Giant Impact Basins Trace the Ancient Equator of Mars

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Abstract.

It is shown in this paper that 5 giant impact basins of Mars, Argyre, Hellas, Isidis, Thaumasia, and Utopia, are located on a single great circle. This suggests that the projectiles' orbital planes coincided with the equator of Mars at the time of impact. The projectiles were lager fragments of a heliocentric asteroid that broke apart as entered the Roche limit of Mars. The mass of the asteroid was at least ~9.8×10^{20} kg, ~1.5×10^{-3} times the mass of Mars.

Introduction

There are many reasons to believe that the rotation axis of Mars has moved relative to its body since the formation of the planet. A general scenario for the evolution of Mars includes the following major stages; chronologically, the accretion of the planet, the chemical differentiation that gave rise to the core and the initial curst, the formation of the northern lowlands, the impacts that produced the giant basins, the formation of Tharsis bulge, and the build up of the shield volcanoes. The major impact cratering, tectonic and volcanic processes have occurred during the first 1-2 Gyr of the planet's history, followed by some minor tectonics and volcanism to the recent past [Hartmann and Neukum, 2001]. There is no convincing evidence that the planet formed as a homogeneous or even a spherically symmetric body. On the basis of buried basins and craters distribution, Frey et al. [2002] suggest that the north-south topographic dichotomy is likely primordial. The variations of W isotopic abundances in the Martian meteorites indicate that the meteorites source regions have preserved ancient heterogeneities, and mantle mixing in Mars was less effective [e.g., Spohn et al., 2001; Reese et al., 2002]. There is, however, good reason to believe that the formation of Tharsis bulge well after the accretion and initial chemical differentiation of the planet has displaced a huge amount of mass inside as well as on the surface of the planet. For example, on the order of 10^8 km^3 volcanic flow is required to explain the gravity and topography of the Tharsis bulge [e.g., Solomon and Head, 1982]. Such a huge redistribution of mass has undoubtedly caused the Martian body to rotate relative to its angular momentum in order to maintain its maximum moment of inertia axis close to the direction of the angular momentum [e.g., Melosh, 1980].

There are several lines of evidence for the polar wander of Mars. The morphology of the polar caps of Mars led Murray and Malin [1973] to propose a polar wander of 10-20 degrees in the last ~100 Myr. Melosh [1980] suggested a polar wander of ~25 degrees induced by the formation of Tharsis bulge. Schultz and Lutz-Garihan [1982] examined

Martian craters larger than 5 km for high ellipticity and butterfly-wing ejecta and other signs of oblique impacts and concluded that the rotation axis of Mars has moved from Utopia region down to Amazonis planitia region and then up to the present location. The resemblance of Mesogaea deposits south of Olympus to the deposits in the polar region led Schultz and Lutz [1988] to suggest a convoluted polar wander path with a total of 120 degrees wandering. The substantial distance between the paleomagnetic pole positions, determined from modeling isolated small magnetic anomalies of Mars, and the present rotation axis of Mars suggested 20-65 degree polar wander of the planet since the magnetic source bodies acquired their magnetization [Arkani-Hamed, 2001; Hood and Zakharian, 2001; Hood and Richmond, 2002; Arkani-Hamed and Boutin, 2004]. And finally, theoretical modeling of the polar wander of Mars showed that the rotation axis of Mars could have moved by as much as 70 degrees within a geologically short time period in response to the emplacement of Tharsis mass [Spada et al., 1996]. The theoretical modeling also demonstrated the crucial effects of the mantle viscosity and the thickness of the rigid lithosphere on the polar wander.

This paper investigates the polar wander of Mars using the locations of 5 giant impact basins Argyre, Hellas, Isidis, Thaumasia, and Utopia. The basins are located on a great circle that most likely traced the equator of Mars at the time of impacts, i.e., before the formation of Tharsis bulge. The impactors were likely fragments of a large heliocentric asteroid that broke apart when it entered the Roche limit of Mars. The lower limit for the mass of the original asteroid is also estimated.

The Ancient Equator of Mars

I investigate 5 giant impact basins of Mars, Argyre, Hellas, Isidis, Thaumasia and Utopia. Two of the basins, Argyre and Hellas, are on the south highland and are well preserved. Isidis overlies the north-south topographic dichotomy, and it is partly covered by the lowland deposits. Utopia basin is completely covered by the lowland deposits. It is delineated by a gentle sagging of the smooth surface of the lowland and an almost circular positive Bouguer anomaly centered at about 36N and 117E. Thaumasia basin centered at about 23S and 272E is recently identified [Arkani-Hamed, 2004] on the basis of (a) its positive Bouguer anomaly which is surrounded by an almost circular negative Bouguer anomaly, and (b) the morphology of the magnetic anomalies over this region, absence of magnetic signature inside the basin and encircling appreciable anomalies in the surroundings which are the characteristics of the magnetic anomalies over impact basins such as Hellas, Isidis and Argyre [Arkani-Hamed, 2004]. The basin has been over flooded during the formation of the Tharsis bulge and presently resembles a plateau. The basin underlies Solis planum, Sinai planum and Thaumasia planum, and is neighbored by Valis Marineris, Syria planum, Claritas Fossae, and Thaumasia highland. Schultz and Frey [1990] used the 1:15,000,000 scale geologic maps of Mars and the revised global topography to determine the centers of Argyre, Hellas, Isidis and Utopia among other multiring basins of Mars (see their Table 1.). However, the exact impact sites of the basins, especially those of Isidis, Utopia and Thaumasia are obliterated due to subsequent tectonic activities, and volcanic and sedimentary deposits. Even Argyre and

