

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 y 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 surprising 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.

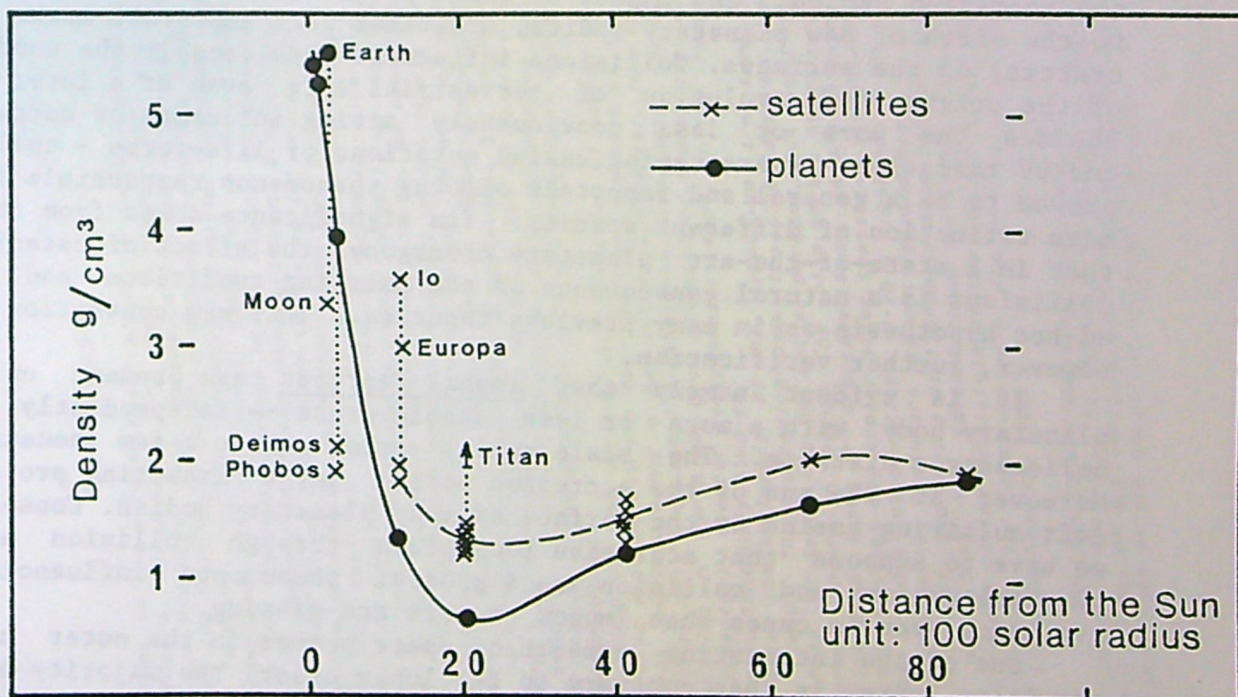


Fig. 1

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, symmetric, 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
- only just enough for melting: spherical shape
- more than enough for melting: spherical shape + geological activity

{ surface alteration
by impact only
gravitational separation

If melted, convection can be induced
by inhomogenities 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 → 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: 9 planets x asteroids x comets	4 giant planets 4 large planets 1 middle-size pl. x small planets (=asteroids) x comets	4 gaseous planets 6 rocky p.b. x rocky debris: asteroids outgassed com. meteoroids	4 gaseous planets 5 crusty p.b. with substantial amount of atmosphere 20 crusty p.b. without atmosphere
planeto-centric 60 sat.	7 large sat. 15 middle-size sat. 38 small sat.	19 icy p.b. x icy debris: comets	x debris without 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/)

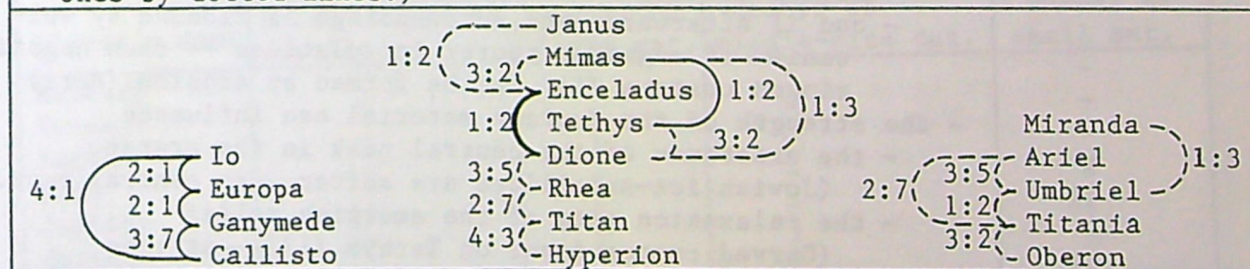
Mixed: expansion and compression

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

Impact may cause some modification of all kinds of deformations.

RESONANCES IN SATELLITE SYSTEMS OF JUPITER, SATURN AND URANUS.

(Recent resonances are represented by heavy lines, the earlier possible ones by dotted lines.)



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

No traces of activity

- only targets of impacts /29/
(all the debris-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/chlatrats
- 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 chlatrat
Triton	N ₂
Pluto	N ₂ ?

