# Planet Mercury

**Audouin Dollfus**

Observatoire de Paris, Section D'Astrophysique, 5, Place Jules Janssen, 92195-Meudon Principal Cedex, France

**Planet Mercury, analysed by telescopic observations over two centuries, and by spacecraft Mariner 10 during three flybys in 1974–75, has a diameter of 4878 km, a density of 5.44 g/cm$^3$ and a rotation period of 58.67 days, which is exactly two thirds of its orbital period. Its interior is made of very large iron cores representing 42% of the total volume and 75% of the planetary radius, a silicaceous mantle and a crustal surface. This surface is comminuted in a layer of very small siliceous fragments resulting from pulverization by impacts of all size meteoroids. It displays impact craters, randomly superimposed, as for the lunar surface. There are extended, darker and lower plains, compression ridges and the cataclysmic huge basin Caloris Planitia, multi-ringed, fractured and partly flooded. A reconstitution of the different phases of evolution of the planetary body is attempted, since its primordial accretion up to its present stage.**

BY the end of the present century, the knowledge already gathered about the planets and satellites in our solar system is the result of two approaches which mutually added to their outcomes. On the one side, a slow, progressive, continuous, meticulous accumulation of data from telescopic observations, which extended already other two centuries. On the other side, the explosive, short, dense, intensive releases of few selected space missions well targeted for specific goals.

For the case of Mercury, there was only one mission already achieved, but the spacecraft involved, Mariner 10 flows by Mercury over three successive occurrences on 29 March 1974, on 21 September 1974 and on 16 March 1975.

For each of these two methods of investigation, the total investments, the overall efforts and the sum of talents exhibited could be compared. The respective scientific releases were of similar fundamental values, but their implementation entered into completely different time scales, centuries for the telescopic observations, a single year for space missions.

## Orbital characteristics

The precise determination of orbital elements for planet Mercury (Table 1) resulted from the accurate meridian-circle telescopic observations, carefully conducted all along the last century. An important input was also the precise timing of the contacts with the solar limb when the planet was observed as a dark spot in front of the solar disk, a rare but important event The history of these positional astronomy telescopic observations remains to be reviewed. With the very large eccentricity of $e = 0.205$, the orbit of Mercury is inclined by $i = 7°$ and the mean distance to the sun is 57.9 million km. At perihelion, the distance is $45.9 \times 10^6$ km, at aphelion it reaches $69.7 \times 10^6$ km. The orbital period is P = 87.97.

The solar globe oblateness produces a drift in the heliocentric longitude of the perihelion. The amount was observed to be 5600 arcsec/century and was found to exceed by 43 arcsec/century the value calculated by newtonian celestial mechanism, a discrepancy which was for long considered an enigma. The French astronomer Urbain Le Verrier tried to interpret it by the effect of a yet unknown new planet, located closer to the Sun than Mercury itself. He calculated some orbital elements and prematurely assigned to the new planet the name 'Vulcain'. This shift in the perihelic longitude of Mercury is now completely explained by the theory of relativity for which Einstein gave the principle in 1915.

The determination of the celestial coordinates of the small asteroid Eros, based upon photographic astrometry

**Table 1.** Planet Mercury

| | | |
|---|---|---|
| Orbit. | Semi-major axis | $a$ = 57 900 00 km<br>= 83 solar radii<br>= 0 357 AU |
| | Eccentricity | $e$ = 0 207 |
| | Inclination | $i$ = 7 0° |
| | Revolution period | Sideral Pr = 87 969 days<br>Synodic Ps = 115 88 days |
| | Rotation period | 58 646 days |
| Diameter | 4878 km<br>0 387 Earth radii | |
| Mass | 330 × $10^9$ tons<br>0 0553 Earth mass<br>1/6 023 000 solar mass | |
| Density | $f$ = 5 43 | |
| Gravity | $g$ = 363 cm s$^{-2}$<br>= 0 38 Earth gravity | |
| Escape velocity | 4 3 km s$^{-1}$ | |

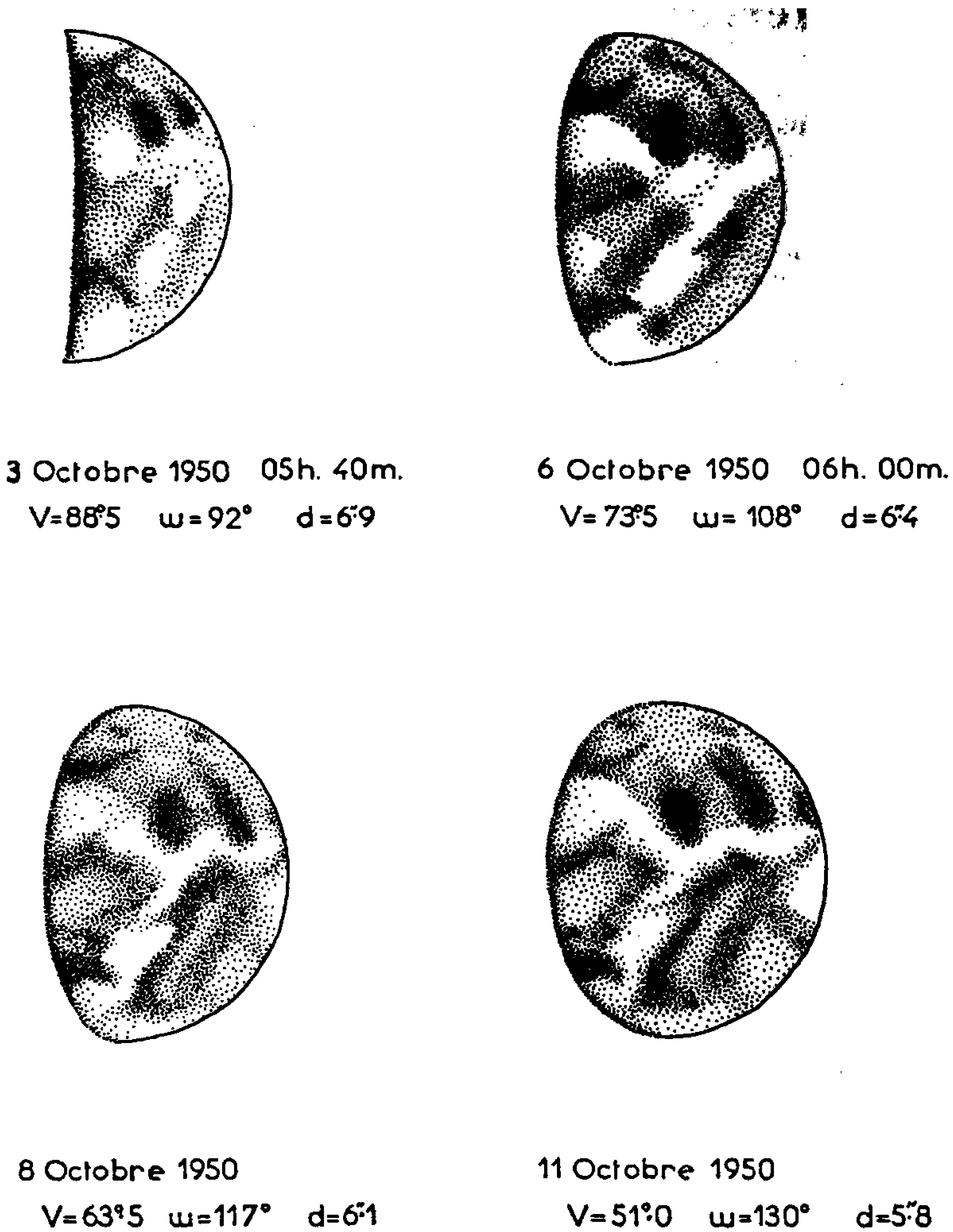


Figure 1. Telescopic aspect of Planet Mercury 24″ refractor at Pic-du-Midi, France, magnification 900 by Audouin Dollfus South is up