Hellas floors have probably been deformed by the flexure of the crust that was induced by the Tharsis loading [Phillips et al., 2001], and by later volcanic and sedimentary deposits that have covered parts of the basins. I estimated the center of the basins using the global Bouguer anomaly map. The selection of a basin is based on the premise that a giant impact which created the basin has most likely fluidized the crust directly beneath by strong shock waves and impact heating [e.g., Melosh, 1989; Mohit and Arkani-Hamed, 2004], and has allowed the mantle to uplift through isostatic compensation in a short time period. The uplift has introduced strong density perturbations in the crust, giving rise to the significant positive Bouguer anomaly associated with the basin. The circular shape of the uplift probably better delineates the impact site, the center of the impact basin immediately after the impact event. The subsequent modifications have likely less effect on the shape of the mantle uplift compared to that on the surface topography. Figure 1a is the Bouguer anomaly map derived from MOLA data and from Yuan et al.'s [2001] spherical harmonic model of the gravity field of Mars. Only harmonics of degree up to 50 are used, because their coefficients are most reliable (A. Konopliv [2002] personal communication). To determine the Bouguer anomalies, the gravity field of the surface topography is obtained using a crustal density of 2900 kg/m^3 and adopting a finite-amplitude topography technique in calculating the gravity field of the topography [Arkani-Hamed, 1999], which takes into account the large dynamic ellipticity of the Martian surface as well as the topographic relief of the basins. The second-degree zonal spherical harmonic is not retained in this figure for better illustration of the local anomalies, although it is included in the calculations in order to account for the dynamic bulge of Mars. The impact basins are delineated in Figure 1a by strong positive circular Bouguer anomalies, except for Thaumasia basin that has a weak and deformed positive Bouguer anomaly, but surrounded by almost circular negative Bouguer anomaly. This basin is selected (but see below) on the basis of the argument put forward by Arkani-Hamed [2004] that the Bouguer anomaly inside the basin has been distorted by the late volcanic deposits from Syria Planum.

Frey et al. [2002] identified many quasi-circular depressions in the lowlands, and interpreted them as buried impact basins that have been overlain by late deposits. It is expected that immediately after a large impact the mantle beneath the impact site ascends in a geologically short time to retain isostatic compensation, and later filling of the compensated basin would enhance its positive Bouguer anomaly. However, none of the quasi-circular basins show Bouguer anomalies, except for the largest one, with a diameter of about 1073 km and centered at 38N and 177E, which has a weak positive and circular Bouguer anomaly. The lack of Bouguer anomalies of the other quasi-circular buried basins is probably due to the fact that the gravity model does not have enough resolution to delineate the smaller basins. The shortest wavelength retained in the 50-degree spherical harmonic model is ~430 km. The largest buried basin has a floor-to-rim relief of a few hundred meters, implying that later deposits have filled almost the entire basin, possibly several km. Moreover, Figure 2 of Frey et al. [2002] shows that this basin has later been asymmetrically cratered, implying asymmetric redistribution of ejecta and later deposits. This basin is not selected for the present study (but see below).

There is a well-defined, though not very circular, positive Bouguer anomaly centered at about 3N and 207E. But there is no obvious surface expression for an impact basin there. Also, there is a broad positive Bouguer anomaly over an extended region between 0-35N and 310-335E which includes Chryse planitia and Ares basin. However, the general shape of the anomaly does not resemble an anomaly related to an impact. It requires a higher resolution gravity model to better resolve the shape of this extended Bouguer anomaly. These two positive Bouguer anomalies do not seem to be related to some buried ancient impact basins. Likewise, a possible buried basin near Daedalia planum suggested by Frey et al. [2003] does not show any Bouguer anomaly in Figure 1a, as expected from an impact basin. These basins are not considered in the present study.

Table 1 lists the centers of the selected basins, and those reported by Schultz and Frey [1990] for comparison. The centers of Argyre, Hellas and Isidis are determined from the Bouguer anomaly map using the most circular part of their Bouguer anomalies, the eastern part of Argyre, the western part of Hellas, and the southwestern part of Isidis. The centers are almost identical to those of Schultz and Frey. There is about 12 degrees difference between the two estimated centers for Utopia. This basin has been completely filled by subsequent deposits of the northern lowland. Its gentle sagging surface does not allow accurately determine the impact site from its surface topography. However, its Bouguer anomaly better delineates the circular nature of the mantle uplift in the south and southeast, which is used to estimate the center of the basin. The Thaumasia basin's center is uncertain, because of huge volcanic flows from Syria Planum, a long-lived (from Noachian to early Amazonian) region of volcanism on Tharsis [e.g., Tanaka et al., 1996; Dohm and Tanaka, 1999; Hartmann and Neukum, 2001]. The volcanic flows not only filled the entire basin, but also added extra deposits on the northwestern part of the basin, creating appreciably asymmetric and positive topography that obliterates the circular shape of the positive Bouguer anomaly possibly associated with the underlying mantle uplift. The center is visually estimated from the surrounding almost circular negative Bouguer anomalies and appreciable magnetic anomalies over its immediate surroundings. The estimate can be uncertain by a few degrees. Although the possibility that an original basin existed beneath the present Thaumasia plateau was clearly demonstrated by Arkani-Hamed [2004], it requires some debate among planetary scientists to establish or dispute this possibility. Therefore, in the following probability analyses both scenarios, with or without Thaumasia, will be considered.