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

- temperature distribution
 - chemistry
- } {
- in the atmosphere
- 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
 - as vapor in the atmosphere dissociated by UV photons
 - in case 2./
- } {hydrogen escaped
oxygen accumulated
- CO₂ in the atmosphere → greenhouse effect strong
 - biomolecules destroyed (if built up)
 - 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
 - lightening 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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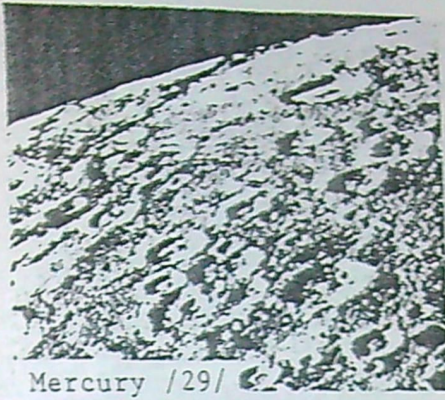
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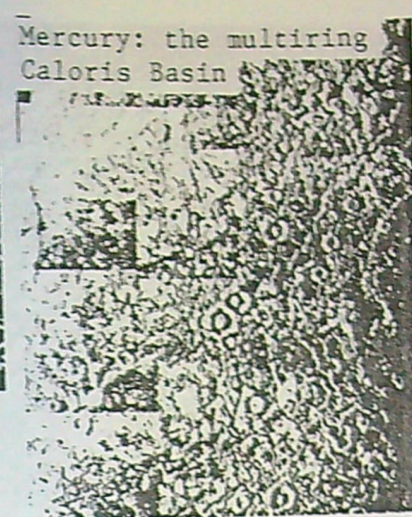
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PLANETS	No	NAME OF PLANETARY BODY	DISCOVERY	P sidereal orbital period	A mean distance from the central body	I orbital inclination with respect to the equator of the central body	e orbital eccentricity	T TEMPERATURE	M mass	D diameter	ρ density	g surface gravity	M visual magnitude	A albedo	S surface distance of highest-resolution space-photos	R highest resolution	S relief	U age	F composition	A atmosphere	O ocean	P polar cap	M magnetic field	L rotation captured?	S shape (0: sphere, 1: irregular)
PLANETS	No	NAME OF PLANETARY BODY	YEAR DISCOVERED	day	km	unit: radius of the central body	degrees	K	unit: kg	unit: km	g/cm ³	m/s ²	unit: mag	unit: mag	unit: km	unit: km	unit: km	unit: 10 ⁹ years	unit: composition	unit: atmosphere	unit: ocean	unit: polar cap	unit: magnetic field	unit: rotation captured?	unit: shape (0: sphere, 1: irregular)
1	1	Earth	1877 Hall	365.256	149,598,262	0.0000017	0.0167	287	5,972,196	12,756	5.515	9.806	-26.74	0.367	384,400	1000	0.000	4.54	Si(100%)	-	-	-	-	-	0
2	2	Mars	1877 Hall	686.97	227,943,847	0.0000034	0.0934	218	641,851	6,794	3.93	3.71	-23.0	0.254	339,700	1000	0.000	4.96	Si(100%)	-	-	-	-	-	0
3	3	Jupiter	1879 Voyager	4,332.54	778,366,000	0.0000048	0.0483	116	1,898,133	142,984	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
4	4	Saturn	1879 Voyager	29,446.86	954,095,000	0.0000047	0.0472	95	568,338	120,526	0.931	10.77	-15.7	0.471	1,065,000	1000	0.000	9.46	Si(100%)	-	-	-	-	-	0
5	5	Uranus	1846 Leverrier, Galle	84,010.75	2,869,664,000	0.0000047	0.0472	45	44,648,000	50,724	1.271	8.87	-17.8	0.481	2,576,000	1000	0.000	4.61	Si(100%)	-	-	-	-	-	0
6	6	Neptune	1846 Leverrier, Galle	164,798.95	4,496,664,000	0.0000035	0.0350	51	45,914,000	46,868	1.281	8.69	-19.5	0.490	4,353,000	1000	0.000	7.96	Si(100%)	-	-	-	-	-	0
7	7	Pluto	1930 Tombaugh	248,094.2	5,900,664,000	0.0000071	0.0710	13	1,328,600	2,306	1.961	0.62	-223	0.501	42,668,000	1000	0.000	30.07	Si(100%)	-	-	-	-	-	0
8	8	Phobos	1877 Hall	0.31898	9,378	0.0000001	0.0000017	218	641,851	22	3.93	3.71	-23.0	0.254	339,700	1000	0.000	4.96	Si(100%)	-	-	-	-	-	0
9	9	Deimos	1877 Hall	1.26244	23,462	0.0000001	0.0000034	218	641,851	12	3.93	3.71	-23.0	0.254	339,700	1000	0.000	4.96	Si(100%)	-	-	-	-	-	0
10	10	Europa	1879 Voyager	0.29527	1,279,600	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
11	11	Amalthea	1892 Barnard	0.48946	181,300	0.0000001	0.0000034	116	1,898,133	240	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
12	12	Themis (7932)	1980 Voyager	0.67512	221,900	0.0000001	0.0000048	116	1,898,133	240	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
13	13	Io	1610 Galilei	1.76913	417,600	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
14	14	Europa	1610 Galilei	3.55118	670,900	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
15	15	Ganymede	1610 Galilei	7.15512	1,070,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
16	16	Callisto	1610 Galilei	16.68912	1,880,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
17	17	Leda	1974 Kowal	240	111,100,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
18	18	Himalia	1904 Perrine	250.6	114,700,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
19	19	Lysithea	1938 Nicholson	260	117,100,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
20	20	Lilaea	1905 Perrine	260.1	117,400,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
21	21	Ananke	1951 Nicholson	617	207,000,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
22	22	Carme	1938 Nicholson	642	22,300,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
23	23	Pasiphae	1908 Melotte	735	23,300,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
24	24	Sinope	1914 Nicholson	750	23,700,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
25	25	Atlas	1980 Voyager	0.604	138,200	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
26	26	Prometheus (80527)	1980 Voyager	0.613	139,400	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
27	27	Pandora (80526)	1980 Voyager	0.629	141,700	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
28	28	Janus (8051)	1966 Dollfus	0.694	151,400	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
29	29	Euphrosyne (8053)	1977 Fountain-Lerson	0.696	151,450	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
30	30	Mimas	1789 Herschel	0.942	185,300	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
31	31	Enceladus	1789 Herschel	1.370	238,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
32	32	Tethys	1684 Cassini	1.888	294,700	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
33	33	Telessto (80513)	1980 Voyager	1.888	294,670	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
34	34	Calypso (80525)	1980 Voyager	1.888	294,670	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
35	35	Dione	1684 Cassini	2.737	377,400	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
36	36	Helene (Dione 8, 8056)	1980 Voyager	2.737	377,400	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
37	37	Rhea	1672 Cassini	4.518	527,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
38	38	Titan	1655 Huygens	15.945	1,222,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
39	39	Hyperion	1848 Bond	71.277	148,100,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
40	40	Japetus	1671 Cassini	79.331	356,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
41	41	Phobos	1898 Pickering	550	129,100,000	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
42	42	Cordelia (86U1)	1986 Voyager	0.336	49,700	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
43	43	Ophelia (86U8)	1986 Voyager	0.372	53,800	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
44	44	Bianca (86U9)	1986 Voyager	0.435	59,200	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
45	45	Cressida (86U3)	1986 Voyager	0.464	61,800	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
46	46	Desdemona (86U6)	1986 Voyager	0.474	62,700	0.0000001	0.0000048	116	1,898,133	1,221	1.326	24.79	-14.7	0.503	628,100	1000	0.000	9.40	Si(100%)	-	-	-	-	-	0
47	47	Jul																							

