

EVOLUTION OF PLANETARY BODIES

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ABSTRACT

A concised treatment of different conditions influencing the evolution of planetary bodies is given on the basis of the literature — following the way of thinking of the author.

INTRODUCTION

Thanks to the results of space research in the past 30 years, there are at least 25 crusty planetary bodies (instead of one) investigated directly i.e. geophysics could turn into an experimental science. Geophysical models created to one single body, the Earth, may be tested now through different initial conditions of many others.

Meanwhile it has been discovered that the eternal fields of ice on the Antarctic collect meteorites like a giant telescope. The slow motion of its glaciers integrates them in time and some slopes bring them into focus en masse, hereby having multiplied the number of accessible samples of heavenly material. Moreover the white icecover helps to collect ancient meteorites without any selection effect.

Both new kinds of investigation, the *in situ* analysis of isotop abundances in particular, made a scientific evaluation of earlier hypotheses in planetary cosmogony possible, rejecting unrealistic ideas and leading to a more or less consistent theory of the evolution of the Solar System.

What are the most important new characteristics of such a theory? First of all accident through collisions played a more important role in the evolution than supposed earlier, not only at the beginning, during the accumulation of small particles, but also later at the end and after the accretion period. The impact of large projectiles gave sometimes rise to the birth of new planetary bodies, sometimes left important marks (i.e. craters) on the surfaces. Collisions influenced considerably the conditions of the origin and evolution of terrestrial life even at a later phase. Besides the more or less continuously acting influence of corpuscular and UV radiation - guaranteeing useful mutations of life-forms - collisions proved to be a general and important ongoing phenomenon responsible for the mass extinction of different species. Its significance comes from the fact that in a state-of-the-art planetary cosmogony the effect of catastrophic collisions is a natural consequence of the existing conditions and not an ad-hoc hypothesis as in many previous theories. This new conception needs, however, further verification.

It is evident namely that impact features are present on every planetary body with a more or less stable crust -- independently of its heliocentric distance. The scale varies from μ m, to a few thousand km. Moreover at the end of the accretion period large impacting projectiles left multiring basins on the surface of many planetary bodies. Consequently we have to suppose that accretion took place through collision not only by condensation and collision was a general phenomenon influencing the evolution even in cases when impact craters are missing.

One of the interesting results of space probes in the outer part of the Solar System is that contrary to the lunar crust the majority of these satellites have an icy composition. This came as a surprise although it

was known previously that the density of giant planets decreases with distance. The fact, however, that the satellites follow the same rule (see Fig. 1) led us to the conclusion that the bulk of the satellites accreted mainly from the circumplanetary matter (the composition of which was determined dominantly by the $T(r)$ function) and modified only slightly by projectiles originating from other parts of the Solar System.

Another surprizing observation was the intensity and influence of tidal heating. Traces of activity have been found in every satellite system and even small icy satellites, without such "traditional" heat sources as gravitational contraction or radioactivity, indicated melting periods by their spherical shape. Moreover, the innermost small bodies proved to be the more active in every satellite system, pointing to the fact that the "belt of life" is not necessarily restricted to a narrow heliocentric distance zone, hence life conditions may be more wide-spread than supposed earlier.

Greenhouse effect has also vital importance in planetary evolution. If the partial pressure of CO_2 is significantly larger than in the terrestrial atmosphere then heat-escape is limited also in other wavebands (e.g. runaway green-house effect on Venus). It means also that there is a serious danger burning fossile fuels or even releasing other kinds of latent energy (e.g. nuclear) on the surface of the Earth since it will contribute to the terrestrial heat balance by warming up the atmosphere and releasing CO_2 . The only solution of this ecological problem is given by any kind of transformation of the solar energy available on the surface by devices like solar panels, wind-engines or hydroelectric stations.

Finally magnetic fields play also an important role in the evolution. A planet is shielded by its own magnetic field from high-energy particles which represent a serious danger for life in interplanetary space. But strong magnetic fields of a planet may influence significantly the radiation hazard for near-by satellites and electric current of their flux tube may generate "hot spots" on their surface (see the case of Jupiter and Io).

Numbers in parenthesis [n] refer to the literature, in /n/ to the figures, in (n) to remarks.

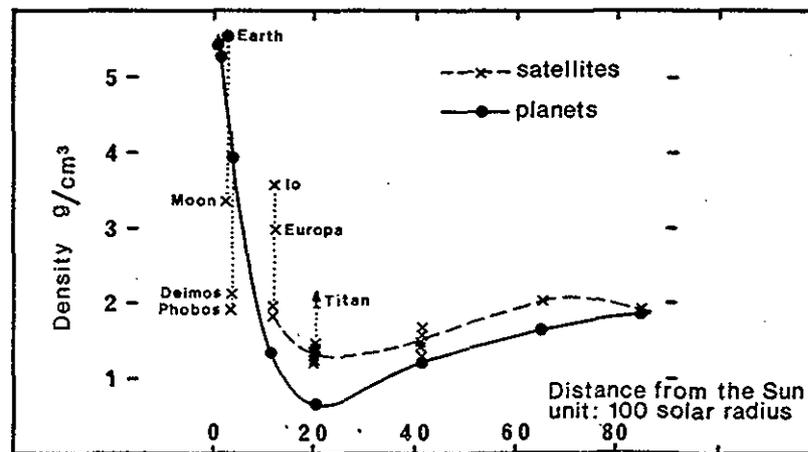


Fig. 1

DEVELOPMENT OF A PLANETARY BODY AFTER ACCRETION:

thermal history + collisional history = heating/cooling as a function of time

Heat sources for a planetary body

- solar radiation surface heating, asymmetric, continuous
- gravitational separation volume heating, symmetric, long term, decays
- radiogenic heating volume heating, asymmetric, long term, decays
- impact heating (1) surface heating, asymmetric, episodic, $\Delta t \sim 0$
- tidal heating (2) volume heating, episodic, $\Delta t \gg 0$
- magnetospheric heating(3) volume heating, asymmetric, continuous

Cooling of a planetary body:

- interior to surface by - conduction
- convection \rightarrow volcanism
- surface - radiation
- sublimation -- escape
- in the presence of an atmosphere by
 - evaporation
 - atmospheric - convection
 - radiation (4)
 - escape

Remarks:

- (1) Impact energy is transformed partly into
 - heat energy \rightarrow surface melting
 - kinetic energy of target ejecta
 - rays/halo around craters /1/
 - escape of material, erosion loss of atmosphere
 - seismic energy: makes tectonism to work
 - fracturing around the impact site
 - antipodal fracturing /2/
 - the impact site will be a local centre of activity
 - acoustic energy
- (2) Tidal heating can be extremely important in regular, interacting satellite systems at times of resonances between evolving orbits. (Violent ongoing geologic activity on Io /3/. Ancient geologic activity on Ganymede, Enceladus, Miranda, Ariel. In the case of Triton the orbit circularization after capture resulted in tidal heating. Pluto-Charon system is completely coupled \rightarrow there is no tidal heating now. No trace of geologic activity is expected if there was no orbital evolution during their previous history. Tidal heating plays some role in the large density and the prolonged geologic activity of the Earth as well.)
- (3) If a satellite without an atmosphere is orbiting inside a planetary magnetosphere then the electric current flowing in the magnetic flux tube may enter into the body of the satellite:
 - the place of the entrance is heated by the current giving rise to
 - higher temperature of the body (Amalthea by 5°)
 - continuous volcanic activity site (Io [10])
 - volumetric electrolysis of water-ice giving rise to the possibility for burning/detonation of electrolytic gas [16,17]
- (4) greenhouse effect can slow down the cooling (Earth [20], significant on Venus, may be important on Titan)

WHAT WAS THE TEMPERATURE MAXIMUM REACHED BY A PLANETARY BODY?