The five giant impact basins are located on a single great circle. Table 2 lists the latitudes and longitudes of the poles of the great circles fitted to the basin centers using different combinations of the basins. First Argyre, Isidis and Hellas are fitted to a great circle and then the other basins are added one by one. The poles determined using the Bouguer anomaly centers are extremely clustered, and those determined from Schultz and Frey's center locations are also clustered. The difference between the two clusters is well within the error limits of the estimates of the basins centers, and has little effect on the main conclusion of this paper. Included in Table 2 are the latitudes of the basins relative to the corresponding great circles. For example, Argyre is located at 2 degrees north with respect to the equator described by the great circle fitted to Argyre, Hellas, and Isidis. The standard deviations of the latitudes show the tight fitting of the basins to the great circles. Figure 1b shows the Bouguer anomaly map of Mars with the equator defined by the great circle fitted to all five basins with a maximum standard deviation of 5.8 degrees. All impact basins centers are located within a maximum latitude of λ_{max} = 8 degrees. It is worth mentioning that the weak positive Bouguer anomaly over the largest buried impact basin reported by Frey et al. [2002] is located at about 17S in Figure 1b, not very far from the equatorial band of width $-\lambda_{max}$ to $+\lambda_{max}$.

The five basins do not trace a small circle at appreciable latitude. To illustrate this point, I fitted small circles to different combinations of the basins in order to avoid the constraint imposed by including the center of Mars in fitting the great circles. The last column of Table 2 shows the latitudes of the small circles relative to their corresponding equators. The latitudes are less than 3 degrees, except for the small circle fitted to Argyre, Hellas and Isidis, which has ~12 degrees latitude that is still not very far from the equator.

To investigate the statistical significance of the estimated great circle fitted to the basins, I examined the probability that 5 randomly distributed impacts occurred within a given angle from a great circle. It is worth mentioning that the great circles were fitted to the centers of the basins regardless of the size of the basins. This is because the size of an impactor is much smaller (by a factor of more than 5) than the size of the basin produced, and the center of the basin is the impact site. Any 2 randomly distributed impacts on a planet define a great circle. The probability that a third random impact occurs within (+-)λ latitudes relative to that great circle is simply $\sin\lambda$. Assuming that the impacts are independent events, the probability that the third, forth and fifth random impactors land within the latitude λ of the same great circle is $\sin^3\lambda$. For a maximum λ_{max} = 8 degrees (Table 2) the probability that the 5 giant basins on Mars are produced by randomly distributed impactors is 0.27%. Excluding Thaumasia basin decreases λ_{max} to 7 (see Table 2) but increases the probability to 1.5%. I also considered the possibility that the center of Bouguer anomaly may not be the exact center of the basin, and thus the exact impact site. The difference between the two estimates of the locations of the centers of the well-defined basins, Hellas, Isidis and Argyre made by Schultz and Frey [1990] and in this paper is less than 6 degrees. Adding this entire difference to λ_{max} increases the probability to 1.4% and 5.1%, with or without Thaumasia basin respectively. These probability values are quite small and emphasize that the five giant basins are not produced by random impacts.

The Origin of the Basin-Forming Projectiles

The five giant basins are essentially coplanar and are located on a great circle, indicating that the projectiles that created the basins were also coplanar. The orbital plane of an asteroid that is captured by a planet essentially describes a great circle on the surface of the planet, as described by the two-body problem. It is, however, quite unlikely that the projectiles that created the giant basins were individual asteroids with orbital planes that just happened to coincide with the same great circle. It is possible that a heliocentric asteroid captured by Mars was fragmented when it entered the Roche limit of Mars, and the large fragments followed more or less the same orbital plane of the original asteroid before impacting on Mars. The fact that the giant basins are on a great circle makes it quite unlikely that the orbital plane of the asteroid had an appreciable inclination relative to the existing equator of Mars. A good example is Shoemaker-Levy comet that broke up into about 20 large fragments, and many small particles, when entered the Roche limit of Jupiter. The comet approached Jupiter at a very high inclination, ~85 degrees, and the ringlet of the fragments remained essentially on the same orbital plain of the original comet and impacted at ~45 degree latitude on Jupiter. The fragments took about 7 days (July 16 through July 22, 1994) to impact on Jupiter, during which time the planet rotated. Consequently the impact sites described a small circle of ~45 degree latitude. The much weaker gravity field of Mars relative to that of Jupiter may allow the fragments to impact Mars at even longer time intervals. For a high orbital inclination of the original asteroid, even one Martian day interval between the first and the last impacts is sufficient to give rise to a complete small circle of the impact sites on Mars because of the rotation of the planet. It is of course possible that a projectile approaching Mars at a high inclination impacts near the equator. But it is unlikely that 5 projectiles on a highly inclined orbit all impact near the equator. To illustrate this point, I explore the probability that a projectile approaching Mars on an orbital plane with an inclination α fragmented and 5 large pieces produced 5 basins lying within (+-)λ_{max} (= 8 degrees) latitudes from the equator at the time of impacts. While the ringlet of fragments was orbiting, Mars was rotating about its axis. Therefore, relative to Mars the orbital plane of the ringlet rotated, and depending on the impact times the 5 pieces impacted on Mars at random longitudes, but within (+-) α latitudes. The probability that a fragment impacted within (+-)λ_{max} latitude band equals to 1 when α =< λ_{max} and equals to ($\sin\lambda_{max}$ /$\sin\alpha$) when $\alpha > \lambda_{max}$. Assuming that impact times, i.e. the impact longitudes, were random, the probability that all 5 fragments impacted within the λ_{max} latitude band equals to 1 when α =< λ_{max} and equals to $(\sin\lambda_{max}/\sin\alpha)^5$ otherwise. Excluding Thaumasia basin changes the probability to $(\sin\lambda_{max}/\sin\alpha)^4$, where λ_{max} is now reduced to 7 degrees. Figure 2 shows the probability as a function of orbital inclination for these two scenarios, with or without Thaumasia basin. The probability rapidly decreases as α exceeds λ_{max}, it reduces to below 1.6% for both scenarios when α exceeds 20 degree. Figure 2 shows that the orbital plane of the fragments was most likely much less than 20 degrees from the equator of Mars at the time of impacts.