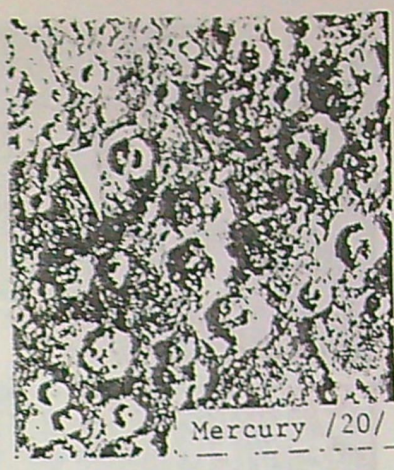
[illegible]



Mercury /29/



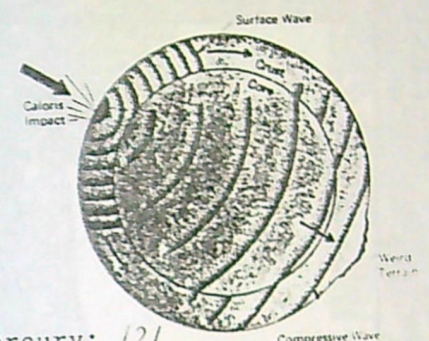
Mercury: the multiring Caloris Basin



Mercury /20/



Moon: rays /1/

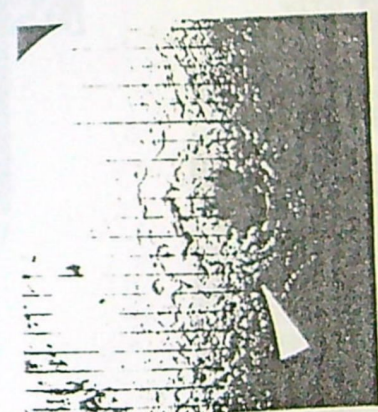


Deimos /29/



Moon: maria /5/

Mercury: /2/ how a multiring basin was born



Moon: Mare Orientale multiring basin

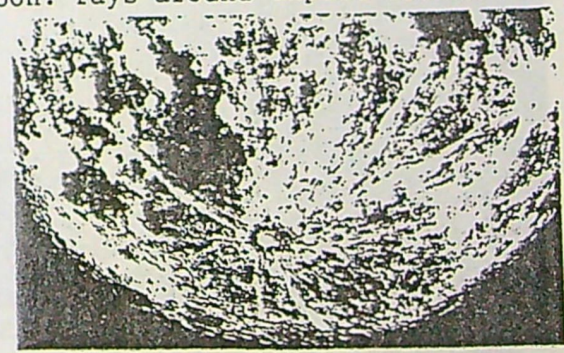


Phobos /29/

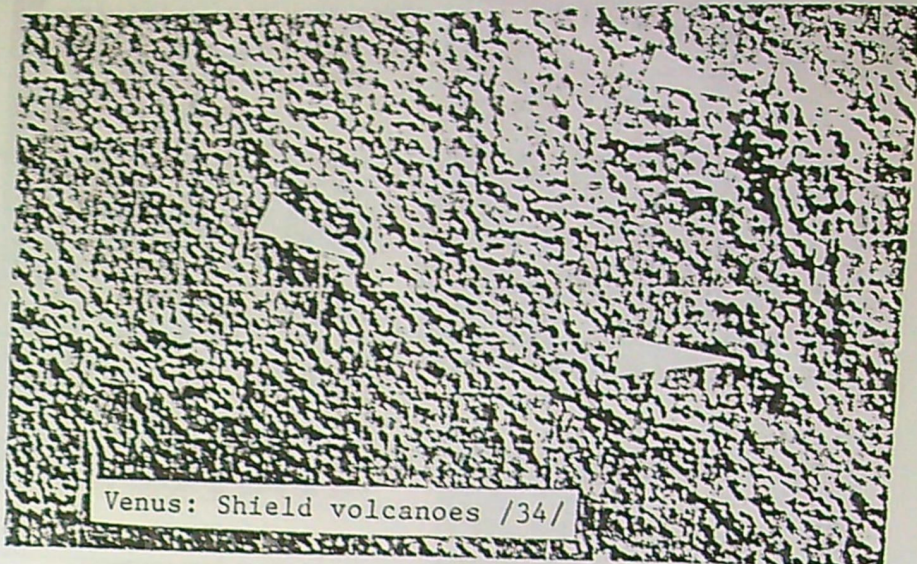


Moon: boundary of a mare /5/

Moon: rays around impact crater /1/



Venus: globe /23/



Venus: Shield volcanoes /34/



Venus: mountain chains /22/

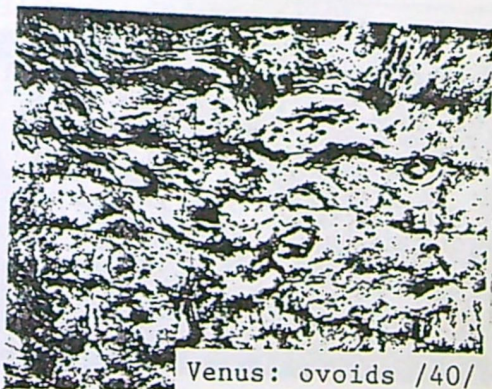