conducted when the small body reached its minimum distance to the Sun not far from planet Mercury, discloses some anomalies which were rightly attributed to the gravitational effect of Mercury. Their analysis enabled the German astronomer Rabe to derive the mass of the planet and was found to be 1/6.120.000 the mass of the Sun or $3.21 \times 10^{29}$ grams. The value was slightly refined later when the spacecraft Mariner 10 flew by Mercury.

### Size of the globe

Observed not far from the very bright Sun, in the twilight, low above the horizon, far from the Earth, Mercury is not a planet for which a telescopic determination of diameter is easy to secure. Altogether, with the filar micrometer, the heliometer, the measurements during transit over the solar disk, after 70 years of survey, sixteen values were available in 1950, but their disagreement was as large as 3%, giving an uncertainty of 10% in the volume and accordingly to the density. This very large margin made meaningless any deduction about internal structure or composition of the globe.

However, taking benefit of the opportunity on the 7 November 1960 transit of Mercury, when the planet was seen as a black disc over the bright solar disk, an international cooperation among five Observatories coordinated by the International Astronomical Union and Observatoire de Paris, combined the techniques of double image micrometry and of black disk photometry, to derive the diameter 4840 km, with an accuracy of 1%. This value was still improved 15 years later with the spacecraft Mariner 10 with 4878 km.

The mean density of the globe was found to be as high as 5.44 $g/cm^3$ to be compared with earth's value 5.52 $g/cm^3$ for a far larger volume, and the consequences will be developed below.

### Rotation of the globe

To scrutinize at the telescope the main features glanced at the surface of the planetary crescent, to reproduce them and to identify their configurations have been for long talented achievements. By the end of the last century, the Italian Giovani Schiaparelli recognized periodically some characteristic features and, in 1889, risked the proposition that the rotation period be the same as the orbital revolution of the planet around the Sun, which is 88 days. In this configuration, the planet faces the Sun always with the same hemisphere as for the case of the Moon with the Earth.

Fortyfive years later, working with the great refractor at Meudon Observatory in France, the Greek Eugen Antoniadi announced a confirmation and published a map on the mercurian surface features which were very similar to the one given by Schiaparelli. The 88 rotation period was claimed as a demonstrated result, although some astronomers like George Fournier, on the basis of his own numerous observations with the Jarry-Desloges telescopes, expressed serious reservation.

From the French high altitude Pic-du-Midi, in 1942, Bernard Lyot achieved sequences of exceptional visual observations, while Henri Camichel recorded for the first time the surface features on photographs. The agreement with Antoniadi was not obvious. In 1950, with the larger refractor yet operational at Pic-du-Midi, the author of these lines detected at the surface of Mercury features not larger than 300 km, with a magnification of 900, a new scale in the approach. The configurations identified by Bernard Lyot were seen again, sharpened in their details.

During the following period, due to the outstanding developments of the new born radar astronomy, the Americans Gordon Pettengill and Ralf Dyce detected, and then analysed, the echos over Mercury of the radar

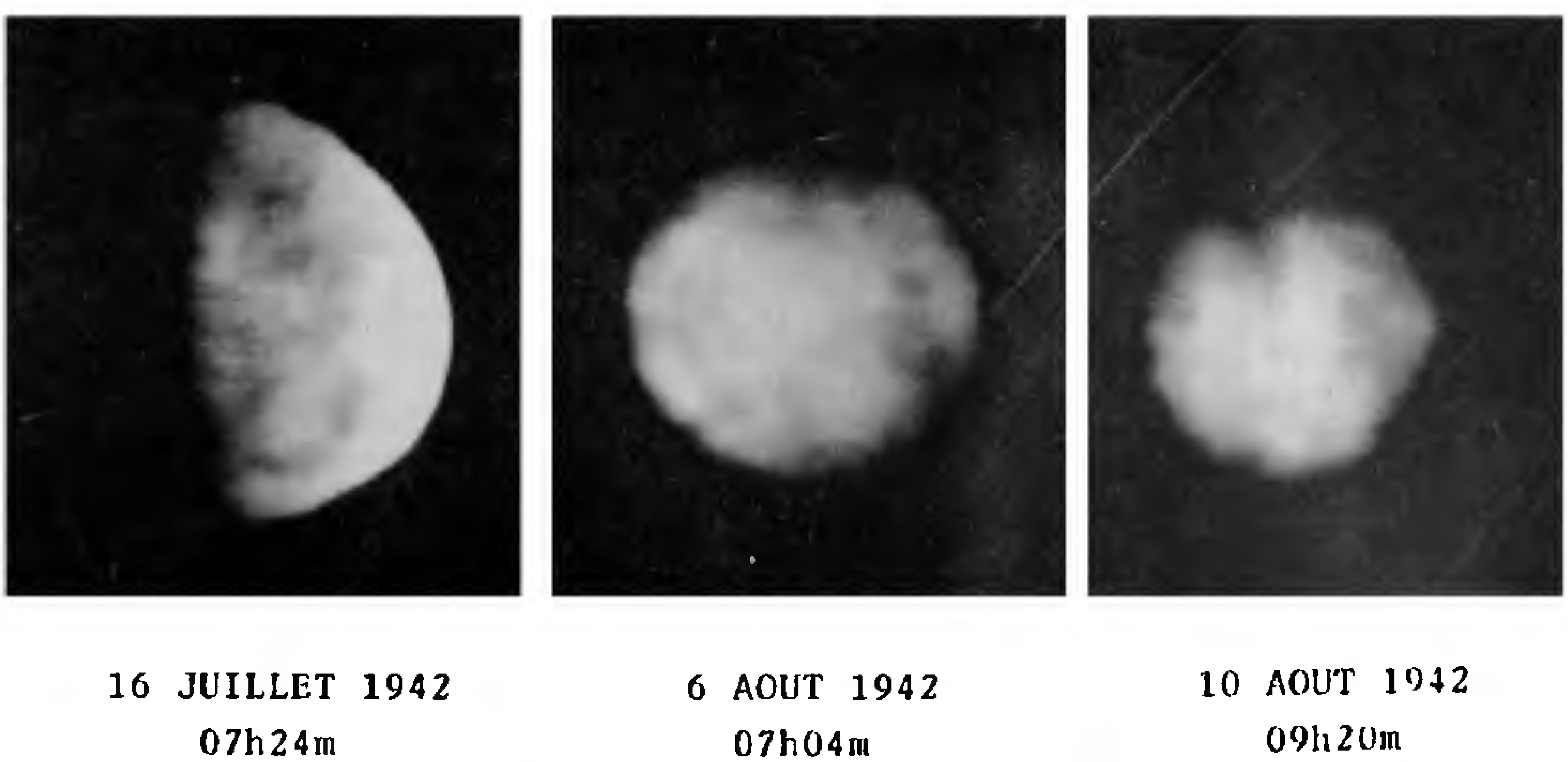


Figure 2. Photographic images of features at the surface of Mercury 15" refractor at Pic-du-Midi by Henri Camichel. The original documents were digitalized and processed for high resolution enhancements at Observatoire de Meudon, France. South is up.

