EVOLUTION OF PLANETARY BODIES

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KFKI-1990-50/C B. Lukács & al. (eds.): Evolution: from Cosmogenesis to Biogenesis

Received on 4th Oct., 1990

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. Geophyisical 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 izotop 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 genaral 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 mu 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.

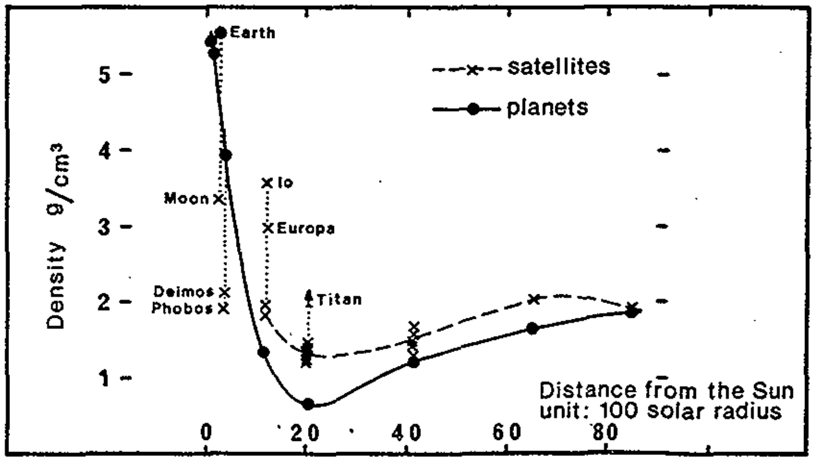


Fig. 1

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,	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 → 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 → 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 → 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 + geological activity } 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)
helio-centric: 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 debries: asteroids outgassed com. meteoroids	4 gaseous planets 5 crusty p.b. with substantial amount of atmosphere 20 crusty p.b. without atmosphere x debries without atmosphere
planeto-centric 60 sat.	7 large sat. 15 middle-size sat. 38 small sat.	19 icy p.b. x icy debries: comets	

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 debries 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 meteorits 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/)

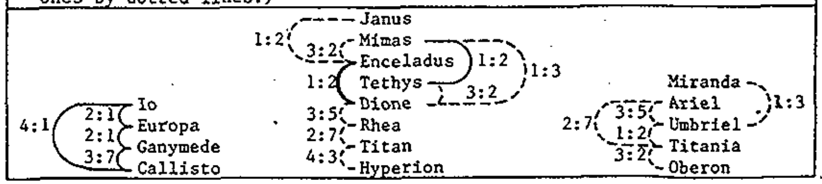
Expansion:
- global: rift valley
  - because of heating
  - because of freezing of the interior of an icy body the
    crust cracks through owing to volume increase /15/
    (Tethys, Titania, Dione?, Ariel?)
- local:
  - rift system because of local heating /16/ (Enceladus, Miranda?)
  - global rift 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 thrusted
    (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 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 differenciation 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 becuse 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 volcamism
  (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_2O, 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_2O
  Titan?: metan, etan, propen, propan? [26,27,28]
- under an ice-crust:
  Europa: H_2O (100 km deep, ice crust 20-30 km thick [21])
  Enceladus?: H_2O
  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)
  CO_2 into charbonates:
  H_2O into hydrated silicates:
  H_2O, CH_4, NH_3, N_2 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_2O
Mars northern polar cap:	H_2O
southern polar cap:	CO_2 / CO_2-H_2O clathrat
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 wapor in the atmosphere dissociated by UV photons
  → hidrogen escaped, oxigen accumulated
- CO_2 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 oxigen 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)

- H_2O, CO_2, CO, N_2, SO_2
- hydrocarbons come from carbonaceous meteorites
- no NH_3/CH_4 neither in ordinary nor in carbonaceous case
- hydrogen (maximum 1%) comes from meteoritic carbids and water (through photoinduced oxidation of dissolved Fe^{2+})
- NH_3 formation by
  - lightening in H_2 rich atmosphere
  - photoreduction of water by nitrogen on rutile (TiO_2) sands in the intertidal and wave zone of the ocean

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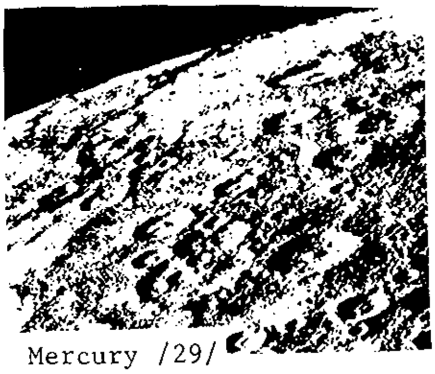
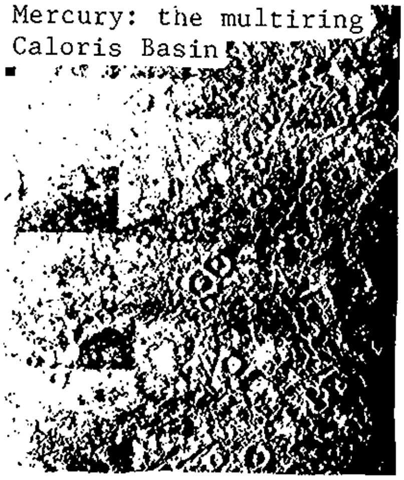
	No. IAU number of satellites	NAME OF PLANETARY BODY	DISCOVERY YEAR DISCOVERER	P sideral orbital period (day)	a mean distance from the central body (km)	a (unit: radius of the central body)	i orbital inclination with respect to the equator of the central body (degrees)	e orbital eccentricity	T TEMPERATURE: ΔT because of e estimated T (Kelvin)	T estimated (on the basis of the visual albedo) (Kelvin)	measured T (Kelvin)	M mass (kg)	M mass (unit: lunar mass)	D diameter (km)	D diameter (unit: lunar diameter)	ϱ density (g/cm^3)	g surface gravity unit: terrestrial g	m visual magnitude	A albedo (%)	smallest distance of highest-resolution-space-photos (km)	highest resolution (km)	SURFACE relief (km)	SURFACE age (unit: 10^9 years)	SURFACE composition	atmosphere	ocean	polar cap	magnetic field	is rotation captured?	shape (O: sphere, ø: irregular)
E	1	Moon		27,322	384000	60,27	5,1	0,055	8	187	403-123	7,35 E22	1,0000	3476	1,000	3,34	0,16	-12,7	7	40	0,001	8	4,6	Si(100%)	-	-	-	-	+	O
MARS	1	Phobos	1877 Hall	0,319	9380	2,76	1,02	0,018	29	315	230	9,6 E15	1,3E-7	27	0,007	1,9 +0,5	0,0009	11,6	5	88	0,01	0,1	>4	C?	-	-	-	-	+	ø
	2	Deimos	1877 Hall	1,262	23500	6,91	1,82	0,002	29	315		2,0 E15	2,7E-8	12	0,003	2,1	0,0004	12,7	5	28	0,01	0,1	>4	C?	-	-	-	-	+	ø
JUPITER	16	Metis (79J3)	1980 Voyager	0,295	127960	1,79	~0	~0	6	145				~40	0,011		0,002	17,4	~5											
	14	Adrastea (79J1)	1979 Voyager	0,298	128980	1,81	~0	~0	6	145				<40	0,011		0,001	18,9	~5	3000										
	5	Amalthea	1892 Barnard	0,489	181300	2,54	0,455	0,003	6	145				240	0,069		0,009	14,1	6	417000	8		>4	Si,S?	-	-	-		+	ø
	15	Thebe (79J2)	1980 Voyager	0,675	221900	3,12	0,9	0,013	6	145				<80	0,023		0,003	15,5	~5											
	1	Io	1610 Galilei	1,769	412600	5,78	0,027	0,000	5	143	133	8,916E22	1,21	3632	1,045	3,57	0,18	5	60	18800	1	10-1	<E6years	Si,S	+		-	?	+	O
	2	Europa	1610 Galilei	3,551	670900	9,40	0,468	0,000	5	125	110- 85	4,873E22	0,66	3126	0,899	2,97	0,14	5,3	60	204200	4	0,2	E7years	Si(97%),H_2O	-	+?	-		+	O
	3	Ganymede	1610 Galilei	7,155	1070000	14,99	0,183	0,001	6	156	145- 85	1,490E23	2,03	5276	1,518	1,93+0,01	0,15	4,6	40	59660	1	0,1	4-3,1	Si(50%),H_2O	-		-		+	O
	4	Callisto	1610 Galilei	16,689	1880000	26,33	0,253	0,007	6	166	155- 80	1,064E23	1,45	4820	1,386	1,83+0,01	0,12	5,6	20	124000	2		4,6-3,8	Si(47%),H_2O	-		-		+	O
	13	Leda	1974 Kowal	240	11110000	155,61	27	0,147	7	170				~14	0,004		0,0003	20,2												
	6	Himalia	1904 Perrine	250,6	11470000	160,65	28	0,158	7	170				~170	0,049		0,004	14,8	~3											
	10	Lysithea	1938 Nicholson	260	11710000	164,01	29	0,12	7	170				<32	0,009		0,0006	18,4												
	7	Elara	1905 Perrine	260,1	11740000	164,43	26	0,207	7	170				~80	0,023		0,002	16,7	~3											
	12	Ananke	1951 Nicholson	617	20700000	290	147	0,169	7	170				~28	0,008		0,0005	18,9												
	11	Carme	1938 Nicholson	692	22350000	313	163	0,207	7	170				~40	0,011		0,0008	18,0												
	8	Pasiphae	1908 Mellotte	735	23300000	326	147	0,40	7	170				~46	0,013		0,0009	17,7												
	9	Sinope	1914 Nicholson	758	23700000	332	156	0,275	7	170				~36	0,010		0,0008	18,3												
SATURN	17	Atlas	1980 Voyager	0,606	138200	2,28	0,3	0,002	6	112				<50	0,014		0,0008	18	~40	219000	13									ø
	16	Prometheus (80S27)	1980 Voyager	0,613	139400	2,31	0	0,004	6	112				<200	0,057		0,006	16,5	~40	246400	7									ø
	15	Pandora (80S26)	1980 Voyager	0,629	141700	2,35	0,1	0,004	6	112				<140	0,040		0,005	16	~40	107000	8									ø
	10	Janus (80S1)	1966 Dollfus	0,696	151400	2,51	0,1	0,007	6	112				<220	0,063		0,005	14,5	~40	121000	3		>4						+	ø
	11	Epimetheus (80S3)	1977 Fountain,Larson	0,696	151450	2,51	0,3	0,009	6	112				<140	0,040		0,004	15,5	~40	222700	3,2		>4						+	ø
	1	Mimas	1789 Herschel	0,942	185500	3,08	1,517	0,020	6	101		3,76 E19	0,0005	394	0,113	1,43+0,10	0,007	12,9	60	88240	2	9	>3,9	Si(31%),H_2O	-	-	-		+	O!
	2	Enceladus	1789 Herschel	1,370	238000	3,95	0,023	0,004				7,4 E19	0,0010	502	0,144	1,20+0,6	0,008	11,8	100	86890	2		E8years	Si(9%),H_2O	-	?	-		+	O
	3	Tethys	1684 Cassini	1,888	294700	4,88	1,093	0,000	6	88		6,26 E20	0,0085	1060	0,305	1,25+0,06	0,015	10,3	80	92470	2	3	3,8-4	Si(13%),H_2O	-	-	-		+	O
	13	Telesto (80S13)	1980 Voyager	1,888	294670	4,88			6	112				<30	0,009		0,0004	19	~40	153500	12									ø
	14	Calypso (80S25)	1980 Voyager	1,888	294670	4,88			6	112				<24	0,007		0,0003	18,5	~40	237320	5									ø
	4	Dione	1684 Cassini	2,737	377400	6,26	0,023	0,002	6	101		1,05 E21	0,0142	1120	0,322	1,43+0,1	0,022	10,4	62	160000	3		>4	Si(18%),H_2O	-	-	-		+	O
	12	Helena(DioneB,80S6)	1980 Voyager	2,737	377400	6,26	0,2	0,005	6	112				<34	0,010		0,0008	10,5	~40	225000	6									ø
	5	Rhea	1672 Cassini	4,518	527000	8,73	0,35	0,001	6	112	99- 73	2,28 E21	0,0310	1530	0,440	1,33+0,1	0,023	9,7	60	72000	1		>4	Si(12%),H_2O	-	-	-		+	O
	6	Titan	1655 Huygens	15,945	1222000	20,3	0,33	0,029	6	114	94	1,36 E23	1,8503	<5150	1,481	>1,9	0,014	8,4	35	3920	1		cloud	Si(42%),H_2O	+!	+?	?	?	+	O
	7	Hyperion	1848 Bond	21,277	1481000	24,6	0,4	0,104	8	120		1,1 E20	0,0015	410	0,118		0,006	14,2	20	470640	9		>4	ices	-	-	-		-!	ø!
	8	Iapetus	1671 Cassini	79,331	3560000	59	14,7	0,028	8	122		1,93 E21	0,0262	1460	0,420	1,2 +0,5	0,02	11,9	50-5!	908340	17		>4	Si(7%),ices	-	-	-		+	O
	9	Phoebe	1898 Pickering	550	12930000	215	150	0,163	8	126				220	0,063		0,005	16,5	5	2075500	38			C?					+	O!
URANUS	13	Cordelia (86U7)	1986 Voyager	0,334	49700	1,94			4	87	80			24	0,007				<10											
	14	Ophelia (86U8)	1986 Voyager	0,377	53800	2,10			4	87	80			32	0,009				<10											
	15	Bianca (86U9)	1986 Voyager	0,435	59200	2,31			4	87	80			48	0,013				<10											
	9	Cressida (86U3)	1986 Voyager	0,464	61800	2,41			4	87	80			72	0,021				<10											
	12	Desdemona (86U6)	1986 Voyager	0,474	62700	2,45			4	87	80			48	0,013				<10											
	8	Juliet (86U2)	1986 Voyager	0,496	64600	2,52			4	87	80			72	0,021				<10											
	7	Portia (86U1)	1986 Voyager	0,513	66100	2,58			4	87	80			88	0,025				<10											
	10	Rosalind (86U4)	1986 Voyager	0,558	69900	2,73			4	87	80			48	0,014				<10											
	11	Belinda (86U5)	1986 Voyager	0,624	75300	2,94			4	87	80			145	0,042				<10											
	6	Puck (85U1)	1985 Voyager	0,761	86000	3,36			4	87	80			170	0,049				7	500000	9									ø
	5	Miranda	1948 Kuiper	1,414	129900	5,07	4,22	0,027	4	81	84	3,4 E19	0,0004	484	0,139	1,26+0,39	0,004	16,5	24	29000	0,6	20	<4	Si,ices	-	-	-		+	O
	1	Ariel	1851 Lassell	2,520	190900	7,46	0,31	0,003	4	79	86	6,7 E20	0,0091	1160	0,334	1,65+0,30	0,01	14,4	31	130000	2,5	1	«4	Si,ices	-	-	-		+	O
	2	Umbriel	1851 Lassell	4,144	266000	10,39	0,36	0,005	4	85	86	7,6 E20	0,0103	1190	0,342	1,44+0,28	0,008	15,3	50-19	325000	11		4	Si,ices	-	-	-		+	O
	3	Titania	1787 Herschel	8,706	436300	17,04	0,14	0,002	4	83	86	1,2 E21	0,0163	1610	0,463	1,59+0,09	0,02	16	28	364000	7	5	<4	Si(50%),ices	-	-	-		+	O
	4	Oberon	1787 Herschel	13,463	583400	22,79	0,10	0,001	4	84	86	8,2 E21	0,1115	1550	0,446	1,50+0,10	0,1	16,2	26	470000	12	20	>4	Si(50%),ices	-	-	-		+	O
NEPTUNE		89N6	1989 Voyager	0,296	48000	1,95	0	0						54	0,014				6		23,6									ø
		89N5	1989 Voyager	0,313	50000	2,02	4,5	0						80	0,026				6		17,4									ø
		89N3	1989 Voyager	0,333	52500	2,12	<1	0						150	0,040				6		16,9									ø
		89N4	1989 Voyager	0,43	62000	2,51	<1	0						180	0,046				5		18,4									ø
		89N2	1989 Voyager	0,554	73600	2,97	<1	0						190	0,058				6		4,1									ø
	3	89N1	1989 Voyager	1,121	117600	4,75	<1	0						400	0,120				6	146000	1,3									ø
	1	Triton	1846 Lassell	5,877	354800	14,36	157	0,001	0	65	38			2705	0,782	2,02		13,6	90	38500	0,8	0,2	<E6years	N_2,CH_4 ices	+	?	+		+	O
	2	Nereida	1949 Kuiper	359,88	5510000	222,63	29	0,75	0	65				340	0,098			18,7	14	4700000	43,3								+	O
PL	1	Charon	1978 Christy	6,387	17000	15,45	105		15	55		1,28 E21	0,0174	1119	0,316	1,84+0,19	0,02	17	42					ices	?	?			+	
PLANETS		Mercury		88	57,9E6	83		0,2056	130	625	703- 88	3,3 E23	4,49	4880	1,40	5,43	0,37	- 0,2	56	318	0,05	3	4,6	Si(100%)	-	-	-	+	?	O
		Venus		224,7	108,2E6	156		0,0068	3	324	773-773	4,87 E24	66,26	12104	3,48	5,24	0,90	- 3,6	72	1000	1,5	10	1	Si(100%)	+	-		-	-	O
		Earth		365,3	149,6E6	215	7,25	0,0167	8	349	288	5,98 E24	81,31	12756	3,67	5,52	1,00		39	200	0,01	10	4,6- <E6	Si(100%)	+	+	+	+	-	O
		Mars		687	227,9E6	328		0,0934	27	306	293-233	6,4 E23	8,74	6787	1,95	3,93	0,38	1,8	16	1500	0,1	25	>4	Si(100%)	+	-	+	+	-	O
		Jupiter		11,86 y	778,3E6	1120		0,0485	6	131	143	1,899E27	25836	142796	41,08	1,326	2,53	- 1,7	70	42800	1		cloud	Si-core,H,He	+			+	-	O
		Saturn		29,45 y	1427 E6	2053		0,0556	7	95	123	5,69 E26	7741	120000	34,52	0,686	1,07	1,3	75	101100	3		cloud	Si-core,H,He	+			+	-	O
		Uranus	1781 Herschel	84,01 y	2869 E6	4128		0,0472	4	67	59	8,7 E25	1183	51200	14,73	1,267	0,90	6	90	81400	2		cloud	Si-core,H,He	+			+	-	O
		Neptune	1846 Leverrier,Galle	164,79 y	4496 E6	6469		0,0086	0	53	59	1,03 E26	1401	49500	14,24	1,64	1,14	7,9	82	4905			cloud	Si-core,H,He	+			+	-	O
		Pluto	1930 Tombaugh	250,3 y	5900 E6	8489		0,250	13	49	55	8,2 E22	1,12	2245	0,63	1,86	0,09	15	61					ices	+		+		-	
		Sun										1,99 E30	2,7 E7	1392000	400	1,41	27,93	-26,86						H(90%),He(9%)	+			+		O

