Exoplanets and their Structure, Rheology and Dynamics

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Abstract – *In the past two decades there have been around hundreds of exoplanets that have been discovered. However as of 2020, there are more than 4000 confirmed exoplanets discovered by the astronomers. Most of the Exoplanets are generally discovered by Transit photometry and Doppler spectroscopy. There are many other methods as well but these two are the most popular. Here, the paper describes the diverse range of Exoplanets such as HD 209458b, Proxima centauri b, Kepler-22b etc. Various components of these planets are showcased. The main components of this paper would describe the general structure of Exoplanets. The following sections put some contrast and describe the rheology of these planets and in the end the display of the dynamics inside, explaining how the orbital dynamics and planetary rotation period affect the dynamics of the planet. Discoveries so far have shown that the terrestrial planets have wide range of climatic regimes. The paper is divided into three main core sections such as structure, rheology and dynamics of the Exoplanets.*

1. Introduction

Since the end of 1900s, the number of detections of Exoplanets have increased exponentially (Bolmont, 2014). There are approximately around 100 gaseous giant planets currently orbiting the stars and about 20 from the total confirmed planets are potentially having the liquid water surface (http://phl.upr.edu/projects/habitable-exoplanets-catalog). The regular finding for the Earth like alternative habitat is increasing exponentially as the main focus of the exoplanet research. In the last few decades we have seen a tremendous increase in finding a different habitat zone (HZ). A special characteristic of these planets is they are located in orbits and very close to the host star, which actually allow them to sustain liquid water on their surface. Few of such exoplanets are HD 209458b, Proxima centauri b, Kepler-22b, Kepler-62f etc. Their characteristics are showcased in the following sections. According to the theory of Orbital dynamics, tidal forces are supposed to maintain synchronous rotation rate with the orbit, which gives rise to the time domain in the planet or in general described as day and night.

2. Structure of Exoplanets

Exploration of interiors of various exoplanets is not scripted. There are many different ways to explore them. In this section, the paper describes the interior of the Exoplanets by considering 'Proxima Centauri b' and 'HD 209458b' as couple of examples. Initially assume that exoplanet is fairly ideal habitat zone. Here, (Brugger, 2016) thinks that Proxima Centauri b would be having similar composition and internal structure as Earth. Therefore, considering the interior of Earth from Oceans to the core such as:

1. The initial layer made up of liquid H2O.

2. The pressure in the ocean increases with depth.

3. Upper mantle's composition is same as Earth.

4. Lower mantle has the same composition as Earth such as silicates, Perovskite etc.

5. The metallic core composed of combination of Iron and its alloys.

But even after having this assumption, there is still a point to predict the thickness of these layers. The following Earth's composition table is used by (Brugger, 2016), in Proxima Centauri b:

Parameter	Value	Description
f_{alloy}	0.13	Fraction of FeS alloy in the core
Mg#	0.9	Mole fraction Mg/(Mg+Fe) in the mantles
Mg/Si	0.131	Mg/Si mole ratio of the body
T_{surf} (K)	288	Surface temperature
P_{surf} (bar)	1	Surface pressure

Table 1. Compositional parameters and surface conditions of the Earth

As far as the internal structure of the planet is concerned, it is basically governed by the CMF and WMF parameters. In other words the composition of the internal structure of a planet can be described by the combination of CMF (Core Mass Fraction) and WMF (Water Mass Fraction) parameters.