- not enough for melting: irregular shape } (surface alteration
- only just enough for melting: spherical shape } (by impact only
- more than enough for melting: spherical shape } (gravitational separation + geological activity)

If melted, convection can be induced by inhomogeneities in composition/temperature within the core/mantle/liquidosphere/atmosphere

Consequences of the convection within the

- core/mantle: magnetic field (core: Mercury, Earth, Mars, Jupiter, Saturn mantle: Uranus, Neptune)
- mantle: volcanism/tectonism \rightarrow outgassing
- liquidosphere/atmosphere: - erosion of the crust - redistribution of energy
- atmosphere: - formation of precipitation - changes in electrical condition of the atmosphere (lightening, recombination)

Diameter limits for melting:

- in the case of radiogenic heating in
 - rocky bodies: ~ 800 km
 - icy bodies : ~ 2000 km
- if tidal heating is switched on : can be as low as ~ 400 km (Hyperion has not but Mimas do has a spherical shape /4/)

NUMBER OF PLANETARY BODIES OF THE SOLAR SYSTEM KNOWN UP-TO-NOW			
grouped according to the			
orbit	orbit and size	composition	phase of its material (temperature)
heliocentric:	4 giant planets	4 gaseous planets	4 gaseous planets
9 planets	4 large planets	6 rocky p.b.	5 crusty p.b. with
x asteroids	1 middle-size pl.	x rocky debris:	substantial amount
x comets	x small planets (=asteroids)	asteroids	of atmosphere
	x comets	outgassed com.	20 crusty p.b. without
planeto-centric	7 large sat.	19 icy p.b.	atmosphere
60 sat.	15 middle-size sat.	x icy debris:	x debris without
	38 small sat.	comets	atmosphere

pl.: planet: p.b.: planetary body: sat.: satellite: com.: comet: x: many

CLASSIFICATION OF PLANETARY SATELLITES				
planet's name	total number of satellites	number of large sat.	number of middle-size sat.	number of small sat.
Mercury	0	-	-	-
Venus	0	-	-	-
Earth	1	1	-	-
Mars	2	-	-	2
Jupiter	16	4	-	12
Saturn	17	1	7	9
Uranus	15	-	5	10
Neptune	8	1	2	5
Pluto	1	-	1	-

WHAT KIND OF MARKS MAY BE LEFT ON THE SURFACES BY THE DIFFERENT EVENTS?

Heating: expansion in general } except in the case of special material

Cooling: contraction in general/ (e.g. water densest at 4°C)

Phase change: expansion or contraction

Impact:

- scars - crater (on every crusty planetary body)
- centre of fracturing
- antipodal fracturing (Mercury antipodal to Caloris Basin /2/)
- crust break-through → volcanism /5/
(maria on the Moon, Triton?, white spots on Umbriel?
light? or dark? material on Japetus?)
- rays/halo around craters as target ejecta spread /1/
- too large core (part of Mercury's crust splashed down
by a huge impact and escaped [1])
- moon (part of Earth's crust splashed down by a huge impact
and a part of it accreted into the Moon [11,24,25]
after explosion of proto-Pluto by a large-body impact
the debris accreted into a binary planet Pluto-Charon [9])
- mascon (Moon)
- blow off the atmosphere (Argyrae /6/ impact on Mars [12,13,22,23])
- implantation of the impactor's material into the atmosphere
("nuclear winter": extinction of living species on Earth)
- which slowly settles down forming an "anomalous layer" on the surface
(e.g. iridium-rich layer on the C-T boundary on Earth)
- deposit of flood caused by tsunamies along the continent's margins
if the impactor reached the ocean (East coast of Africa, C-T boundary)
- shocked quartz grains if the impactor struck continental crust [14]
(North-America, C-T boundary)
- carbon deposit layer settled down after world-wide fire
caused by the impact-heat (Earth, C-T boundary)
- acid rain [15]

The effect of the impact may be modified by the condition of the

- impactor: - coming from planetocentric or heliocentric orbit
(giving rise to a smaller /7/ or a larger /8/ crater)
 - having an angle of impact
 - ~ perpendicular: - spherical crater (common everywhere)
- total explosion of the target
 - flat: - butterfly shaped crater /9/ (Mars)
- escape of intact boulders
(SNC meteorites from Mars)
- splash down of crust: escape of material
- target: - in the presence of atmosphere/liquidosphere
 - the impactor is melted/vaporized/broken/exploded
(lack of small craters on Venus [29])
 - the crater erodes
 - in the presence of volatile rich terrain
 - lobate craters /10/ can be created (Mars)
 - and if afterwards the surroundings is flooded by volcanism of magma -- poorer in volatiles -- then negative ringed craters /11/ can be formed by erosion (Mars)
 - the strength of the surface material can influence
 - the existence of the central peak in the crater
(Jovian ice-satellites are softer → no central peak.)
 - the relaxation rate of the emerging relief
(Curved crater floor on Tethys /12/ → at time

WHAT KINDS OF DEFORMATION CAN BE PRESENT ON THE SURFACES OF CRUSTY PLANETARY BODIES?

Crust fissures because of change of curvature caused by

- tidal deformation (Europa linear features /13/)
- dome formation above mantle upflow (Earth, East-African graben)
- uplift on places of converging mantle flow if
there is no subduction (Venus parquet terrain units [2]/14/)

Expansion:

- global: rift valley
 - because of heating
 - because of freezing of the interior of an icy body the
crust cracks through owing to volume increase /15/
(Tethys, Titania, Dione?, Ariel?)
- local:
 - rift system because of local heating /16/ (Enceladus, Miranda?)
 - global rift network because of global mantle-circulation
/17,18,19/: crust-pieces are spread away by mantle convection
(Earth, mid-oceanic ridges: huge polygonal units on Ganymede,
Ariel [6], Umbriel [7], Triton)