WHAT LEVEL OF GEOLOGICAL ACTIVITY WAS REALIZED ON CRUSTY PLANETARY BODIES WITH DIAMETER LARGER THAN 240 KM

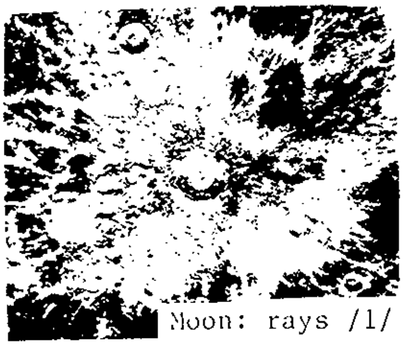
	uniform surface	surface saturated with craters	larger craters (population I)	smaller craters (population II)	multiring basin	rays/haloes around impact craters	bright crix-crax albedo features	rift valley of planet size	contraction (thrust fault)	any traces of out-flowing material	mare (lava of low viscosity)	expansion	rift system	parallel grooves	transform faults	shield volcanoes	calderas	recent volcanism	mountain chains	continents	erosion of flowing material	river bed
Moon	-	+-	+	+	+	+	-	-	-	+!	+!	-	-	-	-	-	-	-	-	-	-	-
Amalthea	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Io	+	-	-!	-!	-	-	-	-	-	+	-	-	-	-	-	-	+!	+!	-	-	+	-
Europa	+	-	-!	~!	-	-	-	-	-	+?	-	-	+!	-	-	-	-	-?	-	-	-	-
Ganymede	-!	+-	+	+	+	+	-	-	-	-	-	+?	+!	+!	+!	-	-	-	-	-	-	-
Callisto	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mimas	+	+	+!	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Enceladus	-	+-	-!	+	-	-	-	-	-	-	-	+?	+!	+!	+!	-	-	-?	-	-	-	-
Tethys	-	+-	+	+	-	-	-	+!	-	-	-	+?	-	-	-	-	-	-	-	-	-	-
Dione	-	+	+	+	-	-	+!	+	-	-	-	+	-	-	-	-	-	-	-	-	-	-
Rhea	-	+	-	+	-	-	+!	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Titan	Nothing visible on the surface because of hydrocarbon smog/snow.																					
Hyperion	+	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Japetus	-!	+	+	+	-	-	-	-	-	+?	+?	-	-	-	-	-	-	-	-	-	-	-
Miranda	-	+-	-	+	-	-	-	-	+?	+	-	-	+!	+!	-	-	-	-	-	-	-	-
Ariel	-	+-	-	+	-	+	-	+	-	-	-	+!	+!	+	-	-	-	-	-	-	-	-
Umbriel	-!	+	+	+	-	-!	-	-	-	+?	+?	-	-	-	-	-	-	-	-	-	-	-
Titania	-	+-	-	+	-	+	-	+	-	+?	+?	+?	-	-	-	-	-	-	-	-	-	-
Oberon	+	+	+	+	-	+	-	-	-	+?	+?	-	-	-	-	-	-	-	-	-	-	-
89N1	+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Triton	-	-	-!	-	-	-	-	-	-	+!	+!	-	+!	-	+?	-	+!	+!	-	-	-	-
Nereid																						
Charon																						
Mercury	+	+	+	+	+	+	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-	-
Venus	-	-	-	+	-	+	-	-	-	+	-	+	?	+	?	+!	+	+?	+!	+!	-	-
Earth	-	-	-	+	-	-	-	-	-	+	-	+	+	+	+	+	+	+	+	+	+	+
Mars	-	+-	+	+	-	-	-	-	-	+	-	+!	-	+	-	+!	+	-	-	-	+	+!
Pluto	-																					

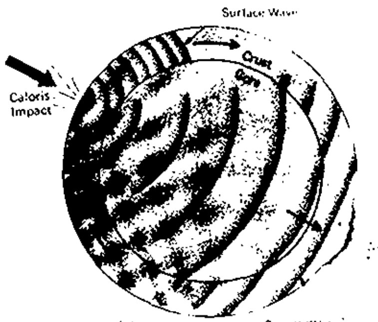

Mercury /29/

Mercury: the multiring Caloris Basin




Mercury /20/


Moon: rays /1/



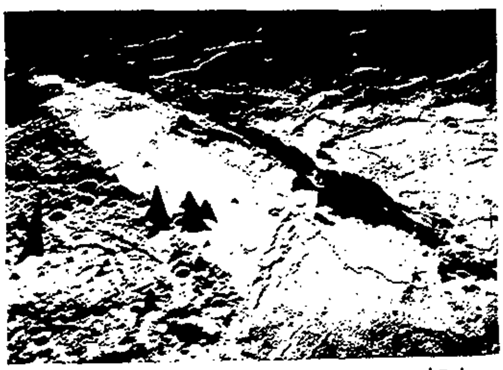
Mercury: /2/
how a multiring basin was born