Venus: parquet terrain units /14/



Venus: Lakshmi Planum /21/

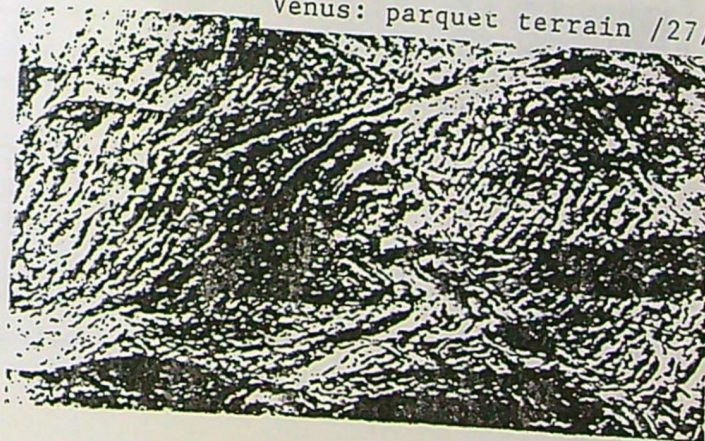


Venus: ovoid (corona) /40/



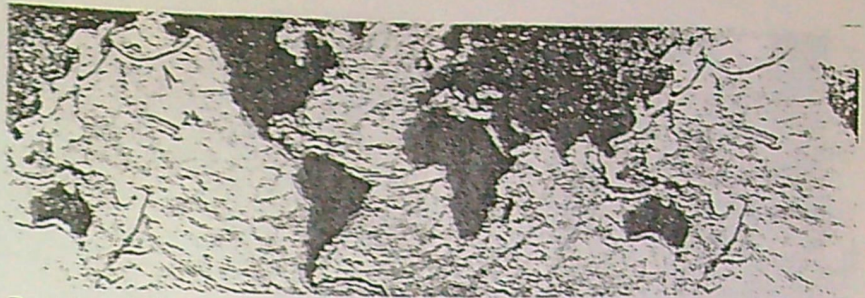
Venus: ovoids /40/

Venus: parquet terrain /27/





Earth:
continents /23/



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



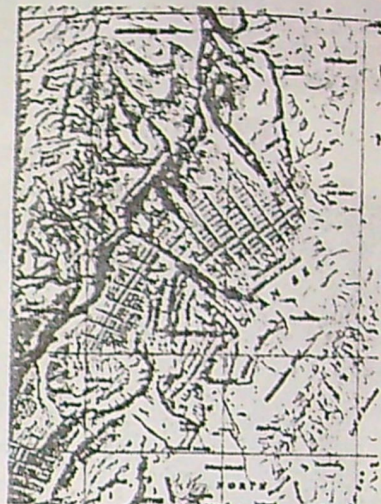
Earth: ovoid /40/



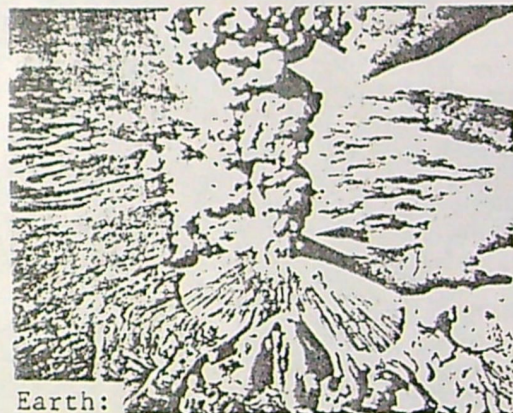
Earth: mountain chains /22/



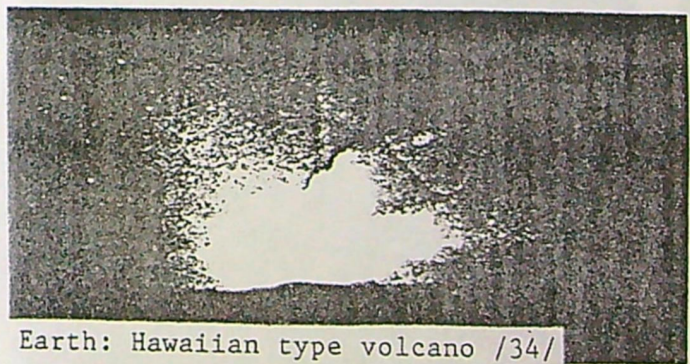
Earth: glaciers /42/



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



Earth:
subductional type volcano /38/



Earth: Hawaiian type volcano /34/



