Physico-Chemical Processes in Planetary Evolution [and Discussion]

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Physico-chemical processes in planetary evolution

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Data returned from exploration of the planets teach us that planets are highly individualistic despite the assumed underlying universality of the processes. It is argued that the diversity of evolutionary outcomes arises mainly because of the interplay of thermal and compositional effects, both in the assembly of planets and in their subsequent convective evolution. The role of compositional differences and phase transitions invalidates any view of planets that relies heavily on models consisting of a small number of homogeneous layers. Four illustrative examples of real planetary behaviour are discussed: sold–solid phase transitions in terrestrial mantles, volcanic styles and recycling in Venus, heat flows of the giant planets and the role of the Lorentz force in the dynamics of the non-metallic portions of giant planets.

1. Introduction

If planets were homogeneous or simply layered, they would be much easier to understand, far less interesting and we would probably not exist. Despite the obvious importance of deviations from simplicity, much of our understanding of how planets work is nonetheless based on models that assume, implicitly or explicitly, a high degree of homogeneity within each of a small number of layers. For example, it is still quite common to think of terrestrial planetary evolution from the perspective of models that assume *thermal convection* and no more (thus implicitly excluding non-thermal causes of buoyancy in the fluid motions). See, for example, Stevenson *et al.* (1983). Most giant planet modelling has been based on the assumption of an adiabatic, thermally convective interior state throughout the entire age of the solar system (Stevenson 1982; Hubbard 1984).

It is perfectly understandable that these approaches should have been so pervasive: they reflect the desire for simplicity in the face of daunting complexity. Moreover, most laboratory and theoretical work on heat transport in fluids has focused on systems where the composition and material properties are constant throughout. It is less understandable that so much of our thinking should tend to be dominated by these simplifications in the face of mounting evidence for their inadequacy. In this paper, I will provide, through examples, some of the evidence and reasons for thinking beyond simple pictures of internal planetary machinery. Obviously, anecdotal evidence cannot be as satisfying as an exhaustive analysis, so this paper is only intended to provide a feeling for the issues that confront us in planetary modelling.

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2. Simple models of planets

I would define as simple a planet in which the interior consists of a very small number of layers, each of which is internally rather uniform in properties. By this definition, there are no simple planets in the solar system (and probably none anywhere). But since so much of our thinking about planets begins with this simple picture, it is useful to summarize this viewpoint. A simple planet could be said to have two epochs: assembly and cooling by thermal convection. I use the word 'assembly' to embody both the accretion of the planet (growth of mass) and the internal, primordial differentiation (e.g., core formation). It is possible, of course, that the assembly process builds the layers one by one so that the core is constructed before the mantle is added. A version of this is still widely held among modellers of giant planet formation, but see Stevenson (1985) and Lissauer *et al.* (1994). The more likely explanation for layering is the strong chemical and density difference between the layers, which allows their separation to proceed to a high level of completeness.

The simple view of planetary evolution is as follows:

(i) *Collisional aggregation of small bodies*

In a widely accepted picture of the earliest stages of planetary growth (cf. Wetherill 1990), small bodies (perhaps upwards of kilometres in size) are formed by a poorly understood process of coagulation due to the chemical stickiness of dust particles that condense in the solar nebula or are delivered from the interstellar medium. These 'planetesimals' then undergo further aggregation aided by gravitational interaction and the inelasticity of collisions. Progressively larger bodies scatter each other, enhancing the orbital eccentricities and inclinations, thereby allowing further collisions.

(ii) *Heating and melting by gravitational energy release*

Collisions at velocities of the order of the escape velocity of the growing planetesimal are predicted. These cause heating which is sufficient to create at least local melting once the bodies grow beyond a few per cent the mass of Earth (greater than the mass of the Moon yet smaller than the mass of Mars).

(iii) *Gravity-driven internal separation*

In a microscopically heterogeneous assemblage of materials, partial melting may allow separation, much as basaltic melt can separate from mantle source rocks to create oceanic crust. Extensive melting may be required if percolation is difficult, as some studies suggest (Stevenson 1990). Gravity-driven internal separation is a self-lubricating process, because it creates more heating. It causes the light stuff to rise and the heavy stuff to sink. This should be particularly pronounced for metallic iron and silicates, since these two components differ so much in density and chemistry.

