THESES OF PHD DISSERTATION

Habitability of Exoplanetary Systems
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Vera Dobos
Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences

Részecskefizika és csillagászat doktori program
Head of program: László Palla

PhD School of Physics, Eötvös University
Head of School: Tamás Tél

Supervisors:
Imre Nagy, College Associate Professor at the Nat. Univ. of Public Service, PhD
Emese Forgács-Dajka, Senior Lecturer at Eötvös University, PhD

Associate Supervisors:
László L. Kiss, Director of the Konkoly Observatory, Corr. Member of MTA
Edwin L. Turner, Professor of Astrophysical Sciences at Princeton University, PhD

Department of Astronomy, Eötvös University

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1 Introduction

The aim of my dissertation is to investigate habitability in extrasolar systems. Most of the time, only planets are considered as possible places where extraterrestrial life can emerge and evolve, however, their moons could be inhabited, too. I present a comprehensive study, which considers habitability not only on planets, but on satellites, as well.

My research focuses on three closely related topics. The first one is the circumstellar habitable zone (HZ), which is usually used as a first proxy for determining the habitability of a planet around the host star. The HZ is determined as a region around a star in which an Earth-like planet could support liquid water on its surface for a long period of time. For calculating the location of the HZ around different stars, usually complex climate models are used which take into account the incident stellar radiation, the atmospheric properties of the Earth and the carbonate-silicate cycle, which regulates the temperature of the planet. Instead this complex climate model, simple equations can be used, too. These formulae are fitted to the results of the more complex climate models. For this simple calculation the stellar temperature and luminosity are needed as input parameters, which can be calculated from the stellar mass. However, different calculation methods give different results. The aim of this work is to compare the results of different methods with measured stellar parameters, and to propose new empirical formulae that provide better results for F, G, K and M main sequence stars.

Whether a planet is habitable or not, its moon might have a suitable surface temperature for holding water reservoirs, for example, if it is tidally heated. Tidal heating is generated inside the satellite and its source is the strong gravitational force of a nearby planet. The second topic of my research explores tidal heating and the habitability of extrasolar moons with and without stellar radiation and other related energy sources. The elevated temperature caused by tidal heating can melt the ice on the body and prevent the snowball state even without significant stellar radiation. For calculating the tidal heating rate in exomoons, usually the so-called fixed $Q$ models are used, which highly underestimate the tidal heat of the body. These models use $Q$ and $\mu$, the tidal dissipation and rigidity (respectively) as constants, however these parameters are functions of the temperature. In addition, the correct values of $Q$ and $\mu$ are extremely difficult to estimate even for Solar System bodies. Their values can vary a few orders of magnitude for similar bodies, which means that their estimation for yet unknown exomoons is not possible, one can only guess or assume some value for these parameters. For these reasons, I apply a viscoelastic tidal heating model for exomoons for the first time, and compare the surface temperature of hypothetical exomoons calculated with both models for different physical and orbital parameters.
Life is possible to form even on icy planetary bodies, inside tidally heated subsurface oceans. Among the satellites in the Solar System, Europa and Enceladus are the best candidates for supporting subsurface liquid water and related potential habitability and hence these are the most actively studied satellites. These moons are tidally heated, hence life might emerge at the bottom of the ocean, where the rocky seafloor interacts with water through hydrothermal vents. The third topic of my research probes the possibility of identifying an ice-covered satellite from photometric observations. A strong indication of surface ice is the high reflectance of the body, which may be measured when the moon disappears behind the host star, so its reflected light is blocked out by the star and a small flux drop occurs in the light curve. The depth of the flux drop is proportional to the albedo and the radius of the moon. I investigate the possibility of albedo estimation of large icy exomoons with next generation telescopes.

2 Methods

2.1 Habitable zone

In order to calculate the boundaries of the HZ, the stellar parameters are needed. Other environmental elements, like the presence of an atmosphere, its thickness, composition, atmospheric pressure, or cloud formation can influence the surface temperature, i.e. the state of the water, as well. Usually complex climate models that include the carbonate-silicate cycle, the atmospheric composition of the planet and the stellar radiation are used for calculating the HZ boundaries.

For faster estimations of the location of the HZ, parabolic equations can be fitted to the results of climate models. To calculate the boundaries of the HZ with these fitted equations, only the stellar temperature and luminosity are needed. These parameters can be calculated from the stellar mass, however, different equations exist that give different results. I compared numerically the formulae to measured stellar parameters by determining the residual sum of squares (RSS). I also fitted parabolic and power functions to the measured stellar parameters to propose new formulae that give more precise results.