Mars:
shield volcanoes /34/



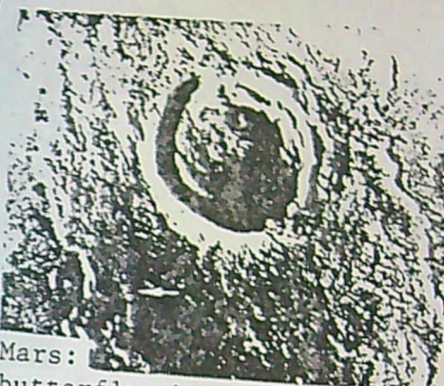
Mars: polar cap /43/



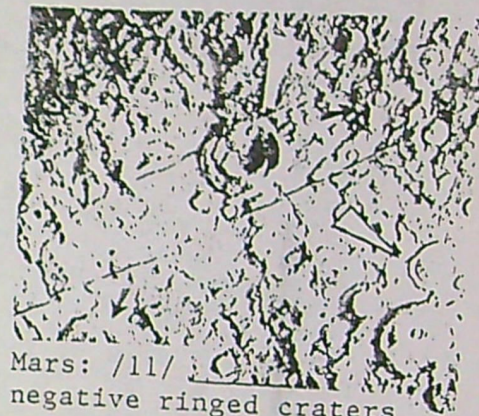
Mars:
rift valley /31/
(Valles Marineris)



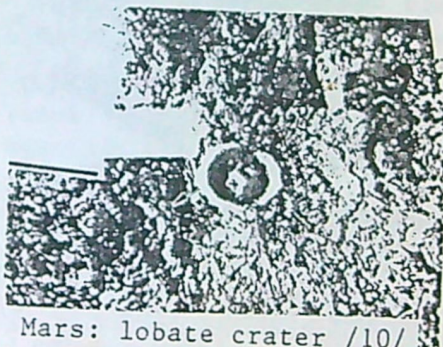
Mars:
Argyrae Basin /6/



Mars:
butterfly shaped crater /9/



Mars: /11/
negative ringed craters

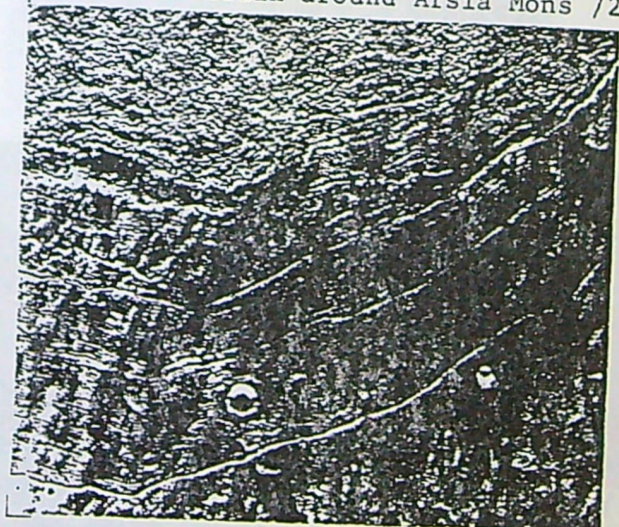


Mars: lobate crater /10/

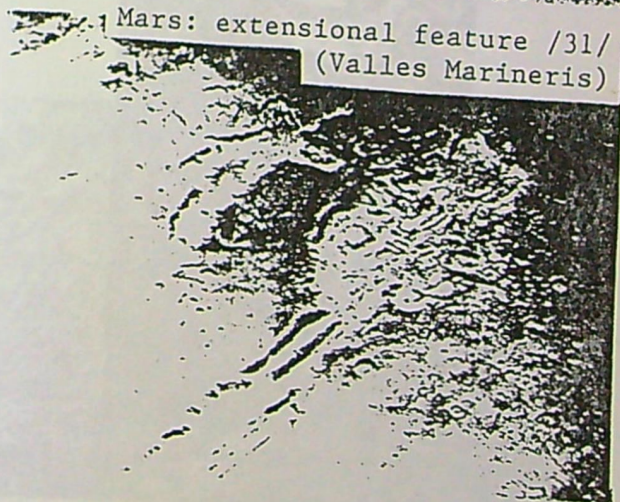
Mars: lobate craters /10/

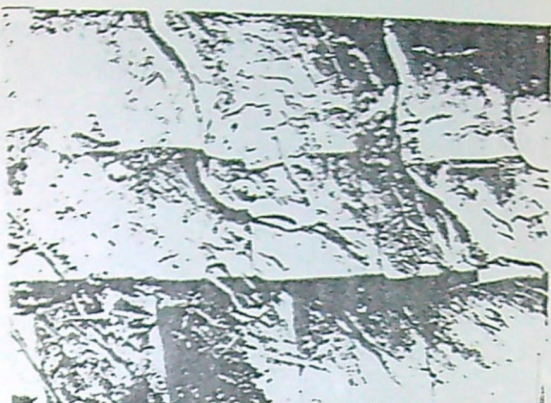


Mars:
grooved terrain around Arsia Mons /26/

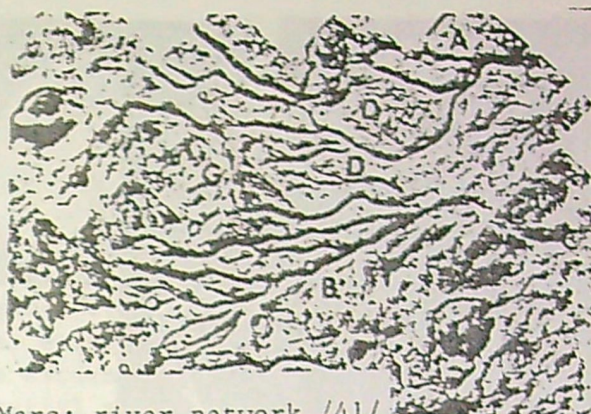


Mars: extensional feature /31/
(Valles Marineris)