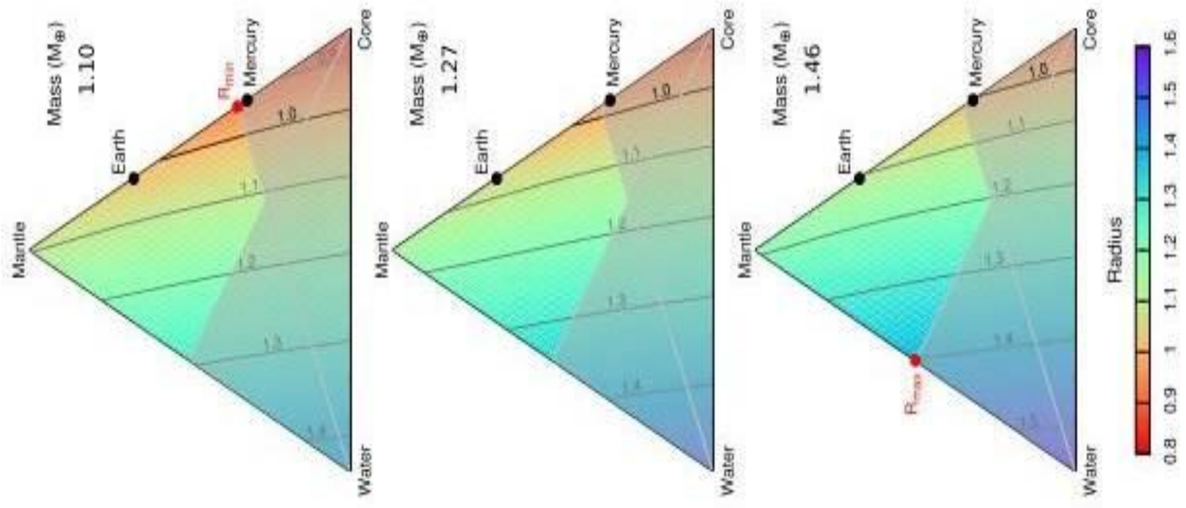

Fig.1. (Brugger, 2016) Ternary diagrams displaying the investigated compositional parameter space for different mass of planet MP values. From top to bottom, diagrams correspond to the minimum, mean, and maximum masses.

Fig.1. describes the results of the computations. There are actually 3 mass MP iterations. Based on that it coincides with the radius. So for Proxima b, the minimum adopted radius is 0.94R⊕ and the maximum is 1.40R⊕. Further it says that the 65% of the planet's mass is located in the core and rest in the mantle. By taking every combination of various planets. The composition for the Proxima centauri b is determined by plugging all the values into the ternary diagram. This diagram actually helps in determining the key composition inside the planet. Although, making use of these diagrams may not be 100% accurate, however they are beneficial in predicting the composition up to maximum extent. According to (Brugger, 2016) the maximum CMF value for this exoplanet is (~65%) and the exoplanet has the proportions of Iron and Silicates. Results show that the presence of water is approx. 70%. Acceleration due to gravity, pressure, temperature and density are mainly the parameters that govern the internal structure of the planet.

$$\frac{dg}{dr} = 4\pi Gp - \frac{2Gm}{r^3} \quad 1$$

$$\frac{dP}{dr} = -\boldsymbol{\rho} g \quad 2$$

$$\frac{dm}{dr} = 4\pi r^2 \boldsymbol{\rho} \quad 3$$

Where, r is the radius of the planet, m is the mass of the planet, G is the gravitational constant **ρ** is the density of the planet. From equation 2, 3 the rate of change in the governing parameters such as pressure and mass can be easily calculated and hence the interior dynamics of the planet can be visualized better. Now considering another Exoplanet named as HD 209458b, it is commonly known as Giant exoplanet. Here, the structure of this planet is described by (Cho, 2003).

The shallow water equations, which are being used here:

$$\mathbf{V} \cdot \nabla V + \frac{\partial V}{\partial t} = -g\nabla \mathbf{h} - \mathbf{f}\ \mathbf{K}\,\mathbf{x}\,\mathbf{V} + \mathbf{Fa} \quad 4$$

$$\mathbf{V} \cdot \nabla h + \frac{\partial h}{\partial t} = -K\,h\,\nabla . \mathbf{V} + \mathbf{Fd} \quad 5$$

Where, V=V (A,B,t) is the horizontal velocity, with A and B are longitude and latitude, h is the thickness of the modelled layer, f = 2 Ω Sin B, where Ω is the Coriolis parameter, K is the local unit vector, g is acceleration due to gravity. Fa = -g**∇**η[1-exp(-T/ta)]CosBCosA and Fd = -(-h-hE)/td, are adiabatic and diabatic thermal forcing. H and η are constants, K/Cp.

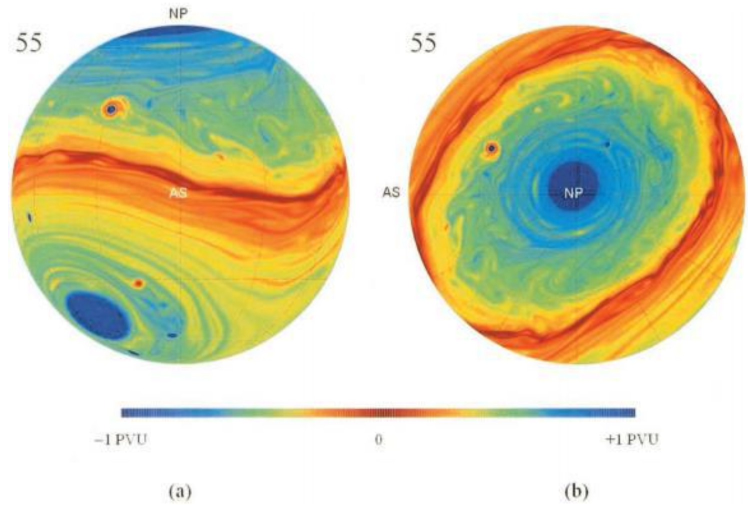

Fig.2. (Cho, 2003) Two views of the dynamical flow tracer, potential vorticity, at grid (resolution simulation) 1024 x 512 of the atmospheric circulation of HD 209458 b: (a) Orthographic projection pointing centered at antistellar (AS) on the left side and (b) polar-stereographic projection centered at the north pole (NP) right side.