Deimos /29/

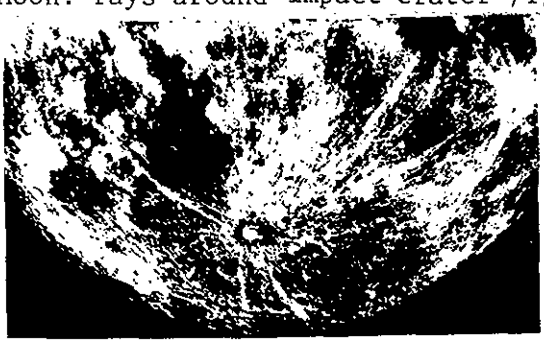

Moon: maria /5/


Moon: Mare Orientale multiring basin

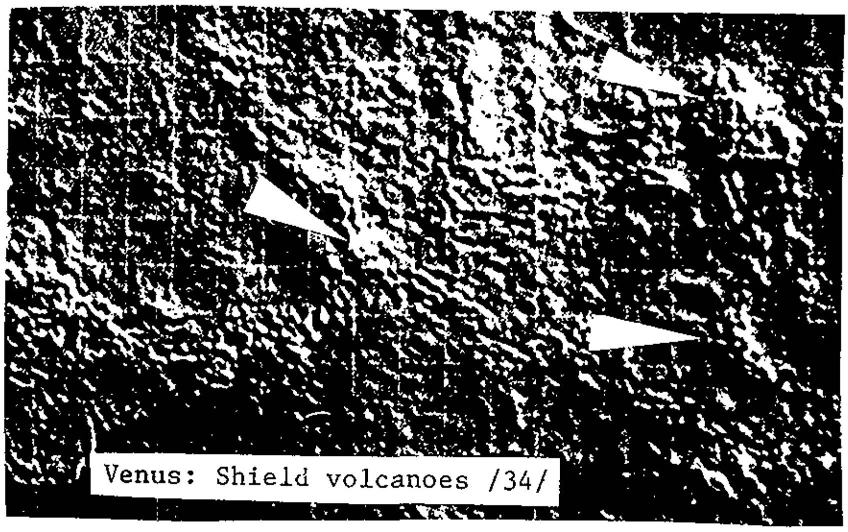

Phobos /29/


Moon: boundary of a mare /5/

Moon: rays around impact crater /1/



Venus: globe /23/

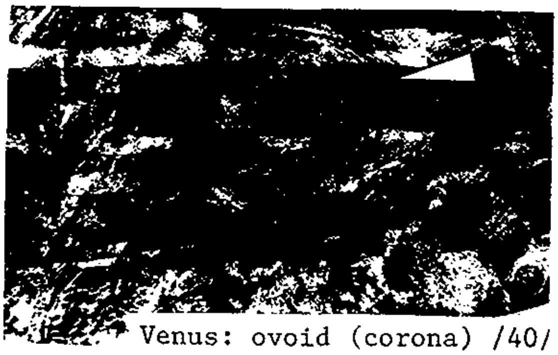


Venus: Shield volcanoes /34/

Venus:
mountain chains /22/

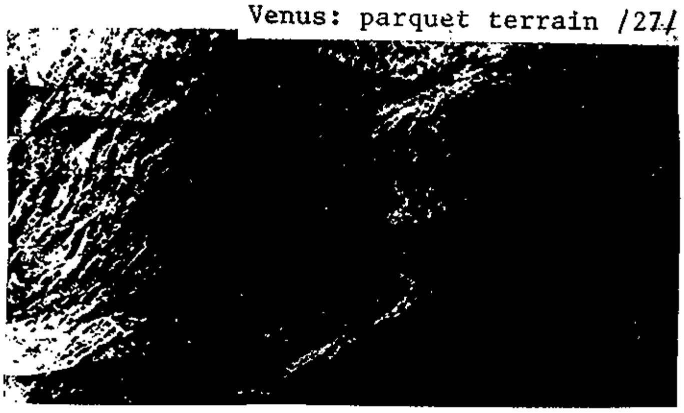
Venus: parquet terrain units /14/

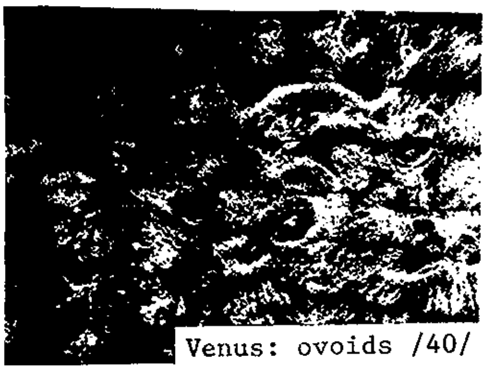
Venus: Lakshmi Planum /21/



Venus: ovoid (corona) /40/

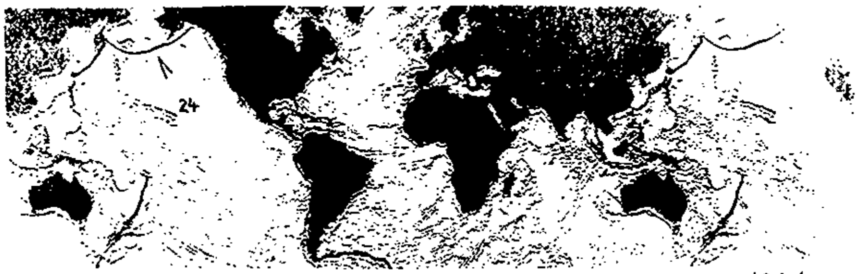
Venus: parquet terrain /27/



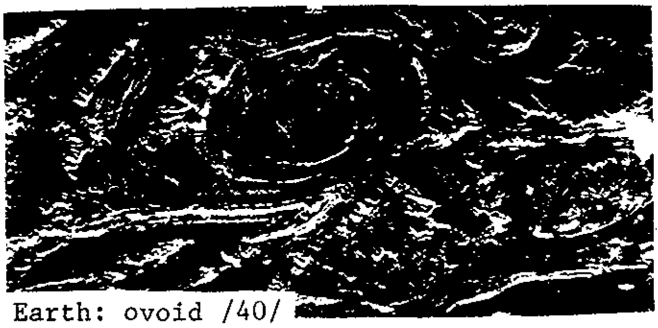


Venus: ovoids /40/

Earth:
continents /23/



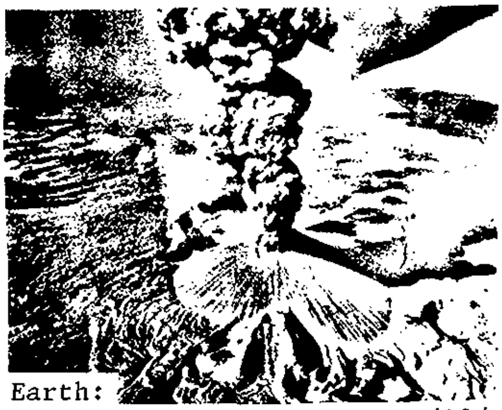
Earth: /28,33,17,18,19/ deep oceanic trenches /24/



Earth: ovoid /40/

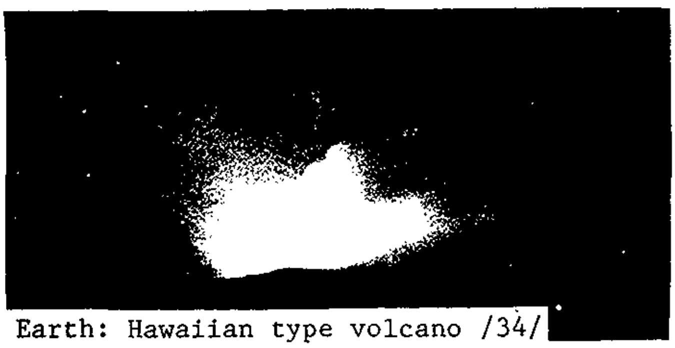
Earth:
mid oceanic ridges /25,18/
with transform faults /19/

Earth: mountain chains /22/



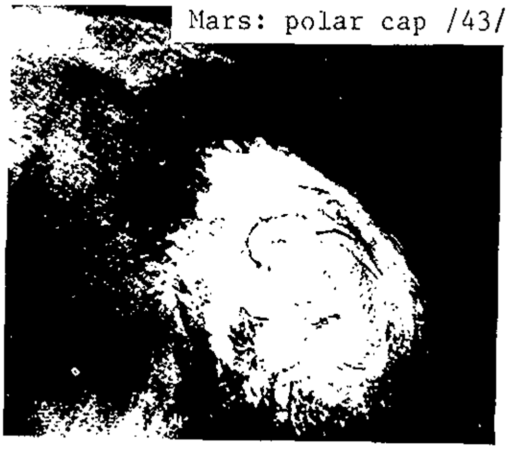
Earth:
subductional type volcano /38/

Earth: glaciers /42/

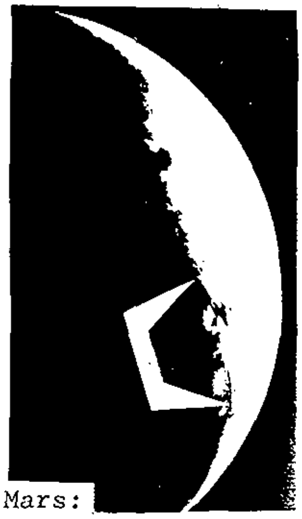


Earth: Hawaiian type volcano /34/

Mars:
shield volcanoes /34/



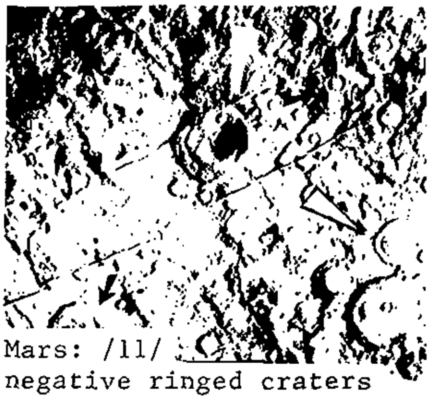
Mars: polar cap /43/



Mars:
rift valley /31/
(Valles Marineris)

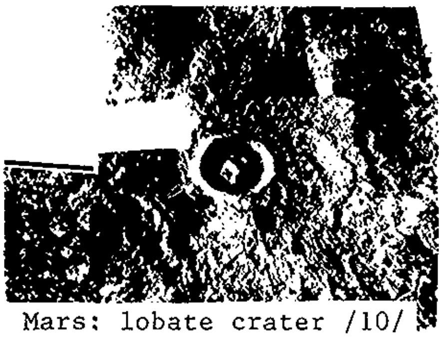
Mars:
Argyrae Basin /6/

Mars:
butterfly shaped crater /9/



Mars: /11/
negative ringed craters

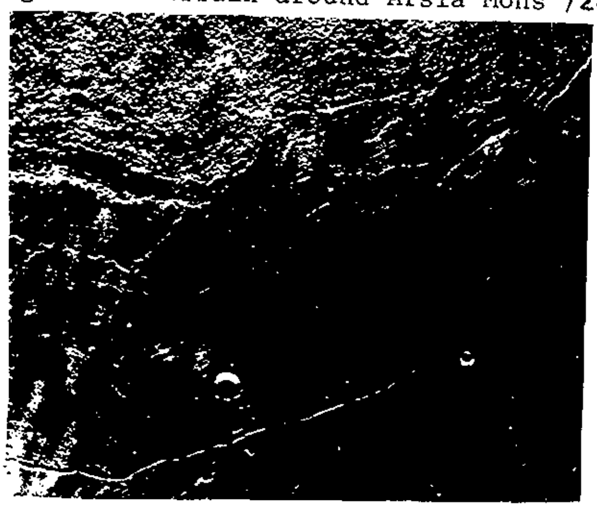
55



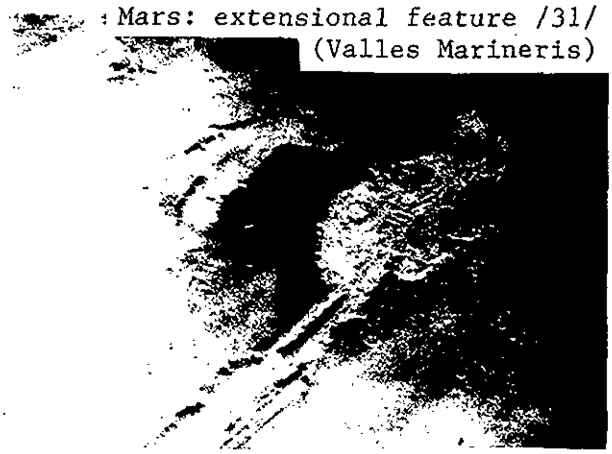
Mars: lobate crater /10/

Mars: lobate craters /10/

Mars:
grooved terrain around Arsia Mons /26/



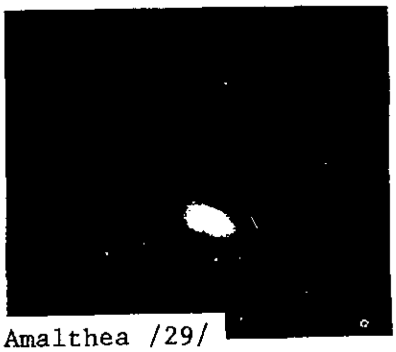
Mars: extensional feature /31/
(Valles Marineris)




Mars: traces of flowing water /41/


Mars: river network /41/

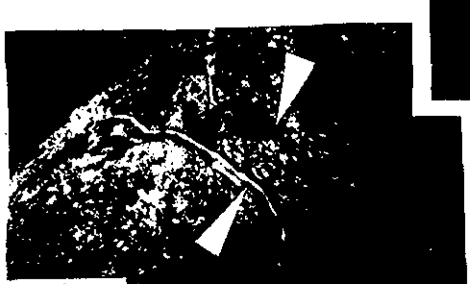
Jupiter with its two moons:
Io and Europa


