar to the Space Telescope. An optical telescope in orbit about Mars will increase the baseline by about a factor of 1.5. If we conservatively assume the same parallax measurement uncertainty (presently limited by instrumental jitter), then the maximum distance becomes 2500 ly. The number of stars accessible for parallax study increases by a factor of 3.4 over that possible in LEO. This will represent a major advance in calibrating the extragalactic distance scale. (The above assumes a relatively clean environment near the telescope/spacecraft.)

<u>HARD X-RAY AND GAMMA-RAY BURST EXPERIMENT</u>

During the early and middle 1970's, enigmatic, extraterrestrial sources of hard x-ray (>10 keV) and gamma-ray (100 keV to 1 MeV) radiation were discovered by a set of Vela satellites which were launched by the Department of Defense. These sources are characterized by a brief (0.01 to 80 seconds) burst of emission which rises hundreds to thousands of times higher than the quiescent background. The distribution of these sources of energetic photons suggest that they are confined primarily to our Galaxy.

Our understanding of these sources has remained poor during the last decade and a half. The best theoretical models suggest that the gamma-

FIGURE 1 - DISTANCE DETERMINATIONS USING STELLAR PARALLAX



In the simplest case, an image of a relatively nearby star is recorded on opposite sides of the Sun during the orbit of a planet or spacecraft. In comparing the two images, the foreground star will appear to move with respect to the distant stellar background. The distance to the foreground star is simply $d = b/p$ where b is the sun-planet (or spacecraft) baseline, and p is the parallax angle (radians). The Hipparchus satellite will be capable of measuring p to within 0.002 arcsec for stars of visual magnitude <17 ray bursts originate from the vicinities of neutron stars. The emission may be produced by matter accreting onto the surfaces of the compact objects or may be due to magnetic field line reconnection resulting from instabilities in the magnetic field geometry. These models are consistent with the size estimates from the burst durations and from the one optical identification made with a supernova remnant in the Clouds of Magellan (Neutron stars are believed to be superdense remnant cores of massive stars which have exploded spectacularly in supernova; e.g., the Crab pulsar).

Information on the gamma-ray bursters has remained sparse for three reasons. First, the hard x-ray and gamma radiation is absorbed by the Earth's atmosphere. Therefore, all observations must be performed from space. Second, the sensitivity of the present detectors is relatively poor, partly because they must also cover a large area of sky. Third, there is at present no method for imaging these very high energy photons. The detection of a strong gamma-ray source with a single detector will typically have a position uncertainty of 1^{o}-2^{o}. With these error boxes, it is impossible to make optical identifications of the sources of the radiation.

However, it is possible to pinpoint the location of these sources using several detectors located at different positions in the solar system. By comparing the arrival times of the bursts in the different detectors, one can determine the direction of the incoming photons. The longer the baselines and the larger the numbers of spacecraft, the more accurately the source position can be determined. The Soviet Konus experiment using eleven separate detectors spread throughout the inner solar system, including four on the Venus Venera probes, was able to reduce the position error box of the March 5, 1979 event so that an optical ID with the supernova remnant in the Magellanic Clouds became possible.

We often find that there are too few spacecraft available to perform these coincidence experiments or even to confirm a gamma-ray burst. The situation will improve with the 1988 launch of the Gamma-Ray Observatory. The detectors will be 10-100 times more sensitive than those on previous spacecraft and will cover a wider range of energies.

A gamma-ray burst detector on the Mars mission would add significantly to our understanding of these sources. The substantially longer baseline could reduce position uncertainties by factors of 2 to 10 when coupled with other detectors in the inner solar system. The sensitivity will certainly be much greater than is currently possible, so that accurate measurements of line radiation within the burst can be performed. There have been suggestions of lines in the range of 40 to 70 keV in the Konus data; the most popular interpretation involves cyclotron radiation.

In any event, if such a detector were on board the manned Mars mission, it would almost certainly add to the interpretation of the physics of these energetic sources. Again, the human presence will reduce the cost and increase the flexibility of these relatively simple detectors.

A MARS MISSION RADIO INTERFEROMETER

Because of the relatively long wavelengths (millimeters to meters), single antenna radio telescopes have poor resolutions in comparison to even modest sized (e.g., 6-inch diameter) ground-based optical telescopes. For example, the largest single dish telescope in the world, the Arecibo radio telescope in Puerto Rico (1000-ft diameter), has a FWHM beam of about 2.2 arcmin at a wavelength of 20-cm. This is comparable to the resolving power of the human eye or 180 times worst than the optical telescope noted above.