2.2 Tidal heating

The viscoelastic tidal heating model is more realistic than the widely used, fixed $Q$ models, because it takes into account the temperature dependence of the tidal heat flux and the melting of the inner material. In the viscoelastic model, instead of $Q$ and $\mu$, the viscosity and shear modulus are used as functions of the temperature.
As a consequence, tidal heat flux has a temperature dependency, as well: it reaches a maximum at a critical temperature and between the solidus and the liquidus temperatures the rocky material partially melts.

The exomoon is considered as a two-layered body: the inner part is fully convective, and the outer layer is conductive. For weak tidal forces, the convective region is smaller, and in the case of strong tidal forces, the convective region will be larger and the conductive layer will become thinner. I assume that the body will reach an equilibrium state between tidal heating and convective cooling with time. I determine the equilibrium temperature of the moon with an iterative method and then calculate the tidal heat flux on the surface.

First, I made calculations for planet-moon systems without a central star, and later, we merged the viscoelastic tidal heating model with a comprehensive climate model which takes into account other energy sources affecting the moon, as well. These energy sources are the stellar insolation, atmospheric retention, planetary illumination and thermal heat from the planet. Eclipses are also considered as energy sinks. The carbonate-silicate cycle is a negative feedback mechanism which regulates climate. The ice-albedo feedback is a positive loop which is responsible for the freezing of the moon at the outer boundary of the circumplanetary habitable zone. Both feedback mechanisms are included in the climate model that we use.

### 2.3 Albedo estimation

During the occultation of a planet or a moon, a slight flux drop can be observed in the stellar flux, which corresponds to the reflected stellar light from the body. By accurately measuring the moon occultation (MO) depth (i.e. the flux change caused by the occultation of an exomoon), one can estimate the geometric albedo of the satellite. I assume that the radius and the stellar distance of the moon are already known from previous transit measurements.

Using simple equations and assuming circular orbits, I calculated the MO depth caused by exomoons of different sizes and albedos, in order to investigate the required precision of future observations. With these calculations, I mapped the phase space of different stellar and planetary distances of hypothetical moons of Solar-like stars.

Small M dwarfs were also considered on the main sequence, since their weaker radiation allows a closer orbit of the planet, which means that the planet and the moon can be closer to the star without melting the surface ice. Such a configuration results in a higher reflectance, although M stars are brighter in the near infrared spectrum, where the albedo of ice is somewhat lower. I calculated the size of the moon for different MO depths and stellar sizes with the stellar distance fixed at the snowline, both in the V and J photometric bands. Also, I calculated the expected
photon noise from the instrument parameters of various next generation missions, and then I compared the results with the signals of different size exomoons.

3 Theses

1. I propose new empirical equations for calculating the temperature and luminosity from the stellar mass. By using numeric investigations, I have found that these formulae reproduce the stellar parameters more precisely than other models that I applied. With the empirical equations, the boundaries of the habitable zone fit well to the ones which were calculated from measured stellar parameters of F, G, K and M main sequence stars between 0.3 and 1.4 stellar masses. [1]

For calculating the boundaries of the habitable zone of different mass stars, I used simple formulae fitted to the results of the more complex climate models. For these formulae only the stellar temperature and luminosity are needed, which can be estimated from the mass of the star. I applied three previously defined models that describe the relation of these parameters, and I also propose new empirical formulae for calculating the temperature and luminosity from the stellar mass. I numerically compared the results to measured stellar parameters, by calculating the reduced chi-square values. I have found that the new equations result in a better reproduction of the boundaries of the HZ (calculated from measured stellar parameters) than the other models.

2. I used a viscoelastic model for describing the tidal heating in exomoons, for the first time. I defined the Tidal Temperate Zone (TTZ) as a circumplanetary region where the tidally induced surface temperature of the satellite is between 273 and 373 K. I have found that the viscoelastic model moderates the surface temperature of the moon, compared to the broadly used fixed $Q$ models, because the inner melting of the body prevents the temperature to rise to extreme heights. For this reason, the viscoelastic model predicts 2.8 times more exomoons in the TTZ, than the fixed $Q$ model, for plausible distributions of physical and orbital parameters. The applied tidal heating models do not take into account the stellar radiation, nor the atmosphere of the moon. [2]

Beside exoplanets, their moons can also be habitable. Using the viscoelastic tidal heating model, I introduced the TTZ, and compared the results to the
fixed $Q$ model. I have found that the location of the TTZ strongly depends on the orbital period of the moon and less on its radius. I applied the calculation method to different densities and orbital eccentricities of the moon. In some cases there was no solution (no equilibrium temperature), because the tidal forces were so weak that they could not induce convective cooling inside the body.

