

Comparative Planetology

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Much of the research in the arts, sciences, and engineering concerns human society and affairs. One of the nice things about the geosciences is that it breaks away from this trend: it is the study of the rest of the planet. But one could argue that we've still been narrow in our focus this semester, because we've focused on our own planet. This is partly true: there are many other planets out there, in our solar system and in others. But it is also true that many of the phenomena we've discussed this semester also occur on other planets. The same concepts we've used to understand terrestrial phenomena therefore also apply to other planets, and you are all already planetary scientists.

I. Origin of planetary diversity

- Recall planetary formation and differentiation lectures
- Solar nebula [PPT]
 - Disk of gas & dust
 - Rotation due to gravity flattens it out
 - Different compounds condense out as it cools
 - Metals and silicates first
 - Volatiles last
 - Temperature gradient plus solar wind create compositional gradient
 - Cooler further from sun, so volatiles condense
 - Hotter closer to sun, so volatiles remain gaseous
 - Solar wind (radiation and particles from sun) exerts pressure that blows volatiles away from inner regions
 - This is primary reason for difference between rocky planets, gas giants, and far-out icy bodies [PPT]
- Accretion and Differentiation [PPT]
 - Gravity and flow vortices cause dust to accrete into km-sized planetesimals
 - Planetesimals collide to form larger bodies. Collisions become rare but more spectacular as these protoplanets grow.

- If planetesimals or protoplanets were large enough, their self-gravitation and heat of accretion caused a density separation. Rocky bodies separated into metal cores and rocky mantles.
- All of this happened within a few tens of Myr
- Subsequent evolution
 - Late-stage impacts or gravitational capture [PPT: Moon-forming impact]
 - Further differentiation [PPT]
 - Accumulation or loss of atmosphere
 - Loss of heat of accretion, but heating by radioisotope decay
 - Interior dynamics and surface evolution
- All these mechanisms combined to produce the diversity we see today

II. Tour of the terrestrial planets

- Definition
 - Formed close to the Sun, and therefore volatile-poor
 - Mainly composed of metals (mainly Fe, Ni) and silicate rock
 - All are differentiated into Fe-Ni core, silicate mantle, and crust
- Mercury [PPT]
 - Smallest of terrestrial planets
 - Essentially no atmosphere
 - Old, heavily cratered surface
 - Very large core relative to planet (largest in SS) – part of mantle may have been driven off by early sun or blown off by large impact
 - 3:2 spin-orbit resonance → long solar day (176 Earth days). This plus lack of atmosphere creates extreme day-night ΔT : 470C/-170C
 - Messenger mission to Mercury just went into orbit in March 2011
- Venus [PPT]
 - Similar to Earth in size, mass, density, but...
 - 90 bar atm of mostly CO₂ with clouds made of sulfuric acid droplets
 - 475C surface T [PPT: Venera lander photo]

- Young surface with lots of evidence of volcanism. Doesn't have large extremes in elevation, but is mountainous, with broad, high plateaus
- Slow, retrograde rotation (most planets orbit and rotate CCW when viewed from north, Venus rotates CW). Produced by giant impact?
- Earth [PPT]
 - Thick 1 bar atmosphere of mostly N₂ with large and highly unusual component of O₂
 - Abundant surface water. If rocky planets are rocky because solar wind drove off volatiles from inner disk, why all the oceans?
 - There was still water in hydrous minerals, and it outgassed during and after (from volcanoes) differentiation
 - Has also been proposed that Earth's water was delivered by volatile-rich late-stage impacts (e.g. comets)
 - Young surface with very few impact craters. Bimodal surface elevations. Large elevation extremes, with long, high mountain chains and deep, arcuate ocean trenches
 - Very large moon relative to its size
 - Strange, self-replicating organic chemistry
- Mars [PPT]
 - Smaller than Venus, Earth
 - Hemispheric elevation dichotomy (pear shape), with older southern highlands and younger northern lowlands
 - 6 mbar atm of CO₂
 - Abundant evidence of past volcanism, but no present activity
 - Surface presently cold and dry, but evidence of abundant water-driven erosion in past (river networks, huge floods). Some evidence of minor ongoing water-driven erosion

