Spherically Averaged Structure
No moment of inertia or seismology means lack of information. Large Fe core implied by mean density. Differentiated structure suggested by surface material that is silicates (Earthlike).

Lateral Variability
Not known, except that 3:2 resonance requires small difference in A and B moments of inertia ($J_2$ already requires C, A to be different). Only about 40% of the surface has been observed in the visible.

Dynamic State
Convective state not known, but scaling laws suggest mantle convection should be present. Magnetic field is enigmatic; might require a dynamo but small enough that other processes cannot be excluded. Core-mantle coupling (with a liquid core) may have been needed to trap Mercury in the 3:2 resonance.

Volcanism Evidence for surface flows, but dating back to before period of heavy bombardment, perhaps to around 4.0Ga. Nothing more recent. Evidence for Na and other volatiles at surface (ice in crater floors?) might be indicative of past volcanic activity but more plausibly related to impacts or sputtering.

Formation Most plausible story for the unusual bulk composition is that proto-Mercury was hit head on in a massive impact that stripped much of the silicates from the surface of an already differentiated body. Presumably happened around 4.55Ga so no evidence remains except the bulk composition. No evidence that composition can be related to distance from the Sun in any simple way.
What does the Surface appearance tell us?

We have only seen one half of the surface at useful resolution. The impact cratering is pervasive although there are variations in impact density, suggestive of a range of surface ages. There are ancient contraction scarps which are interpreted as evidence that Mercury has undergone global contraction to the extent of about a few km. This is plausibly related to cooling and partial freezing of the core, although it is puzzling that there is not evidence for contraction in the last 3 Ga or so. (But would it be visible?) There is no evidence for basalt flows on the surface. (See Jeanloz et al, Science 268 1455; 1995). The interpretation for this is unclear, but one possibility is that crustal separation was early and complete (and largely non-basaltic) and that the subsequent cooling history has not allowed the conditions for basalt generation (which is contingent on modest degrees of melting, e.g., through pressure release.) Or perhaps the basalt is generated but is unable to escape.

Future Exploration

MESSENGER will be launched in a few years but has a long (ballistic) cruise before insertion into orbit around Mercury, in 2009 or 2010. The Europeans also have an ambitious mission called BeppoColombo that may get there at a similar time.

In addition to the obvious things (imaging, magnetic field, gravity), Messenger will be able to get Mercury’s moment of inertia and perhaps determine fluidity of the core. This is possible through geodesy: looking for librations and measuring precisely the obliquity of the planet. (Librations arise because the planet is in a highly eccentric orbit and yet is non-spherical so there are small oscillatory changes in rotation rate as the Sun exerts torque on the planet.)
VENUS

Spherically Averaged Structure
Not well known (no moment of inertia and no seismology). Density suggests an earthlike structure, differentiation to form a core suggested by earthlike surface rocks (basaltic lavas, etc.) Phase transitions expected, as in Earth. Lithosphere is 150 km thick at least, which is incompatible with earthlike heat flow (even after allowing for drier rheology of rocks).

Lateral Variability
Gravity spectrum suggests deep seated density anomalies (presumably convection). Evidence for variability in litho thickness from comparison of gravity and topography regionally. There are Regionalized differences in surface structures (plains, etc).

Dynamic State
Crater population is greatly affected by dense atmosphere (whose history is not known). But latest estimates place mean surface at ~800 Ma in age. Some have favored a catastrophic resurfacing event at this epoch, but evidence seems more compatible with a gradual event. Thick litho suggests this resurfacing “event” might be related to a transition in Venus tectonics, perhaps from “plate tectonics” to the current state of a stagnant lid, with convection underneath. Absence of magnetic field presumed due to absence of convection in the core, perhaps because Venus has no inner core, or perhaps because it is currently heating up.

Volcanism Many structures are attributed to plume volcanoes, but it is not known whether these are due to plumes or more regional upwelling. Decline in volcanic activity in the past few hundred Ma. In the future, litho will surely become thin again, may get more volcanism. Volcanism may also be tied to state of atmosphere.

Formation Presumably like Earth, but perhaps with no large oblique impact to impart rapid rotation and produce a moon. Even if Venus had an
earthlike moon, it would either spiral inwards and crash into Venus (if Venus had current spin state) or perhaps escape.

**Venus Evolution and Structure**

Our current understanding is poor because:

(1) Surface does not appear to preserve history except for last \(\sim\)1Ga.

(2) Venus is slow rotator which means there is no information extractable from the hydrostatic gravity about internal structure (except mean density).

(3) Interpretation of non-hydrostatic gravity and topography is (always) non-unique.

(4) Hot surface precludes some kinds of inferences (e.g., paleomagnetism).

Previous missions (especially Magellan) has allowed the formulation of testable hypotheses about evolutionary state. By far the best tests will come from **seismology**.

*What do we Know?*

1. **Mean density** does not require significant difference in bulk composition between Earth and Venus. Surface rocks thus far sampled also support Earthlike basaltic composition (but this is a weak inference).

2. **Tidal Love number** supports liquid Fe core, similar to Earth's core. (But error bar is still rather large).

3. **Geoid Heights** suggest higher viscosity and greater depth of density anomalies than on Earth. Surprising because of hot surface.

4. **Topographic relief and support of features** argues for stiff near surface layer. Consistent with inference from geoid heights. Cross-correlation implies similar elastic lithospheric thickness to those on earth.