Amalthea /29/

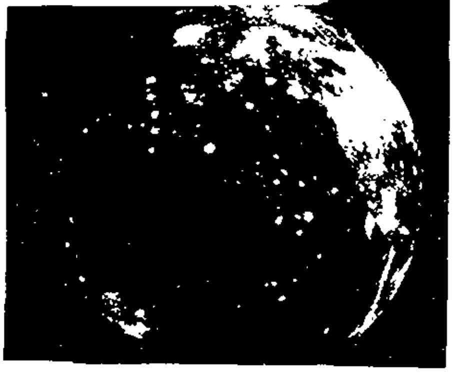

The two sides of Io /3/


Io: traces of flowing
sulphur erosion /41/

Io: Pele volcano

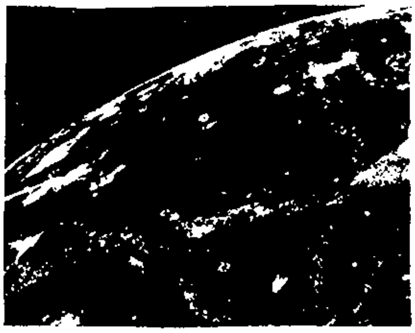

Europa:
bright and dark
linear features /13/

Ganymede /1,17,33/

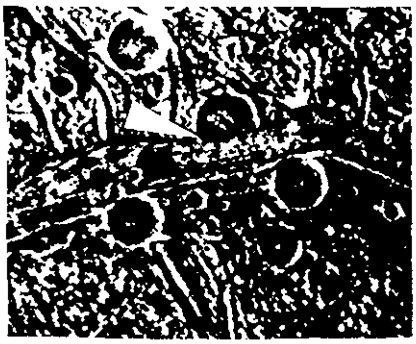


Ganymede : transform fault /19/

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

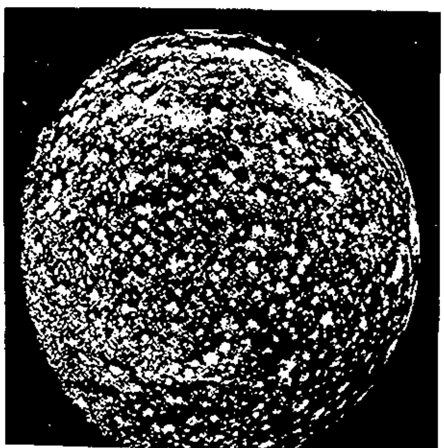


Ganymede : grooved terrain /18/

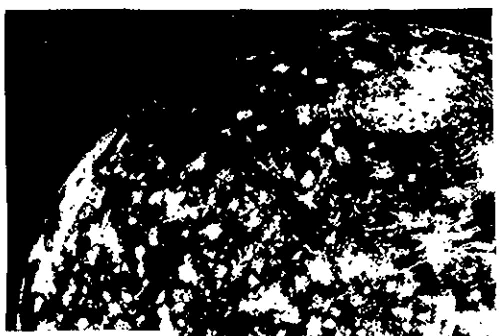


Ganymede : half craters /35/

Ganymede : parallel grooves /18/



Callisto: saturated with impact craters /29/



Callisto: Valhalla multiring basin

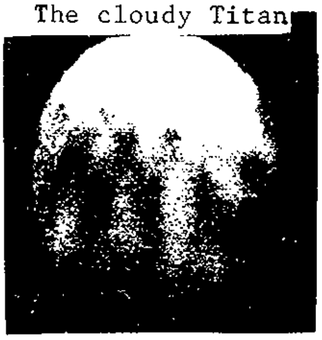
Janus /29/

Dione /29/

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

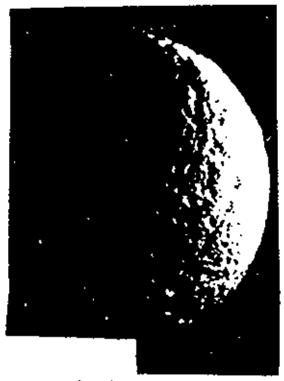
Rhea: full with
impact craters /29/

The cloudy Titan

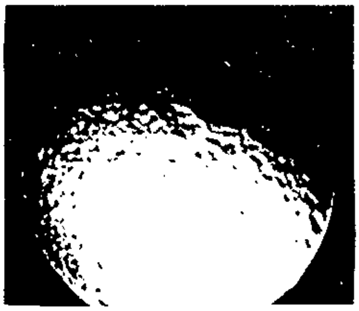


Tethys:
rift valley /15/

Dione: /30/ bright
albedo features

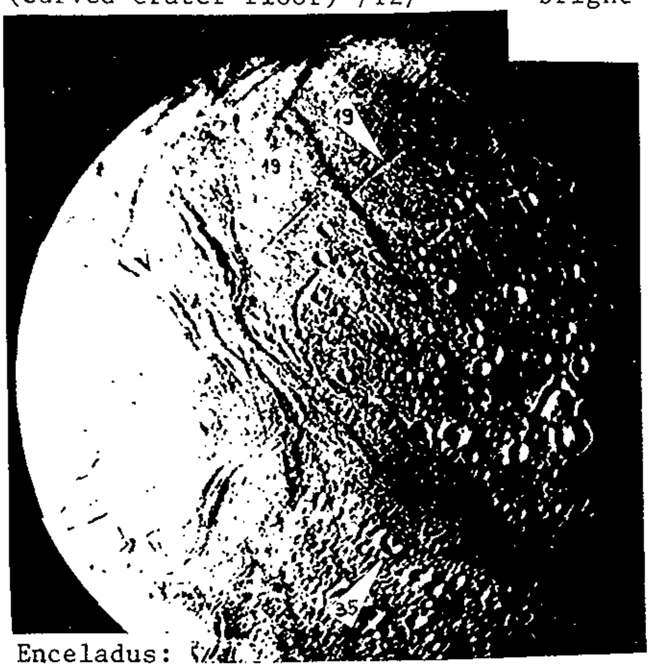


Mimas /4/:
saturated with
impact craters /29/

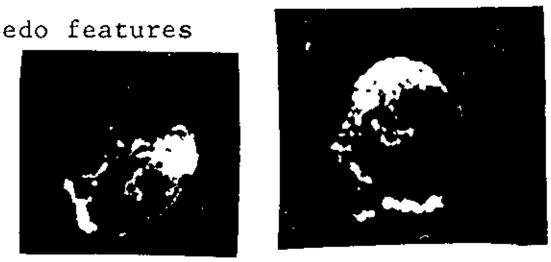


Tethys: Odysseus crater
(curved crater floor) /12/

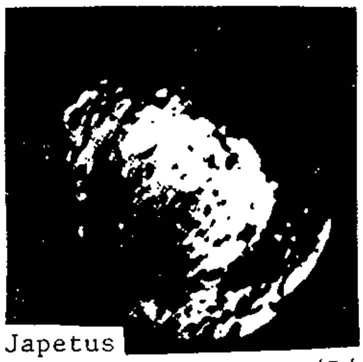
Rhea: /30/
bright albedo features



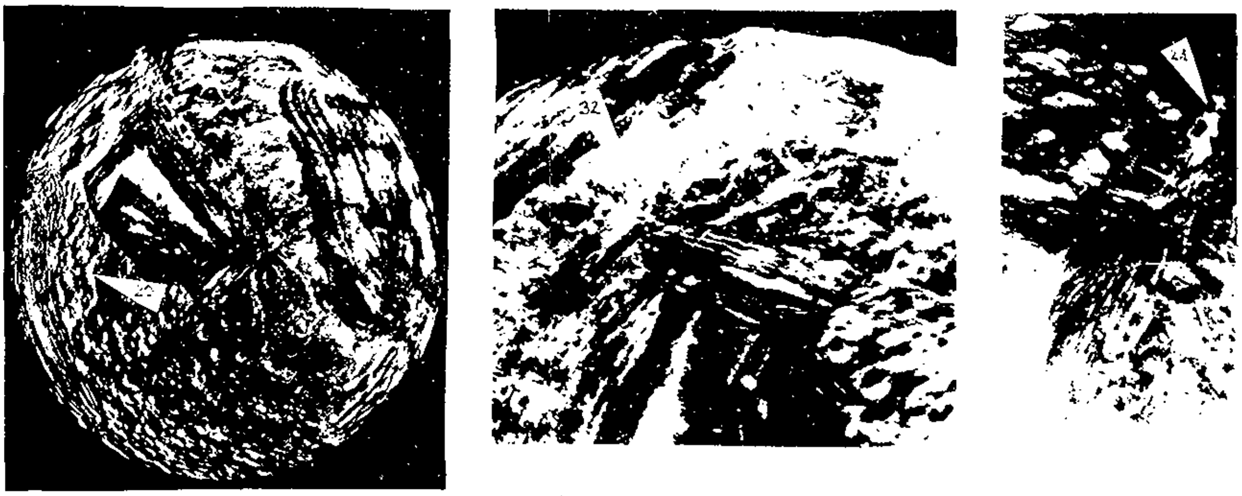
Enceladus:
rift system /16/, half craters /35/,
transform faults /19/, parallel grooves /18/.



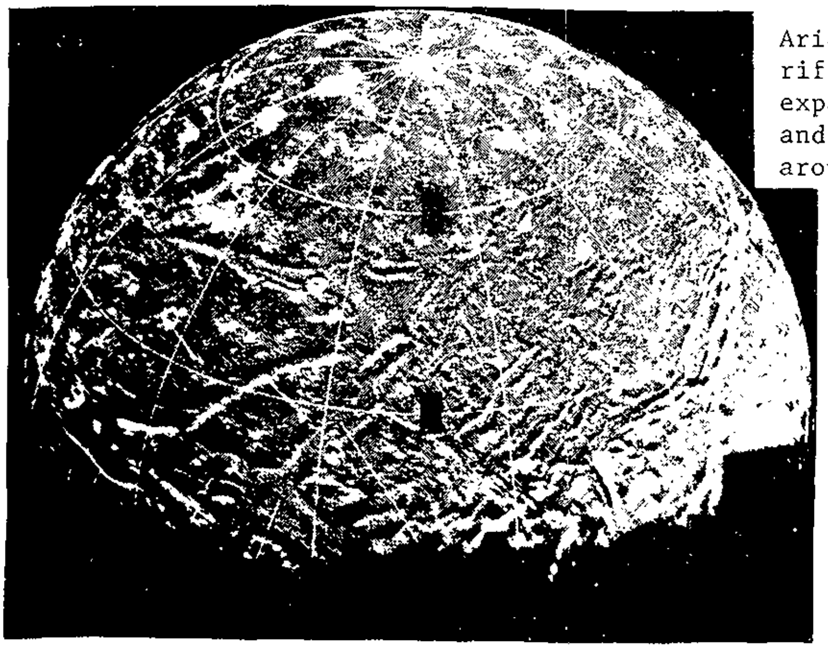
Two sides of Hyperion /4,29/



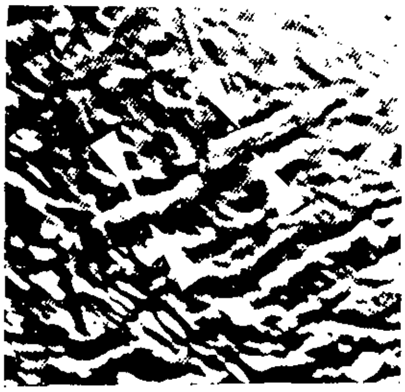
Japetus
in full-moon phase /5/



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

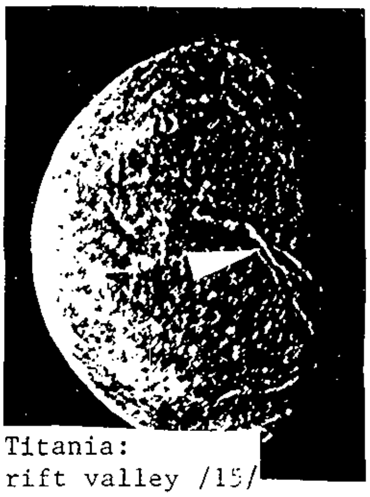


Ariel: rift valley /15/,
rift network /17/,
expansion feature /18/
and bright haloes
around impact craters /1/

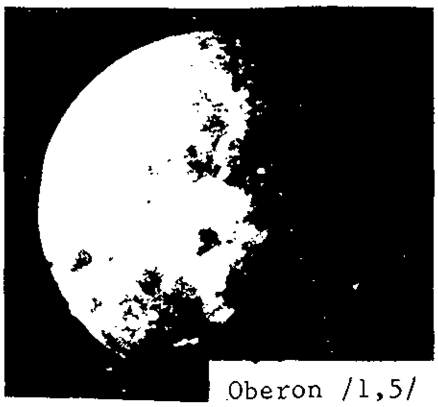


Ariel: ice volcanoes /39/

Umbriel /33/:
bright features /5/



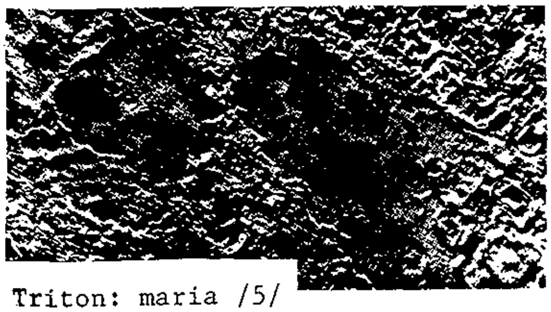
Titania:
rift valley /15/



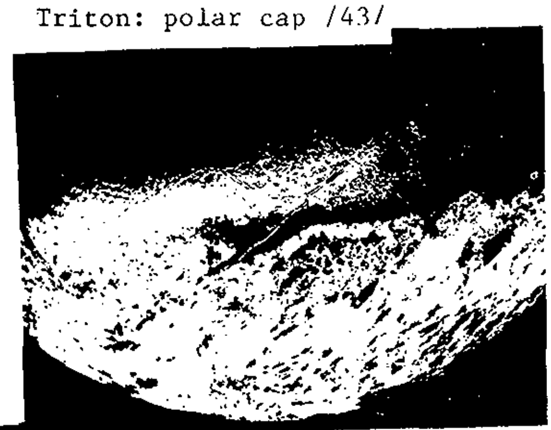
Oberon /1,5/

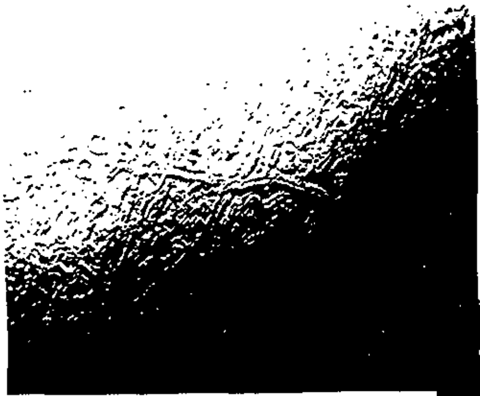
89N1 /29/

Triton: polar cap /43/

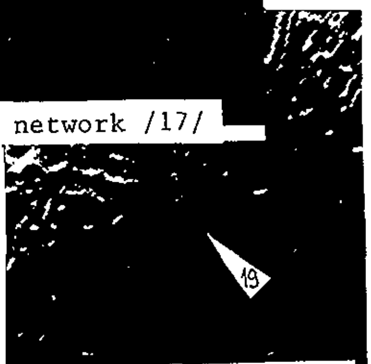


Triton: maria /5/





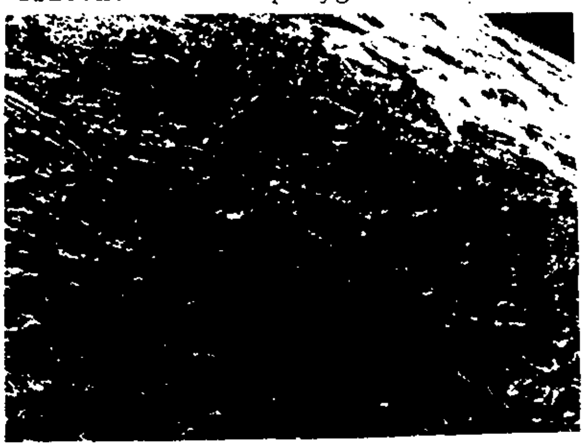
Triton: rift network /17/



transform fault? /19/

Triton: terrain polygons /37/

Triton: calderas?



From: B. Lukács & al. (eds.), Carpathian Basin... KFKI-1993-21/C

PLATE TECTONICS IN THE SOLAR SYSTEM

by E. Illés
Konkoly Observatory

It was realized about 30 years ago that a mechanism of large scale geological activity called "plate tectonics" is continuously in action on the Earth since at least several hundred million years. Its main characteristics can be summarized as follows: the solid crust is broken into several rigid plates that are carried by the circulating molten material of the mantle. Over the upwelling places the plates are moving away from each other, and the upwelling molten material arriving to the surface after cooling forms a new crust that is welded to the edge of the receding plates. As the surface of a spherical body is finite, if the mechanism is working for a long time, the plates on other places must converge and collide to each other either piling up as folded mountain chains or subducting one under the other. In this latter case the subducting plate reaching the molten mantle will also be melted and annihilated as a piece of the rigid crust, at the same time, however, the other plate becomes thicker partly because of the banding and lift off by the subduction, partly because of the volcanic activity caused by the subducted and melted crust rich in volatile material.

Generally at least two conditions are needed to develop these characteristic features on a crusty planetary body. First the crust should not be too thick or too plastic for braeking and for subducting. If a celestial body is too cold and has a thick crust, it can not split anymore into plates. If it is too hot then its crust is thin and plastic. Such a crust can not be broken into pieces and can not subduct because it is not rigid enough. Very probably every celestial body goes through such a phase during the cooling process when its crust is thick and rigid enough for braeking and subducting. The other condition needed is that the rate of cooling should not be too quick giving time for more than one cycle of circulation before the crust gets too thick to stop the process. At the present state of our knowledge we can claim that this mechanism is working only on the Earth. All other crusty planetary bodies in the Solar System are either too cold or too hot for this mechanism.

All other crusty planetary bodies in the Solar System are smaller than the Earth, the only one which is comparable is Venus. As regards the smaller planetary bodies, very probably the cooling was too quick compared with the time scale of plate tectonics, and their crust became thick so quickly that there was no time for even one cycle of plate tectonic movement to be completed. In the case of four of these bodies (Mars with a diameter of 6787 km, Fig. 1; Ganymede with a diameter of 5276 km, Fig. 2; Enceladus with a diameter of 502 km, Fig. 3 and Triton with a diameter of 2705 km, Fig.4) one can observe some traces of splitting started in some period in their history. Moreover in two cases (Ganymede of 5276 km and Enceladus of 502 km) or perhaps in a third one (Triton of 2705 km) there are transform faults so characteristic on plate tectonics — hundreds or thousands of them are present on Earth (Fig.5) — demonstrating that not only splitting but relative movement of plates occured on them.

