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Oct 11th 2007
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THE SCIENTIFIC BULLETIN OF CNES, CENTRE NATIONAL D'ETUDES SPATIALES

Planet, show us your heart

Since 1995, more than two hundred and ten planets have been discovered orbiting stars other than the Sun. Almost without exception, these exoplanets have not actually been observed, but their presence is inferred from the effects of the gravitational action they exert on their stars. Depending on the detection method used, their mass or size can be estimated, but rarely both at the same time. The planets which have been discovered so far are quite unlike the ones in our own solar system.

The authors of the article have developed a theoretical model for describing the likely internal structure of planets and satellites. Using this model, a planet's radius and moment of inertia can be deduced from its mass, provided that its overall composition in heavy elements is similar to that of its star. This model calculates the position, as well as pressure and density profiles, of the various layers making up the body. Before extending these calculations to exoplanets of all types and sizes, the authors verified the model's validity by applying it to many of the bodies in our solar system.

Describing a planet's internal structure involves distinguishing the different layers of which it is made, and mapping their interfaces. This has only been done up to now, for the Earth and the Moon: waves recorded with seismometers give an indication of the thickness and nature of the various layers, whereas meteorites and terrestrial minerals which originated in the deep mantle can be subjected to a geochemical analysis in order to determine the composition of the silicates which formed the Earth.

An initial hypothesis suggests that for solar and extra-solar planets alike, the main components would be clustered around an iron core, with a silicate rock mantle, then a hydrosphere and an atmosphere. However for all planets, the abundance, exact chemical composition and physical state of each layer remains unclear. The atmosphere of some bodies, which varies greatly in thickness and composition, is slightly better defined.

The eight planets of the solar system are traditionally grouped into two large families: telluric, or rocky planets (Mercury, Venus, Earth and Mars) and giant planets (Jupiter, Saturn, Neptune and Uranus). Telluric planets generally consist of silicates and iron, whereas giant planets mainly contain hydrogen and helium. However, this simple distinction does not take into consideration the great diversity of these objects.

In fact, five different families of planets can be distinguished. Mercury should be classified separately from the other telluric planets, as it has a much greater quantity of iron in relation to silicates than Mars, Venus or Earth. Among the giant planets, Jupiter and Saturn are different to Uranus and Neptune. The solid part of the latter two consists mainly of water ice. They

Sources

Mass-radius curve for extrasolar Earth-like planets and ocean planets
C. Sotin, O. Grasset, A. Mocquet
Icarus, 2007

Notes

Gravitational action:
According to the law of attraction discovered by Isaac Newton in 1687, masses attract each other in proportion to their respective mass and in inverse proportion to the square of the distance, between their centres of gravity. This explains how objects on Earth are attracted to the ground, as well as why planets turn around the Sun, etc. When two bodies are in rotation, they constitute a system, and act upon each other. Under certain conditions, therefore, it is possible to deduce that a star is accompanied by one or more planets.

Moment of inertia:
The moment of inertia quantifies a body's resistance when undergoing rotation. A point's moment of inertia is calculated by multiplying the product of its mass by the square of its perpendicular distance from the axis of rotation. The sum of these elementary moments gives the total moment of inertia for the body in question.

Equation of state:
A material's equation of state describes the relationship between the different functions of state, such as pressure, volume and temperature. There are many kinds, depending on the nature of the phases (solid, liquid and gas) and the orders of

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Mantles and envelopes

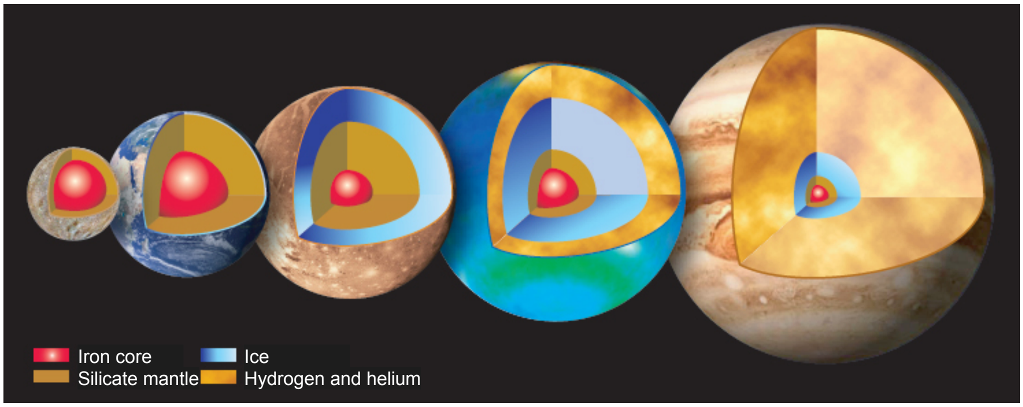

Fig 1: General characteristics of the main families of planets considered. From left to right: Mercury-type planets, Earth-/Mars-/Venus-type planets, ocean planets (such as Europa), intermediate planets (Uranus, Neptune) and gas giants (Saturn, Jupiter). For a given mass, the relative size of the different layers in each family has been respected. Conversely, the relative size of the families with respect to each other is merely an illustration to give the reader a rough idea.

therefore appear to be intermediate bodies, halfway between the telluric planets and the gas giants. Lastly, the frozen satellites of giant planets, which (in mass) consist of half ice and half silicates and iron, form a fifth family: that of the 'ocean' planets (see fig. 1).