(iv) *Addition of gas (giant planets only)*

In the conventional view of giant planet growth, formation of a solid embryo is followed by inflow of roughly solar composition gas. Large amounts are accreted in the case of Jupiter, and smaller amounts apply for Saturn. The envelopes of

Uranus and Neptune might simply be hydrostatic concentrations of nebula gas rather than hydrodynamically acquired (but see Lissauer *et al.* 1994).

(v) *Thermal convection within layers*

All planets are too large to lose internal heat primarily by conduction or radiation. Simple thermal convection within layers then determines the thermal and dynamical history of the planet. Each layer is bounded above and below by a thermal boundary layer; internal interfaces will be 'double' thermal boundaries in which the heat from the upper boundary layer of the lower shell is passed on to the bottom boundary layer of the upper shell. Although computationally complex, the behaviour of such a system is conceptually easy to understand.

3. Reality

Realistic models share with simple models the ideas of planetary accumulation outlined in (i) and (ii) above. However, they differ in their assessment of the outcome of gravitational differentiation in two very fundamental ways. First, it must be recognized that even the hypothesized uniform layers within planets (e.g., the Earth's mantle) are multimineralic assemblages involving components of varying density and melting point. Upon partial melting or upon crystallization of a completely molten state, differentiation can be expected to proceed to some degree. This may not be as dramatic as the separation of core from mantle, but it is nonetheless at a rate sufficient to create a compositional gradient. Indeed, detailed models of a crystallizing magma ocean (Solomatov & Stevenson 1993) show that some separation can occur despite the homogenizing tendencies of vigorous convection. Second, realistic models must acknowledge that the separation of core from mantle involves chemistry: the composition of the core-forming material can depend quite strongly on the temperature and pressure at the time of separation. This is likely, for example, in the incorporation of oxygen (as FeO). Since the temperature and pressure of separation change with time during planetary assembly, compositional gradients arise. This predicts, for example, that the Earth's core should start out compositionally stratified. In the giant planets, delivery of material that partially but imperfectly mixes with the target also creates compositional gradients. In all cases, the separation of the planet into a small number of homogeneous layers would seem unlikely.

Even aside from primordial heterogeneities (layers within layers), subsequent evolution can be expected to create compositional gradients. An example is the formation of basaltic crust which can have as important an effect on buoyancy as thermal contraction. On the present Earth, the success of the simple boundary layer theory of thermal convection might lead one to think that this is unimportant but, as discussed further below, these compositional and phase transition effects become more important as one goes back in geologic time.

4. Why complexity is unavoidable

Since no-one likes to introduce complications unless they are unavoidable, it is worth summarizing why it is that planets will tend to be more complicated than most laboratory systems or simple models. There are three principal reasons:

(i) *The multicomponent nature of planetary materials*

The outcome of nucleosynthesis and chemistry is a broad mixture of elements in the nebula from which planets form. This leads unavoidably to planetary building blocks that have typically at least three major mineral phases coexisting. The multicomponent phase diagrams of these assemblages exhibit complex melting behaviour and imperfect miscibility/immiscibility behaviour, especially at high pressure and temperature. In short, the thermodynamics are highly non-ideal. Planetary materials are much more complicated than stellar materials!

(ii) *The dramatic change of properties with depth*

Planets are large enough that the chemical character of the constituents can be very different deep within a planet than near the surface. Quantitatively, this is expressible by the similarity of the atomic scale of energy and the gravitational energy per particle:

$$\frac{GM\mu}{R} \approx \frac{e^2}{a_0} \tag{4.1}$$

where G is the gravitational constant, M is the planetary mass, μ is a typical atomic mass, R is the planetary radius, e is the electronic charge and a_0 is the first Bohr radius. (The right-hand side is 27.2 eV.)