5. **Crater densities** suggest a mean surface age of \(\sim\)700 to 800 Ma. But this could have up to a factor of two uncertainty?
Popular Ideas or Inferences

1. Venus is in a transitional or oscillatory regime with current heatflow lower than “equilibrium”. Equilibrium is defined by current radiogenic heating. So lower heat flow would mean interior is currently heating up? This state could have been precipitated by a “catastrophic” overturn of the lithosphere, or by a transition from mobile lid to stagnant lid convection. Surface conditions might also change.

2. Venus is dry. This helps to explain the retention of surface topography despite high surface temperatures. May also help to explain geoid and convective regime, though these inferences are non-unique because we lack independent information on evolution and structure.

3. Venus lacks a magnetic field because of its thermal state. Too hot for an inner core or current heating up of interior causes convection to turn off.

4. Venus volcanism is largely plume-driven. Much lower than mid-ocean ridge levels of volcanism. But what is the origin of the internal or bottom boundary layer to generate this?

5. (More controversial) Various terrain types on surface have distinctively different ages. But cratering record prevents going beyond statistical arguments for “ages”.

Things We Would Like to Know

1. Time variation of surface environment (Were there large volcanically-driven fluctuations in CO₂? Did this lead to changes in surface morphology and chemistry?).

2. Time Variation of tectonic environment. (Secular trends as the planet cools or episodicity?)

3. Did Venus start internally hot with early differentiation? Early core formation? (Isotopes and siderophile indicators?) Any surviving crust from early times?
4. Did Venus have a Moon? Could have spiraled in or even escaped. Strongly coupled to the rotation history of Venus.

5. Did Venus have a magnetic field? Does Venus have an entirely liquid core of partially solid or entirely solid? Size of core? Is it underdense relative to Fe (like Earth’s core).


**What would We Like to Do?**

1. **Seismology:**
   Technically challenging but seismicity likely (similar to intraplate on Earth?). Possibility of atmospheric excitation of normal modes. Can address many questions and remove ambiguity of interpretation of geoid, etc.

2. **In Situ or Sample Return Geochemistry**
   Technically challenging & great difficulty in getting adequate or useful samples. Chemical modification?

3. **Geodesy** Changes in length of day and pole position tell us about response of planet to torques. *This is easy to do relative to #1 and 2!*

**Debatable Ideas:**
4. **Heat flow**
5. **Paleomagnetism.**
6. **Radar interferometry to look for changes on ~year timescale. Or GPS.**
7. **Electromagnetic sounding.**
8. **More gravity (but need major improvements).**
Commentary on the Following Four Pages:

First Page shows the trade-off between measured love number for the detected tidal distribution of Venus and the moment of inertia. Also the observed crater distribution and inferred surface age.

Second page shows the interpretation of topography and gravity on Venus, which generally support the idea that Venus has a thick elastic lid and no asthenosphere. This is only consistent with the hot surface if Venus is dry and has a heat flow much lower than Earth.

Third Page shows a cartoon of what might be going on inside Venus, and a map illustrating the very large number of volcanic edifices, suggestive of regionalized volcanism rather than something organized around plate boundaries or rifts.

Fourth Page displays a model of what might have happened if Venus had transitioned from a mobile lid to a stagnant lid style of convection about 800 million years ago. This would explain many of the things we see.
Figure 2. Love number $k_2$ vs moment of inertia with lines joining models with common mantle molar fraction $f_0 = (\text{Mg}/(\text{Fe} + \text{Mg})$. The solution parameters for $f_0 = 0.89$ and $R_c = 3100$ km example are: $C = 0.3366 M R^2$, $C_r = 0.0282 M R^2$, mean core density $\bar{\rho}_c = 10.16 \text{ g cm}^{-3}$, $\delta \rho_c = 0.08 \text{ g cm}^{-3}$, and Love numbers: $k_2 = 0.252$, $l_2 = 0.5031$ and $l_2 = 0.077$.

W. B. McKinnon et al.

Figure 5. Simulated Venus craters, using the master power-law distributions for asteroids (Eq. 6) and the same cometary distributions as in Fig. 4. The fit is aesthetically pleasing between ~5 and 80 km diameter. Calibrated to produce a cumulative 940 craters, the nominal surface age is 800 Myr.
Figure 6. Comparison of the stagnant lid model of Solomon and Morelli (1996) to profiles of geoid and topography at Beta Regio. The profiles are taken from -86.65'E, 11.71'N to 53.39'E, 31.13'N. Temperature contours at 30°C after the convective motion are shown for the convection model at the bottom. The model has a resolution of 0.01 km and a viscosity contrast of 10^7.
Figure 5. Global synthesis of Venus (figure modified from Phillips and Hansen 1994).

Figure 13. (A) Map showing the global distribution of large and intermediate volcanic edifices, shield fields (white symbols), and calderas (open circle with dot), in relation to arachnoids, coronae, and stellate fracture centers ("novas") (black symbols). Base map is a global SAR image mosaic; modified Miller cylindrical projection.
Figure 14. A schematic of convection in Venus before the cessation of the mobile regime around 0.5 Gyr ago and at present and a sketch of the depth profiles of temperature before and after the event.

Figure 15. Parameterized convection calculations of the thermal evolution of Venus with the hypothesized change from the regime with mobile plates to the stagnant-lid regime 0.5 Gyr ago.