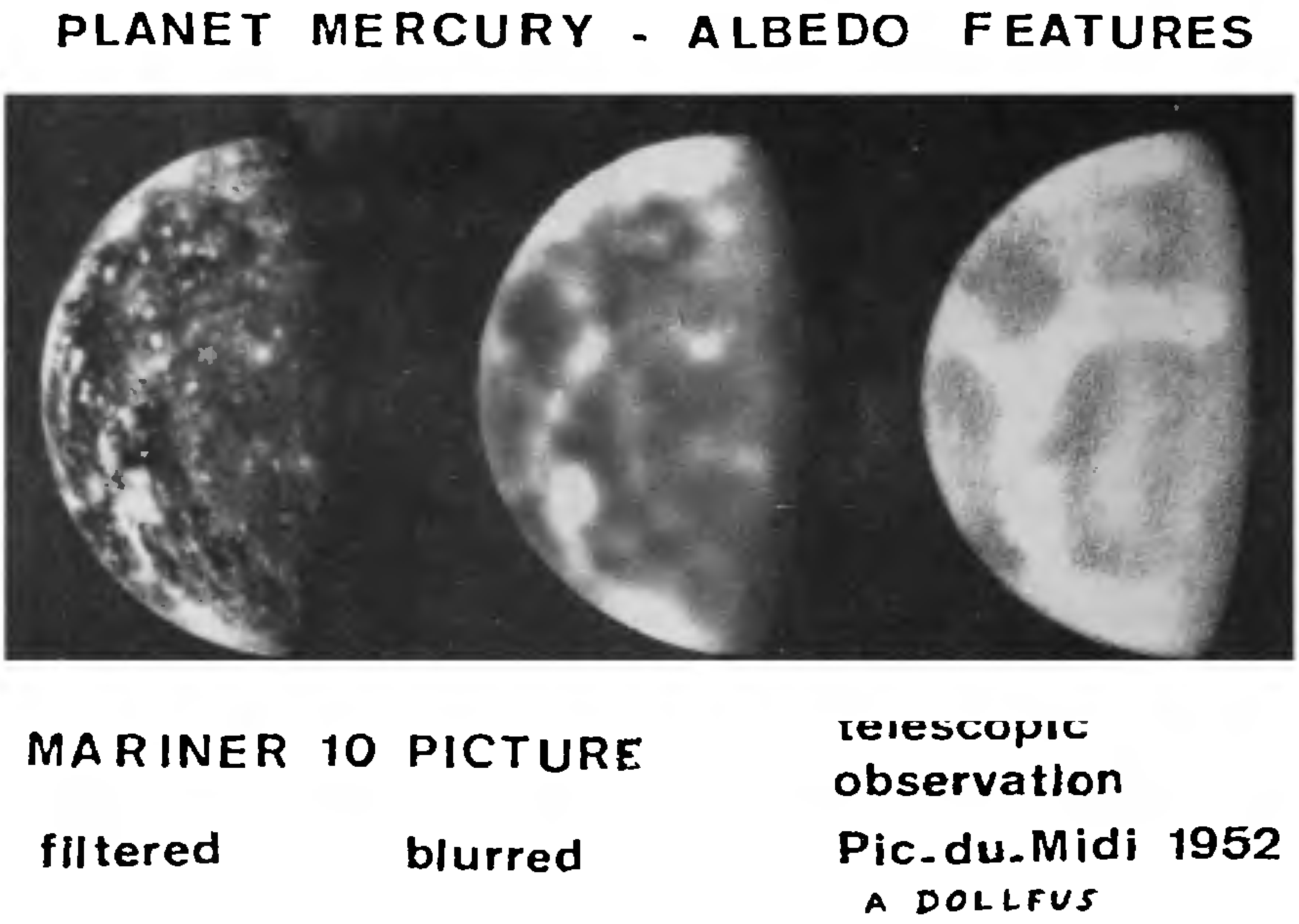


**Figure 3.** Surface of Mercury Comparison of telescopic observations with spacecraft images Left Mariner 10 image (1974) processed to remove the phase effect on luminance Centre same Mariner image, further processed to blur the resolution and enhance the contrast Right Telescopic observation at Pic-du-Midi for the same presentation

signals emitted by the large antenna disk of Arecibo. The Doppler broadening of the pulses was interpreted as produced by a rotation in 59 ± 3 days.

At the same time, the Italian Guiseppe Colombo demonstrated that a resonance 3/2 could be at work under the effect of the solar tidal forces acting upon the rotation of the globe. The radar value of 59 days suggested that such may well be the case. In such conditions, around the epoch of mercurian passages near perihelion, the planet faces the Sun alternatively with a given hemisphere and then at next passage with the opposite hemisphere.

A reanalysis of the whole telescopic surface marking observations of Schiaparelli from Milan, and Antoniadi from Meudon, exhibited the consequences of a selective stroboscopic effect between the rotation period and the epochs during which the planet was suitably placed in the sky for telescopic observations, with the consequence that the same areas were reobserved each time. At Pic-du-Midi, the observations made on daytime needed different constraints and presented another part of the planet, which were reobserved twice the same, 8 years apart by Bernard Lyot and by Audouin Dollfus.

After 1965, in order to break this stroboscopic effect, Audouin Dollfus selected different epochs of observations with the Pic-du-Midi telescope, and then was able to analyse the different faces of the planetary globe. The surface markings were seen to drift over the disk in agreement with a rotation period of exactly 58 67 ± 0.03 days, which is precisely 2/3 the orbital period.