In fig.2. The Characterisation of the global flow is done by two circum-polar cyclonic (rotating in the same direction as the planet—counterclockwise in the figure) vortices at high latitudes and high-amplitude planetary waves at low latitudes. For modelling the gas giants and atmospheric dynamics, (Cho, 2003) has used the higher resolution shallow-layer models in spherical geometry. (Cho, 2003) may know that exoplanet HD 209458b is a huge gas giant, then making use of the deep convection circulation models can help in exploring the exoplanet, also deep convection model can also work based on Jupiter's parameter (both being the giant gas planets). Interpretation of results in (Cho, 2003) show that, at dynamic equilibrium the velocity reaches to 400 m s-1 .It also shows that the interior has a shallow layer of turbulence, wind is blowing eastward. In the nutshell, initially assumptions are made to simplify the circulation models. Models can be initiated making use of the frictionless sphere having low viscous gas inside, varying the gravitational field and associating that sphere with a Coriolis component. These implementations can be made on the model if nothing is known about the Exoplanet. However, task becomes slightly easier if any of the physical parameter is known. Further comparing it with similar planet (whose physical parameters are known) then determining the structure of the Exoplanet becomes slightly easier. However there are many other ways to identify the structure of an Exoplanet.

3. Rheology of Exoplanets

From the past few decades, there is no doubt that Exoplanets are one of the most popular and targeted topics in space exploration. Researchers have been actively looking for alternate habitats. They have been quite successful as well, as there are hundreds of Earth like Planets discovered so far. But the requirement is to have the similar and suitable climatic conditions to Earth. Considering Kepler 62f, one of the Kepler series of Exoplanets as an example because it has quite similar habitable zone as Earth (Quintana, 2014). According to him, this planet is potentially rocky but has radius larger than Earth. Planets having short orbital period and have larger radius have habitable zone (HZ) suitable as an option of alternative habitat (Quintana, 2014), after they made use of planetary thermal evolution models, they found out that the radius of Kepler 186 planets less than 1.5 $R_\oplus$, therefore, which is relatively small and therefore it cannot dominate the effect of H/He gases.

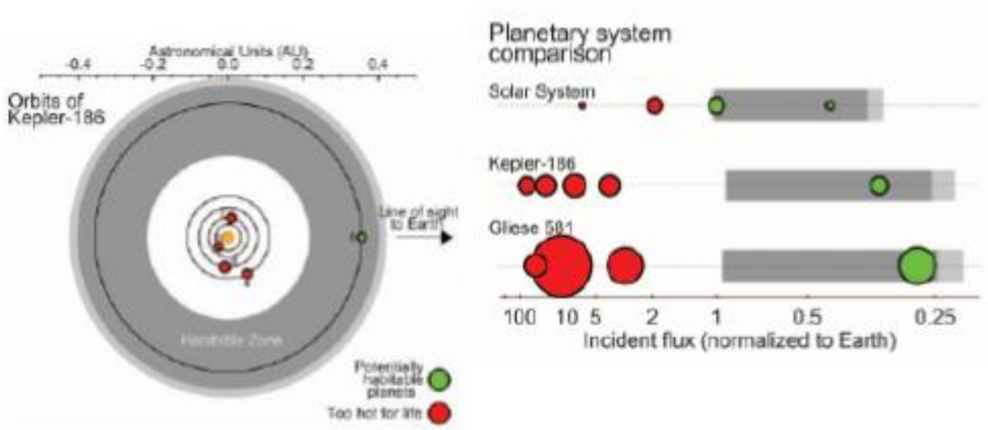

Fig.3. (Quintana, 2014) A schematic diagram of the Kepler-186 system. (Down) A top down view of the system during a transit of planet f. The relative planet sizes are correct but are not on the same scale as the orbits (shown as black curves). (Up) A side-on view comparing Kepler-186 with the solar system (with Earth and Mars in the HZ) and the Gliese 581 planets.