As regards Venus, with a diameter of 12104 km, its surface is almost totally governed by volcanism suggesting that the crust is very thin. Along the equator, however, there are some deep large valleys of asymmetric cross section (Dali and Diana Chasmas, Fig. 6) considered earlier as deep oceanic trenches. Furthermore, there is a region around Lakshmi Planum with folded mountain chains (Freya, Akna, Danu, Maxwell Montes; Fig.7) that could be considered as compression zones. On the basis of these two surface features some scientists suggested that Venus had plate tectonics. But after the high resolution Magellan mission this idea was dropped. Anyway, Venus is the only place in the Solar System outside the Earth, where mountain chains were formed. Moreover, Freya Mons shows no trace of relaxation, that means, that compressional forces are still in action, that is, Venus is still an active planet not only because of its volcanism. The existence of these mountain chains and the tessera regions (Fig. 7.c) suggest that some region of the crust are moving relative to each other, but we can not even guess whether they are spreading or converging. It is, however, more probable that Lakshmi Planum is a convergence zone. In the case of Venus the very massive atmosphere prevents heat loss, moreover, the runaway greenhouse effect keeps the surface temperature very high (about 500 K). Even, if there were separated plates moving in such a high temperature, the rocks were too plastic for subduction. Instead of subduction the very thin crust becomes crinckly at collision. Very probably Venus represents a former stage of evolution of our Earth, but it is not certain, whether it will follow later its sister-planet, as regards plate tectonics. If Venus will cool slowly enough, perhaps it can happen.

There is another very interesting planetary body in the Solar System, namely Io, the innermost Galilean moon of Jupiter with a diameter of 3632 km. It is not larger than the other small crusty planetary bodies, but in spite of this, it shows up an extra strong volcanic activity even today. There is no trace of separated surface pieces or relative movement of such pieces. In this case the ongoing tidal heating prevents the cooling of the interior. If the tidal heating would switch off, Io would cool very probably as quickly as the other smaller planetary bodies did, i.e. too fast for developing plate tectonics.

What could be the reason that not the largest crusty planetary body has the thinest crust but Venus and Io? The explanation in the case of Io is clear: the tidal heating is added to the radiogenic heating. But what can we say about Venus? Very probably we have to say something about the Earth instead of Venus as the moonless Venus may represent the normal way of evolution. I wonder whether this explanation could be in connection with our Moon. It is highly probable that during the giant impact that initiated the birth of the Moon, all the ancient atmosphere of the Earth was blown off — as in the case of the Argyrae-impact on Mars. With a thin atmosphere the crust of the Earth started to cool quickly in accordance with the first condition of plate tectonics, but after that the tidal heating originating from the Moon slowed the cooling down making plate tectonic circulation possible for at least several cycles. Pluto and Charon may be another example for such a tidal heating during the synchronization process if they have captured each other. Titan, on the other hand, with its massive atmosphere can be a similar case to Venus where the thich atmosphere can slow the cooling. Therefore, it can not be ruled out that traces of plate tectonics are present on Pluto/Charon and also on Titan.

Summing up we can be almost certain that 1./ by now only the Earth has plate tectonic mechanism as a heat loss process, and 2./ not only the size and age of a planetary body determine what happens on its surface but the atmosphere and the presence of additional heat source (e.g. tidal heating) may play an important role slowing down the cooling or even heating up the interior.

Size of the

Crusty Planetary Bodies

Name	Diameter (km)
Earth	12756
Venus	12104
Mars	6787
Ganymede	5276
Titan	5150
Mercury	4878
Callisto	4820
Io	3632
Moon	3476
Europa	3126
Triton	2705
Pluto	2302
Titania	1610
Oberon	1550
Rhea	1530
Japetus	1460
Umbriel	1190
Charon	1186
Ariel	1160
Dione	1120
Tethys	1060
Enceladus	502
Miranda	484
Proteus	416
Hyperion	410
Mimas	394

Fig.1
Mars with Valles Marineris in the middle

Fig.2
A transform fault on Ganymede

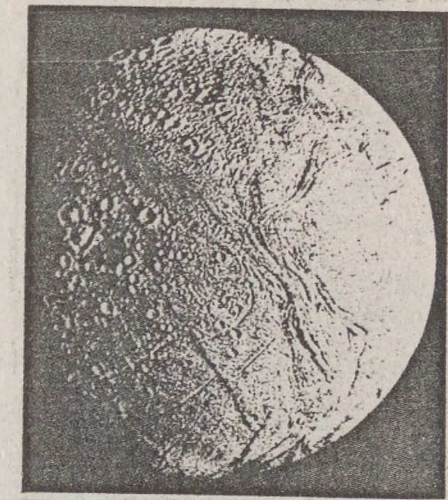


Fig.3
Transform faults on Enceladus

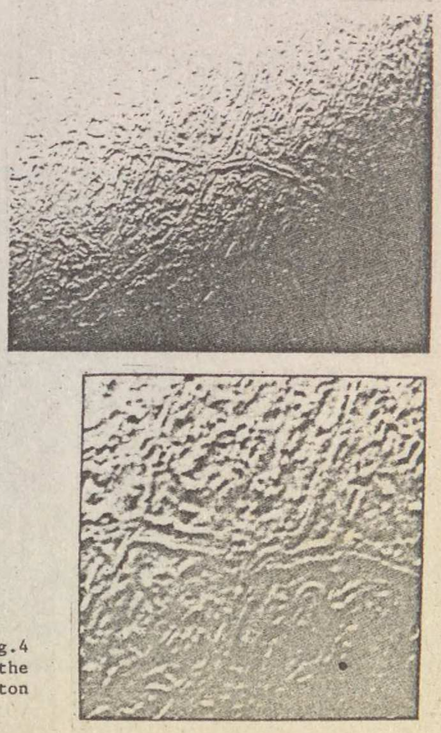


Fig.4
A part of the surface of Triton

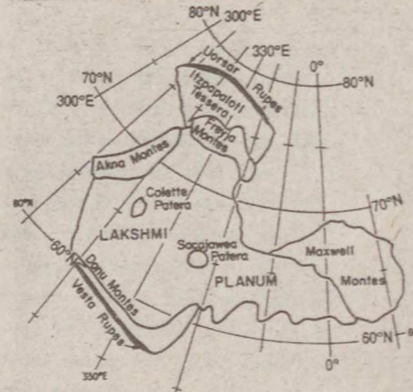
Fig. 5

Transform faults on Earth.

Fig. 6

Enormous valleys on Venus.

a



b

c

Fig. 7

Region of folded mountains on Venus

a: Magellan radar (lower part, middle)

b: map

c: Freya Mons (lower part) and Itzpapalotl Tessera (upper part).

PLANETARY EVOLUTION: COMPARISON OF THE TECTONICS OF THE ROCKY AND ICY PLANETARY BODIES

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Comparing the thermal history of planetary bodies of different composition Holba and Lukács [1] in their simple model investigated the evolutionary track of planetary bodies containing different ices. Their results can be summarized as follows. A planetary body containing cca. 50% water and 50% rocky material (taking into account only radiogenic heating) can be in the same evolutionary stages if it has a radius of about 2600 km as the rocky Earth. Taking ammonia instead of water the appropriate radius will be 2100 km, or metan instead of water 1200 km. The authors did not calculate the evolutionary stages for mixtures of ices.

Four planetary bodies can be found near the above sizes in the real Solar System: Ganymede and Titan of radii ~2600 km within the water-ice zone (Titan can be even younger than the Earth because of the higher ammonia content) and Triton and Pluto of radii ~1200 km within the metan-ice zone (Triton can also be younger than the Earth having larger radius than 1200 km).

Two of the four planetary bodies, however, can not be used for comparison as we have no information about the level of their activity. Titan has a thick atmosphere with smog in it, so its surface could not be mapped, and no planetary probe has visited Pluto up till now. But the mutual eclipses of the Pluto-Charon binary system made it possible to scan their surfaces. So it is known that they are not similar: the surface of Charon contains water-ice while that of Pluto metan-ice [2]. It has been determined further that Pluto now has an atmosphere and polar caps.

<u>What level of geological activity can be observed</u> on the surfaces of the crusty planetary bodies in the Solar System? We can distinguish three kinds of surfaces:

1./ There is no trace of any kind of geological activity. The surface shows up only impact craters, that means, the body was only a passive target of impacts throughout its lifetime, as for example our Moon, Callisto (Fig. 1.A) or Rhea.

2./ There is some trace of geological activity, but it ceased to exist sometime in the past as indicated by the presence of impact craters on the regenerated part of the surface as in the case of Mars (Fig. 2.B,C), Ariel, Enceladus (Fig.2.A). From the number of craters it can be assessed how long ago the activity has stopped.

3./ If almost no impact craters can be observed on a surface it means tha either the activity is continuing even today – as in the case of Earth, Io (Fig. 3.A), and Triton (Fig. 3.B) – or the activity has stopped only recently, as in the case of Venus (Fig. 4.A) and Europa (Fig. 4.C).

The table contains in five groups all crusty planetary bodies with diameters greater than 200 km. The groups are arranged according to their distances from the Sun. Within each group the bodies are arranged according to their sizes because simple geophysical models suggest that in the case of quasi identical composition the greater is the body the longer lasts its time of activity, that is the younger is its surface.

The first group contains the rocky planetary bodies. Io is included because of its composition although it is orbiting in the Jovian system and is not even the largest one of the Galilean moons.
The second group is formed by the other three members of the Jovian system containing ~50% rocky material and ~50% water ice.
The third group is formed by the satellites of the Saturnian system, where besides water ice the ammonia ice can also be an important constituent.
The fourth group is formed by the large satellites of the Uranian system where besides water and ammonia ices metan ice is also present.
In the fifth group besides the above mentioned ices the nitrogen ice plays also an important role.

Excluding Io the rocky bodies are more or less fitting to the model, only the high level of volcanism on Venus (Fig. 4.B) is a problem. Does it mean that Venus is more active than the Earth, or it represents only an other style of tectonism (buble tectonism [3])? In any case the size and very probably the composition of Venus and Earth are so similar, that a very different level of geological activity is not likely. There was one case, however, when the scientific community was surprised from such a phenomenon: on the surface of Ganymede and Callisto (Fig. 1.A,B) – in spite of their very similar position, size and composition – a very different level of geological activity has been found.

The picture is more complicated in the satellite systems of the giant planets than in the case of the rocky bodies. In the separate groups the most active bodies are generally not the largest ones! For example besides the above mentioned cases of Ganymede and Callisto the smaller Io is a more active member of the Jovian system; even in the group of the rocky bodies the tiny Io has an outstanding virulent activity.

The fact that the most active members of the Jovian, Saturnian and Uranian satellite systems are not the largest ones points to the fact that the Holba-Lukács model can be used only for the comparison of more or less isolated bodies. In systems of satellites namely the orbital energy can be a heat source through tidal dissipation of even comparable magnitude to the radiogenic heating therefore the activity-order based on the size of the bodies can be perturbed.

<u>The tidal heating can be longlasting or episodic</u> as compared to the lifetime of the Solar System. It is longlasting in the case of the Earth because of the presence of the Moon. Similarly longlasting is in the case of Io because of the forced excentricity of its orbit. For episodic tidal heating an example is the capture-process as in the case of Triton when its orbit became circular [4]. An other example is the resonance-process, when the inclination/excentricity of an orbit changes considerably, as in the case of Enceladus or Ariel. This latter type of tidal heating, moreover, can occur even more than once in the lifetime of a satellite moving in a satellite system.

In the case of episodic tidal heating the rule of the continuously diminishing level of geological activity can turn over as well. Namely, in the life of a satellite such an active period can occur at any time, the consequence of which can be the renewal of the whole or of a part of the surface. The tidal heating, namely, is not necessarily the same in the whole body, so it can cause local phenomena for example local centres of volcanism or tectonism.

In such episodic cases the character of the cooling can change at once; the conduction can change suddenly into convection. Such a sudden conversion could also contribute to the surface dichotomy of Ganymede and Callisto [5].

The above mentioned facts make the two surfaces on which the Holba-Lukács model could be controlled also problematic, because both of them suffer from tidal heating. Nevertheless they are not contradictory to the model, as Ganymede has one of the two surfaces upon which a transform fault can be seen (Fig. 5.A; the other is Enceladus with a diameter of 500 km, Fig. 2.A). On the surface of Triton in the crossing of a pair of fractures, however, a very early stage of the formation of a transform fault can be recognized (Fig. 5.C, [6]), so the surface of Triton can be considered even younger than that of the Earth; plate tectonics is just starting on its surface.

Any case, in the Solar System plate tectonics in a developed form can only be found on the Earth (Fig. 5.B). The existence of plate tectonic movements was previously suspected on the surface of Venus as well, but Magellan results refuted this hypothesis [3]. In the case of Mars the existence of Valles Marineris (Fig. 2.B,C) makes it probable, that once upon a time the formation of a fracture of expansion character (Fig. 2.C) started that could be similar to the oceanic trenches on Earth. The process came to an early end, however, because of the too quick thickening of the crust.

What can be the cause of the exeptional situation on the surface of the Earth? I suppose the cause may be found in the existence of the Moon [6]: on the one hand in the process of its birth, and on the other in the nonsynchronous rotation of the Earth with respect to the revolution of the Moon. Namely, plate tectonics can produce such manyfold traces (Fig. 5.B) on a surface only, if it could go through several cycles. If the velocity of the mantle circulation is too slow compared to that of the cooling and consequently to that of the thickening of the crust, then the splitting of the crust into plates will not occur for a long time. In such a case perhaps an extensional feature – like Valles Marineris (Fig. 2.C) on the surface of Mars – can be observed. Or if the cooling was a little slower, then there was enough time for the forming of one (Ganymede; Fig. 5.A) or two (Enceladus; Fig. 2.A) transform faults before the whole process stopped. The surfaces of the planetary bodies suggest that – except on the Earth – the cooling was everywhere quicker than would be needed to the longlasting operation of the plate tectonic process. Since the Earth is the only planet being in a double planet-system the rotation of which is not synchronized yet, I consider possible that the tidal heating originating from the Moon's orbital motion can – at least partly – compensate the heatloss by cooling and thus helps to keep the crust permanently sufficiently thin but rigid. According to the giant impact theory the Earth got an enormous quantity of impulse by the impact which could help to initiate a quick circulation in the mantle and in the outer core. This could explain why the magnetic field of the Earth is so strong compared with other rocky bodies, making the Earth more similar to the giant planets in this respect. The traces of the impact may remain not only in the pattern and velocity of the mantle/outer core circulation but even in the oscillation of the position/shape of the inner core [7].