(iii) *The smallness of thermal buoyancy*

Planets are made of degenerate matter; this means that $\alpha T \ll 1$, where α is the coefficient of thermal expansion and T is the absolute temperature. It follows that relatively small compositional effects (sufficient to change the density by a few per cent) can compete with thermal buoyancy. This means, for example, that even a modest compositional gradient can be sufficient to suppress or modify the convection and thermal history.

I turn now to some examples of these general principles. The first two examples concern terrestrial planets (especially Earth and Venus) while the last two examples concern the structure of the giant planets.

5. Solid–solid phase transitions

It is characteristic of terrestrial mantle minerals that they undergo structural phase transitions at high pressure. These have long been detectable seismically through the evidence for discontinuities in seismic velocity at about 410 km and 670 km depth in the Earth's mantle. Through laboratory experiments, it has been possible to identify with a high degree of confidence the nature of these transitions. The larger of the two, at 670 km depth, involves a density jump of around 8% and corresponds to the disproportionation reaction:

$$\mathrm{Mg_2SiO_4}\ \text{(spinel)} \rightarrow \mathrm{MgSiO_3}\ \text{(perovskite)} + \mathrm{MgO} \tag{5.1}$$

(here simplified to omit the effect of iron substituting for some magnesium). The most important feature is the onset of perovskite, an octahedrally coordinated silicate structure. The right-hand side corresponds to the high-pressure equilibrium assemblage (the lower mantle). At first sight, one might suppose that this has a strongly inhibiting effect on convection since the density jump across 670 km is far larger than any plausible density anomaly associated with thermal convection (as hinted earlier). However, the situation is more complicated since one must consider what fraction of the material in a convective upwelling or downwelling is in a phase different from that of laterally adjacent, ambient mantle (Christensen 1989). The 670 km phase transition is endothermic, meaning that the phase transition pressure decreases with increasing temperature. This means that a cold convective downwelling will displace the phase transition downward (to higher pressure), thus requiring upper mantle material to persist to greater depth. Since this material is less dense, the convection is inhibited. The inhibition is related to both the density change of the phase transition and the Clapeyron slope $(\mathrm{d}P/\mathrm{d}T)_{\text{phase boundary}}$.

Numerical calculations of convection (Peltier & Solheim 1992; Honda *et al.* 1993; Tackley *et al.* 1993, 1994) reveal that for realistic parameter values, the 670 km phase transition can have a major effect on the convection. This does not mean that the convection is layered: circulation through the phase transition is largely unimpeded. However, the horizontal length-scale of the convective motion is increased to values rather similar to the size of the largest plates on Earth (Tackley *et al.* 1993, 1994), mainly because the flow through the phase transition is confined to a small number of very large cylindrical downwellings. These calculations reveal that smaller-scale motions (e.g., individual sheet-like downwellings or 'slabs') are often impeded. There is some evidence for this in seismic tomography (e.g., Fukao *et al.* 1992). More precisely, the phase transition is a strong inhibition to circulation involving small-scale features or motions. As one goes back in geologic time, the heat flow increases, the Rayleigh number increases and the characteristic length-scale of convection (the boundary layer thickness) diminishes. This enhances the tendency toward layering. Thus, one can have an Earth evolution in which the earlier part of the history is characterized by layered convection (separate circulations in the upper and lower mantle) followed by a later breakdown of this layering as one approaches the present time. There need be no inconsistency between having whole mantle convection and having some degree of chemical heterogeneity in the mantle, even of the major elements (e.g., the Mg/Si ratio). Numerical models show how this behaviour might develop (Weinstein 1992).

Preliminary results from Tackley and co-workers suggest that the tendency toward layering may be more pronounced for Venus, apparently because of the influence of the more rigid boundary condition (Venus does not have anything like the extent of Earth's lithospheric mobility). This could have major consequences for how Venus evolves, and allows Venus to have a different mantle structure from Earth despite their very similar mean densities.

This example illustrates how a phase transition can have a major influence on convective style, layering, thermal history and the preservation of heterogeneity. None of these things are evident in laboratory experiments or the simpler versions of thermal convection.

