Mars

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Cultures throughout the world have known of Mars since antiquity as a "wandering star," and most have given it names related to war, blood, iron, or fire in recognition of its reddish color. Its transition from a mere light in the sky to a place that can be mapped and known—indeed, a place comparable in area to Earth's continental landmass—could not begin until the invention of the telescope. Galileo observed the red planet in 1609, but it was Huygens, in 1659, who made the first sketches of surface features. The first published map of Mars, by lunar cartographers Beer and Mädler in 1840, is notable mainly because of the placement of the prime meridian in a sharply forked albedo feature near the equator, where it remains (give or take 3°) to this day. Subsequent 19th century maps introduced competing systems of nomenclature, in part because Martian albedo features were found to change over time. Schiaparelli's outstandingly detailed maps of the 1870s used a system of regional names drawn from classical geography that was widely accepted and is the basis of the system still in use today (see http://planetarynames.wr.usgs.gov).

Despite the invention of photography, maps through the early 20th century were based on visual observation, which could take advantage of brief moments of optimal "seeing" to pick out detailed features. Unfortunately, the human visual system is error prone, and maps from the 1850s onward included increasing numbers of fine linear features that reflect the tendency of the brain to "connect the dots" rather than the actual nature of Mars. This trend reached its peak around the turn of the century with Percival Lowell, whose painstaking maps and globes included more than 400 linear "canals" (as he translated Schiaparelli's more neutral Italian term "canali" or channels). The properties of Mars that were known by this time (seasons similar to Earth's, with advancing and retreating polar caps; cloud-bearing atmosphere thought to be 1/10 as dense as ours; and changes in regional brightness and color that might plausibly be ascribed to the growth of vegetation) painted a picture of a world at least marginally hospitable to life, and the "canals" took Lowell and the popular imagination to the next level of a gradually drying world inhabited by a race of highly advanced engineers. From here it was a short leap to the Martian invasion of Earth as pictured by H.G. Wells, O. Welles, and their numerous less talented successors. It would take a technological revolution a half-century after Lowell to dispel the view of Mars that he popularized.

Beginning in the early 1960s, the United States and Soviet Union each launched robotic probes toward Mars at the opportunities offered by the laws of celestial mechanics, approximately every 26 months. A variety of technical failures doomed most of the Soviet missions and several of the American ones, but the successes gradually revealed a new world. The US Mariner 4 imaged about 1% of Mars at 1-km resolution in 1965, revealing a heavily cratered, moonlike surface. The probe also demonstrated, by passing a radio signal through the Martian atmosphere, that the surface pressure was an unbreathable 1/200th of Earth's. In 1967, Mariners 6 and 7 imaged the entire planet at resolutions of a few km and selected areas at 100 m to 1 km. An inventory could now be made of the physiographic regions of Mars—and it did not include canals.

In 1971, Mariner 9 became the first probe to orbit another planet successfully (Soviet missions also reached orbit but, unlike Mariner, were unable to delay their observations until a global dust storm had subsided, revealing the surface). Global image coverage at 1–3 km resolution was obtained for the first time, along with samples at 100 m resolution. Mariner 9 revealed enormous volcanoes and canyon systems, as well as smaller channels resembling rivers that partially rekindled expectations that Mars had a more earthlike climate in the past. Finally, in 1976, the US Viking mission dispatched two identical orbiters and two landers to Mars. The success of Viking exceeded all expectations, and, in particular, the orbiters took over 50,000 images. These provided global coverage at ~300-m resolution, global color and stereo at a few km, and extensive regional coverage at higher resolutions down to 8 m. The Viking Orbiter images formed the basis of Mars cartography (and geoscience) for the following two decades, the next successful orbiter not reaching the planet until 1997.

These early missions posed severe challenges for cartographers. Apart from the fundamental problem of mapping a world from the outside with essentially no ground control (the Viking Landers eventually provided two, rather insecure, known points on the entire planet), the process was hampered by the small format of the images (in today's parlance, ~1 Mpixel at best), narrow field of view on the order of 1°, and substantial and variable distortions inherent in the vidicon sensors used. A global control network was nevertheless established with Mariner 6–7 data through the pioneering work of Merton Davies and colleagues at RAND, and was gradually expanded and refined to include more than 9,000 points measured mainly on Viking and Mariner 9 images. Because of the dearth of stereo information, points of the RAND network were constrained to lie on an ellipsoidal surface, and their planimetric coordinates were estimated with typical accuracies of 1–6 km.