The original asteroid was most likely heliocentric and not a natural satellite of Mars. The presently existing satellites, Phobos and Deimos, are orbiting essentially on the equatorial plane of Mars, their orbital plane inclinations with respect to Mars's equator are 1 and 2.8 degrees, respectively. Schultz and Lutz-Garihan [1982] showed that the elliptical craters of Mars are not randomly oriented. This led them to propose the moonlet hypothesis for their origin, that Mars had more satellites originally and some of them have impacted on the surface and produced the elliptical craters. Bottke et al. [2000] re-examined the relationship between the impact angle and the ellipticity of the crate, and showed that the moonlet hypothesis is unnecessary for explaining the origin of the elliptical craters. The orbit of a natural satellite may decay due to tidal interaction and the satellite eventually impacts the surface. For example, with a semi-major axis of 9,378 km, Phobos is presently in the route for collision and it will impact on Mars in the future. In the course of approaching Mars, a satellite enters the Martian atmosphere and experiences aerodynamic drag, which causes the satellite to spiral quickly and increases the impact angle. The aerodynamic drag, however, has less effect on the orbital dynamics of large satellites. Large spiraling satellites, or a fragment of an originally larger satellite, impacts at a very low-angle and produces a highly elliptical crater. Gault and Wedekind [1978] experimental results suggest that at an impact angle of 4.75^o, or less, the crater is always elliptical. The crater ellipticity decreases as the impact angle increases and at the impact angle greater than about 10^o the crater is always circular. More recent studies suggest that the threshold impact angle is about 12^o, rather than 4.75^o, and even larger for bigger impactors. On the basis of the spiraling moonlet model for impacts on Mars, the crater ellipticity is about 30 for an impactor of 50 km diameter [see Table I of Bottke et al., 2000], which is still smaller than the impactors that created the giant basins (see Table I). The almost circular shape of the giant impact basins shows that the impact angles were quite large, indicating that the impactors were not natural satellites of Mars, nor fragments of a larger natural satellite of Mars. The original asteroid was most likely heliocentric that fragmented and produced smaller bodies that impacted on Mars at large impact angles. In general the orbital plane of a heliocentric asteroid is independent of the equatorial plane of a planet. A viable scenario is that the orbital plane of the original asteroid, and thus the orbital plane of the fragments that created the 5 giant basins, just happened to almost coincide with the equatorial plane of Mars described in Figure 1b.

The pole of the great circle, determined from the giant impact basins, defines the rotation axis of Mars at the time of the large impacts, most likely occurred prior to the formation of Tharsis bulge, shield volcanoes, and major tectonic and volcanic processes. The appreciable redistribution of mass through these processes resulted in subsequent polar wander of Mars. For example, Figure 1b shows that Tharsis bulge was formed in the south. It has moved to its present location, centered at ~ 7 N and 112 W (Zuber and Smith, 1997), as a result of the polar wander induced by its load, later formation of shield volcanoes, and other redistributions of mass. There is no agreement between the rotation axis determined in this paper and that implied from the paleomagnetic pole positions of Mars determined from modeling small isolated magnetic anomalies [Arkani-Hamed, 2001; Hood and Zakharian, 2001, Hood and Richmond, 2002; and Arkani-Hamed and Boutin, 2004]. Also, the rotation axis presented in this paper does not agree with the pre-Tharsis rotation axes estimated by Melosh [1980] and Willemann [1984], but it is close to the rotation axis determined by Schulze and Lutz-Garihan [1982] from their class 3 elliptical craters. Mars likely had substantial and convoluted polar wander in its early history, when the Martian mantle was relatively hot, less viscous and more dynamic, and the thin and relatively hot lithosphere was too weak to hamper significant polar wander. Theoretical models by Spada et al. [1996] suggest that the density perturbations, caused by the formation of shield volcanoes alone (Olympus, Ascreaus, Pavonis, and Arsia Montes) can induce ~70 degree polar wander within 100 to 800 Myr for the mantle viscosity of 10^{21} to 10^{23} Pa s and the lithosphere thickness of 100-300 km. The thermal evolution models of Mars [e.g., Schubert and Spohn, 1990; Breuer and Spohn, 2003] suggest that the mantle viscosity within the first 500 Myr of the planet's history was likely much lower, by orders of magnitude, than these values and the lithosphere was much thinner. For example, the models by Hauck and Phillips [2002] predict that a partially molten region, and therefore very low viscosity zone, probably existed within 100-200 km depths during the first 2 Gyr of the planets history. The acquisition time of the magnetization by the magnetic source bodies, the time of large impacts that produced the giant basins, and the formation times of Tharsis bulge and shield volcanoes span a geologically long period, more than a billion years. Significantly large and convoluted polar wander could have occurred during this long period and since [Schultz and Lutz-Grihan, 1982; Schultz and Lutz, 1988]. The pole position estimated from the giant impact basins is essentially a snapshot (at the time the impacts occurred) in this long period of polar wandering. Schultz and Lutz [1988] suggested that polar-like deposits predate the early stages of Tharsis volcanism. The polar-like deposits in the east of Apollinaris Patera, centered at (6S, 180E) and designated as Region B by the authors, are located close to the pole position determined in the present paper. If this is the case, then the age of the deposits in Region B is a good estimate for the time of giant impacts on Mars.

The determination of the polar wander path of Mars on the basis of the present locations of surface features, such as shield volcanoes, Tharsis bulge, and giant basins is essentially an inverse problem with a well-know non-unique solution. It is impossible to uniquely determine the original location of an excess surface mass after it is shifted to the equator through polar wandering. Our understanding of the history of the rotational dynamics of Mars is essentially very poor at best. A better understanding of the relationship between the orbital dynamics of an asteroid and the resulting crater morphology requires considering many factors, some of which are discussed by Bills [1992] for craters on Venus. The original heliocentric asteroid was likely fragmented into many pieces and the orbital motion of 5 large fragments evolved rapidly and produced the giant basins. Many small bodies likely scattered and spread over a larger volume, and some out of the orbital plane of the original asteroid. It is possible that these small fragments were eventually collapsed on the equatorial plane and impacted on Mars at very low angles, creating some of the class 3 elliptical craters reported by Schultz and Lutz-Garihan [1982]. Also, there is no reason to believe that all large basins of Mars originated from fragmentation of a single asteroid. Some large basins, such as Chryse, Ares, and buried basins may have been produced by other heliocentric asteroids.