6. Styles of volcanism and recycling

Density differences are continuously created by partial melting. On Earth, oceanic crust is made at mid-ocean ridges by the extraction of melt from fertile peridotite, leaving behind a buoyant, depleted residue. The entire assemblage (crust, residue and deeper imperfectly depleted mantle) is then recycled by subduction. Water is also carried down in the recycling process and some small fraction of this water (and some other volatiles) may make their way back into the deep mantle. On one-plate planets, by contrast, there is little or no subduction and the recycling is accordingly far less efficient. This is likely to apply to both Venus and Mars. Partial melting in the mantle is then limited by the height to which pressure-release melting can reach, impeded by the overlying layer of previously depleted mantle. Earth-bound scientists, lulled into a false sense of confidence by the remarkable success of simple thermal boundary layer theory for Earth, have been slow to acknowledge the importance of this problem, though some rather crude attempts at modelling recycling on Venus now exist (Herrick & Parmentier 1994).

One-plate planets tend to ‘run hotter’, others things being equal, because the upper thermal boundary layer does not include the cold, stagnant surface material. This means that pressure-release melting can occur at greater depth, perhaps leading to pervasive regionalized volcanism, driven by Rayleigh–Taylor instabilities of partial melt (Tackley & Stevenson 1993). This is an alternative to plumes as a source of volcanism and illustrates how the style of volcanism can be modified in major ways by the nature or magnitude of recycling.

The major underlying question is: why does Venus not have plate tectonics? Or, perhaps more appropriately, why does Earth have plate tectonics? There is no entirely satisfying answer to this question yet, though one suspects that the presence of water (and perhaps carbon-bearing volatiles) may be important for Earth. It is remarkable that seemingly minor components could have such a major role to play in planetary evolution.

7. Stable stratification within giant planets

One of the major triumphs of planetary evolution modelling was the recognition that the present internal heat flow of Jupiter could be explained as the leakage of primordial heat (Hubbard 1984). The Kelvin model of planetary cooling, which does not apply to either Earth or the Sun, applies quite well to Jupiter. According to that model, the characteristic time-scale τ defined by

$$\tau = \alpha(\text{planet heat content})/(\text{intrinsic planet luminosity}) \tag{7.1}$$

equals the time elapsed since planet formation (where α is a known numerical factor somewhat less than unity). The startling simplicity of this result arises from the fact that the planet loses memory of its initial very hot phase (because of the strong dependence of black body luminosity on temperature) and because the assumed adiabatic structure leads to a very simple relationship between internal and photospheric temperature.

Unfortunately, this model works far less well for the other giant planets. For Saturn, τ is about a factor of two less than the age of the solar system (or, equivalently, the model predicts a present-day heat flow lower than that observed). For Neptune, τ is about a factor of two longer than the age of the solar system (i.e., observed heat flow is lower than predicted). The Uranus internal heat flow is very low and consistent with zero so τ is then either very large or undefined.

The explanation for Saturn's discrepancy evidently lies in the ongoing rainout of helium within that planet, which releases gravitational energy that is then converted to heat (Salpeter 1973; Hubbard & Stevenson 1984). However, this explanation only works for Saturn at the expense of destroying the success of the simple cooling model for Jupiter, since there is no way of arranging the parameters so that differentiation occurs only in Saturn and not in Jupiter. Moreover, the Voyager results for atmospheric composition suggest some helium depletion in the Jovian atmosphere, consistent with theoretical prediction. I then find that you cannot explain all the observations for Jupiter and Saturn except by saying that a major fraction of the deep interiors of these planets is not participating in the cooling (i.e., the relevant internal heat content that enters equation (7.1) must be decreased). The only physically sensible way of achieving this is to suppose that the inner 20–40% of the planet mass is stably stratified because of a compositional gradient.

The evidence for this effect is even stronger for Uranus and Neptune. Since a hot beginning is unavoidable given the energy of gravitational assembly, I find that about 40% of Neptune's mass and 60% of Uranus's mass is not contributing to the outgoing heat flow (Hubbard *et al.* 1994).