## Surface feature configurations

The visual observations at Pic-du-Midi, the photographic documents by Henri Camichel, those also recorded in USA at New-Mexico State University by Bradford Smith, altogether offered a complete coverage of the planetary surface. A cartography with coordinate references was derived in 1967. The nomenclature for these albedo features, inspired by mythologic names related to the God Mercury, was endorsed by the Inter-

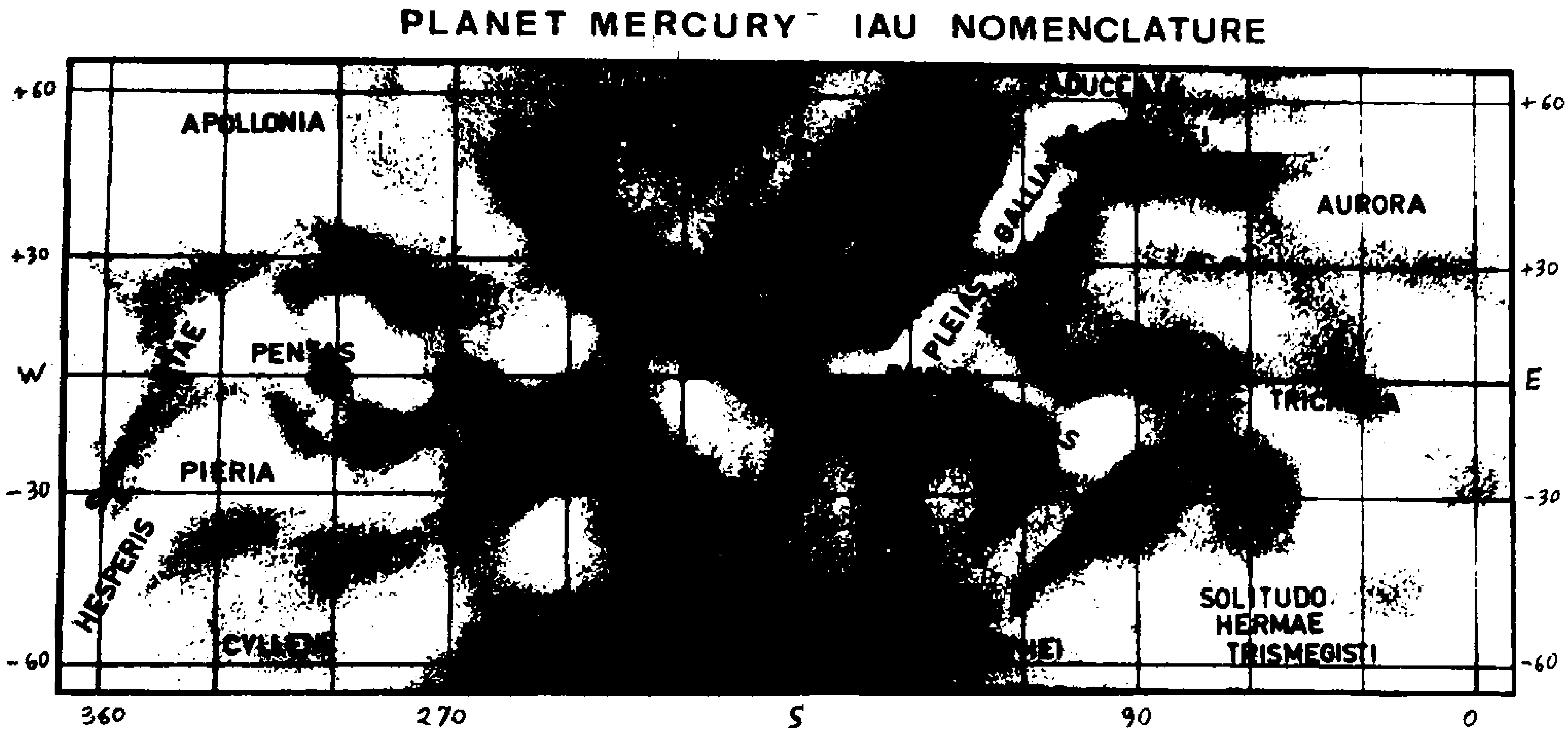


Figure 4. Mercury Map of the albedo features from the Pic-du-Midi visual and photographic observations, by H Camichel, A Dollfus and J Murray North is up Nomenclature according to International Astronomical Union

national Astronomical Union in 1978 and was implemented for Mariner 10 spacecraft observations, although the spacecraft coverage is limited to only one half of the planetary surface. The other hemisphere remains yet only known by the telescopic observations.

## Soil surface texture

In 1929, when the French astronomer Bernard Lyot initiated polarimetry for the study of planetary surfaces, he found that Mercury polarized the light almost identically to the case of the Moon. The two planetary bodies must have the same soil surface texture. Later, the method was developed extensively at Meudon Observatory by Audouin Dollfus. Mercury, like the Moon, has to be covered with a dusty layer of small grains. The small fragments of this so-called regolithic layer were interpreted as resulting from the long-term comminution of the rocks under the effect of impacts by meteoroids and other objects wandering through the solar system and crashing at the surface of Mercury. This effect was considered as implying the presence of impact craters at the surface of Mercury, as for the case of the Moon. But, despite careful searches, they remained out of power for the best Pic-du-Midi telescopes.

The cameras on board the spacecraft Mariner 10 disclosed the craters indeed. In addition, it appeared that the temperature remains constant around + 75°C at a depth of around 1 meter below the surface, although strong thermal variations occur, between – 185°C and + 430°C, at the top surface. The effect of the dust layer is also recognized here, as a result of its low thermal conductivity.

The albedo of the light hued terrains is around 0.144 as demonstrated by polarimetry. The spectrum recorded by the American Thomas McCord is rather flat and reminiscent of the lunar terra surfaces. It characterized a composition similar to the lunar crust. The dark patches produce an albedo of 0.122 which remains slightly lighter than for the lunar mare basaltic terrains.

## Surface morphology

Three successive fly-bys of the planet by the same spacecraft Mariner 10 disclose surface topographies with a resolution similar to the best telescopic images of the Moon. Only half of the planetary surface has been analysed, however. The analogy with the case of the Moon is impressive.

*Impacts craters* are widespread and often superimposed in a way almost identical to the case of the Moon. Densities and size distributions are the same. Careful analysis of crater morphologies recognize the effect of an higher average velocity for the impacting body in this part of the solar system, but essentially the effect of the