In parallel with this effort, Sherman Wu of the U.S. Geological Survey (USGS), Flagstaff, Arizona, constructed a three-dimensional control network incorporating some of the RAND measurements but with height constraints from the low-resolution Viking stereo images, as well as atmospheric sounding, occultation, and radar data. Additional topographic details were eventually added by analytic photogrammetry, resulting in a global set of elevation contours with 1-km spacing but absolute accuracy of only 1–3 km, and regional topomaps with higher precision. Wu also pioneered the use of an equipotential surface as a reference for Martian elevations. The results revealed a world with relief dwarfing that of Earth, from 25-km high volcanoes to a 5-km deep basin. The best-fit ellipsoid was triaxial, with the longer of its equatorial axes oriented toward the largest volcanic province. Because of the departures of many km from this ellipsoid (and the theoretical complications of mapping a triaxial body), however, an oblate spheroid has always been used as a reference surface for maps of Mars.

Authority over the coordinate systems and cartographic constants of Mars and other planetary bodies lies with the International Astronomical Union (IAU). In 1970, the IAU general assembly approved

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the use of "planetographic" coordinates for extraterrestrial mapping, consisting of planetographic latitudes (i.e., measured normal to the ellipsoid, equivalent to geographic or geodetic latitude on the Earth), and the direction of positive longitude chosen such that the longitudes seen by an outside observer increase with time. This longitude convention follows traditional astronomical usage, and results in positive West longitude for Mars and many other bodies. At the same time, the IAU also approved "planetocentric" coordinates with planetocentric (equivalent to geocentric) latitude and positive East longitude giving a right-handed spherical coordinate system. The two types of latitude differ by about 0.3° (20 km) in the Martian midlatitudes, but are identical at the equator and poles.

In 1973, the Martian prime meridian was defined to pass through a 500-m crater, Airy-0, which lies within a 56-km crater named for George Airy, the astronomer who played a key part in defining the terrestrial prime meridian. More recently, a 49-km crater on the Martian prime meridian has been named for Merton Davies to commemorate his role in creating the discipline of planetary geodesy. In 1976, the IAU established a Working Group on the Cartographic Coordinates and Rotational Elements of Planets and Satellites. This group, chaired by Davies for many years, reports triennially on the preferred rotation rate, spin axis, prime meridian, and reference surface for planets and satellites. Since 1985, the group has been co-sponsored by the International Association of Geodesy.

The following paragraphs describe Mars maps made by the USGS, which has been the primary producer of planetary cartography in the United States. The types of maps that could be created prior to 1990 were limited by the available technology. Controlled, but unrectified, photomosaics were produced by hand-laying prints of individual images. Airbrush drawings portraying shaded relief, with or without albedo markings, were based on the mosaics (plus photointerpretation of additional images) and were the primary map product at all scales. The airbrush maps and mosaics were also used as bases for geologic maps. The lack of a means to make orthorectified image mosaics led to topographic contours being presented either on an airbrush base (at small scales) or, at larger scales, with no map base at all. The formats that were defined for printed maps in the early years remain in use.

Global maps on a single sheet, with latitudes -56° to 56° in Mercator projection and 56° to the poles in polar stereographic, were produced at 1:25,000,000 scale. (Global maps with hemispheres centered on 0° and 180° longitude in Lambert azimuthal equal area projection have appeared in both US and Soviet atlases of the solar system.) Mercator and stereographic projections were also used for 1:15,000,000 scale maps, with 180° of the equatorial band on each of two sheets, and both poles on a third. Maps at 1:5,000,000 scale were produced as a series of 30 "Mars Charts," and the designations MC-1 to MC-30 are still commonly used to describe regions of the planet. This series comprises eight Mercator maps from 0°–30°, six Lambert conformal conic sheets from 30°–65°, and one polar stereographic from 56°–90° latitude in each hemisphere. The same projections were used for maps at 1:2,000,000 scale, with the MC quadrangles subdivided into four, five, or (for the poles) ten sub-quadrangles. In all these series, scale factors are chosen to give matching scales at the latitudes where the maps in different projections join. The nominal scale applies at 35.83° and 57.19° (the standard parallels of the Lambert conic sheets) for the 1:2,000,000 series, but at the equator in the other series.

Finally, a 1:500,000 scale map series was defined, with most sheets in a Mars Transverse Mercator (MTM) projection with 20° zones having scale factor 0.996 on the central meridian. Between ±47.5° latitude, the quadrangles are 5°×5°, from 47.5° to 62.5°, their longitudinal extent is increased to 7.3333°, from 62.5° to 77.5°, it is 10°, and from 77.5° to 82.5° a single quadrangle spans the entire 20° zone. The region pole ward of 82.5° is divided into 10 sheets in polar stereographic projection, with nominal scale at 87.5° latitude. The total number of quadrangles in this scheme is thus 1964, but only a fraction of the possible maps have been produced, mostly as either geologic or topographic contour maps. On occasion, regions consisting of two or four adjacent MTM quads have been mapped at 1:1,000,000 scale.

