様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　２ 年　 ６ 月 １９ 日現在

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研究課題名（和文）Can planetesimal accretion break planet resonance?

研究課題名（英文）Can planetesimal accretion break planet resonance?

研究代表者
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交付決定額（研究期間全体）：（直接経費）　　3,200,000円

研究成果の概要（和文）：系外惑星にどのような傾向があるかを調べるために、ニューラルネットワークを使用した。元々は微惑星の降着によって惑星半径が増大するかどうかを調べるために設計したが、観測で直接測定することができない惑星の特性を推定することに、より威力を発揮した。2番目の論文では、ウェブブラウザで実行することのできるシンプルな気候解析プログラムを開発した。これによって、ユーザーは地球に似た系外惑星のほんのわずかな違いが全く違う環境につながることを体験することが出来る。3番目の論文ではニューラルネットワークによる画像識別を用いることで、火星表面の自動クレーター計数ソフトを開発した。

研究成果の学術的意義や社会的意義
While many exoplanets have been found, the measured properties of individual planets is small. This situation will not change, as observation techniques are sensitive to particular properties and orbits. To understand the exoplanet catalogue, techniques must be developed to impute missing values.

研究成果の概要（英文）：This research explored the use of neural networks to identify trends in the exoplanet archive. Originally designed to explore the increase in planetary radius due to accretion, greater success was achieved with imputing missing properties (including planet mass and radius) based on the multidimensional density function found by the neural network. Neural networks excel at finding trends in multidimensional data that are difficult to identify through plotting or other means. Such interpolation is necessary for properties that cannot be measured through observations. A second paper developed a simple climate code that could run on a web-browser to allow users to explore how small changes to an Earth-like planet could hav a major impact on the environment. This also utalised a neural network to render the planet and bring it to a wider audience. A third paper used the image identification of neural networks to develop an automatic crater counter on the surface of Mars.

研究分野：Astrophysics

キーワード：catalogue　exoplanet　planet formation　neural networks　machine learning　astrophysics　planetary science

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Since the early 1990s, thousands of exoplanets have been discovered. Yet despite this high number, only a few properties about each planet are measured. This is a consequence of the detection techniques, which are sensitive to different planet properties and orbits. For example, a planet on a longer orbit will be less likely to transit the star, making a measurement of the planet's radius impossible. This situation will therefore not improve with more observations and the exoplanet catalogue will remain large but sparsely populated with measured properties. This has made utalising the exoplanet archive difficult, presenting challenges for comparing planet formation theories against the collected data.

２．研究の目的

The original goal of this project was to use numerical simulations to supplement missing observations and explore a potential pattern between planet radius and a history bombardment. This was less successful than planned, due to the difficulty with modelling the planet atmosphere sufficiently well to constrain a small increase in radius. We therefore moved to consider the use of neural networks to find patterns in the properties listed in the exoplanet archive. The goal was to see if missing planet properties could be estimated by the network and if these estimations could reveal information about the planet population that could be used to better understand planetary formation and evolution.

３．研究の方法

Neural networks excel at identifying patterns in high dimensional data. They have been traditionally used in image processing tasks and –more recently—in exoplanet science to identify the location of a transiting planet in noisy data. This was the first time that a neural network has been applied to the problem of generating missing planet properties.

The network is trained on planets with a set of properties that all have measured values. The network generates a probability distribution in multi-dimensional space that represents the known properties of the planets. By drawing from this space, the network can generate likely values for missing planet properties, based on the known measurements. Repeatedly drawing from the probability distribution creates a distribution for the missing property that can both estimate the value but also inform on that region of the parameter space. For example, a bimodal distribution for a missing mass value indicates two types of planets can be found with similar periods and radii.

４．研究成果

(1) The neural network was able to estimate the mass of a planet observed with the radial velocity technique (measured minimum mass and no radius) with an average error of 1.5 the true value. The radius of these planets could be estimated with an average error of 1.4 the true value. For planets observed with the transit technique where the radius is measured but there is no mass, the planet mass could be estimated to within 2.7 of the true value. This research was published in the Astrophysical Journal.

(2) In addition to estimating a single value for the missing property, a distribution of possible values could be calculated and used to inform on trends within the exoplanet catalogue. Bimodal distributions in mass or radius indicate that two difference populations of planets commonly exist around stars with similar masses on similar orbits. For example, the neural network predicted that the mass and radius of WASP-8b could be either a hot Jupiter or super Earth (see figure 1 below).