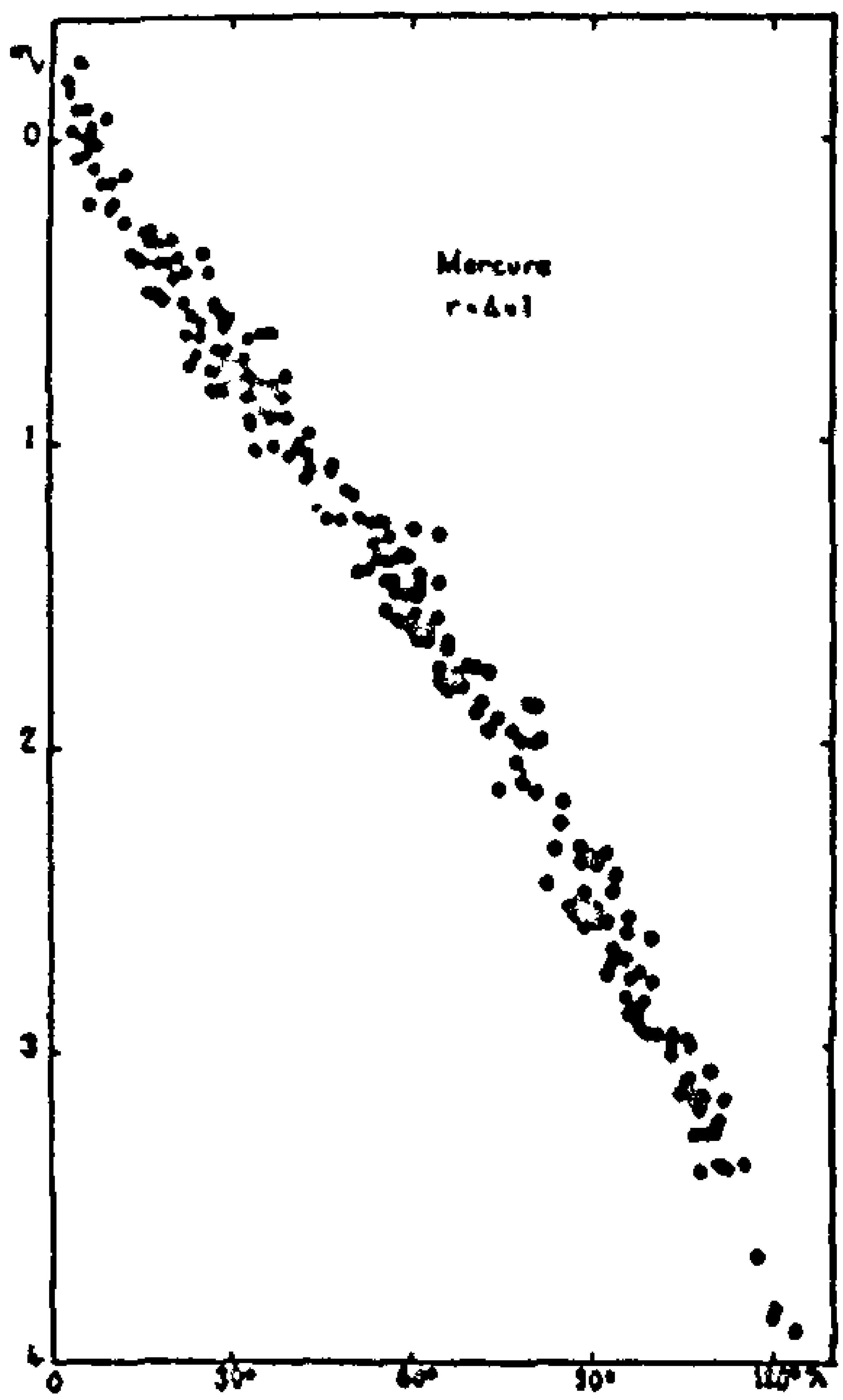

Figure 5. Mercury Photometric curve Variation of magnitude with phase angle (at 1 AU from Sun and Earth), from André Danjon This curve is similar to the case of the Moon and characterizes a same type of very rough terrain

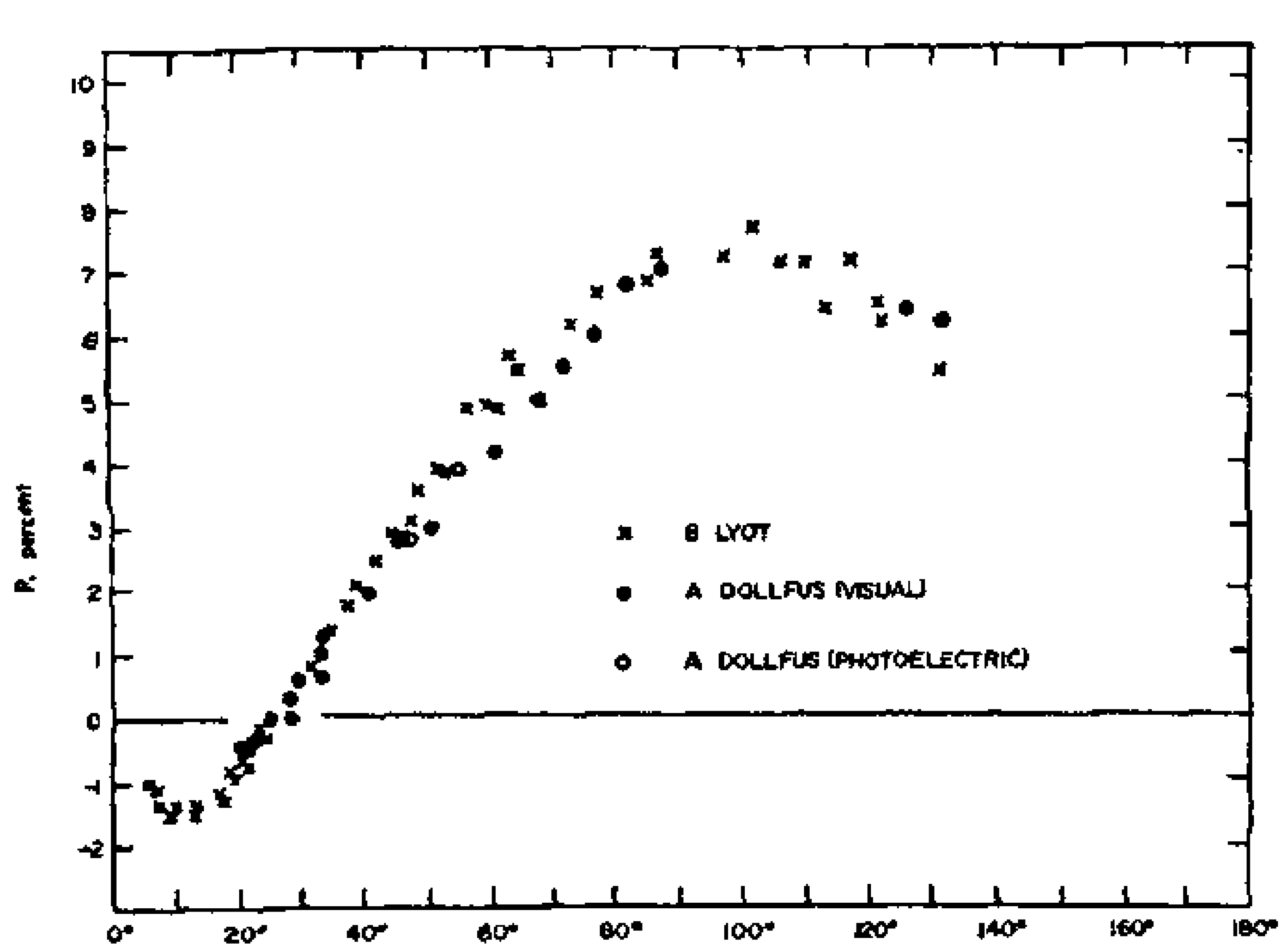


Figure 6. Mercury Polarization curve Variation of the degree of linear polarization with phase angle, from Bernard Lyot and Audouin Dollfus This curve characterizes a finely divided and cohesive dusty soil, as for the Moon.

higher planetary gravity, which shorten the range of the fragments ejected at impact. Aureolas, rays and secondary impact scars remain closer to the rim of the crater itself than for the case of the Moon.