In all four planets, I would attribute this central stably stratified core to a compositional gradient that was created during planetary accumulation. It is highly unlikely that the accumulation process is as simple as the accumulation of solids followed by the infall of gas. In fact, observational evidence for atmospheric enrichment of elements (e.g., carbon) relative to cosmic abundance strongly argues for mixing of gas and condensate. Since the rock and ice components are likely to be miscible in hydrogen at high pressure and temperature (Stevenson 1985), imperfect mixing during assembly will lead to an imperfectly separated planet. (In this respect, giant planets are fundamentally different from terrestrial planets which have a core that is immiscible in the mantle.)

8. A magnetic radius

My final example will be described rather briefly since it concerns incomplete work. I include this example to show how one might have a well-defined radius in a planet where there is *no* change in composition or phase, and yet there is a change in convective style.

In all planets, the electrical conductivity can be expected to increase rapidly with depth, because the outer parts of planets are ionic conductors or semiconductors in which the availability of mobile charges is determined by an Arrhenius relationship:

$$\sigma = \sigma_0 \exp(-\Delta E/kT) \tag{8.1}$$

where σ is the conductivity, ΔE is an activation energy or band gap, k is Boltzmann's constant and T is the absolute temperature. In terrestrial planets, this behaviour is truncated at the core–mantle boundary, where there is an abrupt transition to a highly conducting metal (probably always liquid because of the presence of antifreeze; see Stevenson *et al.* 1983). In giant planets, there is likely to be a continuous transition in the fluid (no phase or compositional change) as one follows a radial downward path from material that has negligible conductivity to material that is nearly metallic in conductivity. Regions of significant conductivity can be defined as those for which the currents associated with the planetary dynamo would lead to a Lorentz force comparable to other dynamically important forces. Kirk & Stevenson (1987) studied some of the consequences of this and concluded that there should be a well-defined radius at which one makes a transition from flow that is unaffected by the Lorentz force to flow for which the Lorentz force is important. This 'magnetic radius' must not be confused with the metallic core! It can be much further out than the metallic core because conductivities far less than metallic values can be dynamically important. Work in progress suggests that this radius may have an associated field geometry that is so arranged to make the Lorentz torque at the equator especially small. This is a testable hypothesis, given sufficiently accurate field models.

9. Concluding comments

The rich phenomenology of planetary structure and evolution arises because of the complicated mixture of phases and species, together with the remarkable range of behaviours of convection in the presence of several sources of buoyancy. A physicist raised in the reductionist tradition may find this disconcerting, but others find it a source of interest and challenge. I believe that our emerging perspective of the planets, largely driven by the remarkable data return from planetary missions, teaches us the individuality of planets without challenging the underlying universality of the processes.

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Discussion

R. HUTCHISON (*Mineralogy Department, Natural History Museum, London, U.K.*). The point was made that layering in the Earth developed early, through melting or heterogeneous accretion. It is difficult to see how the Earth's upper mantle could have formed because of its high magnesium to silicon ration. The atomic ratio is about 1.25 and higher than that of any group of meteorites, which argues against heterogeneous accretion as the explanation. Some 35% of the silicon must have been lost from the primitive upper mantle to the core or lower mantle, or to space by vaporization, if the original composition was chrondritic.

D. J. STEVENSON. It is possible that the upper and lower mantles have different compositions but the most likely explanation is that the "missing" silicon is in the core.

W. M. KAULA (*UCLA, U.S.A.*). I have philosophical objection to saying that Venus differs from Earth because it does not have plate tectonics. Plate tectonics is an empirical paradigm, a consequence rather than a cause. The more fundamental cause is the rheology of the near surface materials in response to stresses induced by mantle convection. We have an effective viscosity – ratio of stress to strain rate averaged over time and space – that is dependent not only on temperature, but also highly nonlinearly on stress (as we are reminded eight nights ago in Los Angeles) and composition – primarily water content, secondarily silicate character.

D. J. STEVENSON. I agree with your point; the difficulty is that we lack a sufficient understanding of the required conditions for plate tectonics.