A multiple-antenna radio interferometer, on the other hand, can achieve resolutions superior to that of the best ground-based optical telescopes. Each antenna baseline samples one Fourier component of the radio source brightness distribution at a given instant. It is desireable to sample as many of these components (i.e., many baselines at many different position angles) as possible for proper reconstruction of the radio source structure. The goal here is to synthesize an aperture using individual antennas. Martin Ryle was the first to recognize that the rotation of the Earth could greatly assist in the aperture synthesis by sampling many Fourier components per baseline as the source is tracked across the sky. This basic idea is illustrated in Figure 2.

The most sophisticated example of this synthesis technique is the Very Large Array (VLA) radio interferometer located in west central New

APERTURE SYNTHESIS

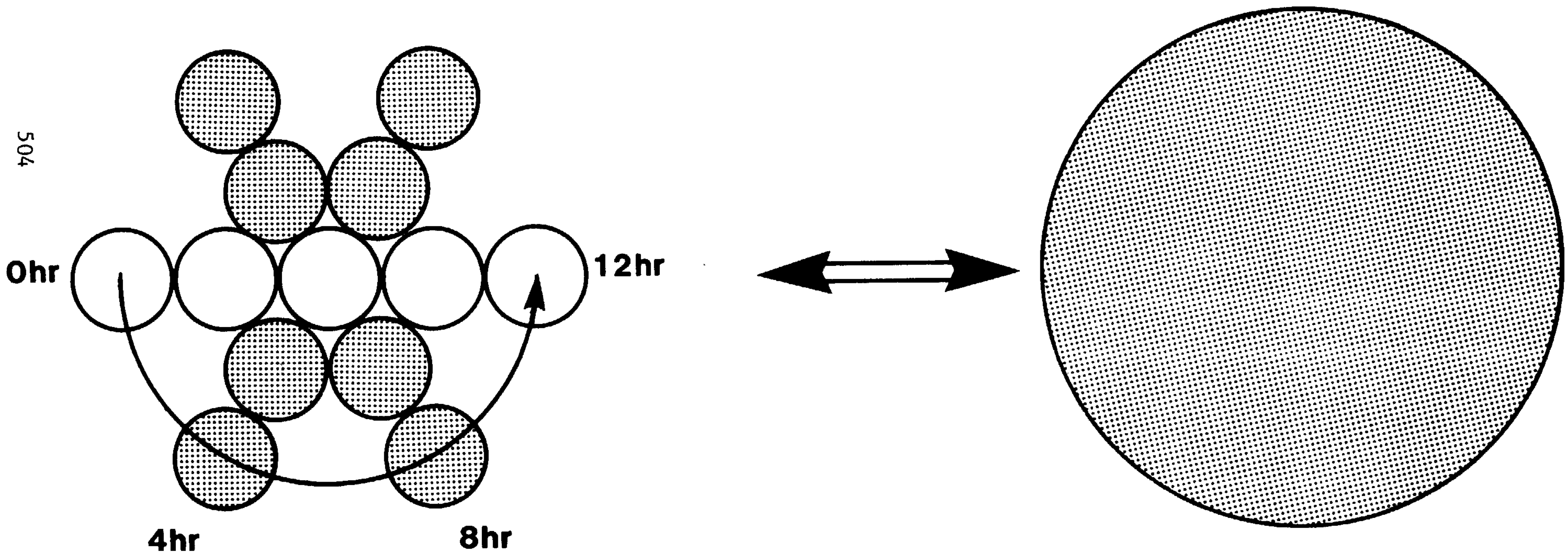


FIGURE 2 - THE PRINCIPLE BEHIND EARTH ROTATION APERTURE SYNTHESIS IN RADIO INTERFEROMETRY

Imagine that an observer is stationed above the North Pole of the Earth looking down upon a linear array of 5 antennas. As the Earth rotates, the line sweeps out portions of a filled aperture. In 12 hours, the line has synthesized a circular aperture with diameter equal to the maximum baseline between the outmost antennas. This is equivalent (in terms of resolution) to observing a radio source with a single very large antenna.

Mexico and operated by the National Radio Astronomy Observatory. It consists of 27 individual antennas distributed in a Y-configuration. The resolution of this telescope is 0.1 arcsec at 2-cm wavelength in its longest baseline mode (maximum baseline of 35-km).