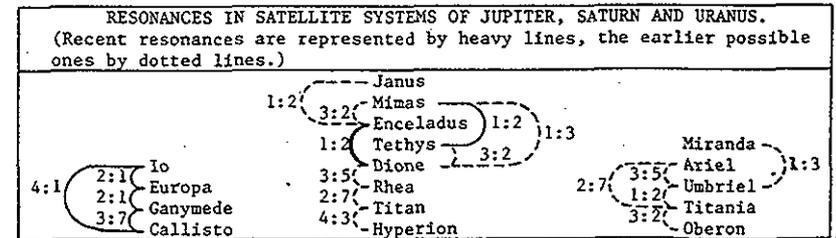
Compression

- global: drying up (contraction) of a planetary body: thrust faults
/20/ (Mercury, Miranda [5])
- local: material towering
 - on sites of converging mantle flows:
 - lift off of crust blocks /21/ (Tibetian Plateau on Earth,
Lakshmi Planum on Venus, Miranda?)
 - chains of mountains /22/ (Earth, Venus)
 - continents /23/ (Earth, Venus)
 - subduction /24/ (deep oceanic trenches on Earth)
 - parallel grooves when new crust is formed and older one is thrust
(Ganymede, Enceladus, inside the expansion graben on Ariel,
mid-oceanic ridges on Earth /25/)
 - collision of slipping material with stable crust fragments around
 - mountain slopes: grooves around mountains /26/
(Mars, circular grooves around large shield volcanoes)
 - the slopes of bulges (Mars, around Tharsis bulge)
 - the slopes of uplifts formed by converging flows
(Venus parquet units and
parquet terrain inside a parquet unit [2]/27/)

Mixed: expansion and compression

- transform fault /19/ (Earth, Ganymede, Enceladus, Triton?)
- global plate tectonism /28/ (only on Earth)

Impact may cause some modification of all kinds of deformations.



WHAT LEVEL OF GEOLOGICAL ACTIVITY WAS REALIZED ON THE VARIOUS PLANETARY BODIES?

No traces of activity

- only targets of impacts /29/ (all the debries-satellites, Mimas, Hyperion)
- albedo features: frost along cracks /30/ (trailing side of Dione and Rhea)

Freezing of interior of an icy body: rift valley of planet-size /15/ (Tethys, Titania, Dione?, Ariel?)

Drying up (contraction of the core): thrust fault /20/ (Mercury, Miranda? [5])

Traces of differentiation on the surface

- rays/halo of albedo feature around impact craters /1/ (Mercury, Venus, Moon, Ganymede, Callisto, Titania, Oberon, Ariel)
- mare /5/: low viscosity lava flow
 - probably in connection with break-through of young crust (Mercury, Moon, Mars, Triton, Japetus?, Umbriel?, Oberon?)
- linear albedo features at rift network /13/ because of crust fissures in connection with change of curvature (Europa, light and dark)

Traces of mantle circulation

- rift valley of somewhat smaller than planet-size /31/ (large canyon on Venus, Valles Marineris on Mars)
- local groove-system because of
 - local heating /16/ (Enceladus) or
 - rising or sinking of boulders /32/ (Miranda)
- huge polygonal units of ancient crust /33/ (Ganymede, Ariel, Umbriel [7], Triton, Earth)
 - together with global rift network /17/ (Ganymede, Ariel, Triton, Earth)
 - with parallel groove system inside the grabens of the rift network /18/ (Ganymede, Earth, Ariel [6])
 - and transform faulted parallel grooves /19/ (Earth)
- shield-volcano (hot spot volcanism) /34/: local mantle upflow (volcanoes on Venus and Mars, Hawaiian type volcanoes on Earth)
- material outflow along cracks: new crust forming, thrusting because of compression: parallel groove system /18/ (Ganymede, Enceladus, Ariel, Earth)
- traces of crust vanishing: (half craters /35/ on Enceladus and Ganymede deep oceanic trenches /36/ on Earth)
- transform faults /19/: displacing of crust-pieces on surface of a sphere
 - local (Ganymede, Enceladus, Triton?)
 - global: global plate tectonism (Earth)
- lift off of crust pieces /21/ (Miranda, Venus, Earth)
- crease of crust: chains of mountains /22/ (Earth, Freya and Akna mountains on Venus)
- continents /23/ (Earth, Ishtar Terra on Venus)

Traces of small-scale terrain circulation within the crust: terrain polygons /37/ (Triton?, Earth)

Traces of slipping on slopes in connection with

- mountains /26/ (Mars)
- bulge (Mars around Tharsis bulge)
- dome /27/ (parquet terrain on Venus)

VOLCANISM

Kind of volcanism:

- along cracks: the largest amount of volcanic material is emerging to the surface by this kind of volcanism (Mid-oceanic ridges on Earth /25/, Moon, Mars, Europa, Ganymede, Enceladus, Ariel, Triton)
- hot spot volcanism /34/ (Venus, Mars, Io, Earth: Hawaiian-type volcanoes)
- subductional volcanism with volatile-rich lava /38/ (only on Earth from volcanoes along the deep oceanic trenches)

Material of "lava":

- silicate magma (Mercury, Venus, Earth, Moon, Mars)
- sulphur (Io)
- water (Europa?, Enceladus?)
- ice /39/ (Ariel [18])
- nitrogen (Triton [19])

Result of volcanism:

- ovoid /40/ (unsuccessful volcanism) (Earth, Venus)
- resurfacing (flooding, erosion)
- outgassing

Recent active volcanism

(Earth to ~10 km high, Io to ~250 km high, Triton to ~8 km high, material from Enceladus forms the E-ring?)

ATMOSPHERES OF CRUSTY PLANETARY BODIES			
name of the planetary body	surface pressure (atm)	composition	corresponding percentages
Mercury	10 ⁻¹⁵	He, H ₂	98%, 2%
Venus	90	CO ₂ , N ₂	96,4%, 3,4%
Earth	1	N ₂ , O ₂ , H ₂ O, Ar	78%, 21%, 0,1%, 0,9%
Mars	0,007	CO ₂ , N ₂ , Ar	93,3%, 2,7%, 1,6%
Io	10 ⁻¹²	SO ₂ , S, Na	
Titan	1,6	N ₂ , Ar, CH ₄	85%, 12%, 3%
Triton	10 ⁻⁷	N ₂ , CH ₄	
Pluto	?	CH ₄ [8], N ₂ ?, Ar?	

TRACES OF RUNNING LIQUID ON THE SURFACES /41/	
Traces of running liquid's erosion: Earth, Mars (water), Io (sulphur)	
River beds on the surface: only on Earth and Mars	
Recently running water: only on Earth	
Liquid ocean:	
- on the surface:	
Earth : H ₂ O	
Titan?: metan, etan, propen, propan? [26,27,28]	
- under an ice-crust:	
Europa: H ₂ O (100 km deep, ice crust 20-30 km thick [21])	
Enceladus?: H ₂ O	
Triton?: nitrogen (from the depth of 20-30 km?)	