All these craterization characters attest for the intense collisional episode which operated during the initial solidification of the crust. Ubiquitously at work in every part of the solar system, this phase of cosmic evolution did not exclude planet Mercury. We know that the collision rate decreased rather steeply. The number of projectiles remaining was already reduced some 3.8 million years ago. But the effect is still at work presently at a very reduced rate, and micrometeoroids continue to rejuvenate the surface layer of regolith.

*Plains* extend over a large fraction of the surface. They are slightly darker hued than the old terra crust, at lower altitude by 1–3 km, smoother and less densely craterized because they are more recent. These terrains are not duplicate of the dark 'Mare' regions of the lunar surface, which are basaltic flows dating from after the termination of the intense bombardment phase. The plains result rather for the spreading of extruded molten rocks, older than the basaltic lunar events, and possibly contemporaneous of the period of intense bombardment itself.

*Compressional ridges* are detected in every type of terrains over the fraction of the planetary surface already explored by Mariner 10. But, conversely, there is no trace of extensional features. The information is that the crust experienced an overall global compression. A possible explanation is related to the presence, at the centre of the globe, of a very large metallic core, as will be demonstrated below. Metals have a larger thermal dilatation coefficient than silicates. During the overall cooling phase of the planet, the core sinked in volume more than the crust was able to afford, producing a readjustment of its surface by compressional features, as observed.

There is, at the surface of Mercury, the remnants of a very remarkable event. *Caloris planitia*, a huge circular basin, has a diameter as large as 1300 km. Only half of this fantastic feature was exhibited by the Mariner 10 cameras, the other half, in darkness, was not illuminated by the Sun during the observation. The feature, despite its size, is not unique in the solar system. There is Orientale planitia on the Moon, Hellas planitia on Mars, of approximately the same size. They attest for the occurrence of late catastrophic collisions, at a relatively low velocity, with rather large objects which remained in the solar system. Around Caloris basin, there are several concentric rims. A double net of radial and tangential fractures attest for the readjustment of the basin from after impact, with down sink followed by an uplift. The bottom floor of the basin was invaded with lavas pulling by extrusions through the fractures.

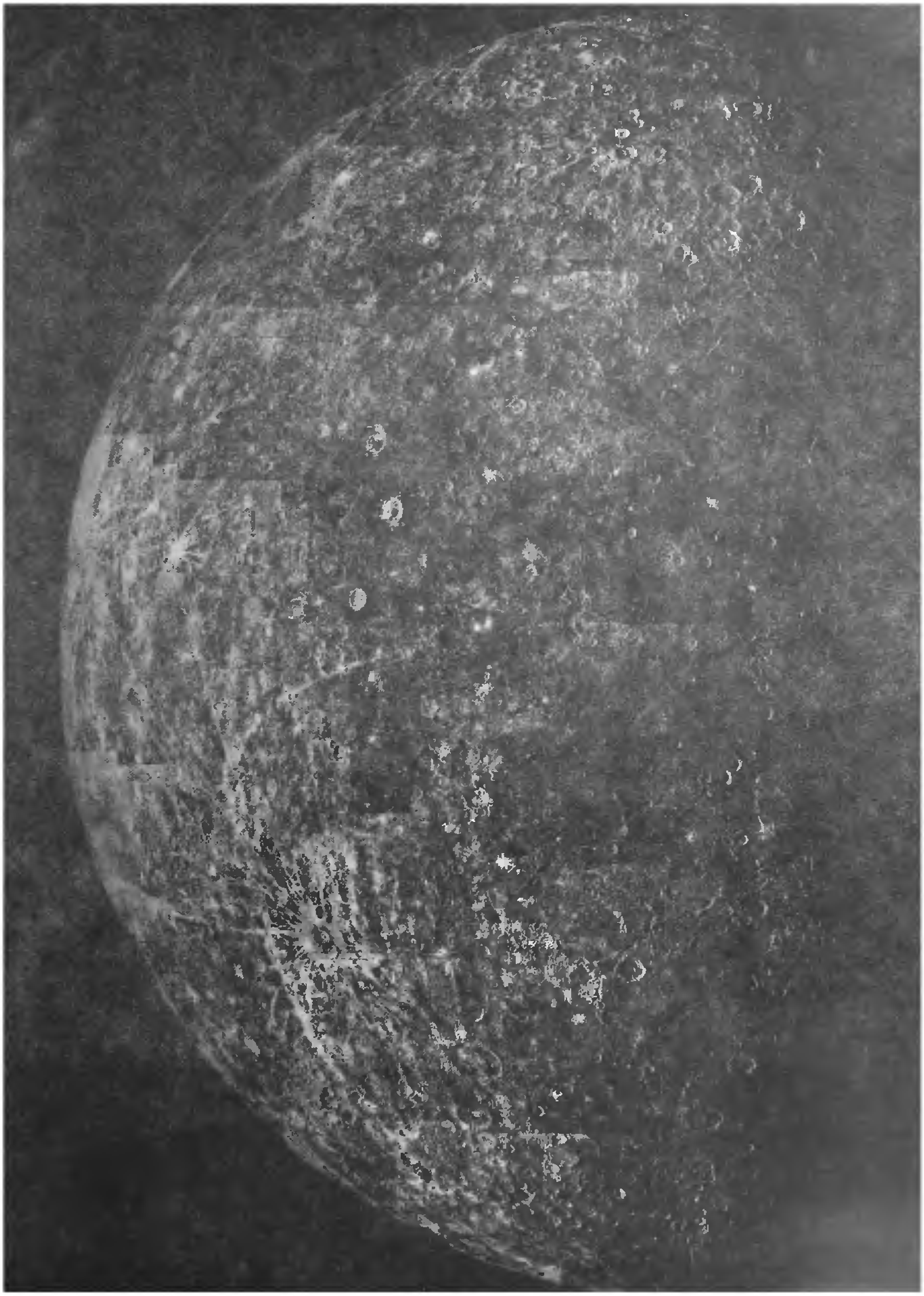

Figure 7. When approaching Mercury on 29 March 1974 spacecraft Mariner 10 discloses a planetary body covered with craters of all sizes and randomly distributed, very reminiscent of the lunar telescopic aspect (Document NASA.)