I compared the results with the fixed $Q$ model and investigated the statistical volume of the TTZ using both models. I have found that the viscoelastic model predicts 2.8 times more exomoons in the TTZ with orbital periods between 0.1 and 3.5 days than the fixed $Q$ model for plausible distributions of physical and orbital parameters. The viscoelastic model provides more promising results in terms of habitability because the inner phase transition of the body moderates the surface temperature, acting like a thermostat.

For Earth-like bodies other habitability limits than the 0 and 100 °C were used, as well. The lower limit for microbial activity in salty solutions is around −20 °C, and the upper limit for complex eukaryotic life is approximately 60 °C, which also corresponds to the runaway greenhouse limit on Earth. For most of the calculations these probable limits of habitability were also considered when applicable ($\rho \approx \rho_{\text{Earth}}$ and $R \approx R_{\text{Earth}}$), because these are related to biological and atmospheric constraints. When investigating the volume of habitable orbits, I have found that the results were similar to the ones of the TTZ, but the volume was larger for Earth-like moons.

3. We have also used a 1D energy balance model of Earth-like exomoon climates, and found that the circumplanetary HZ is significantly wider with viscoelastic tidal heating, and extends much farther from the planet, than with the fixed $Q$ model. We have shown that if the moon’s orbit is inclined, then the outer edge completely disappears for any eccentricity of the moon’s orbit for as large semi-major axes as 0.15 Hill radius. [3]

The applied 1D climate model contains stellar and planetary insolation, atmospheric circulation, infrared cooling, eclipses and tidal heating as the principal contributors to the moon’s radiative energy budget. The model also takes into account the carbonate-silicate cycle and the positive ice-albedo feedback system. We used both the viscoelastic and the fixed $Q$ models for calculating the tidal heating inside the moons. We have found that the circumplanetary HZ is much wider with viscoelastic tidal heating, than with the fixed $Q$ model.

In the case of zero inclination of the moon’s orbit relative to the planet’s equator there is a well-defined outer edge to the circumplanetary HZ, due
to a combination of eclipses and ice-albedo feedback. We have shown that if the moon’s orbit is inclined so that eclipses are unlikely, the outer edge completely disappears for any eccentricity of the moon’s orbit, even for relatively large semi-major axes of the moon.

4. I have proposed a new method to estimate the albedo of exomoons using occultation light curves. High albedo may indicate the presence of ice cover on the surface. I compared the flux drop caused by the moon’s occultation with the estimated photon noise of next generation missions. My calculations in the J photometric band show that E-ELT MICADO’s photon noise is just about 4 ppm larger than the flux difference caused by a 2 Earth-radii icy satellite in a circular orbit at the snowline of a 0.1 stellar mass star. I conclude that occultation measurements with next generation missions are far too challenging. [4]

If the albedo of the moon is high, it implies that the surface is covered with ice, however methane ice is very reflective, too. In order to determine whether the surface ice is of water or methane, I suggest to make measurements in several photometric bands, especially in the J band, where the two kinds of ices show different spectral features, but they are still very reflective.

Clouds can also cause high albedo on a planetary body. Since water is very abundant in the Universe, I assumed that water clouds might be common, and I compared the spectrum of the Earth’s water cloud with spectrum of ice. I have found that the cloud’s reflectance significantly drops in the F140M photometric band, where the ice’s albedo is still very high. In order to distinguish clouds from surface ice, I propose to make measurements in this photometric band, too, upon the instrumentation available for such precise observations.

I made simple calculations for different stellar masses in the V and J photometric bands, and compared the MO depth and the estimated photon noise of next generation observatories and survey missions with $5\sigma$ confidence. I have found that albedo estimation by this method is not feasible for moons of solar-like stars, but small M dwarfs are better candidates for such measurements, because their weaker stellar radiation brings the snowline closer to the star, and if the planet-moon system orbits the star at a closer distance, then they will reflect more light. Because of other noise sources that were not included in my calculations, I conclude that occultation measurements with next generation missions will be very difficult experiments, even in the case of large, icy moons at the snowline of small M dwarfs.

I also discussed the role of different parameters (some of them were neglected
in the calculations, e.g. inclination, eccentricity, orbiting direction of the moon), and categorised them by their influence on the measurements. The most substantial influencing factors are the stellar distance, the size of the exomoon, its albedo, the star-planet size ratio and the planetary distance. I also predict that the first albedo estimations of exomoons will probably be made for large icy moons around the snowline of M4 – M9 type main sequence stars.

4 Publications

4.1 Publications served as basis of the theses


4.2 Additional publications in the research field