During the past decade, this synthesis technique has been applied to even longer baselines, stretching across the U.S. and in Europe. Very Long Baseline Interferometry (VLBI) differs from the VLA in that the data is recorded on Tape at individual antennas (using accurate time Marks generated from hydrogen maser clocks) and later correlated with data from other telescope stations. Using hybrid mapping techniques to partially recover phase information in the data, VLBI maps of radio sources are now being made with dyanamic ranges rivaling those of short-integration VLA maps, but at a resolution of less than a milliarcsecond.

There are proposals to extend the radio interferometry baselines to radio telescopes in Earth orbit and on the Moon. A 10-meter radio antenna will be deployed from the cargo bay of the Space Shuttle to test the feasibility of space VLBI during the next several years. A joint European-American consortium has proposed a free-flying 15-meter VLBI radio antenna called Quasat (Quasar satellite) to be launched in the early to middle 1990's. Finally, I have suggested that a relatively simple antenna built as part of a permanent colony on the Moon could effectively serve as a long baseline component of a spaceborne VLBI network. In this case, the orbit of the Moon around the Earth would aid in the aperture synthesis. The resolution of such a telescope will be 30 microarcsec at 6-cm wavelength and improve as a direct proportionality with wavelength at shorter wavelengths.

It is an exciting possibility to extend the baselines even further by carrying a 15-meter class radio antenna on the manned Mars mission. Such a deployable antenna is lightweight and could be folded into the cargo bay of the spacecraft. At the maximum Earth-Mars separation of $3.8x10^8$ km, the diffraction limited resolution at a given wavelength will be a factor of 1000 times better than that of the Moon-Earth Radio Interferometer and a factor of 10^7 times that of the VLA!

However, it is unlikely that we will be able to achieve the full diffraction limit at centimeter wavelengths due to the scattering of radio waves by electrons in the turbulent fluctuations at high galactic

TABLE 1

THEORETICAL RESOLUTIONS OF A MARS MISSION INTERFEROMETER*

OBJECT	DESCRIPTION	DISTANCE (LY)	LINEAR RESOLUTION (KM)	COMMENTS
Proxima Centauri	Nearest Star	4.3	0.8	Resolve active regions and star-spots for stars in local neighboor
Sagittarius A	Galactic	32,000	6000	Resolve a 10^4 M black hole+
M31	Andromeda	2.2×10^6	4×10^5	Resolve individual stars in Local Group Galaxies
Centaurus A	Nearest Active Galaxy	1.6×10^7	3×10^6	Resolve Accretion Disk and 10^6 M black hole.+
3C273	Quasar	1.7×10^9	3×10^8	Resolve Accretion Disk and 10^8 M black hole.+

*These calculations assume a resolution of 4 nanoarcsec at 1-mm wavelength. Actual detection of source components on these scal sizes will depend upon the sensitivity of the radio telescope and the strength of the components.

+Resolve a Schwarzschild radius.

and extragalactic radio sources using the Mars Mission Radio Interferometer is illustrated. The potential science is indeed impressive.

The radio telescope will function during the entire trip to and from Mars as well as in orbit. The motion of the spacecraft with respect to the Earth will provide the aperture synthesis necessary to crudely map radio sources at very high resolution. The theoretically expected fraction of the Fourier transform plane (i.e., the aperture) which will be sampled for 1999 Mars opposition profile is shown in Figure 3. In this plot, the interferometer is assumed to be centered on the Earth and the source is perpendicular to the ecliptic plane. Although the coverage is not spectacular, it compares favorably with fractional coverages for present ground-based VLBI experiments. The inner portion of the transform plane could be filled more completely by linking the Mars mission radio telescope with a ground-based VLBI network, an orbiting radio antenna, and a Moon base radio dish.

As in the two previously proposed telescopes, the human crew will greatly simplify the operation and maintenance of the radio telescope. A very simple and inexpensive pointing scheme could be envisioned for this human-operated telescope, unlike the elaborate schemes needed for remote operation. Furthermore, the antenna could be constructed in flight, much like that planned for the space station, thus saving space and reducing costs on the mission.