Detailed investigation of the orbital dynamics of the projectiles that created the giant basins is beyond the scope of this paper. It is not possible to predict the outcome of fragmentation of an asteroid when it enters the Roche limit of a planet. It is expected that large fragments stay on the same orbital plane of the original asteroid, and smaller fragments scatter. Whether the resulting fragments impact in a short time period, like the fragments of Shoemaker-Levy comet mentioned above, or some of the fragments remain on the plane for a longer period can be predicted only after the fragmentation. The crater counts inside the basins cannot resolve impact intervals of a few thousand years. Moreover, it is required to take into account both visible and buried craters to decide the age of a basin. For example, Isidis rim looks younger than Hellas rim if only visible craters are considered, but the two basins have a similar age if both visible and invisible craters are counted [Frey et al., 2003].

The Size of the Original Asteroid

Here I estimate a lower limit of the size of the original asteroid, assuming that the impacts were major fragments of the asteroid. Using the relationship between the excavation volume of an impact basin and the energy of the impactor, Mohit and Arkani-Hamed [2004] estimated the energy of the projectiles that created Argyre, Hellas and Isidis basins. Using heliocentric projectile velocities of 8-12 km/s [Neukum and Wise, 1976; Ivanov and Yu, 1988], and assuming basaltic impactors of 3000 kg/m^3 density, they estimated the impactors radii of 95-140 km, 210-310 km, and 130-200 km for Argyre, Hellas and Isidis respectively. Hood et al. (2003), using the pi-scaling method, estimated projectile radii of 230-340 km and 150-220 km for Hellas and Argyre for impact velocities of 7.5-15 km/s. Included in Table 1 are rough estimates of the average radii of the impactors and their masses, calculated on the basis of their surface topography and gravity anomalies (see Mohit and Arkani-Hamed [2004] for details) and assuming that they were basaltic. Utopia and Thaumasia impactors are assumed to be identical to Hellas impactor. The total mass of the projectiles, ~9.8×10^{20} kg, is ~1.5×10^{-3} times the mass of Mars. This is a lower limit for the mass of the original asteroid, because many smaller fragments are likely produced during the fragmentation of the asteroid.

Conclusions

I investigated 5 giant impact basins of Mars, Argyre, Hellas, Isidis, Thomasia and Utopia, and showed that they are located essentially on a single great circle, within the error limits of their impact sites that are estimated from the shape of their Bouguer anomalies. Two different probability calculations are made, one the probability that 5 randomly distributed impacts occur within a +-8 degree great circle band, and the other the probability that 5 impactors orbiting on an inclined plane impact within +-8 degree of the equator of Mars. In both cases the probability is found to be very small. This led to the conclusion that the basins were most likely produced by fragments of a large heliocentric asteroid that broke apart as it entered the Roche limit of Mars. The asteroid was at least ~9.8×10^{20} kg, ~1.5×10^{-3} times the mass of Mars.

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References

Arkani-Hamed, J., Timing of the Martian core dynamo, J. Geophys. Res., Vol. 109, No. E3, E03006, 10.1029/2003JE002195, 2004.

Arkani-Hamed, J., Paleomagnetic pole positions and pole reversals of Mars, Geophys. Res. Lett., 28, 3409-3412, 2001.

Arkani-Hamed, J., The high-resolution gravity anomaly of the lunar topography, J. Geophys. Res., 104, 11,865-11874, 1999.

Arkani-Hamed, J., and D. Boutin, Paleomagnetic poles of Mars: Revisited, J. Geophys. Res., Vol. 109, No. E3, E03011, 10.1029/2003JE002229, 2004.

Bills, G. B., Venus: Satellite orbital decay, ephemeral ring formation, and subsequent crater production, Geophys. Res. Lett., 19, 1025-1028, 1992.

Bottke, W.F., S.G. Love, D. Tytell, And T. Glotch, Interpreting the elliptical craters population on Mars, Venus, and the Moon, Icarus, 145, 108-121, 2000.

Breuer, D., and T. Spohn, Early plate tectonics versus single-plate tectonics on Mars: Evidence from magnetic field history and crust evolution, J. Geophys. Res., 108, 5072, doi:1029/2002JE001999, 2003.

Dohm, J.M., and K.L. Tanaka, Geology of the Thaumasia region, Mars: Plateau development, valley origins, and magmatic evolution, Planet. Space Sci., 47, 411-431, 1999.

Frey, H.V., Large-diameter visible and buried impact basins on Mars: Implications for age of the highlands and buried lowlands and turn-off of the global magnetic field, LPSC, Abstract 1838, 2003.

Frey, H.V., E.L. Frey, W.K. Hartmann, and K.L.T. Tanaka, Evidence for buried “Pre-Noachian” crust pre-dating the oldest observed surface units on Mars, LPSC, Abstract 1848, 2003.

Frey, H.V., J.H. Roark, K.M. Shockey, E.L. Frey, and S.E.H. Sakimoto, Ancient low lands on Mars, Geophys. Res. Lett., 29, 10, 1384, 10.1029/2001GL013832, 2002.

Gault, D.E., and J.A. Wedekind, Experimental studies of oblique impacts, Proc. Lunar Planet. Sci. Conf., 9, 3843-3875, 1978.