By the late 1980s, digital cartographic processing of images became practical. The global mosaicked digital image model of Mars produced by the USGS from Viking images and known as MDIM 1.0, is described in more detail in the paper by Rosiek *et al.* in this issue (see pp. 1187-1198). This product was accompanied by a global digital topographic model gridded at 64 pixels per degree, generated by interpolating the USGS contour maps described above. Mosaic bases for geologic maps at 1:500,000 have also been produced digitally. The projection used for these digital maps (and many others for other planets) is the sinusoidal projection *in its spherical form*. This choice reflects the pragmatic approach of planetary cartographers in the US: for a digital database, it is useful to have digital data in a projection that is approximately equal-area, to minimize the volume of data, but exact equality of area is less important than the simplicity (hence speed of computer manipulation) of the projection equations. It is expected that the data will be re-projected from the sinusoidal "database projection" to true equal-area, conformal, or other projections, as needed for particular applications. The MDIM and other digital maps are divided into data files or "tiles" of a size chosen to be manageable with the computers of the day. Where possible, this division matches the quadrangles of one of the printed map series. So, for example, MDIM 1.0 files correspond to the 1:500,000 MTM quadrangles, and contain 1.5 MB or less of data. The central meridian of projection for each file is placed in the center of the file to minimize distortions, and the polar regions are commonly prepared in polar stereographic as well as sinusoidal form.

The exploration and mapping of Mars resumed in 1997 with the successful arrival of the Mars Global Surveyor (MGS) orbiter, carrying a Mars Orbiter Camera (MOC) with 1.5 m/pixel narrow angle and 240 m/pixel wide angle pushbroom scanners, and a Mars Orbiter Laser Altimeter (MOLA), among other instruments. Both the cameras and the altimeter have produced data of tremendous value for both science and cartography, but it is MOLA that has truly revolutionized the mapping of Mars. Before its transmitter failed in 2001, the instrument made more than 600 million measurements of the Martian surface with a vertical precision of better than 1 m. A comparison of the altimetric profiles at the millions of locations where they cross one another allowed errors in the spacecraft orbit to be corrected and effectively turned each MOLA measurement into a ground control point with an absolute accuracy better than 100 m horizontally and approaching 1 m vertically.

MOLA thus provides the ultimate source of geodetic control for mapping with other data. The prime meridian has been defined with an accuracy better than 500 m by locating the center of Airy-0 and the nearest MOLA profile within a single MOC image, and an ellipsoidal reference surface (equatorial radius, a = 3396.19 km, polar radius, b = 3376.20 km) has been defined by least squares fitting to the MOLA surface model. This reference ellipsoid is symmetric about the center of mass of Mars, despite the fact that the center of figure is displaced about 3 km toward the south (i.e., the southern hemisphere stands nearly 6 km higher than the northern as a result of the internal structure and dynamics of the planet). These parameters were approved by the IAU/IAG working group in 2000 (Seidelmann *et al.*, 2002, *Celestial Mechanics and Dynamical Astronomy*, 82: 83–110), along with rotation axis and rate based on both Viking and MGS observations. The precision of the measurements and long temporal baseline make it unlikely that these definitions will be changed in the next decade.

As described by Rosiek *et al.* in this volume, the MOLA dataset exposed and quantified the positional errors in the existing RAND control network and in MDIM 1.0, but also provided the means to mitigate those errors. The RAND network, now maintained by the USGS and with the MDIM images incorporated into it, was constrained both vertically and horizontally by using the MOLA data, reducing absolute positional errors to the order of an image pixel (200 m) and mismatches between the orthorectified images to a fraction of a pixel in most places. The MOLA data have also been used to derive topographic maps at 1:25,000,000 scale with digitally generated shaded relief, color-coding, and contours, and would support mapping at larger scales as well.