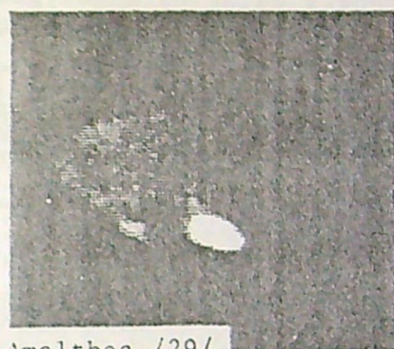
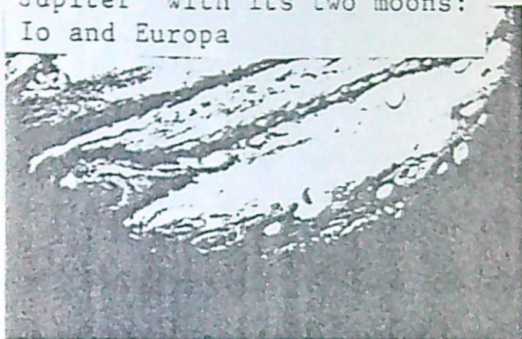


Mars: traces of flowing water /41/



Mars: river network /41/

Jupiter with its two moons:
Io and Europa



Amalthea /29/



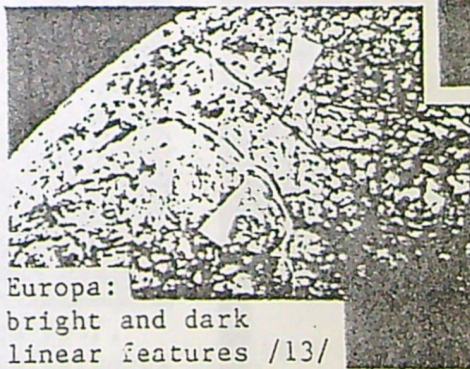
The two sides of Io /3/



Io: traces of flowing
sulphur erosion /41/



Io: Pele volcano



Europa:
bright and dark
linear features /13/

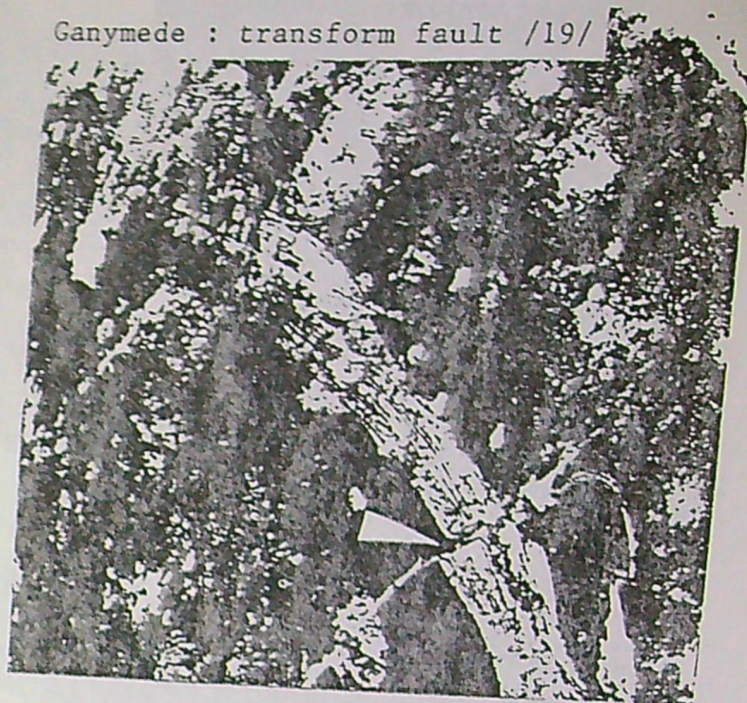
Ganymede /1,17,33/



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



Ganymede : transform fault /19/



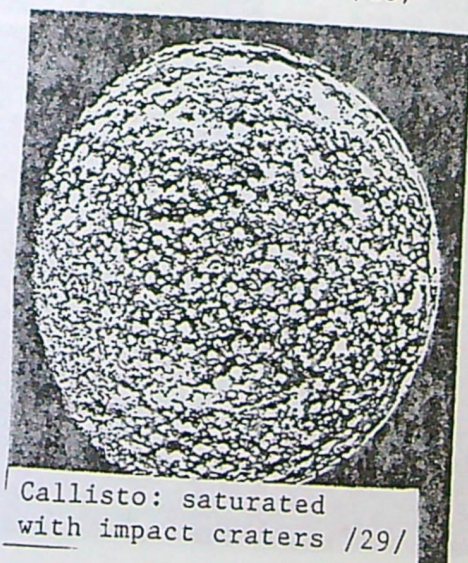
Ganymede : half craters /35/



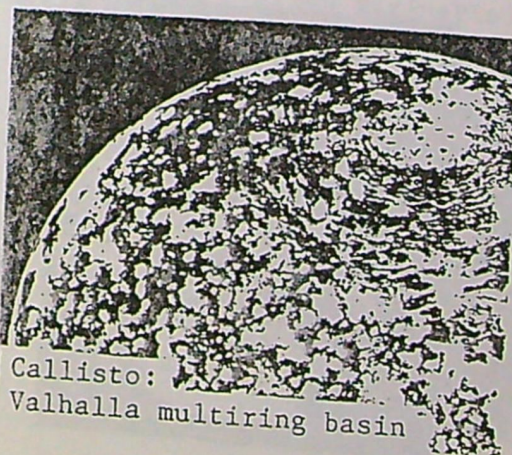
Ganymede : grooved terrain /18/



Ganymede : parallel grooves /18/



Callisto: saturated with impact craters /29/