III. Comparisons

- Atmospheres and Climate
 - Why are Venus, Earth and Mars so different, when they might have started out with similar inventories of volatiles?
 - To stay at a comfortable temperature, a planet must maintain a greenhouse effect, but not too strong a greenhouse

- CO₂ is produced by volcanism, and can be removed by dissolution in liquid water and storage in carbonates (which form in water)
- Venus may have gotten just hot enough (perhaps because it is closer to the sun) that all surface water boiled off into vapor in atmosphere (even the water stored in hydrated minerals). With no sink for CO₂, it accumulated through continued volcanism, producing a runaway greenhouse that got progressively hotter. Lack of magnetic field also makes it easier for solar wind to blow off H.
- Mars may have gotten cold enough that the atmosphere collapsed, with H₂O and CO₂ freezing out. Its smaller size might have contributed:
 - Faster cooling could have resulted in less volcanic activity, delivering less CO₂ to the atmosphere
 - Weaker gravity means faster escape of light compounds
 - Again, lack of magnetic field makes water loss easier
- Magnetic fields
 - Magnetic fields are produced by a dynamo of circulating, conducting fluid, usually a metal (but can be salts in icy planets) [PPT]
 - Ingredients for a dynamo:
 - Conducting liquid. In terrestrial planets, this means a liquid outer core. This requires heat.
 - Temperature gradient across outer core to make it convect
 - Rotation, to make the convection currents align and produce a coherent (usually dipole) field
 - Mercury was recently confirmed to have a weak magnetic field. If it's an existing dynamo, it's surprising given Mercury's small size and slow rotation
 - Venus has no dynamo. Hot surface reduces temperature gradient, slow rotation further impedes dynamo formation.
 - Earth: check. And this is probably a big part of why we're here:
 - Protects atmosphere
 - Protects DNA
 - Mars: No dynamo now, but crust has remanent magnetism that implies an ancient dynamo [PPT]. May have shut down as Mars cooled rapidly.

- Tectonics
 - One of the most interesting but least understood problems in comparative planetology
 - Mercury: global-scale compressive faulting, probably from thermal contraction [PPT]
 - Venus
 - Widespread volcanism [PPT-Volcano] implies lots of melting in hot mantle, many upwelling zones [PPT-Coronae]
 - Lack of extreme elevations suggests weak, thin crust
 - Inferred vigorous convection with lots of small cells that break crust up into small pieces – “flake tectonics” [PPT]
 - Has even been suggested that young surface results from catastrophic overturns
 - Earth
 - Cooler mantle allows thicker, stronger lithosphere that breaks up into coherent plates that behave more or less rigidly
 - Bimodal lithosphere: continental lithosphere that persists and is reworked, and oceanic lithosphere that is recycled
 - Plate motion aided by asthenosphere – appears to be associated with seismic low-velocity zone. Water-rich?
 - Mars
 - One-plate planet with very thick lithosphere
 - Evidence of minor compressive features, possibly some extensional canyons, but no evidence that there were ever plate boundaries
 - Huge volcanic complex (Tharsis) [PPT] suggests that there may have been a long-lived hot spot without any relative plate motion [PPT: Olympus Mons]
 - Perhaps plate motion on Mars was impeded by lack of water in mantle, and therefore lack of an asthenosphere.
- Surface processes [PPT]
 - There are 3 major factors:
 - Rates of volcanic resurfacing and tectonic activity
 - Cratering

- Fluid erosion and sediment transport
- Mercury: cratering and some tectonic features. Meh.
- Venus: dominated by volcanism
 - Coronae (collapsed lava bubbles?)
 - Shield volcanoes
 - Volcanic plateaus
- Earth: abundant fluid erosion and sediment redistribution, tectonic features, and rapid recycling of crust
- Mars: Not much going on now, but evidence of a wetter past [PPT: Warrego Valles, Meander] full of dramatic extremes [PPT]: huge floods, much larger volcanoes than on Earth, immense canyons, maybe even oceans. The rest is mostly wind and cratering.

IV. And then there's everything else... [PPT: HST Ultra-deep field]

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