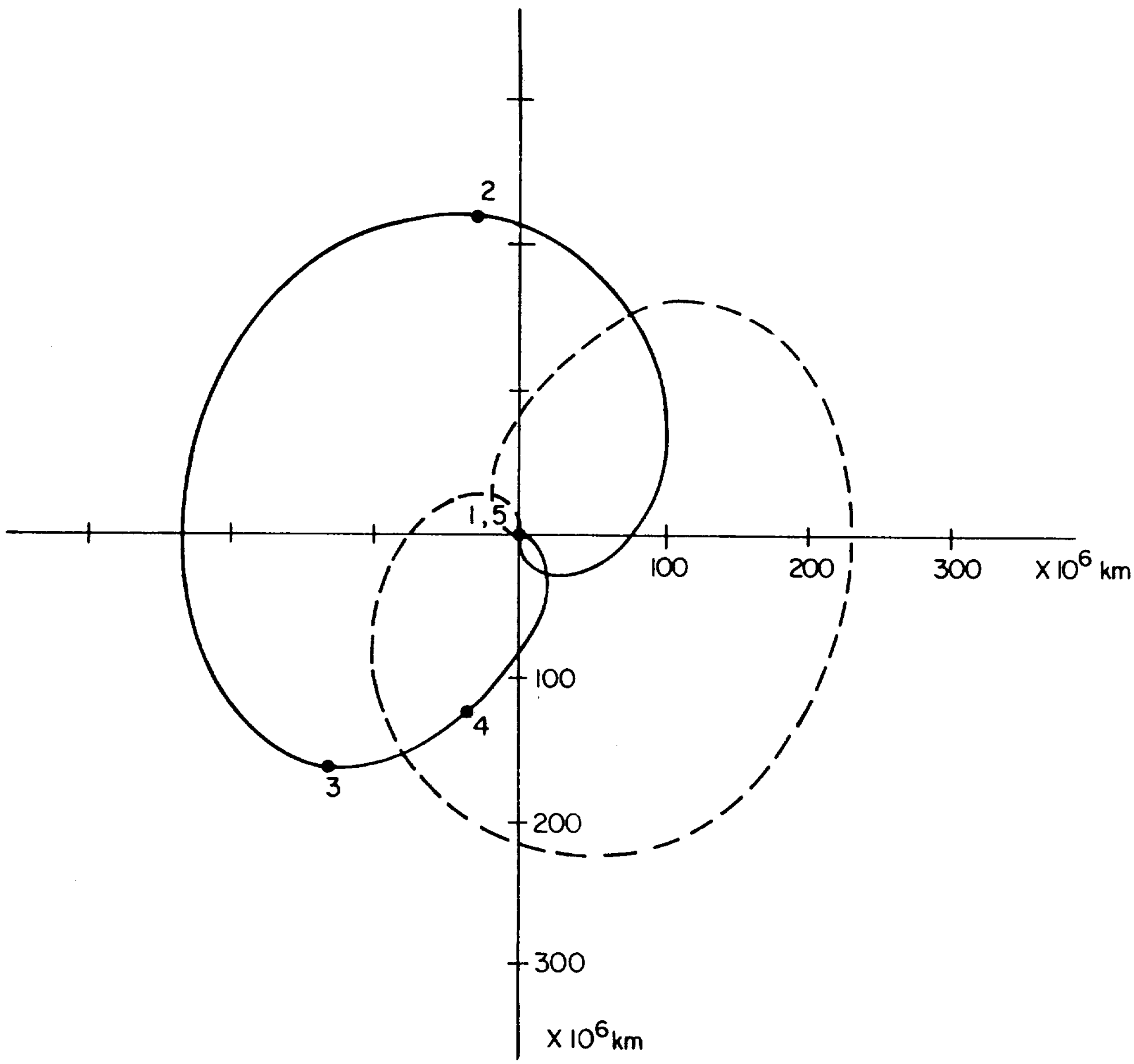
CONCLUDING REMARKS

The three projects described above merely scratch the surface of possible astronomical experiments that could be performed during a manned mission to Mars (including a reduced magnetic field and particle flux from the solar wind). The radio telescope may also be operable at both longer wavelengths (for scintillation studies of compact radio sources) and at millimeter wavelengths (for spectral line studies of molecular clouds). In a related vein, fundamental experiments on inertial mass and the gravitational constant (G) could be performed to test for variations in different regimes of gravity.

Because these telescopes will be operated and maintained by a human crew on the mission, the cost savings over completely automated robot probes will be enormous. The weight of each telescope is small and thus

FIGURE 3

THE PORTION OF AN APERTURE SYNTHESIZED
BY A MARS MISSION RADIO INTERFEROMETER



The array is assumed to be centered on the Earth. The coverage is based upon a trajectory which will include a Venus outbound swingby on route to Mars. Earth launch occurs on 1/27/99 at 3, Mars departure at 4, and Earth return on 11/19/99 at 5. The dashed curve represents the additional sampling produced by the Hermitian property of the Fourier transform plane.

will not significantly impact on the launch costs. Thus, for a relatively low expenditure, major new astronomical telescopes can "piggy-back" on the Mars mission. The long Earth-Mars baselines can be used to gather data that is beyond the scope of telescopes in the Earth-Moon Environment.