The other double planet in the Solar System is the Pluto-Charon pair. In their case the synchronisation is completed already, so contrary to the general opinion I am not expecting the presence of traces of recent geological activity on their surfaces; on the other hand traces of ancient activity yes [8]. The composition of Pluto and Charon are namely so different, that we can expect with good reason that these two planetary bodies came into being in different regions of the solar nebula; so not in company like other regular satellite systems and not from a common material like the Earth and Moon. Very probably they approached later and captured each other with the gravitational assistance of another body (because of their orbital period this third body might be Neptune). Their relative orbits became circular and their revolutions synchronous by the mutual tidal forces. As they are nearer to each other than the Earth and Moon (only 20 with respect to 384 thousand km) and their masses are more similar (mass ratio is 11 with respect to 81) the period of synchronisation caused stronger tidal heating in both of them with possibly high geological activity even on Pluto (because of its composition), and the total synchronisation of the system took place quicker.

But why is Venus active if it has no large moon? It is very probable that its massive atmosphere is responsible for this situation. Not only by its insulating effect slowing the cooling down but also by its runaway greenhouse effect keeping the surface temperature high.

There is another essential point in plate tectonics. Geophysicists consider the existence of water on the surface of the Earth in connection with the presence of plate tectonics very important. They think it helps to slip the plates as a lubricant. The lack of plate tectonics on Venus is usually explained by the absence of water on its surface besides the extremely high surface temperature that makes the crust too plastic to be able to subduct.

Earth is really exceptional with its flowing water on its surface. Although even there is a possibility of control. Namely, on the contrary to the other two icy Galilean satellites of Jupiter, in the case of Europa (Fig. 4.C) H_2O forms a separate layer of ~100 km thickness above the rocky core with a ~10-20 km thick icy crust on it [9]. This ocean is, however, ten times deeper than the terrestrial analogue but because the gravitational acceleration on the surface of Europa is only about a tenth of the terrestrial one, the conditions could be about the same on the floor of the ocean of Europa. It would be interesting to know whether there are features characteristic of plate tectonics; and if there are, whether they are similar to the terrestrial ones. May be radar technics on appropriate wavelength can map the rocky surface of Europa as it did help in the case of Venus through the thick ocean of clouds.

Summarizing the two planetary bodies, Ganymede and Triton, that can be used to control the composition dependent scaling of the size dependent thermal history do not contradict the model. An overview of the whole Solar System, however, points to the fact that the improvement of the model is necessary in two directions. On the one hand it would be desirable to take into account the mixture of ices in the calculations, on the other hand it would be necessary to add the tidal heating to the radiogenic heating. But to carry out such calculations a more precise knowledge of the composition, the inner temperature and resonance situations would be necessary.

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TABLE

composition of the group				
name of the planetary body	**radius (km)**	**density (g/cm^3)**	**age (year) if < $3 \cdot 10^9$**	**level of activity at any time**
rocky				
Earth	6378	5.52	10^6	AAAA
Venus	6052	5.24	10^8	AAAA
Mars	3393	3.93		A
Mercury	2439	5.43		–
Io	1816	3.57	10^6	AAAA
Moon	1738	3.34		–
rocky + H_2O				
Ganymede	2638	1.93		AA
Callisto	2410	1.83		–
Europa	1563	2.97	10^7	AA
rocky + H_2O + NH_3				
Titan	2575	>1.9		?
Rhea	765	1.33		x –
Japetus	730	1.2		–
Dione	560	1.43		x –
Tethys	530	1.25		x –
Enceladus	251	1.83	10^8	AA
Mimas	197	1.43		–
Phoebe	110	?		?
rocky + H_2O + NH_3 + CH_4				
Titania	805	1.59		x –
Oberon	775	1.50		–
Umbriel	595	1.44		–
Ariel	580	1.65		AA
Miranda	242	1.26		AA?
rocky + H_2O + NH_3 + CH_4 + N_2				
Triton	1352	2.02	10^6	AA
Pluto	1151	2.1		?
Charon	593	1.4		?
Nereid	170	?		?

The number of A-s indicates the level of geological activity visible on the surface. The x indicates a kind of cracking on an otherwise inactive body.

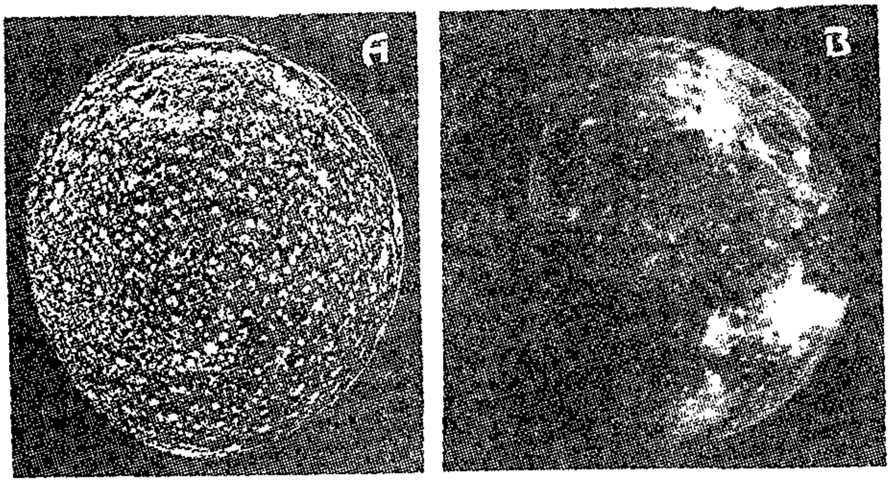
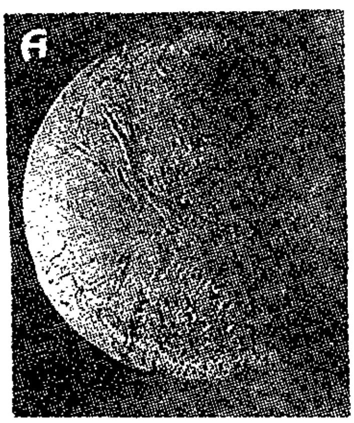
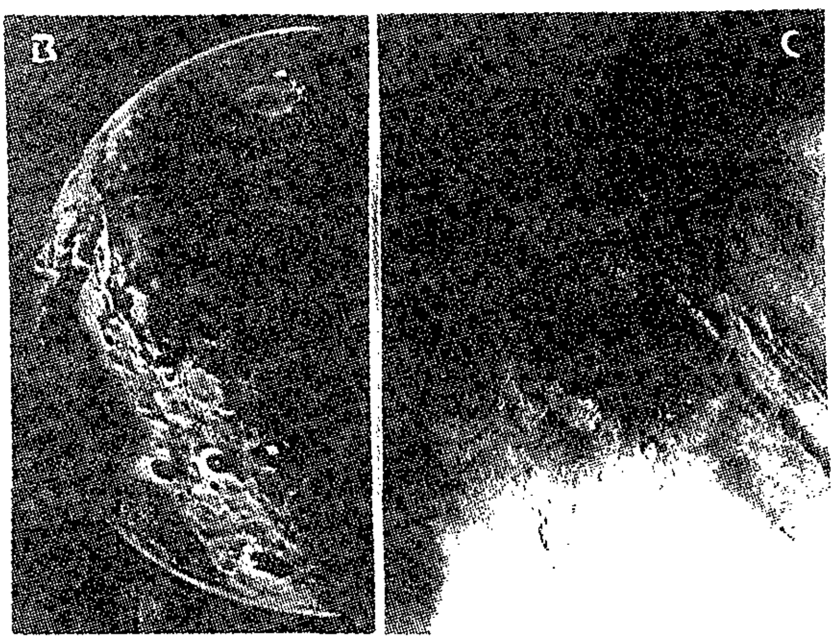


Fig. 1
Callisto (A)
Ganymede (B)

Fig. 2
Enceladus (A)
Valles Marineris
on Mars (B,C)





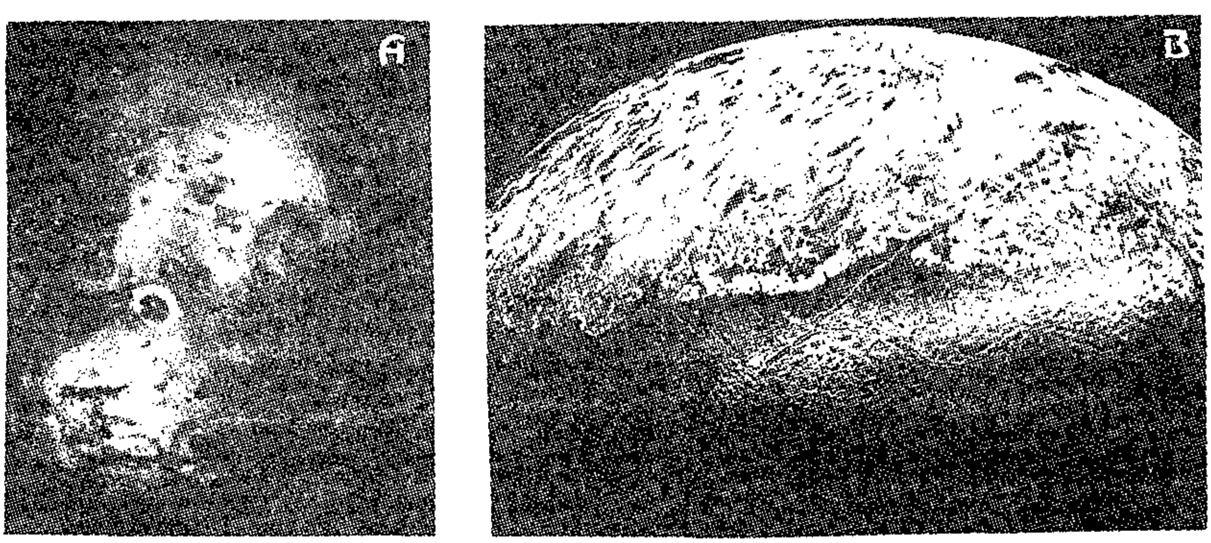
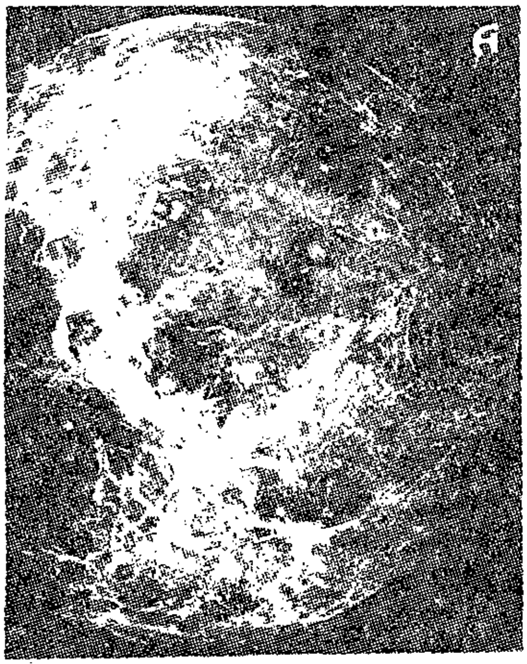


Fig. 3 Io (A), Triton (B)



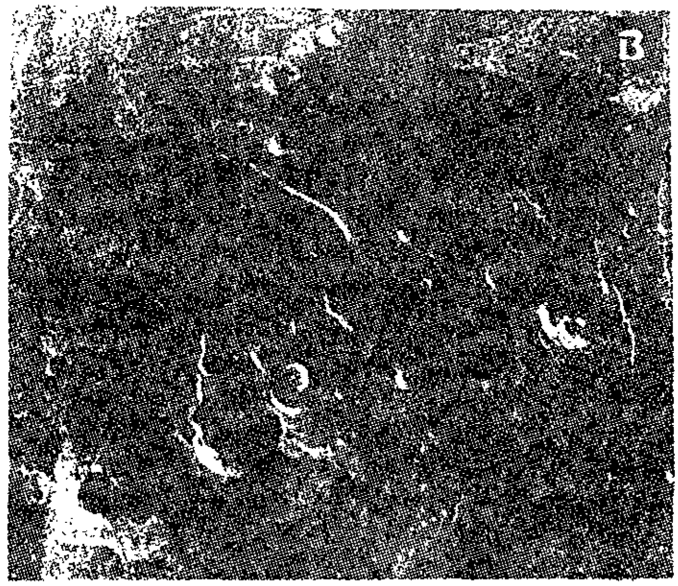


Fig. 4
Venus (A)
Central part of Quetzalpetlatl Corona on Venus (B)
Europa (C)

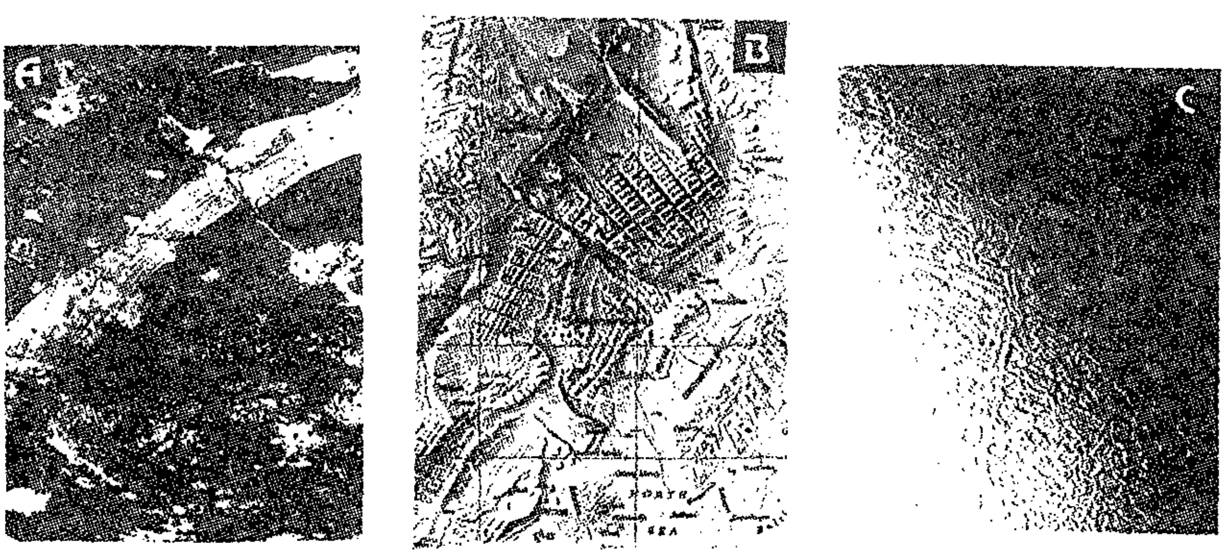


Fig. 5 Transform faults on Ganymede (A), on Earth (B) and perhaps on Triton (C)

A POSSIBLE TERRESTRIAL ANALOGY OF THE "CANTALOUPE TERRAIN" ON TRITON'S SURFACE

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An extensive unit termed the "cantaloupe" terrain dominates the western part of the equatorial region of Triton. It consists of a dense concentration of pits or dimples criss-crossed by ridges of viscous material. Most of the dimples fall into two roughly uniform size classes of about 5 km and 25 km diameter ([1], Fig. 1,2).