Hartmann, W., and G. Neukum, Cratering chronology and the evolution of Mars, Space Sc. Rev., 96, 165-194, 2001.

Hauck II, S.A.,and R.J. Phillips, Thermal and crustal evolution of Mars, J. Geophys. Res., 107, NO. E7, 10.1029/2001JE001801, 2002.

Hood, L.L., and N. Richmond, Mapping and modeling of major Martian magnetic anomalies,LPSC XXXIII, abstracts 1128, LPI, Houston, 2002.

Hood, L.L., and A. Zakharian, Mapping and modeling of magnetic anomalies in the northern polar region of Mars, J. Geophys. Res., 106, 14601-14619, 2001.

Hood, L.:L., N.C. Richmond, E. Pierazzo, and P. Rochette, distribution of crustal magnetic fields on Mars: Shock effects of basin-forming impacts, Geophys. Res. Lett., 30, 10, 1029/2002GL016657, 2003.

Ivanov, B.A., and O. Yu 1988. Effect of modification of impact craters on the size-frequency distribution and scaling law. *Lunar Planet. Sci.* XIX., 531-532.

Melosh H.J., Tectonic patterns on a reoriented planet: Mars, Icarus, 73, 745--751, 1980.

Melosh, H.J., Impact Cratering, A Geologic Process, Oxford University Press, New York, 1989.

Mohit, P.S., and J. Arkani-Hamed, Impact demagnetization of the Martian crust, Icarus, 168, 305-317, 2004.

Murray, B.C., and M.C. Malin, Polar wandering on Mars?, Science, 197, 997-1000, 1973.

Neukum, G., and D.V. Wise 1976. Mars: a standard crater curve and possible new time scale. *Science* 194, 1381-1387.

Phillips, R.J., et al., Ancient geodynamics and global-scale hydrology on Mars, Science, 291, 2587-2591, 2001.

Reese, C. C., V. S. Solomatov, and J. R. Baumgardner, Survival of impact-induced thermal anomalies in the Martian mantle, *J. Geophys. Res.*, 107, 10.1029/2000JE001474, 2002.

Schubert, G., and T. Spohn, Thermal history of Mars and the sulfur content of its core, J. Geophys. Res., 95, 14095-14101, 1990.

Schultz, P.H. and A.B. Lutz, Polar wandering of Mars, Icarus, 73, 91-141, 1988.

Schultz, R.A., and V. Frey, A new survey of multiring impact basins on Mars, J. Geophys. Res., 95, 14,175-14,189, 1990.

Schultz, P.H. and A.B. Lutz-Garihan, Grazing impacts on Mars: A record of lost satellites, J. Geophys. Res. Suppliment, 87, A84-A96, 1982.

Solomon, S.C., and J.W. Head, Evolution of the Tharsis province of Mars: the importance of heterogeneous lithospheric thickness and volcanic construct, J. Geophys. Res., 87, 9755-9774, 1982.

Spada, G., R. Sabadini, and E. Boschi, Long-term rotation and mantle dynamics of the Earth, Mars, and Venus, J. Geophys., Res., 101, 2253-2266, 1996.

Spohn, T., et al., Geophysical constraints on the evolution of Mars, Space Sci.ev., 96, 231-262, 2001.

Tanaka, K.L., J.M. Dohm, and T.R. Watters, Possible coronae structures in the Tharsis region of Mars, Lunar and Planet. Sci., XXVII, 1315-1316, 1996.

Willemann, R.J., Reorientation of the planets with elastic lithosphere, Icarus, 60, 701-709, 1984.

Yuan, D.N., W.L. Sjogren, A.S. Konopliv and A.B. Kucinskas, Gravity field of Mars: A 75th degree and order model, J. Geophys. Res., 106, 23377-23401, 2001.

Zuber, M.T., and D.E. Smith, Mars without Tharsis, J. Geophys. Res., 102, 28,673-28,685, 1997.

Table 1. The centers of the giant impact basins and the radii and masses of their projectiles. Lat and Long stand for latitude and longitude.

Basin	This paper		Shultz & Frey (1990)		Projectile	
	Lat (Deg.)	Long (Deg.)	Lat (Deg.)	Long (Deg.)	Radius (km)	Mass (10^{20} kg)
Argyre	-50	317	-50	318	130	0.28
Hellas	-41	64	-43	69	285	2.91
Isidis	12	86	13	88	185	0.79
Thaumasia	-23	272	---	---	285	2.91
Utopia	36	117	48	120	285	2.91