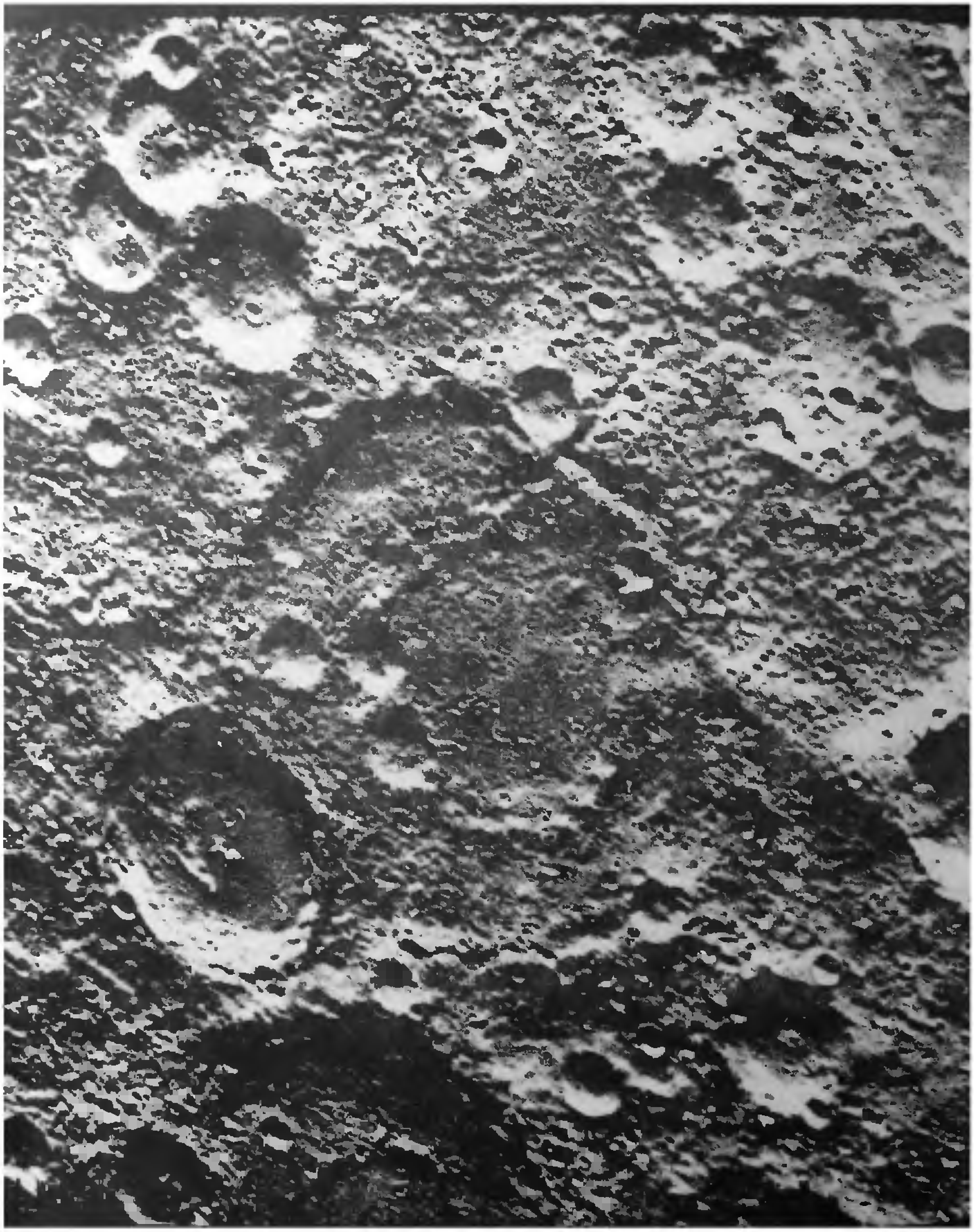

Figure 8. The old crust was subjected, since its solidification and during more than 4 billion years, to the bombardment by solid bodies wandering within the solar system. When hitting the planet, the craters which were formed accumulated at random, with all sizes often superimposing previous features, erasing and replacing older reliefs (Document NASA.)

Figure 9. Taken at a distance of 55 000 km this Mariner 10 image discloses two adjacent types of terrains at the surface of Mercury. At bottom, the old crust is heavily cratered. At top, a smooth plain which is thought to be volcanic in origin, with successive pourings of fluid lava flows (Document NASA)

Exactly at the antipodal region of the impact point, on the Mercury globe, the terrain is observed to be violently broken and chaotic. The seismic waves produced at impact travelled through the mantle and focused at the opposite point to produce this cataclysmic seismic disturbances.

## Interior of the globe

We reported already that the mean density of the globe reaches 5.44 g/cm$^3$. In order to derive the nature and composition of this globe, the internal pressure effect is to be considered. Near the centre, the pressure decreases the distance between the molecules, with the net effect of increasing the density. After computed correction for this effect, the mean density of the mercurian material shifts to 5.3 g/cm$^3$. This value is very high. In the same conditions, the Earth, a particularly dense planet, reached only 4.4 g/cm$^3$. The silicates produce 2.4 and the ferrous metals 5.5. The composition of Mercury must include a large amount of iron, by the presence of a large size metallic core. For the Earth, the ferrous core involves 16% of the total volume and occupies 54% of the radius. On Mercury, the metallic part represents 42% of the volume and covers 75% of the planetary radius.

Convection within the interior of a planetary globe is known to produce magnetic field. Spacecraft Mariner 10 detected a dipole type magnetic field around Mercury of a terrestrial type but weaker. A convective process is advocated, within the outer shelves of the conductive metallic core. It implies that the large mercurian metallic core must still be rather fluid, at least in its

Figure 10. This 120 km diameter fresh crater was photographed by Mariner 10 from a distance of 34,000 km. The material ejected at impact deposited closer to the rim than for similar events on the Moon. The gravitational field is 2.3 times greater than on the Moon and limited the range of the ballistic ejectas. (Document NASA.)

outer parts. But theoretical computations predict, however, that a pure iron core need less than four billion years to be completely solidified and should be rigid now. Impurities within iron decrease the solid state critical temperature and sulphurs are the relevant candidates. The implication is for a core made of iron, but including several percent of sulphurs.

## Planetary formation

On the basis of these results, one can realistically attempt to reconstruct the sequence of events which led to the initial formation of the planetary body. One can also derive and still more safely, the subsequent episodes of the planetary evolution.

A detailed description of the accumulation processes which assembled the material initially spread among the circumsolar envelope to produce the planetary embryo is not yet at hand.

But a simple cosmochemical consideration, first advocated by John Lewis in 1972, then further improved, assumed that the primordial proto-planetary nebula had a same uniform initial elemental composition on every part, irrespective of the distance to the Sun. This composition is the same as for the Sun itself and is also recognized on the giant planets except for hydrogen which escaped in part during the accumulation process. But when the central proto-Sun initiated ignition, a temperature gradient appeared within the large disk. Far from the Sun, the low temperature permitted solidification of all materials including the most volatile


Figure 11. The compressional ridges which is seen at right in this Mariner 10 image is a common type of feature at the surface of Mercury. A contraction of the inner part of the globe is required. The large metallic core, when cooling, is able to reduce significantly its volume (Document NASA.)

molecule $H_2O$ which formed the major constituent of the multitude of satellites and cometary icy bodies. But, within the inner parts of the proto-solar system, the higher temperature excluded formation of the too volatile condensates, and solid bodies were produced essentially with the most refractory elements. Accordingly, silicates and metals are the dominant components of the internal planetary bodies, the so-called telluric planets.