An unexpected outcome of the MGS mission was a revolution in the coordinate system used for most Mars mapping. The MOLA team adopted the IAU "planetocentric" system of planetocentric latitude and positive East longitude, and the importance and precision of the MOLA products led many NASA missions and instrument teams to adopt the same system. After vigorous debate in the planetary community and a formal review by NASA, in 2002 the USGS adopted the planetocentric system for future Mars products. The most important aspect of this change is that digital products now use the spherical forms of the "database" projection with planetocentric rather than planetographic latitude. Thus, MDIM 2.1 was prepared in equirectangular projection with equal sampling in planetocentric latitude, versus sinusoidal with equal planetographic sampling used in earlier versions. (The size of data files was also increased and their number reduced; MDIM 2.1 is divided into sections corresponding to the 30 MC quads.) Conformal projections are still used in their ellipsoidal form, e.g., in the production of printed maps. However, the bounding parallels of both digital and hardcopy maps, as well as the standard parallels for maps in conic projection, are now defined at specific planetocentric latitudes (30°, 56°, etc.) rather at planetographic latitudes equal to these values. This change necessitates small adjustments to the scale factors in order to match the scales at the latitudes where maps in different projections join. Additional steps taken to make the change in coordinate system easier to users include careful labeling of longitudes as East or West, and the inclusion of dual graticules (planetocentric primary grid and planetographic secondary tick marks in a distinct color) on printed maps. It is important to note that the planetographic coordinate system is still recognized by the IAU/IAG and is used by some organizations, so that software to translate between the two systems is essential.

Additional robotic spacecraft have been dispatched to explore Mars at every opportunity since 1997, with both US and an increas-

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ing number of non-US missions planned for the future. The trend toward ever-higher resolution imaging that was apparent even in the 1960s continues, but advances in technology have substantially increased the area that can be imaged at a given resolution. The NASA 2001 Mars Odyssey Orbiter carries a Thermal Imaging System (THEMIS) that obtains visible images at 18 m/pixel and thermal infrared images at 100 m/pixel (see article by Kirk *et al*. in this issue). Global coverage of infrared images may be obtained by the end of the Odyssey extended mission, with perhaps 50% of the planet imaged in the visible, and preliminary planning has already taken place for the production of a new generation of high-resolution global image mosaics from the data.

MGS and Odyssey were joined at the beginning of 2004 by the European Space Agency's Mars Express orbiter, which caries a High Resolution Stereo Camera capable of 12 m/pixel imaging with simultaneous three-line stereo and four-filter color at slightly lower resolution. The elliptical orbit of Mars Express also allows for imaging of larger areas at reduced resolution from higher altitudes, so that a substantial fraction of Mars may eventually be imaged at 50–100 m resolution. The HRSC team includes numerous mapping professionals in addition to geologists, and photogrammetry and cartography are important elements of the investigation plan, as described in the papers by Scholten *et al*. and Albertz *et al*. in this issue. The inclusion of US cartographers in the team has ensured that the cartographic constants and geodetic control adopted for HRSC maps are consistent with those used by US mappers, and that standards for digital and printed maps are consistent with current usage.

The high resolution of the HRSC has, however, necessitated the definition of a new 1:200,000-scale map series. The quadrangles are not obtained by subdividing the existing 1:500,000 series, but they can themselves be divided into quarters and sixteenths for mapping at 1:100,000 and 1:50,000 scales, respectively. The series consists of 10,372 defined quadrangles, 10,324 in sinusoidal projection (spherical form with planetocentric latitude) and 24 surrounding each pole in Lambert azimuthal equal-area projection. The quadrangles span 2° in latitude, with those in the ±25° latitude zone also 2° in longitude and the others having increased longitudinal extent in order to keep the area approximately constant. These 2° regions are so small that the angular distortions of the chosen projections are judged acceptable for printed maps as well as for the digital archive. This new map series and its subdivisions are likely to suffice for large-scale mapping of Mars for some years to come, although an increasing number of maps are likely to be made on an ad hoc basis, covering only the areas for which high-resolution imagery is available. In particular, the 30-cm resolution of the HiRISE camera on board the Mars Reconnaissance Orbiter, which was successfully launched in August of this year, will support mapping at a scale of 1:5,000 or even larger but typically only for 0.1°x0.3° areas.

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Randy Kirk joined the U.S. Geological Survey, Flagstaff, Arizona, in 1987 after receiving his PhD in Planetary Science from Caltech. His research focuses primarily on the development of digital techniques (both photoclinometry/shape-from-shading and the adaptation of commercial stereo photogrammetric software for planetary use) for topographic mapping of planets and satellites, and application of the resulting topographic data to study the processes by which planetary surfaces evolve and to assess the safety of potential landing sites. This work has led to his participation in imaging investigations on numerous planetary missions, including, at present, the Mars Reconnaissance Orbiter HiRISE, Mars Express HRSC, and Mars Exploration Rovers Athena teams and the Cassini-Huygens RADAR and DISR teams. He also plays an active role in directing the ongoing program of planetary cartography conducted by the USGS on behalf of NASA.