VOLATILE ELEMENTS (ATMOSPHERE, LIQUIDOSPHERE)

Sources: only giant planets are able to capture the surrounding gases, in all other cases the bulk of the volatile content directly inherited from gases occluded in the solid planetesimals from which the planetary body accreted

- outgassed from the interior of the planetary body (active volcanism speeds it up)
- volatile content of an impactor body may also contribute
- implantation from solar wind (generally negligible except in the case of Mercury)

Losses:

- escape (slow mechanism)
 - growing with temperature
 - decreasing with the mass-increase of the planetary body (growing escape velocity)
 - the escaped volatiles of satellites are exhausted gravitationally/electromagnetically by their own planet (Apparent at the orbit of Mimas, Enceladus, Tethys, Dione, Rhea, Titan. Spectacular in the case of Io.)
 - in the presence of an own magnetic field ions can be accelerated by electric fields to escape velocities (polar wind at Earth)
- solar wind erosion (slow mechanism) especially strong in the lack of own magnetic field (Venus, at high solar activity in the case of Mars)
- blow off in connection with impacts (episodic, quick mechanism) it may occasionally be significant (Mars, Argyrae impact /6/)
- fixed into the soil (slow mechanism)
 - CO₂ into carbonates:
 - H₂O into hydrated silicates:
 - H₂O, CH₄, NH₃, N₂ into ices/clathrats

- freezing onto the surface /42/ (slow/quick mechanism depending on the temperature and its variation) (glaciers only on Earth /42/)

Regain: given material is regained only in certain temperature ranges by

- rain-fall (Venus: sulphuric acid, hydrochloric acid
Earth: water, sulphurous acid, water with hydrochloric acid)
- snow-fall/hoar-frost (Earth: water
Mars: water, carbon dioxide
Io: sulphur, sulphur dioxide
Titan: hydrocarbon aerosols of larger molecular weight [27]
Triton: nitrogen, metan)

Recycling: in substantial amount only in the case of Earth because of global plate tectonism

POLAR CAPS IN THE SOLAR SYSTEM /43/	
Earth	H ₂ O
Mars northern polar cap:	H ₂ O
southern polar cap:	CO ₂ / CO ₂ -H ₂ O clathrat
Triton	N ₂
Pluto	N ₂ ?

WHAT ARE THE MOST IMPORTANT PARAMETERS FOR THE ORIGIN OF LIFE [3]?

- temperature distribution } { - in the atmosphere
- chemistry } { - in the ocean
- } { - on the surface of the crust

Both depends strongly whether

- 1./ the source material was already emplaced when planetesimal formation began
- 2./ during the accretion there was a continuous infall of interstellar material into the circumsolar region

Temperature

- in case 1./ continuously high (run away accretion)
- in case 2./ continuously low after cessation of early runaway accretion (the impact hot spots were distributed in time and space, they could cool down before the next impact)

Surface composition

- in case 1./ - magma-ocean on the surface
 - water - as solution in melt → decomposed by metallic iron } {hydrogen escaped
 - as vapor in the atmosphere } {oxygen accumulated dissociated by UV photons
 - CO₂ in the atmosphere → greenhouse effect strong
 - biomolecules destroyed (if built up)
- in case 2./ - always a water ocean on the surface with present day mass at the end of the accretion
 - water bound in sediments
 - water loss and oxygen production slow (present day level)
 - continental territory small
 - ocean shallow
 - many islands because of extensive volcanism →
 - many places for biomolecules being screened from UV radiation under an overlying layer of water
 - many places for accumulation of rust and clay minerals

Composition of the primordial atmosphere

(supposing that the bulk of it is identical with the volatile content of ordinary chondrites — since they could be the end-product of interstellar dust aggregates — a minor part of it came from carbonaceous chondrites and the rest is atmospheric by-product)

- H₂O, CO₂, CO, N₂, SO₂
- hydrocarbons come from carbonaceous meteorites
- no NH₃/CH₄ neither in ordinary nor in carbonaceous case
- hydrogen (maximum 1%) comes from meteoritic carbids and water (through photoinduced oxidation of dissolved Fe²⁺)
- NH₃ formation by
 - lightning in H₂ rich atmosphere
 - photoreduction of water by nitrogen on rutile (TiO₂) sands in the intertidal and wave zone of the ocean

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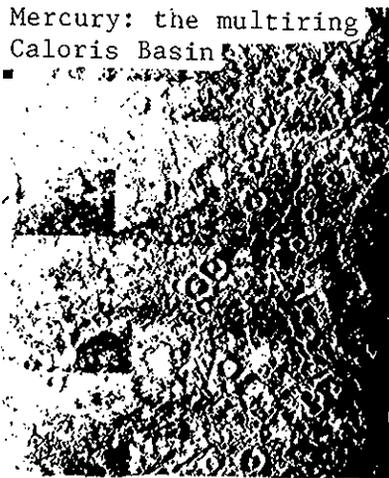
No	NAME OF PLANETARY BODY	DISCOVERER	P orbital period	A mean distance from the central body	i orbital inclination with respect to the equator of the central body	e orbital eccentricity	T TEMPERATURE (estimated) (on the basis of the visual albedo)	H MASS	D DIAMETER	ρ DENSITY	g SURFACE GRAVITY	M VISUAL MAGNITUDE	A ALBEDO	SMALLEST DISTANCE OF HIGHEST-RESOLUTION SPACE-PHOTOS	HIGHEST RESOLUTION	S U R F A C E	A C E COMPOSITION	ATMOSPHERE	OCEAN	POLAR CAP	MAGNETIC FIELD	IS ROTATION CAPTURED?	SHAPE (0: sphere, 1: irregular)
1	Mercury	1610 Riccioli	88 d	57.909 AU	0.0046	0.2056	330 K	0.330 × 10 ²² kg	4.880 km	5.430 g/cm ³	0.37	-1.2	0.11	1000 km	0.05	4.6	Si, Fe, S	-	-	-	-	0	0
2	Venus	1610 Riccioli	224.7 d	108.206 AU	0.0008	0.0068	324 K	4.869 × 10 ²³ kg	12104 km	5.242 g/cm ³	0.90	-3.6	1000 km	0.01	4.6-56	Si, Fe, S, CO ₂	-	-	-	-	0	0	
3	Earth	1610 Riccioli	365.3 d	149.600 AU	0.0000	0.0000	288 K	5.972 × 10 ²⁴ kg	12756 km	5.515 g/cm ³	1.00	0.0	1000 km	0.01	4.6-56	Si, Fe, S, CO ₂	-	-	-	-	0	0	
4	Mars	1610 Riccioli	687 d	227.936 AU	0.00934	0.0934	210 K	0.642 × 10 ²³ kg	6786 km	3.930 g/cm ³	0.38	1.8	1000 km	0.01	4.6-56	Si, Fe, S, CO ₂	-	-	-	-	0	0	
5	Jupiter	1610 Riccioli	11.86 y	778.561 AU	0.00485	0.0485	133 K	1.898 × 10 ²⁷ kg	142780 km	1.328 g/cm ³	2.53	-1.7	1000 km	0.01	4.6-56	Si, Fe, S, CO ₂	-	-	-	-	0	0	
6	Saturn	1610 Riccioli	29.45 y	1427.56 AU	0.0556	0.0556	95 K	5.68 × 10 ²⁶ kg	120000 km	0.687 g/cm ³	1.07	1.9	1000 km	0.01	4.6-56	Si, Fe, S, CO ₂	-	-	-	-	0	0	
7	Uranus	1781 Herschel	84.01 y	2869.83 AU	0.0462	0.0462	59 K	4.46 × 10 ²⁵ kg	25559 km	1.271 g/cm ³	0.89	3.9	1000 km	0.01	4.6-56	Si, Fe, S, CO ₂	-	-	-	-	0	0	
8	Neptune	1846 Le Verrier, Galle	164.8 y	4496.58 AU	0.0086	0.0086	49 K	1.024 × 10 ²⁶ kg	24746 km	1.644 g/cm ³	1.14	7.9	1000 km	0.01	4.6-56	Si, Fe, S, CO ₂	-	-	-	-	0	0	
9	Pluto	1930 Tombaugh	90.5 y	5900.58 AU	0.250	0.250	33 K	1.3 × 10 ²² kg	2300 km	1.86 g/cm ³	0.62	-15.8	51	4900 km	0.01	4.6-56	Si, Fe, S, CO ₂	-	-	-	-	0	0
10	Sum																						
11	13000		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
12	13001		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
13	13002		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
14	13003		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
15	13004		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
16	13005		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
17	13006		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
18	13007		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
19	13008		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
20	13009		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
21	13010		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
22	13011		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
23	13012		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
24	13013		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
25	13014		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
26	13015		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
27	13016		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
28	13017		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
29	13018		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
30	13019		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
31	13020		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
32	13021		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
33	13022		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
34	13023		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
35	13024		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
36	13025		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
37	13026		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
38	13027		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
39	13028		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
40	13029		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
41	13030		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
42	13031		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
43	13032		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
44	13033		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
45	13034		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
46	13035		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
47	13036		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
48	13037		27.322 d	380000 km	0.0027	0.0027	273 K	1.3 × 10 ²² kg	1000 km	1.905 g/cm ³	0.16	-1.2	400 km	0.008	0.1	4.6	Si, Fe, S	-	-	-	-	0	0
49	13038		27.322 d	380000 km	0.0027	0.0027																	