Callisto: Valhalla multiring basin



Janus /29/



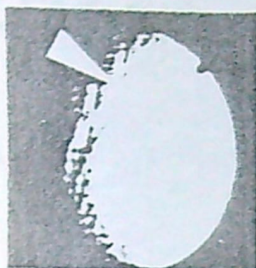
Dione /29/



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



Rhea: full with
impact craters /29/



Tethys:
rift valley /15/



The cloudy Titan



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: /11/ rift system /16/, half craters /35/,
transform faults /19/, parallel grooves /18/.



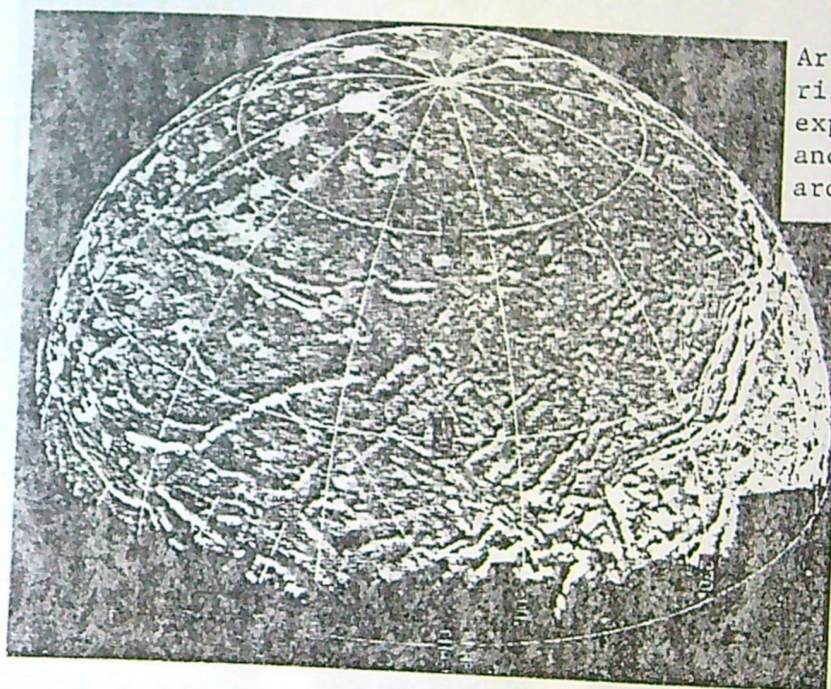
Two sides of Hyperion /4,29/



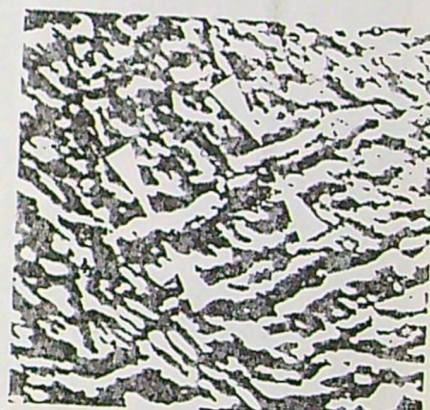
Japetus
in full-moon phase /5/



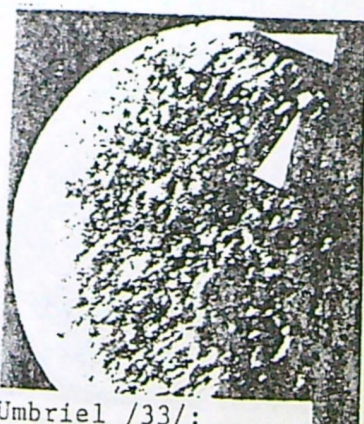
Miranda: ovoids, thrust fault /20/, groove system /32/, lift off /21/



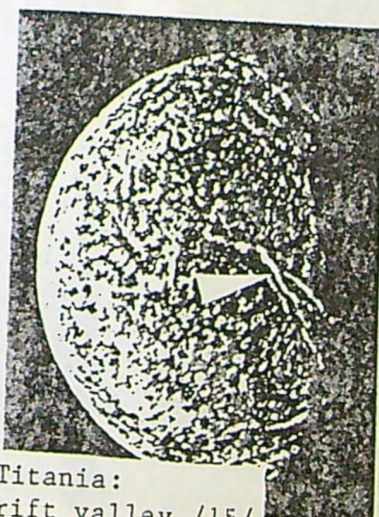
Ariel: rift valley /15/,
rift network /17/,
expansion feature /18/
and bright haloes
around impact craters /1/