All went very well with this interpretation, down to Mercury. Here, the very large excess of iron departed. Adaptations or refinements were required. In 1978, Stuart Weidenschilling risked the idea that, during the first collisional processes which occurred between the

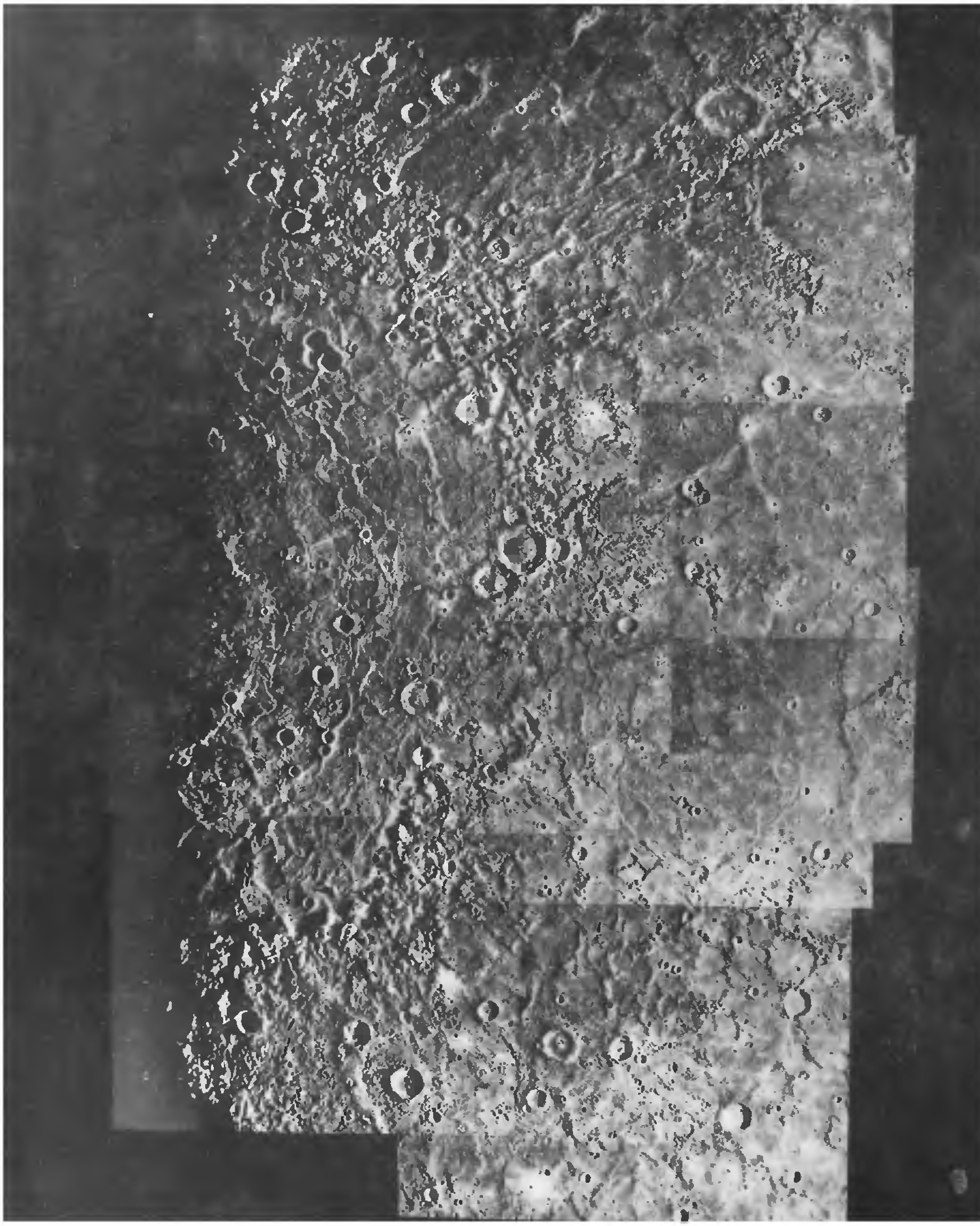

Figure 12. 'Caloris' basin, which is partly seen at the terminator at left, is 1300 km in diameter. The projectile which produced the impact had to have several tens of kilometers in size. Several concentric remparts, more than 2 km high, are circling the feature. Radial as well as tangential fractures are also formed. (Mosaic of 18 images of Mariner 10, Document NASA.)

very first globules resulting from the primeval condensates, the lightest aggregates could be preferentially expelled outward to reach the outer part of the protoplanetary nebula, but the heavier metallic elements remained; Mercury was formed by the accumulation within this metal-enriched environment. Other scientists suggested that, after the first phase of its formation, the Sun encountered a short but intense period of instability, like the T Tauri type stars. The torrential outflow of radiations and particules could have partly volatilized the silicaceous mantle of Mercury, thus eliminating part of the silicates without changing the iron core volume. But yet more recently, a new idea made its way, along the new theory now advocated to explain the formation of the Moon. A collision occurred, very early, between two proto planets already independently accreted at the same distance to the Sun. At impact, the lightest elements are the easiest to be lost. George Wetherill analysed the problem mathematically in 1988 with some success.

## Subsequent evolution

Following the initial accretion phase, the fluidal property of the new born globe permitted the heavier elements to percolate toward the centre, but the lightest elements to reach the surface, in compliance with the so-called differentiation process. So was born the core. The potential energy thus released added a contribution to the heating produced by radioactivity and the resulting temperature maintained a certain fluidity, except near the top surface where cooling by radiations produced a solid crust. On the crust were accumulated the traces of hits by the relique pieces of the multi-body accretion process. The large number of small bodies, simultaneously formed in this part of the proto-solar system, acting as projectiles, punched the surface with numerous craters.

The crust cooled initially more rapidly than the inner part of the globe and contracted more than its molten floor, thus producing the opening of fractures. Through them, the underlying fluid silicaceous material found ways to reach the surface. The pouring of this lava produced the plains, less than a billion years after the initial accretion process. Then, the cooling reached deeper layers, the metallic core itself cooled and reduced its volume, the surface crust compressed. To readjust the figure the fractures welded and were replaced by compression ridges.

Around this period, a particularly large body, remnant of the initial accretion process, which could have been candidate nucleus for the building up of a new planet, was recuperated by the dominant body. Caloris basin attests for its impact at the surface of Mercury, with its multi-ring huge rim formation, traces of oscillation of its floor, cracks, lava pouring and cataclysmic crust outbreak at the opposite of the planet.

Then the succession of events somewhat stranded. The situation stayed along the remaining three billion years, almost as it was, now offering for our investigations a quiet witness of the tumultuous events which dominated this remote period.

What remain now, essentially, are a sort of maturation of the upper surface by the micrometeoroid impacts and solar wind particles, a large surface temperature variation of more than 600°, and some seismic consequences of the solar distance variations along the eccentric orbit at the period of 59 days.