WHAT LEVEL OF GEOLOGICAL ACTIVITY WAS REALIZED ON CRUSTY PLANETARY BODIES	WITH DIAMETER LARGER THAN 240 KM	PLANETARY BODIES																										
		Moon	Amalthea	Io	Europa	Ganymede	Callisto	Mimas	Enceladus	Tethys	Dione	Rhea	Titan	Hyperion	Japetus	Miranda	Ariel	Umbriel	Titania	Oberon	89N1	Triton	Nereid	Charon	Mercury	Venus	Earth	Mars
uniform surface		-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
surface saturated with craters		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
larger craters (population I)		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
smaller craters (population II)		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
multiring basin		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
rays/haloes around impact craters		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
bright crix-crax albedo features		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
rift valley of planet size		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
contraction (thrust fault)		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
any traces of out-flowing material		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
mare (lava of low viscosity)		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
expansion		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
rift system		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
parallel grooves		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
transform faults		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
shield volcanoes		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
calderas		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
recent volcanism		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
mountain chains		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
continents		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
erosion of flowing material		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
river bed		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

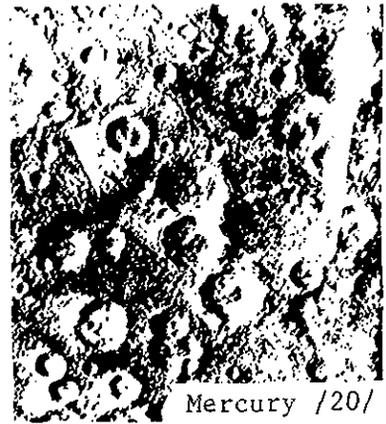
Nothing visible on the surface because of hydrocarbon smog/snow.



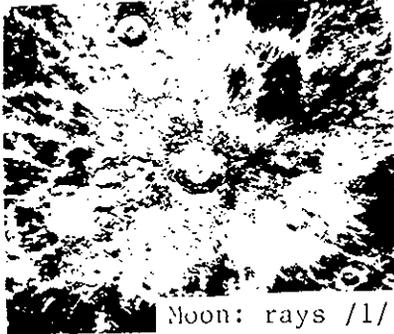
Mercury /29/



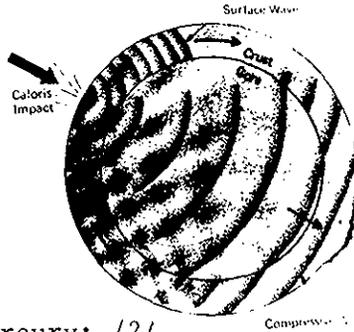
Mercury: the multiring
Caloris Basin



Mercury /20/



Moon: rays /1/



Deimos /29/



Moon: maria /5/

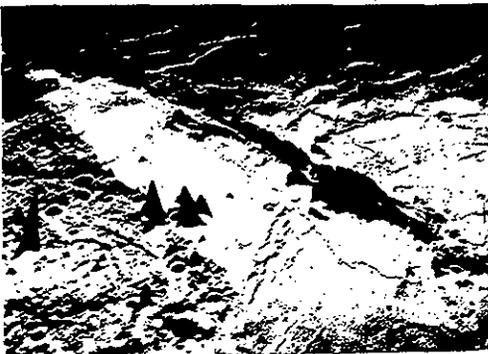
Mercury: /2/
how a multiring basin was born