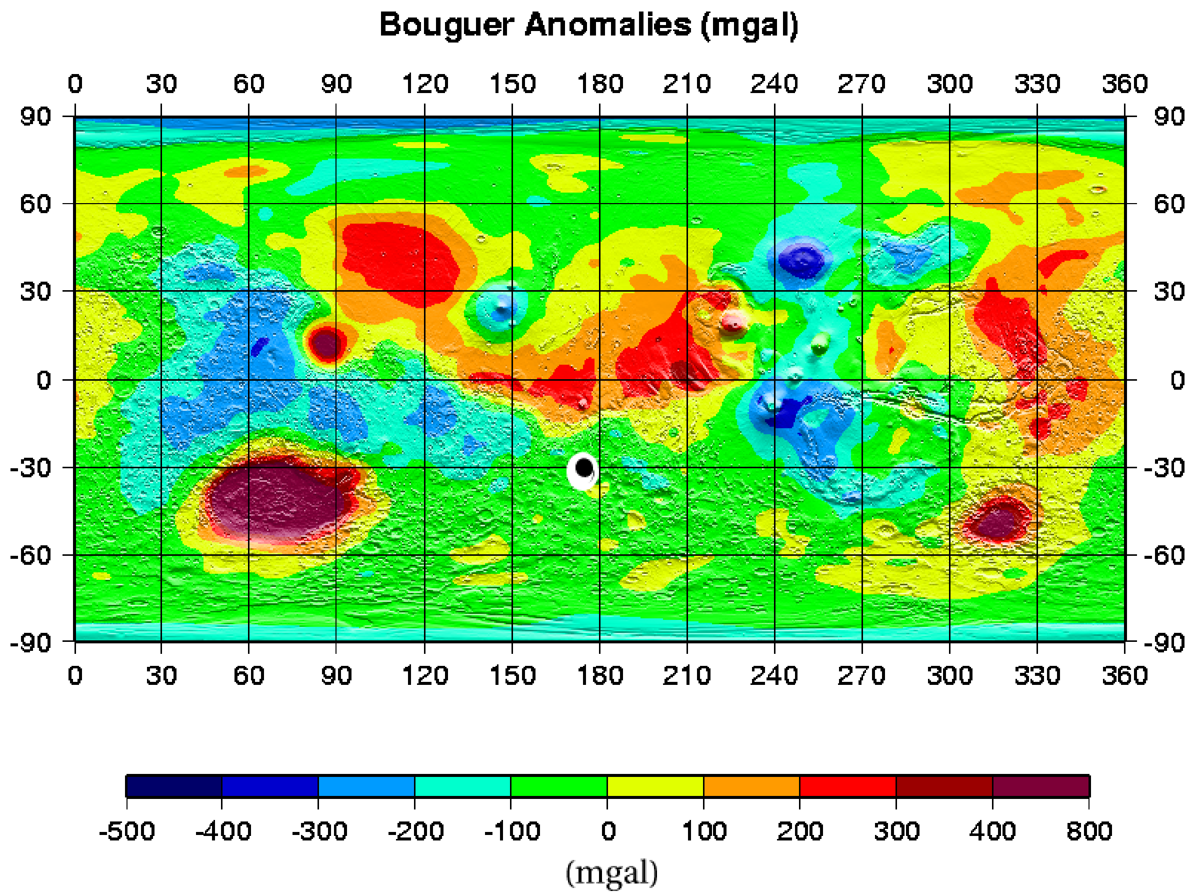
Table 2. The south poles of the great circles, and latitudes of the basins relative to the circles. A =Argyre, H = Hellas, I = Isidice, U = Utopia, and T = Thaumasia. Lat and Long are latitude and longitude. σ is the standard deviation of the basin center latitudes relative to the corresponding great circles. The last column, Latitude, denotes the latitudes of the small circles fitted to the basins. Latitudes and longitudes are in degrees.

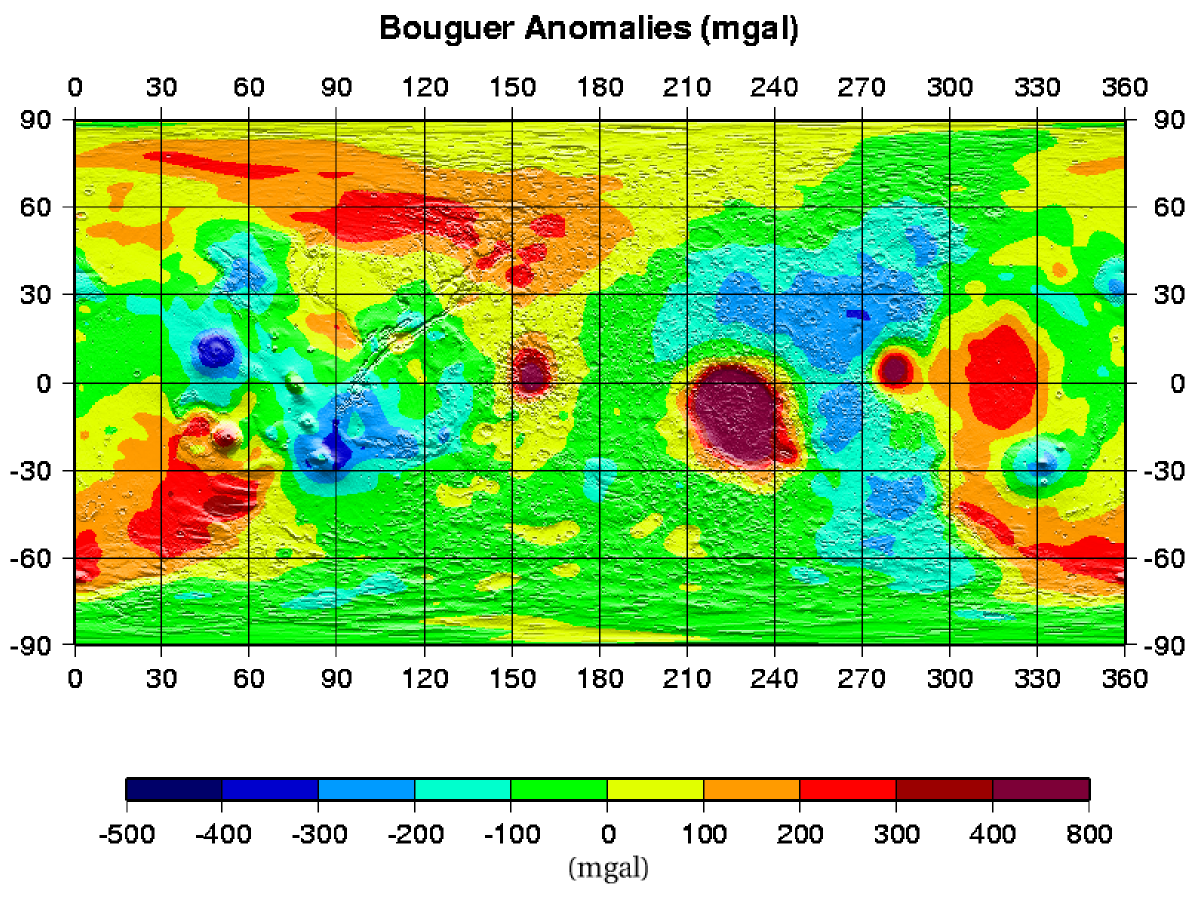
Basins fitted	Shultz & Frey		This paper		Latitude of the basins (this paper)						
	Lat	Long	Lat	Long	A	H	I	T	U	σ	Latitude