The Earth's core contains a large proportion of iron, as well as a considerable quantity of lighter elements whose characteristics remain the subject of fierce debate. Its poorly-defined temperature is probably less than 5,000 K at the centre of the Earth.

The silicate layer and the core consist of eight elements: Silicon (Si), Magnesium (Mg), Iron (Fe), Oxygen (O), Calcium (Ca), Aluminium (Al), Nickel (Ni) and Sulphur (S). In order of abundance, the leading four elements (Si, Mg, Fe, O) provide at least 95 % of the total mass of the core and silicates system. The other four constitute 4.99 % of the remaining mass. If they were overlooked in an initial estimate, the resulting error would correspond to less than 1% of the total mass.

Therefore, working out from the centre, a planet consists schematically of a core of pure iron, possibly accompanied by iron sulphide (FeS). Its silicate mantle can be characterised by four elements: O, Si, Fe and Mg. The hydrosphere and the frozen layer, where it exists, are assumed to be composed of pure water. The gaseous envelope of the intermediate and giant planets consists of 90% hydrogen and helium. The mass of the atmosphere of telluric planets is negligible and is not taken into consideration in this model.

Notes

magnitude taken into account for pressure and temperature. With regard to the interior of planets, the most commonly-used equations for solid materials below 500 Giga Pascal are the Birch-Murnaghan and Mie-Grüneisen-Debye equations.

Corot:
Corot is a French satellite, fitted with a 27 cm, afocal telescope. Its camera's four CCD detectors are extremely sensitive. Corot uses a technique known as astroseismology, to study the physical phenomena occurring inside stars. It can also detect, using photometry, periodic micro-eclipses caused by planets passing in front of their parent star.

Kepler:
This NASA mission, scheduled for 2008, will also be using photometry to detect exoplanets.

Darwin:
This European mission, slated for 2015, will involve four or five satellites flying in formation. Using interferometry, it will be able to detect planets of a similar size to Earth. By identifying the different spectra of light emitted by each extra-solar planet, Darwin will analyse the different components of their atmospheres, in order to detect the chemical signatures of any life that may exist there.

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Planet found elsewhere

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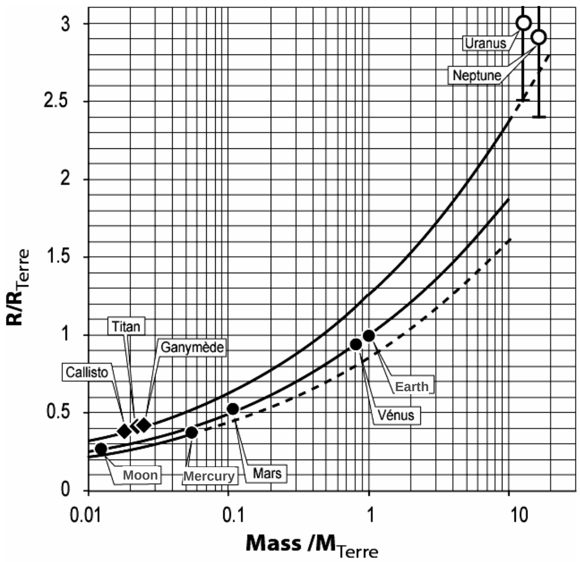

Fig. 2: Mass-Radius relationships of the various families of solid planets. The models correctly reproduce variations in radius as a function of mass for the main bodies in the solar system. It is possible to extrapolate to a larger mass, as shown by the positions of Uranus and Neptune. For both planets, their respective positions on the graph correspond to their solid part (excluding the atmosphere), according to estimates made by Hubbard et al. (1995). Upper curve: Ocean planets; middle curve: super-Earth; lower curve: super-Mercury.

When the model is applied using the limited information available while setting the same proportions of the various elements (Si, Mg, Fe, O) as for the Sun, the calculated radius for a planet whose mass is equivalent to Earth varies between 6,400 and 6,478 km. These limits are based on hypotheses about the thermal profile and the equations of state used. The values are to be compared with the measured Earth radius of 6,371 km. For planets with a different mass, but the same proportions as for the Sun, the model's predictions agree with observations and calculations made for the main bodies of the solar system (see fig. 2).

This model for studying internal structures will be used to improve data processing for the COROT satellite mission, and to prepare for the forthcoming Kepler and Darwin missions.

The model is not yet complete, and its accuracy should improve as we learn more about how materials behave under extremely high pressure. In coming years, new planets will be discovered and their study may lead to the investigation of new families, such as carbon-rich planets.

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