The term "patterned ground" on the Earth's surface (as for example in Fig. 3) refers to natural regularities defined by stones, ground cover or topography that assume forms such as circles, stripes and polygons in water-laden soil that undergoes repeated – seasonal or daily – freeze-thaw cycles. Such patterns are found throughout the world, at sea level in polar and subpolar regions and at higher elevations in more temperate climate zones. Some of the patterns stretch over square kilometers while others cover less than a square meter. Some patterned ground on Earth results from free convection of water and some from cracking or from a combined effect of the two phenomena. Seasonal freeze-thaw cycles give rise to patterns larger than those produced by daily cycles. Depending on pattern geometry, the width ranges between three and five times the depth of the layer in which the free convection of water occurs [2].

The aim of this paper is to draw attention to a phenomenon that can be brought into connection with the surface characteristics of Triton and enrich the variety of possible explanations. Specifically, the pattern called "cantaloupe" terrain on the surface of Triton shows up some similarities with some kinds of patterned ground (terrain polygons) on the surface of the Earth. The pits or dimples are not destroying each other – as, e.g., the impact craters or multiple volcanoes do – but tile entire pieces of the surface and belong to uniform size classes. This fact suggests a steady state process of a longer characteristic time scale rather than an instantaneous or random process. The analogy may be of interest in spite of the fact that water obviously can not be the cause of the small scale structure of Triton's surface because of its low surface temperature (37-38 K).

There are, however, many open questions in connection with such an explanation. What is the circulating fluid? Probably nitrogen. What kind of soil is there? A mixture of ammonia/methane/water-ice/clathrate? The onset of circulation may be helped by a solid state greenhouse effect of nitrogen ice. The existence of geysers on Triton's surface and the fact that in some valleys and ruptures there are traces of flowing material permit us to suppose that there is some heating beneath the surface that can also advance the onset of fluid convection.

The author is indebted to Gy. Gábris and to Gy. Kovács for useful discussions.

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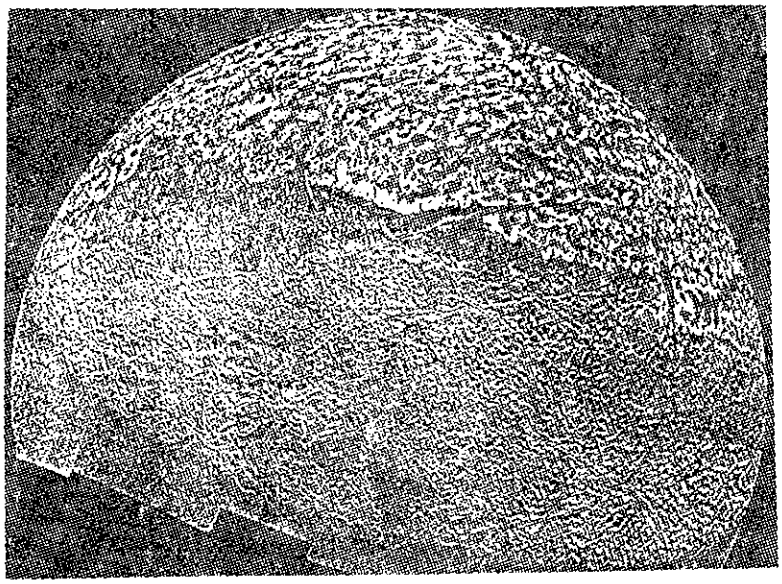

Fig. 1
The "cantaloupe" terrain on the equatorial region of Triton. Voyager-2 photomosaic. Resolution 1.5 – 3 km

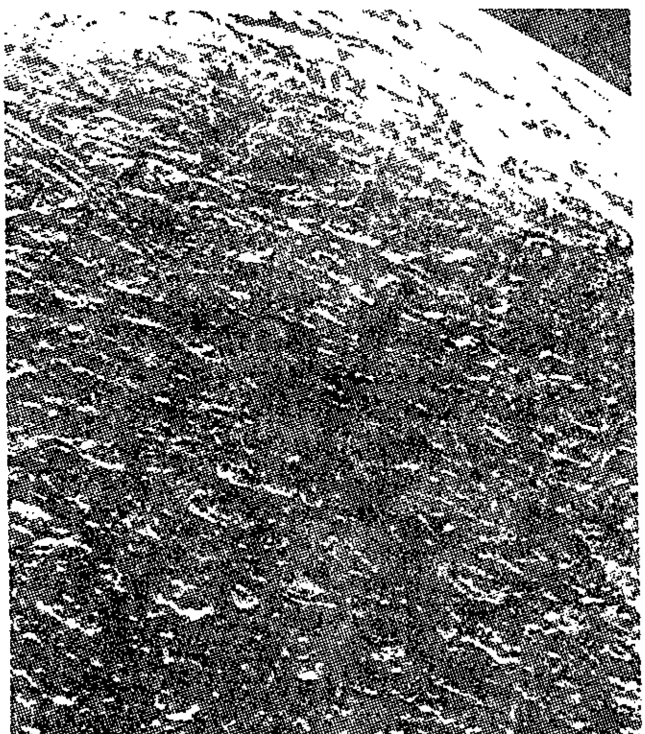

Fig. 2
A close up view of the cantaloupe terrain with 0.8 km resolution.

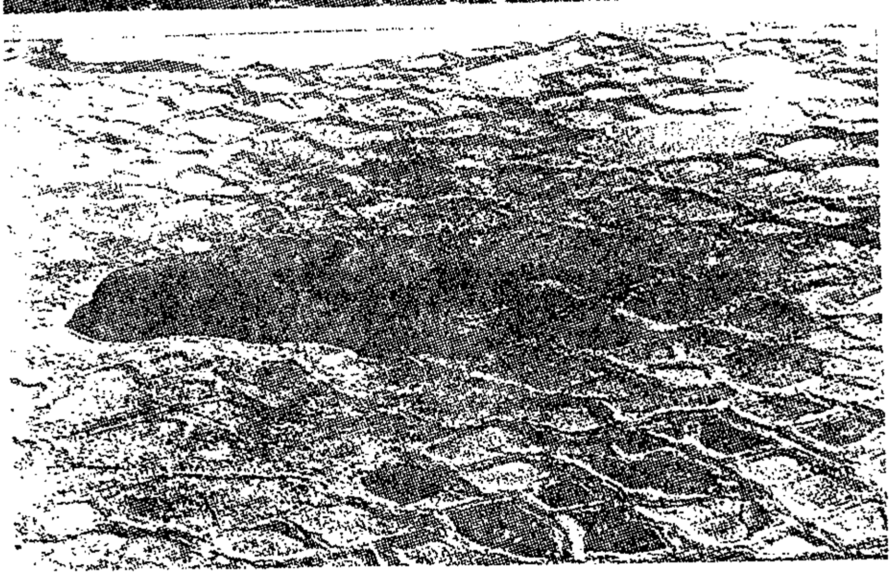

Fig. 3
Terrain polygons in Finland.

THE INFLUENCE OF PLANETARY ATMOSPHERES ON INCOMING BODIES

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Abstract

An overview is given on the examples of recent and past events concerning the influence of planetary atmospheres on incoming bodies.

Introduction

There are many traces of impacts on Earth and other planetary bodies in the form of impact craters, but the event itself is observed only in a few cases. Here we mention three of them that have some connection to the issue mentioned in the title:
- the series of impacts of comet Shoemaker-Levy 9 on Jupiter,
- the fall of the Peekskill meteorite in the USA and
- the Tunguska Event.

As regards the traces, a crater field on Earth and the radar images of Venus obtained by the Magellan space probe give some idea about the atmospheric effect on impacts. It is understandable that atmospheric effect was observed only on Venus among the Solar System bodies because of its massive atmosphere and the very low level of erosion. Besides Venus principially one could await atmospheric effects only on two other planetary bodies because of their sufficiently dense atmosphere, namely on Earth and on Titan. But on Earth the very strong erosion generally covers up the traces very quickly. On Titan, on the contrary, we could not observe any trace on the surface because of its non-transparent atmosphere.

On the basis of the Magellan imagery on Venus several kinds of atmospheric effects can be separated:
- lobate ejecta blanket, and/or missing of some sectors of the ejecta blanket,
- synchronous impacts of chunks of exploding bodies.
- cut off of crater diameters.
- traces of "tunguska events"

Impact of Comet Shoemaker-Levy 9 (SL-9) on Jupiter

The only impact event of a natural body that was forecasted and consequently observed so far in the history of mankind is the impact of comet Shoemaker-Levy 9 into Jupiter [1]. The comet was fragmented at least into 22 pieces beforehand because of Jupiter's tidal effect. The series of impacts spread over 6 days between 16-22 July 1994. In spite of the fact, that some people doubted that any effect could be observed from the Earth, many telescopes – almost every in orbit – followed the events. The effect in some cases was extremely violent. The scenario observed was as follows:

- The meteor flash phase: when the body arrived into the atmosphere it was heated up and glared because of the air drag. The temperature reached 10,000 K at this first flash.
- Breaking apart: after a long path in the atmosphere the incoming body was heated up to such a degree that it exploded.
- The explosion was followed by the fireball phase: the material of the impactor was launched (Fig. 1) as high as 3000 km above the cloud deck into the upper atmosphere and the temperature reached 30,000 K.
- Some 5-10 minutes later a splash down of the launched material occured, it fell back on the lower layers of the atmosphere with a velocity of 5-12 km/sec, that caused a heating of the atmosphere by cca 2000 K.
- After 90 minutes a dark spot appeared on the impact site (Fig. 2) the material of which is unknown. Around a central dark spot that spread out with smaller velocity, another almost concentric dark egg shaped ring appeared and spread out with the sound velocity of the minimum temperature layer like a wavelike phenomenon. It reached about 20,000 km size in some cases.

The molecules that were detected: in the first 2 minutes strong emission of NH_3 and strong absorption of CH_4, in the 4th minute strong emission of CO (2000-3000 K is needed), in the 6th minute ultraviolet emission of H_3^+ (1400 K is needed), in the 12th minute H_2O was detected. In the 16th minute H_2, in the 30th minute Li, Na, K, Ca, Fe, Hα, after the 45th minute S and neutral and ionized metal (MgI, MgII, FeI, FeII, SiI) emerged. After 8 days SiO_2, C_2H, H_2O then, CO, HCN, CS appeared in emission that went into absorption by September. CS_2 could be detected even in April 1995.

On the basis of the observations (with 10^{15} g mass coming in) a thermochemical model indicates that everything has been vaporized, the material of the impactor and the neighbouring atmospheric envelop as well. Then photolysis, chemical reactions, condensation took place as well as interaction among participants. Consequently, there is no chance for the original molecules of the impactor to be observed.

The Peekskill meteorite

The fall of a larger chunk of meteoroid occured on 9 Oct. 1992 at 23 hour 48±1 min UT over the Eastern part of USA [2, 3]. The 700 km path of the falling body between 46.4-33.6 km altitudes was recorded by 14 videocameras. This is the first case when moving pictures stay at disposal on a bolide. The orbit could have been reconstructed. This is only the fourth case when the orbit of a meteorit is known up till now. The inclination was 3.4° to horizontal. At 41.5 km height break up occured and afterwards more than 70 pieces could be observed (Fig. 3). The bolide's velocity outside the atmosphere was 14.72±0.05 km/sec. and 12.4 kg ordinary chondrite has been found.

The "Tunguska Event"

The so called Tunguska meteoroid earlier was thought to be a comet that blew up at about 6-9 km height over the Tunguska River in Siberia on 30. June 1908, $0^h\ 14^m$ UT with energy about 20-50 Mtn TNT [4]. The site of the event was visited only later. No fallen material was found, the trees of the forest were hurled down and they are lying radially.

Computer simulation [5] for a comet with relative velocity not more than 72 km/sec and with a 5×10^{13} g mass could describe the observations – with fusion energy release in the gas cap only 5×10^{-3} Joule. The arising inclined cilindrical shock front caused the trees to fall away from the centrum (Fig. 4). The pressure reached 25,000 atm. Between the body and the shock wave the temperature could reach 400,000 K. But another computer simulation [6] exclude the possibility of a comet, because it should have been exploded 2-3 times higher. The body could be rather a stony asteroid, because of its 6-9 km explosion height (an iron asteroid, on the contrary, would explode even lower).

The traces of a grazing impact in Argentina

The crater field at Rio Cuarto city, Argentina [7, 8] (Fig. 5, 6), counts at least 10 long elliptical features the largest of which being 4.5×1.1 km. It is a remnant of a grazing impact of an asteroid that also exploded coming through the atmosphere. The identification happened recently, in spite of the fact that geophysicists recognized it already earlier, but they thought it was created by water or winds. Such elliptical craters are known on other planetary bodies as well, for example many on Mars, some on Venus and on the Moon, but on Earth, besides the above mentioned, only one has been discovered in Campo del Ciclo, Argentina.

Traces of the atmospheric effects on impacts on Venus

Among the impact craters found on Venus [9] one can easily observe the effect of the atmosphere because of its massive nature. (The surface pressure is about 100 atm.)

The craters with a diameter of more than 15 km are similar to those found on other bodies in the Solar System but their ejecta blanket differ very much. The inner part of the ejecta blanket – between 0.5 and 0.8 crater diameter – is ballistic and similar to those found on other bodies. But there is an outer part of the ejecta until 2.5 (instead of 1.4) crater diameter, that is superballistic. Here only smoother material can be found. The outermost part (until 3-4 crater diameter and even beyond) is very smooth i.e. radar dark (Fig. 7). This smooth ejecta blanket is obviously overlain by the strong winds that blew radially from the impact site at the time of the impact. The flower shape outer feature of the superballistic ejecta blanket can also be caused by the turbulence of the atmosphere after the impact, that was throwing down the picked up matter cauliflower-like at the edges of the ejecta blanket (Fig. 8). The turbulent movement of the atmosphere can be the cause of the lack of the ejecta blanket in some directions as well. The direction of the lack indicates the direction of the approach of the incoming body, if it was coming in obliquely.