Moon: Mare Orientale
multiring basin

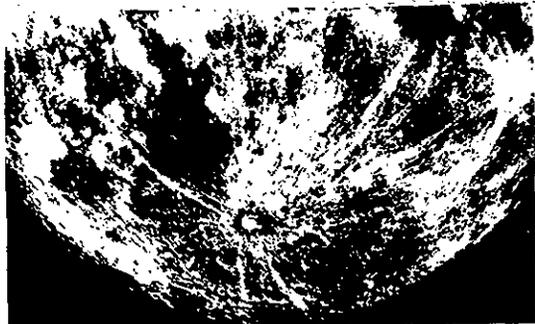


Phobos /29/

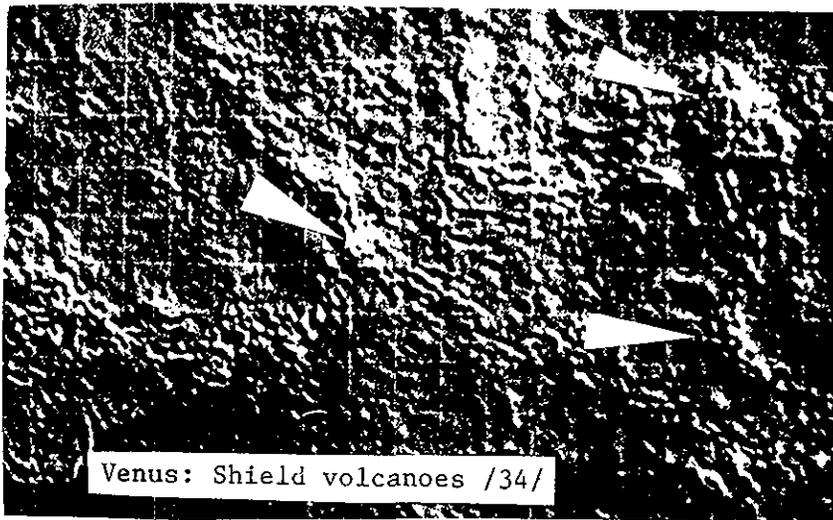


Moon: boundary of a mare /5/

Moon: rays around impact crater /1/



Venus: globe /23/

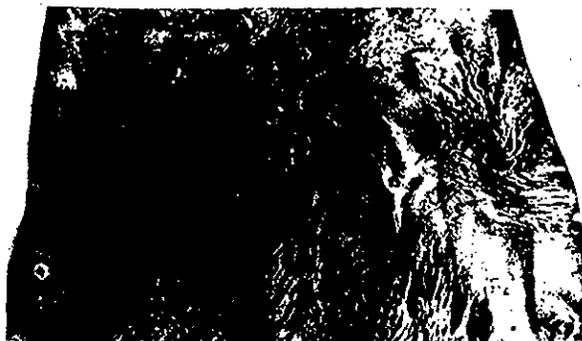


Venus: Shield volcanoes /34/

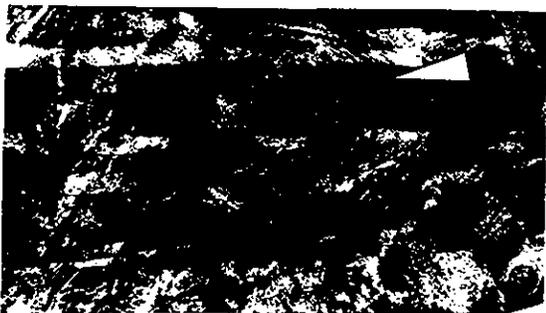


Venus:
mountain chains /22/

Venus: parquet terrain units /14/

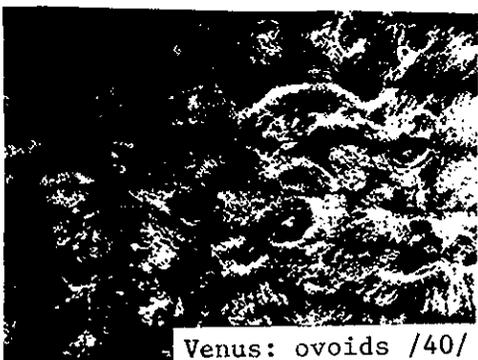


Venus: Lakshmi Planum /21/



Venus: ovoid (corona) /40/

Venus: parquet terrain /27/



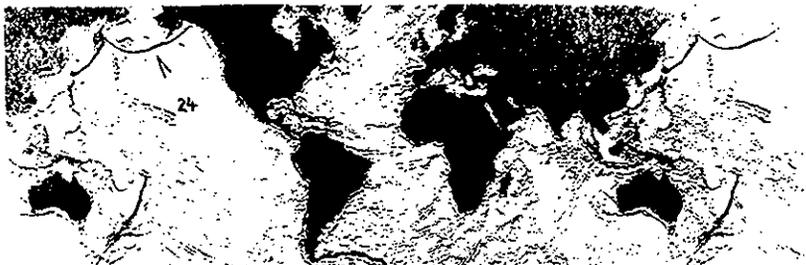
Venus: ovoids /40/



53



Earth:
continents /23/



Earth: /28,33,17,18,19/ deep oceanic trenches /24/



Earth: ovoid /40/



Earth:
mid oceanic ridges /25,18/
with transform faults /19/



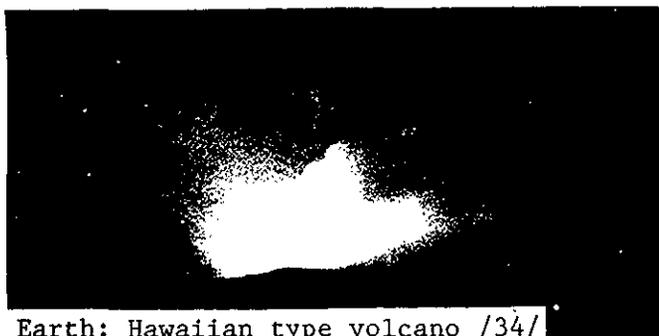
Earth: mountain chains /22/



Earth:
subductional type volcano /38/



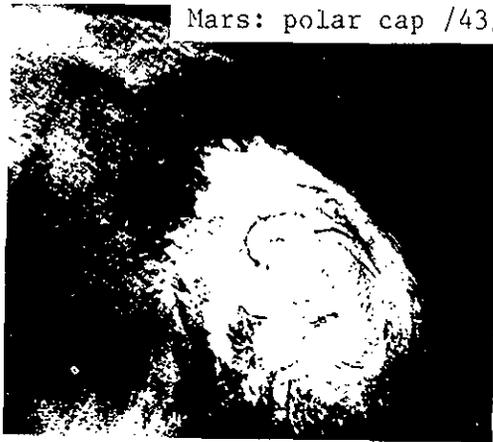
Earth: glaciers /42/



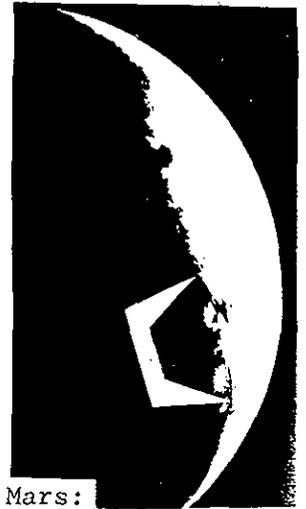
Earth: Hawaiian type volcano /34/



Mars:
shield volcanoes /34/



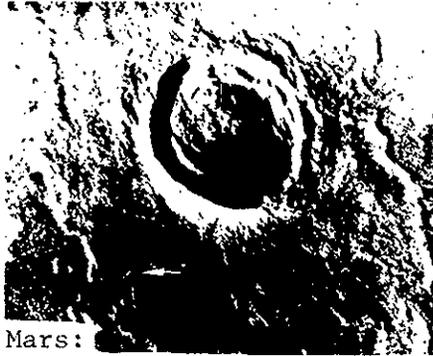
Mars: polar cap /43/



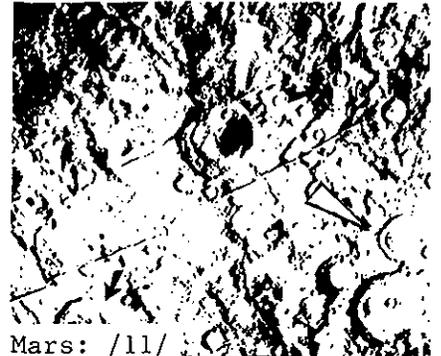
Mars:
rift valley /31/
(Valles Marineris)



