Internal structure and atmospheres of planets

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Sizes and masses



Radius vs. mass



Results of modeling.

Old (relaxed) planets.

Colors correspond to different fractions of light elements.

Light elements contribution



Results of modeling.

Different slopes above and below ~100 Earth masses are due to different regimes of gas accretion.

Density and mass



Mass-density. Observations. Heating.



Planet structure



Even about the Earth we do not know many details of the internal structure. Data about other planets is very incomplete and indirect.





Structure of the Solar system planets



What Solar system planets are made of?



Except Jupiter and Saturn planets are mostly made of elements heavier than helium.

Even icy-giants – Neptune and Uranus, - are mainly made not of H+He.



Structure of giant planets



Except Uranus giant planets might not have solid cores. However, there cores are made of heavy elements. And so often they are called made of rocks.



Temperature and pressure in atmospheres of giants



For Jupiter direct data are available due to Galileo probe measurements.

Hydrogene equation of state



Still, there are important uncertainties even for the hydrogen equation of state.

Some regimes have been never measured in laboratories.

Hydrogen plus helium mixture



Diamond anvil cells



Merkel (2013)

Diamond cells are used to reach high pressures in laboratory experiments. However, it is not enough, and in many cases we have to base only on

numerical models.



Bouchet et al. (2013)

Diamond cell



http://serc.carleton.edu/NAGTWorkshops/mineralogy/mineral_physics/diamond_anvil.html

Scheme of the experiment



How to press?





1st class lever drive



Pin - guide screw drive



Screw piston drive



2nd class lever drive

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Fluid - bellows drive				









six basis ways of providing force in the DAC (Bassett, 1979)

### How to heat the matter



Electric current (for lower temperatures) or laser (for higher temperature).



Above 1300K

http://serc.carleton.edu/NAGTWorkshops/mineralogy/mineral_physics/diamond_anvil.html

### Comparison with conditions in the Earth



http://mini.physics.sunysb.edu/~pstephens/downloadable/ehm_dac.pdf

### Mass-radius models for planets



Relatively simple model based on just 8 key elements.

Good results for Solar system planets.

### Mass-radius diagram for exoplanets



Planet radius, of course, depends on its composition.

Light planets typically do not have extended gas envelopes.

Oppositely, giant planets might hath very thick gas envelopes.

Very often data on mass and radius can be explained by different combinations of ingredients.

### Theory vs. observations



### Three main ingredients: gas, ice, rock





### Three main types of planets



### Thick atmospheres for M>4M_{Earth}







### Kepler-51. Crumbly planets.



Solar type star. Three planets with masses 2-8 M_{earth} and low densities: <0.05 g/cm³

Orbital periods 45-130 days.

### Superearths. Diversity of properties.



Wikipedia

### Sizes of superearths



Typical radii 1-4 of the Earth <u>I.e., betw</u>een the Earth and Neptune).

Sometimes low density planets in the range are called mini-Neptunes.

#### Predicted sizes of different kinds of planets Sun-like star $\mathbf{H}$ 10,000 mi Earth analog 1 M_e 5 M_• Pure Silicate Pure Carbon Pure iron water carbon Pure planets planets monoxide planets planets hydrogen planets planets

### Superearths: mass-radius



Superearths are very numerous planets. Only those with well-determined mass and radius are shown.

Inner cores can consist either of rocks (and iron) or of ices.

Some of superearths obviously have thick gas envelopes. This is a challenge to formation models.



### Superearths models



For less massive planets parameters are mainly determined by the core. For more massive – by the outer envelope.

Heating can be also important.

Results are shown for planets with solid earth-type cores.



### Just add water



Let us fix the planet mass and change the fraction of ice.

Here water is added as an ice layer above a solid (rocky) core.

Only for lower masses it is possible to distinguish (by radius measurements) between pure-ice cores and pure-rock cores.