In figure 3, the stars are located at the bottom edge of the plots. The dark gray regions represent conservative estimates of the HZ, gray regions are more-optimistic significance of the HZ around each star. Kepler186f receives the incident flux as that of Earth receives from the Sun. This puts Kepler-186f comfortably within the conservative HZ, which ranges from 0.25 to 0.88 of Earth's incident flux for this star. Kepler-186f receives a similar incident flux as Gliese 581d, which has been shown to be capable of hosting liquid water.

In figure 3. Planets with red colour display that they are too hot for life. They are generally very huge and there is no (HZ) on these planets. The presence of H/He gases are highly compact and therefore the temperature and pressure parameters are very high. One of the main reasons is the red planets are coming across larger incident flux. Planets with green colour are relatively smaller in size. They are quite far, that they are coming across very less amount of incident flux as compared to red planets. Due to that, the amount of H/He gas/es are comparatively lesser than the red colour planets.

Generally, huge gas giants are made up of several volatiles and the core is very dense. If there is a hydrostatic equilibrium condition with homogenous density, then pressure can be written as, $P = 3GM^2/8\pi R4$, Where, P is the pressure, G is gravitational constant, M is the mass of the planet, R is the radius of the planet.

4. Dynamics of Exoplanets

After the discovery of another alternative habitat, there are still many constraints before life actually exist there. The impact of tides on the orbital evolution of planets can affect the climatic conditions. This can also influence the surface water. The presence of surface liquid water depends on many physical parameters. It will not just depend on the pressure and temperature, but also on the orbital dynamics (Bolmont, 2014). Also, the climate of the planet can be affected by the rotation period of the planet and orbital eccentricity.

The climate change can get affected by the influence of stellar tide and planetary tide (Bolmont, 2014):

a. Effect of stellar tide: The force created by the stellar tide impact semi major and minor axes and the inclined path of the planet's orbit. As the difference in the masses of Star and Planets is big enough. Therefore, Start and Planet can be distorted from each other and its impact would last longer.

If the Star is rotating very fast, it decreases the eccentricity of the axes and the inclination also gets reduced, which bring back the orbital axis to the equatorial axis.

b. Effect of Planetary tide: The semi major axis and eccentricity of the orbit gets affected by the force generation of the planetary tide. If the planet is revolving and reaches the synchronised velocity for which he time rotation period of the planets becomes equal to the orbital time interval. But during the case where the orbit is eccentric, the pseudo-synchronization is achieved. Eventually the eclipse, and (d) one-quarter before the next transit.

In figure 4, the temperature on this layer ranges from 1011 K (dark) to 1526 K (bright). In the condition of radiative equilibrium, panel section (a) would be darkest and section (c) would be brightest. Due to the revolving movement, the globes show that there is a difference in observed flux from the planet between the leading and trailing phases of its orbit— section (b) and (d) is a sign of winds.

5. Concluding Remarks

Researchers are enthusiastic in finding various exoplanets and seeking alternative habitats. But for that, three major components are actually significant in determining if an exoplanet is similar to Earth and suitable for living or not. The paper visited those components in the form of internal structure of the planet, rheology of the exoplanets, and the dynamics of the planet. All three are responsible for determining a suitable and similar habitat to Earth The paper displayed few approximations based on which the simplification on circulations and deep convection models can be simulated. Likewise, in the first section the structure of the Exoplanets are described based on the Ternary diagrams approach after making use of Earth's physical parameters. This approach proven to be vital for calculating the radius of Proxima, which falls under the range of 0.94 to 1.40 $R_\oplus$. The lower value signifies the planet made up of 65% of iron in the core and rest 35% mass is in the mantle. In the nutshell, making use of an internal structure model to calculate the radius of the planet along with gradually exploration of different layers of the planet, but assuming that the mass and the bulk composition are known.

The next section describes the Rheology of the Exoplanets of Kepler series (e.g. Kepler 62f) that finding the water traces are not just important, but also few other physical parameters are equally important. For a suitable habitat zone few conditions such as the location of the planet is essential to fight against the magnitude of heat flux, for example if the planet is too close to the star, its surface temperature is very high and may reach the new gravitational equilibrium at a faster rate because the viscosity is dependent on temperature. Radius of a planet is also vital, especially to dominate the effects of H/He gases. If the radius is less than 1.5 $R_\oplus$, then the gases will dominate in the planet.

The third section illustrates the dynamics of the Exoplanets. This section has described the role of orbital dynamics in making life possible on a planet. By touching the effects of stellar tide, planetary tide, which affect the planetary rotation can put impact on the surface liquid water as well.

The climate of a planet depends on many parameters such as atmospheric pressure, temperature, orbital distances, rotation of planet, heat flux, and eccentricity of the orbit. Therefore, the dynamics of tidal evolution and the climate of a planet both are linked to each other.

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