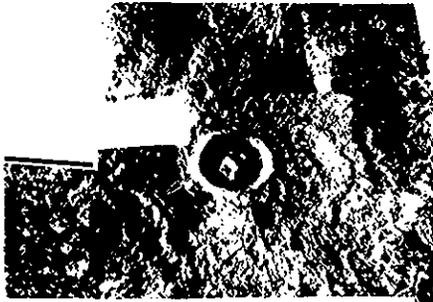
Mars:
Argyrae Basin /6/



Mars:
butterfly shaped crater /9/



Mars: /11/
negative ringed craters

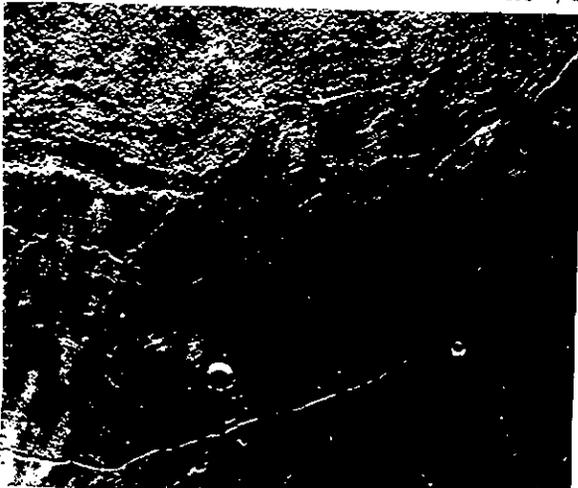


Mars: lobate crater /10/

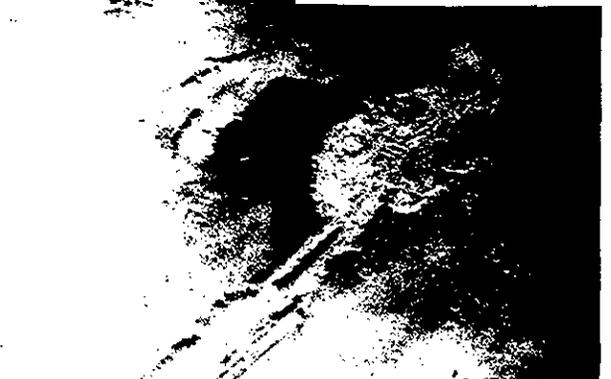
Mars: lobate craters /10/



Mars:
grooved terrain around Arsia Mons /26/



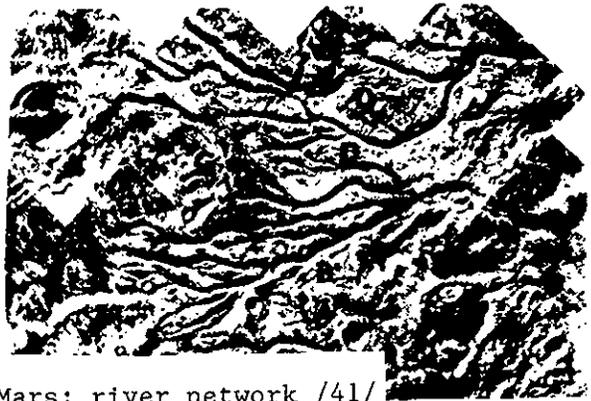
Mars: extensional feature /31/
(Valles Marineris)



55

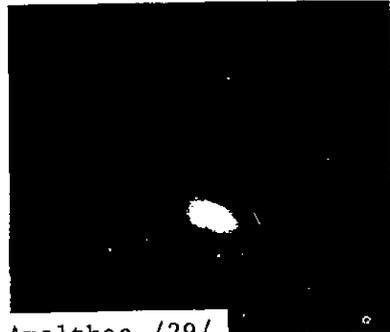


Mars: traces of flowing water /41/



Mars: river network /41/

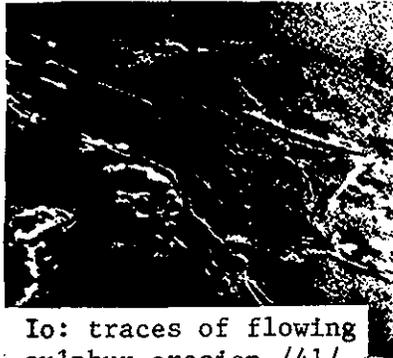
Jupiter with its two moons:
Io and Europa



Amalthea /29/



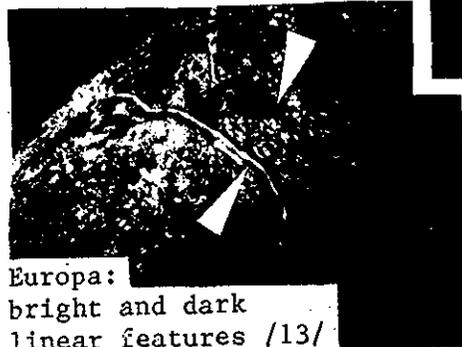
The two sides of Io /3/



Io: traces of flowing
sulphur erosion /41/

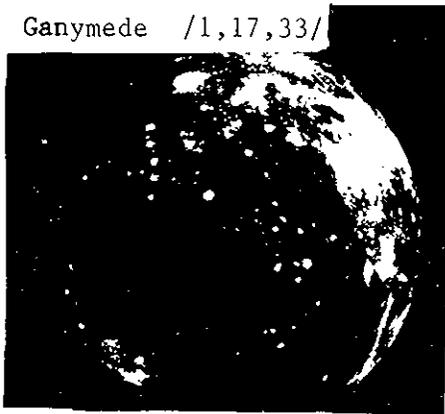


Io: Pele volcano

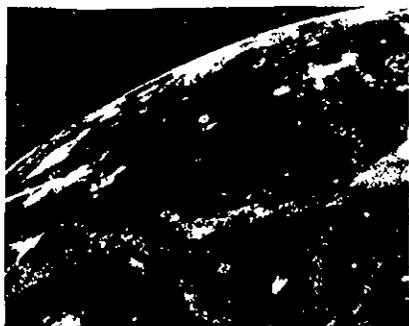


Europa:
bright and dark
linear features /13/

Ganymede /1,17,33/



Ganymede : large dark polygonal surface elements /33/ with brighter linear features /17/



Ganymede : half craters /35/

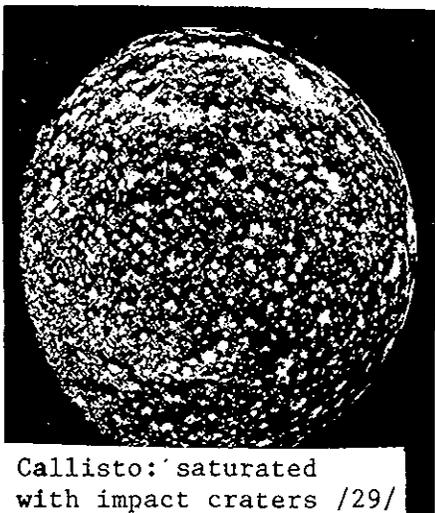
Ganymede : transform fault /19/



Ganymede : grooved terrain /18/



Ganymede : parallel grooves /18/



Callisto: saturated with impact craters /29/



Callisto: Valhalla multiring basin



Janus /-9/



Dione /29/

The cloudy Titan



Mimas: /29/
deep crater floor.
The excavated
material escaped.