### Under pressure



Interiors might have high pressure and density

### Soil and water



Mass (M_e)

Wikipedia

### Atmospheres



### Transits and atmosphere studies



### Transits and atmospheres

0.0149 0.1220 HD209458b 0.0148 0.1215 0.0147 .12100.0146 eigh ).12050.0145 Rp/Rs Transit depth 0.0144 0.0182 XO-1b 0.0180 0.1340 0.1335 0.0178 .1330 0.0176 1320 0.0174 Rp/Rs 0.0172 1.2 1.4 1.6 Wavelength (microns)

Transit observations in different wavelengths allow to determine properties of the planet atmosphere.

Size can be different in different wavelengths.

In addition, light curve can look different due to atmospheric dynamics. Heat redistribution due to strong winds modifies the flux from the planet.





### Featureless spectrum of GJ 1214b



Obscured by clouds.

#### Hubble space telescope spectrum shows no details.

This is interpreted as the result of the presence of a thick cloud layer in the outer atmosphere of the planet.

### Phase dependence

Depending on the phase we observe different parts of a disc.

Results of observations correspond to:

HD 189733b – upper panel; HD 209458b – lower panel.

Both planets are hot jupiters.

Note, that in the case of HD 209458b planetary disc is strongly non-symmetric in terms of the emitted flux.



### Scanning planetary discs



### Dynamics of outer layers of hot jupiters



Planet has internal and external heat sources.

This results in violent winds and convection in the outer gas envelope.

### Wind on HD 209458



Wind velocity can be directly (!) measured.

The planet is a VERY hot Jupiter.

Wind velocity is ~ 2 km/s

### Modeling winds on hot jupiters



General property:

Strong equatorial wind from the West to the East.

### Modeling of HD209458 b





### Exomoons: how to form

Regular satellites Are formed together with planets from the circumplanetary disc Irregular satellites Capture or collision





System of 37 rings extending up to 0.6 AU around a stellar companion.

The star is young (16 Myrs), and so, probably, the system of rings is just forming. Satellites might regulate the shape of the ring system.



### Which planets might have detectable satellites?



To be large respect to the host-planet the satellite might be irregular.

Systems with many planets are more favorable.

Larger planets have larger moons.

Hot jupiters (and neptunes) can loose planets during migration.



### Modeling satellite formation



### Satellite capture in three-body interaction



Results of modeling of a satellite capture. The body initially had a companion which was lost during three-body interaction. This scenario requires a massive planet. Such interactions can happen in the habitable zone.

### How to find an exomoon



Potentially, all methods for exoplanets discovery can work.

However, presently methods related to transits seems to be more favorable:

- 1. TTV
- 2. TDV

3. Orbital plane changes.



### Joint transits



### How strong is the effect?



### An example: Jupiter with satellites over the Sun



### A planet with a moon ... but without a star?



### New measurements and a candidate



### Tidal heating



Satellites can be heated by tides.

Effect can be so strong, that a satellite with an atmosphere can experience the greenhouse effect.

### Planetary magnetospheres



It is argued that magnetic shield can be important for life. A satellite can ``use'' the planetary field.

However, if the satellite is too close to the planet – then tides can heat it up. If it is too far – it can be out of the magnetosphere.



### Can JWST see exomoons?



A satellite might be large (as the Earth) and warm (also as the Earth, at least).

Potentially, such satellites can appear around massive planets far from the star, where it is easier to see them. A satellite can be heated by tides.

### Literature

arxiv:1604.06092 Exoplanetary Atmospheres - Chemistry, Formation Conditions, and Habitability

arxiv:1507.03966 Observations of Exoplanet Atmospheres

arxiv:1401.4738 Planetary internal structures

arxiv:1312.3323 The Structure of Exoplanets

arxiv:1501.05685 Exoplanetary Geophysics -- An Emerging Discipline

arxiv:1701.00493 Illusion and Reality in the Atmospheres of Exoplanets

arxiv:1411.1740 Seismology of Giant Planets

arxiv:1709.05941 Exoplanet Atmosphere Measurements from Transmission Spectroscopy and other Planet-Star Combined Light Observations