If the crater diameter is smaller than about 15 km, than 50%, if smaller than 12 km than almost all of the craters are irregular (Fig. 9) indicating the synchronous impact of several chunks – or the craters are in clusters (Fig. 10) referring to the explosion of the impactor close to the surface. Smaller than 3 km diameter craters do not exist indicating that bodies smaller than about 100 m can not survive the transit through the atmosphere. But there are a lot of radar-dark (that is smooth) areas without craters (Fig. 11). These are very probably the traces of so called "tunguska events" when the incoming body exploded in the atmosphere, and the arising shock wave was strong enough to smooth the boulders and the soil out.

Conclusion

The events reported in this paper – the SL-9 impact in particular – indicate that the breaking apart and the explosion of a relatively large interplanetary body during the transit of a dense atmosphere seems to be inevitable. If this happens at least partially, then evolving temperatures are high enough to modify principially both the physics and chemical composition of the entering body and its surroundings. Therefore one should not expect to find the original molecular composition in the remnants of such an impact: neither H_2O in the traces of comet SL-9 after its impact on Jupiter, nor chemically intact traces of interplanetary matter in spherules previously modified by an explosion in the terrestrial atmosphere.

Aknowledgement: The author is indebted to Mr. P. Decsy for his able help in the preparation of the paper.

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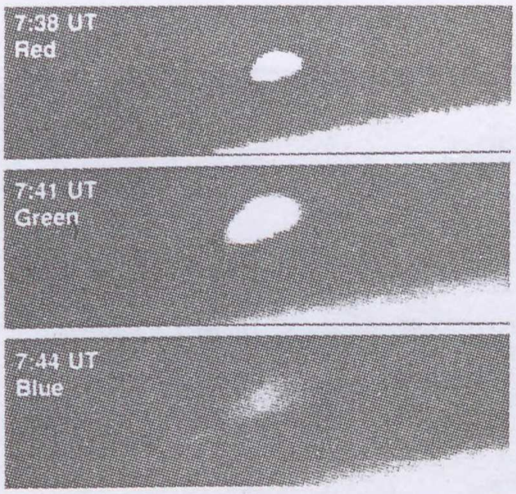

Fig. 1. Above the disk of Jupiter the fireball glares after the impact of the first fragment (designated by A) of comet Shoemaker-Levy 9 as observed in different wavelengths by the Hubble Space Telescope.

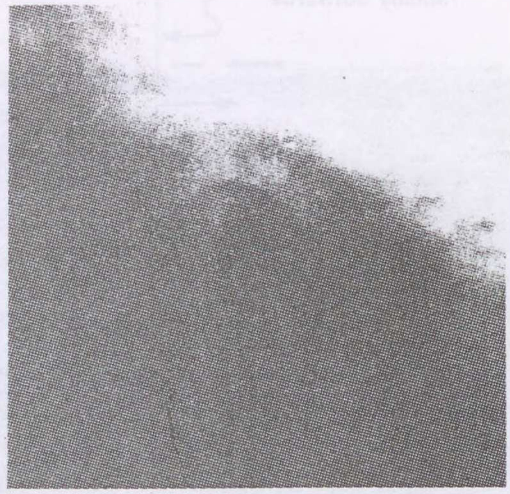

Fig. 2. The dark spot and the egg-shaped ring after the impact of fragment G of comet Shoemaker-Levy 9 as observed by the Hubble Space Telescope. The smaller dark spot to the left is the aftermath of fragment D.

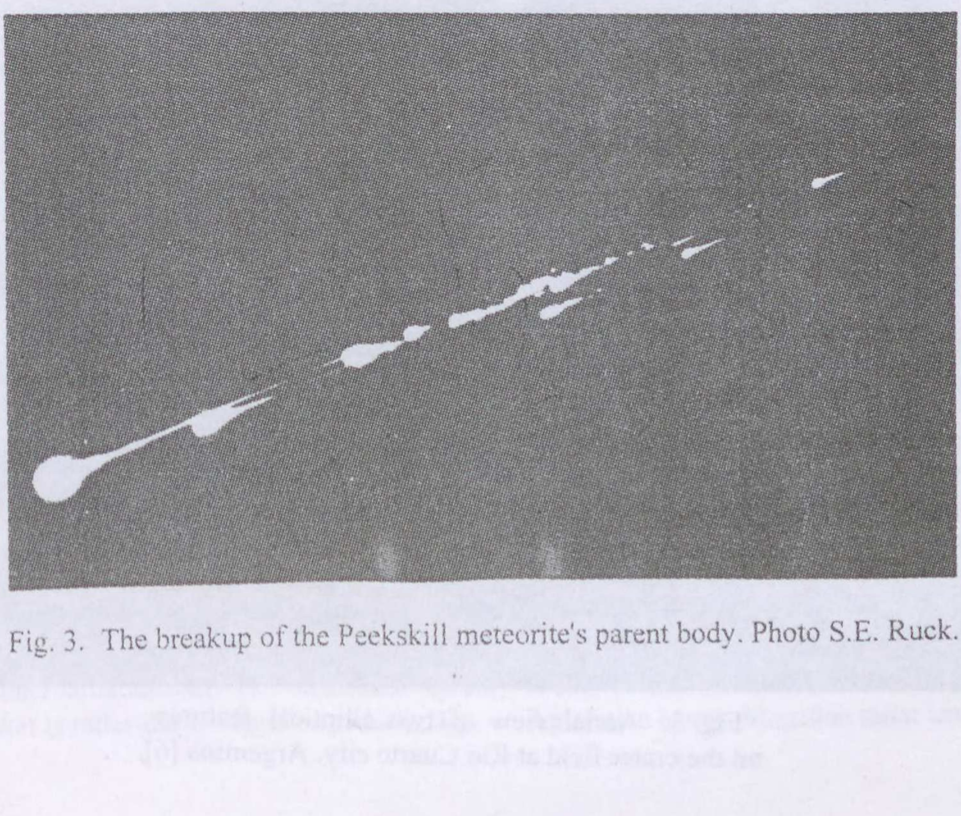

Fig. 3. The breakup of the Peekskill meteorite's parent body. Photo S.E. Ruck.

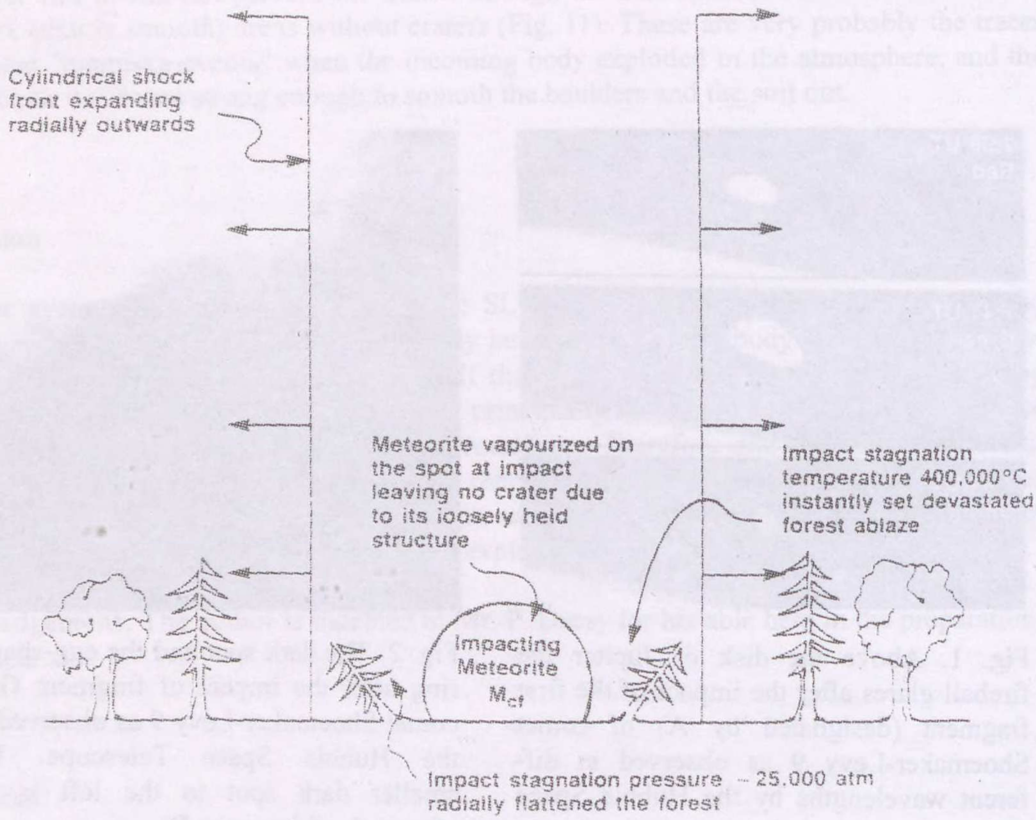

Fig. 4. A Conception how the Tunguska Event has flattened the forest radially [3].

Fig. 5. Aerial view of two elliptical features
on the crater field at Rio Cuarto city, Argentina [6].

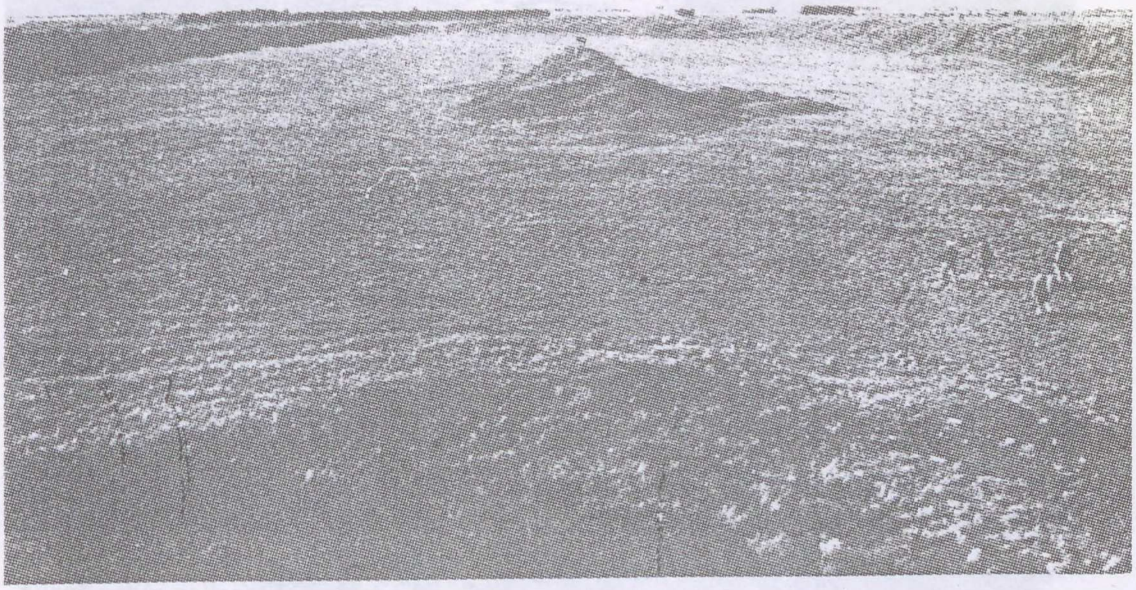

Fig. 6. Inside panorama of one of the craters within the craterfield at Rio Cuarto city, Argentina [6].

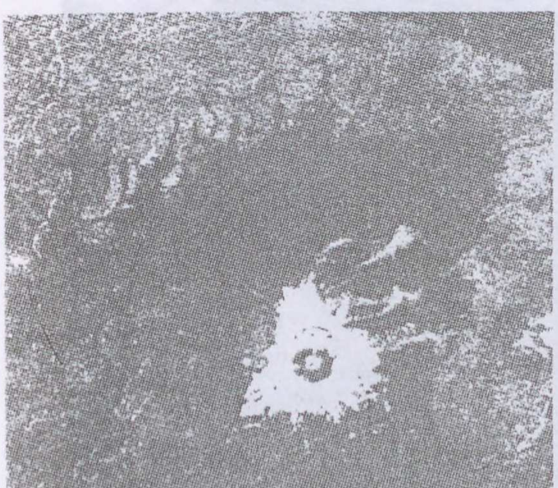

Fig.7. A typical larger impact crater on Venus. Its inner part is ballistic, its outer part is superballistic and the outermost ejécta blanket is radar-dark. Magellan radar image.

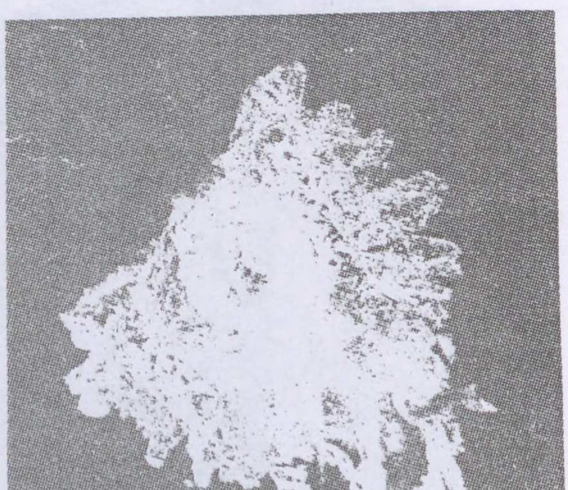

Fig. 8. A typical larger impact crater on Venus with couliflower-like edges and a missing sector of the ejecta blanket in one direction. Aglaonice crater. Magellan radar image.

Fig. 9. A typical irregular impact crater on Venus suggesting the synchronous impact of several fragments of a body that exploded just before the impact. Magellan radar image.

Fig. 10. A typical crater cluster on Venus suggesting the explosion of the impactor close to the surface. Magellan radar image.

Fig. 11. Typical traces of "tunguska events" on Venus with radar-dark, i.e. smooth areas – some of them without any crater (upper part), some with a small impact crater inside (lower part). Magellan radar image.