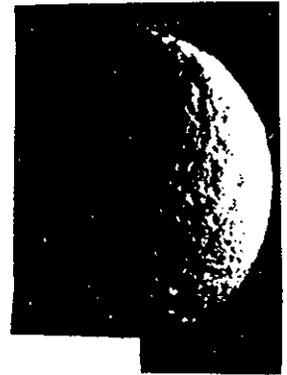
Rhea: full with
impact craters /29/



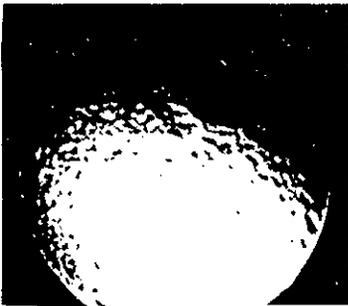
Tethys:
rift valley /15/



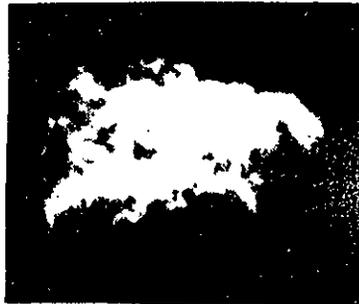
Dione: /30/ bright
albedo features



Mimas /4/:
saturated with
impact craters /29/



Tethys: Odysseus crater
(curved crater floor) /12/



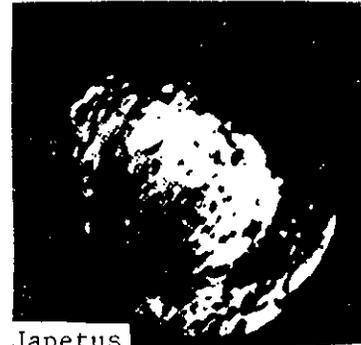
Rhea: /30/
bright albedo features



Enceladus: rift system /16/,
half craters /35/,
transform faults /19/,
parallel grooves /18/.



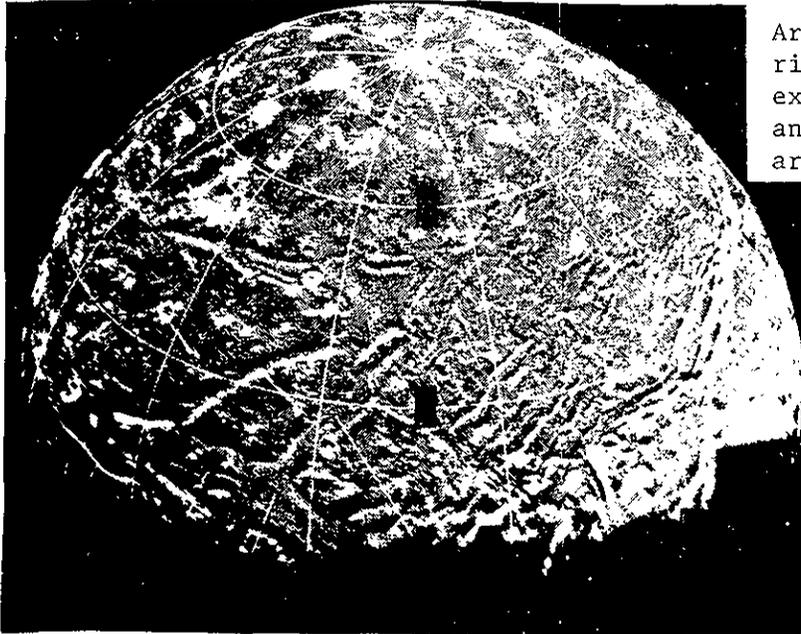
Two sides of Hyperion /4,29/



Japetus
in full-moon phase /5/



Miranda: ovoids, thrust fault /20/, groove system /32/, lift off /21/



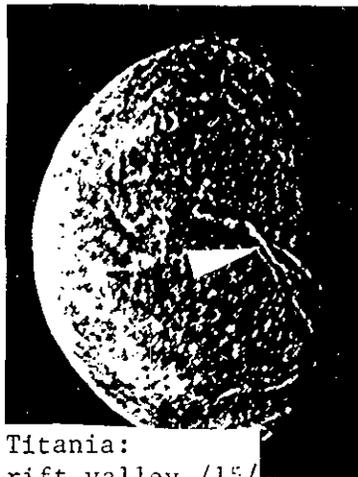
Ariel: rift valley /15/,
rift network /17/,
expansion feature /18/
and bright haloes
around impact craters /1/



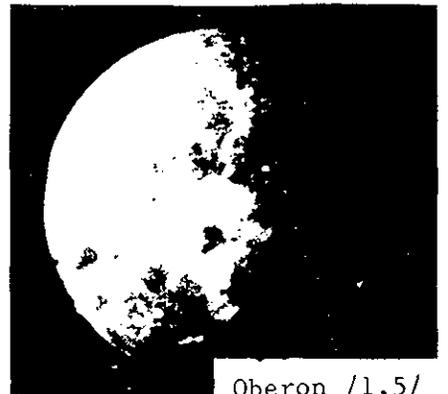
Ariel: ice volcanoes /39/



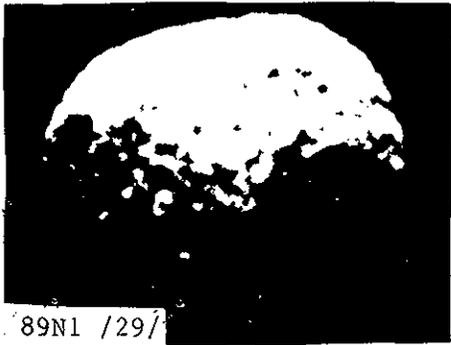
Umbriel /33/:
bright features /5/



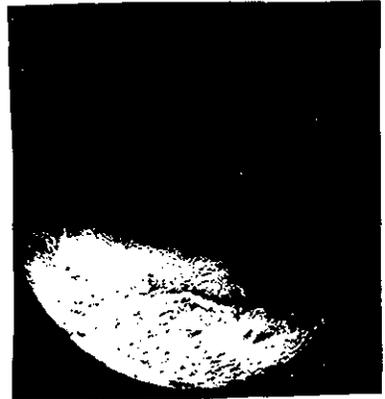
Titania:
rift valley /15/



Oberon /1,5/



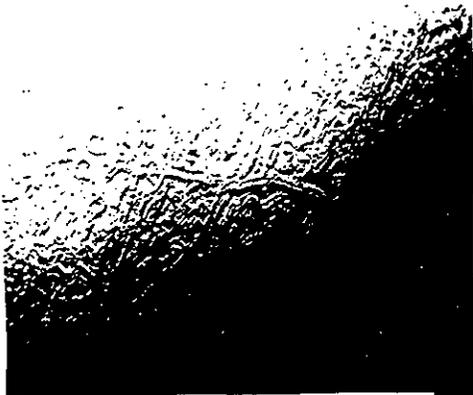
89N1 /29/



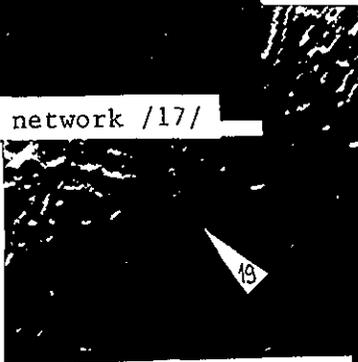
Triton: polar cap /43/



Triton: maria /5/



Triton: rift network /17/



transform fault? /19/



Triton: terrain polygons /37/



Triton: calderas? /