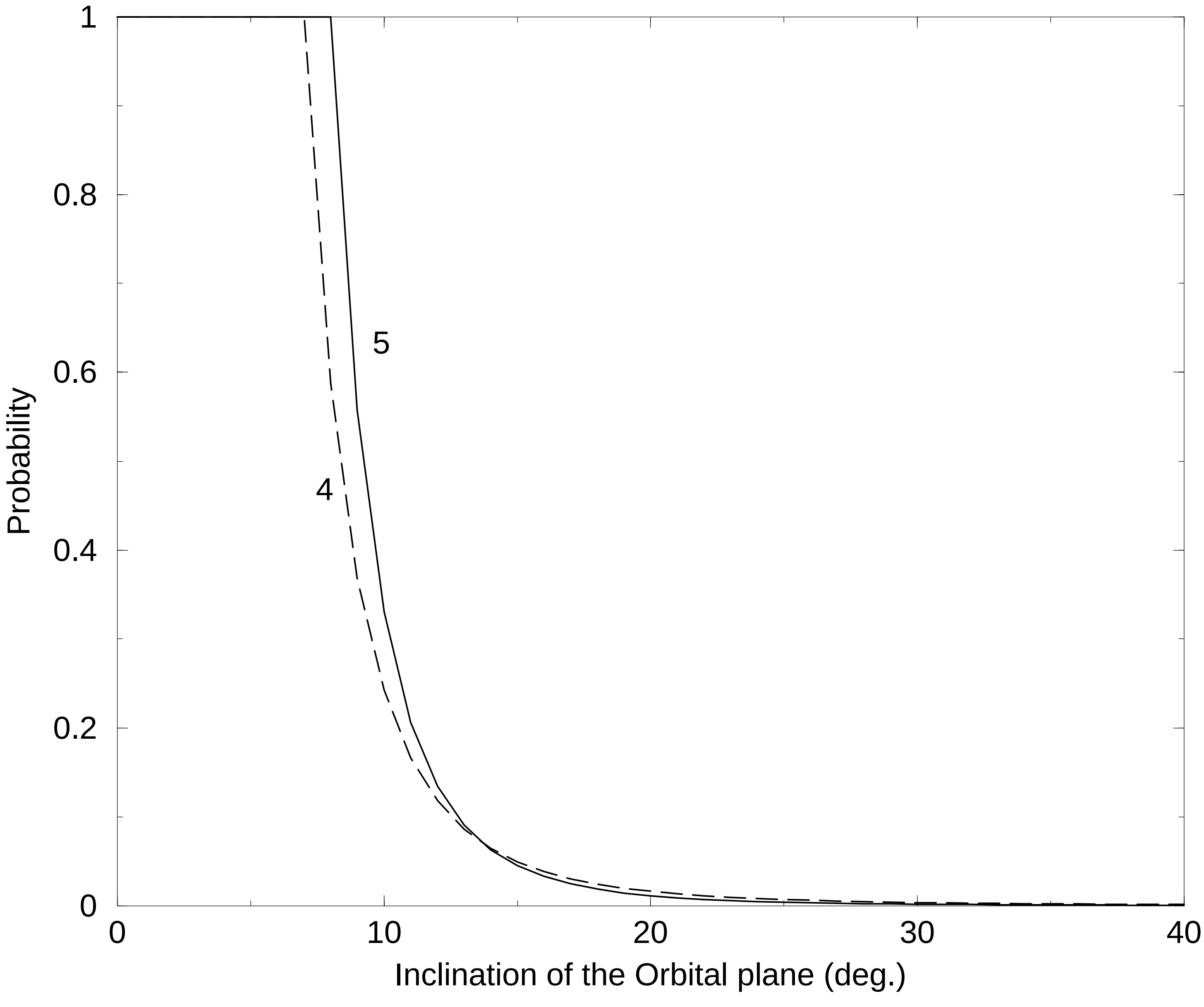
A+H+I	-29	178	-30	175	2	-6	5	-6	-5	5.6	12.2
A+H+I+U	-28	177	-32	176	1	-6	6	-7	-2	5.6	-0.5
A+H+I+U+T	-28	174	-32	174	2	-8	4	-6	-4	5.8	-2.9

Figure 1. a) The Bouguer anomaly map of Mars at present. The black dot at latitude -30 and longitude 175 is the pole of the great circle fitted to all 5 basins. b) The Bouguer anomaly map rotated to make the equator coincide with the great circle determined using all 5 giant basins.

Figure 2. The probability that projectiles on an inclined plane impact inside an equatorial band defined by (+-)λ_{max}. The numbers on the curves denote the number of projectiles. λ_{max} is 8 degrees for 5 projectiles and 7 degrees for 4 projectiles.


Bouguer Anomalies (mgal)
0 30 60 90 120 150 180 210 240 270 300 330 360
90 60 30 0 -30 -60 -90
-500 -400 -300 -200 -100 0 100 200 300 400 800
(mgal)


Bouguer Anomalies (mgal)
0 30 60 90 120 150 180 210 240 270 300 330 360
90 60 30 0 -30 -60 -90
-500 -400 -300 -200 -100 0 100 200 300 400 800
(mgal)


1
0.8
0.6
0.4
0.2
0
Probability
0
10
20
30
40
Inclination of the Orbital plane (deg.)
5
4