Ariel: ice volcanoes /39/



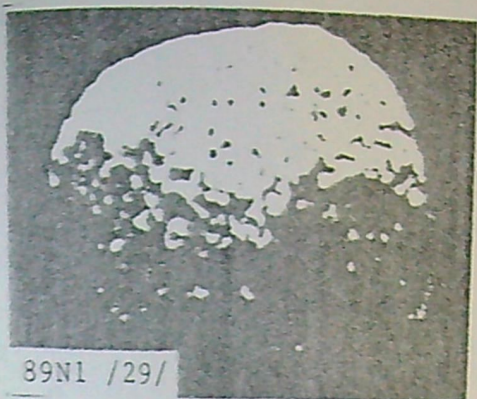
Umbriel /33/:
bright features /5/



Titania:
rift valley /15/



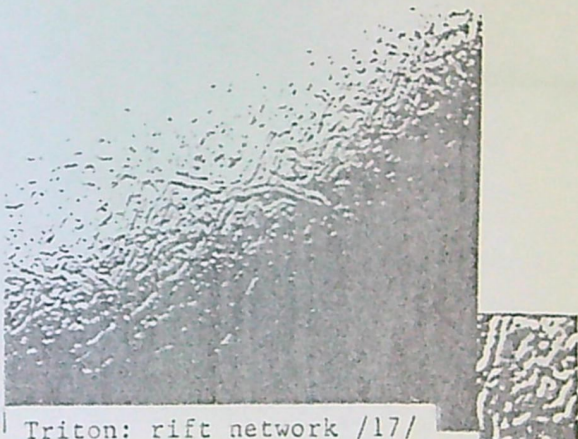
Oberon /1,5/



89N1 /29/



Triton: maria /5/



Triton: rift network /17/



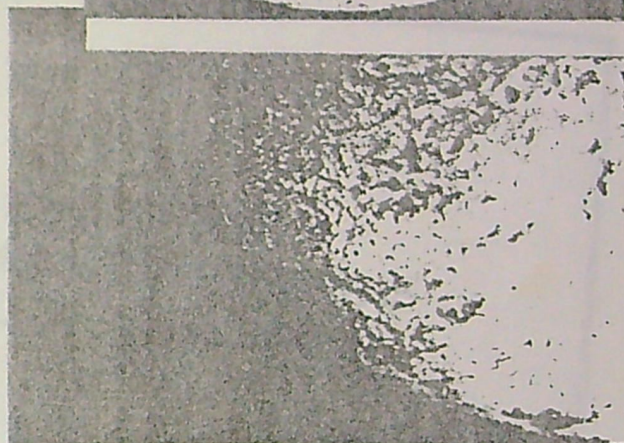
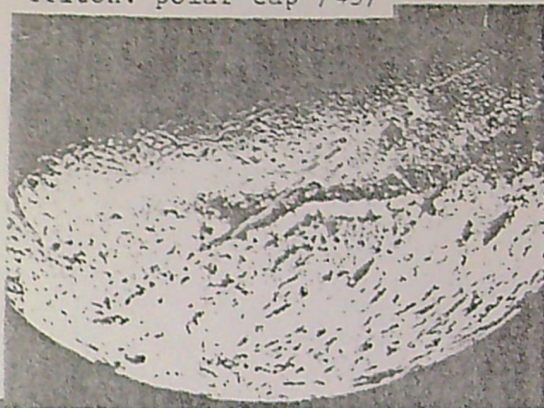
transform fault? /19/



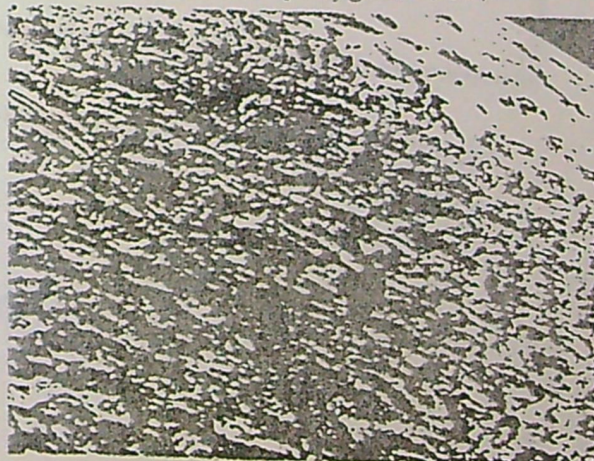
Triton: calderas?



Triton: polar cap /43/



Triton: terrain polygons /37/



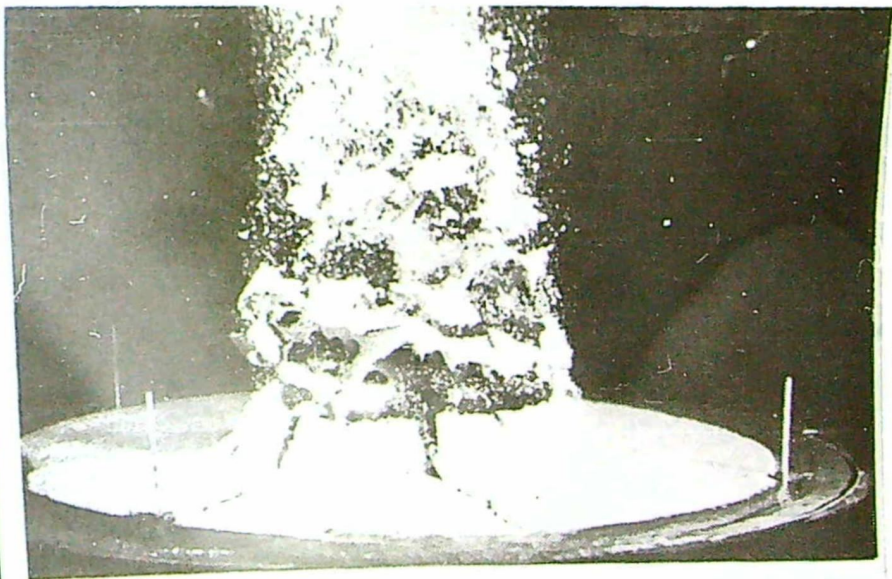


FIGURE 1. Shot 800643 showing impact (energy = 490 joules) into 1.2 cm