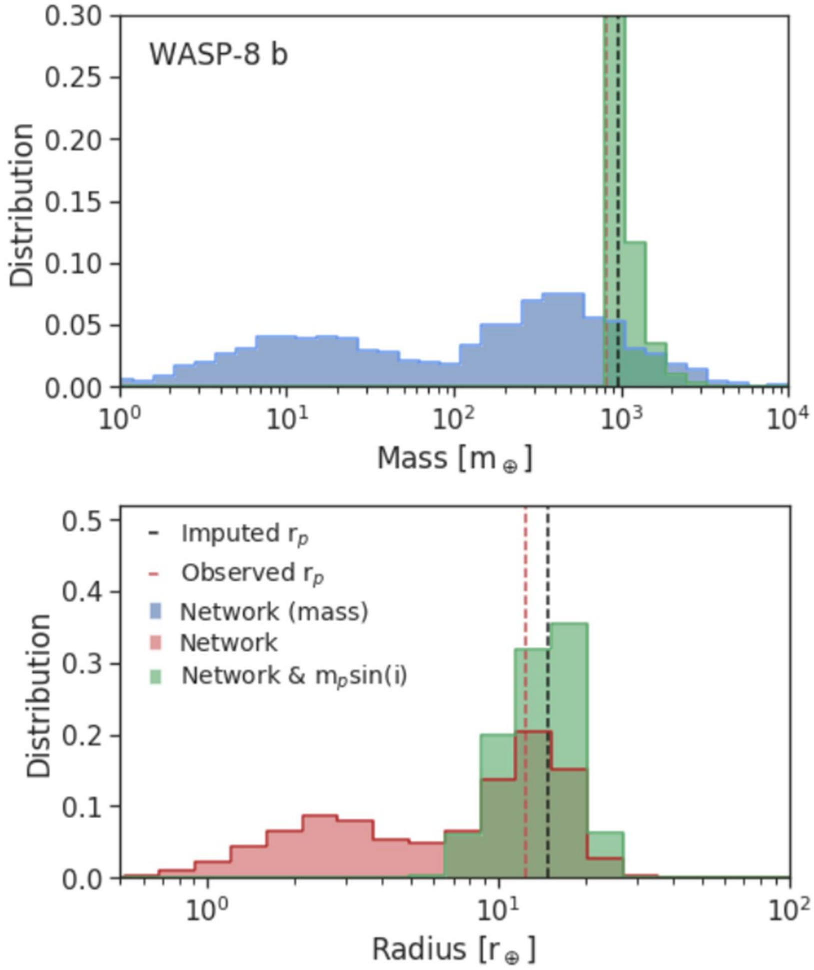

Figure 1: The neural network was tested for accuracy on planets with measured values. The top graph show the estimated distribution for the planet's mass, based on measurements for stellar mass, orbital period, number of planets in the system and effective temperature in blue. The green distribution is when a measurement for the minimum mass is included. Bottom graph is the same, but for the planet radius. The bimodal distribution suggests two possible planet classes commonly exist with similar orbits around similar stars.

Notably, both the mass and radius of this planet are bimodal. This suggests two distinct classes of planet co-exist in the same orbital space, rather than a single class of planet that may experience an inflated atmosphere. This points against the trend proposed in the original goal for this project that inflated atmospheres are common through evolution events such as planetestimal accretion.

WASP-8b is in truth a hot Jupiter, whose measured minimum mass could break the network degeneracy. Models for planet formation therefore need to allow these two distinct planetary groups to evolve to exist in the same orbital space around the star, despite the fact their formation and migration rates should differ.

(3) A challenge in the planetary science community is to explain the potential for planetary diversity within the exoplanet catalogue outside the field. Media and even journal papers frequently describe Earth-sized planets as "Earth-like" despite the presence of the near-equal sized Earth and Venus in our own Solar System.

To combat this, a simple climate model was developed to mimic the Earth's carbon cycle. The model was light enough to run on a website and users can experiment with changing the land fraction, habitable zone position and volcanic rate and see how it impacts the average surface temperature. The goal is to demonstrate how even small changes in properties can make a big difference to a planet. The website is at earthlike.world. A neural network was used to render a possible image of the planet surface, based on its properties. This was published in the International Journal of Astrobiology.

(4) The image processing abilities of neural networks were utilised in an additional project to identify craters on the surface of Mars. Crater counting is commonly a tedious job performed by hand. The results are used to age the surfaces of celestial bodies. Neural networks can potentially accelerate the task by learning to recognize crater locations and sizes. This network has a success rate for identifying craters between 65% - 76% in common with human annotated data. This work was published in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing.

５．主な発表論文等

〔雑誌論文〕　計12件（うち査読付論文　11件／うち国際共著　9件／うちオープンアクセス　0件）

１．著者名 Authors: Takahira, Ken; Shima, Kazuhiro; Habe, Asao; Tasker, Elizabeth J.	４．巻 70
２．論文標題 Formation of massive, dense cores by cloud-cloud collisions	５．発行年 2018年
３．雑誌名 Publications of the Astronomical Society of Japan	６．最初と最後の頁 S58,S70
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/pasj/psy011	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Authors: Pettitt, Alex R.; Egusa, Fumi; Dobbs, Clare L.; Tasker, Elizabeth J.; Fujimoto, Yusuke; Habe, Asao	４．巻 480
２．論文標題 The changing GMC population in galaxy interactions	５．発行年 2018年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 3356,3375
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/sty2040	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Nguyen, Ngan K.; Pettitt, Alex R.; Tasker, Elizabeth J.; Okamoto, Takashi	４．巻 475
２．論文標題 The impact of galactic disc environment on star-forming clouds	５．発行年 2018年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 27-42
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stx3143	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Takahira, Ken; Shima, Kazuhiro; Habe, Asao; Tasker, Elizabeth J	４．巻 -
２．論文標題 Formation of massive, dense cores by cloud-cloud collisions	５．発行年 2018年
３．雑誌名 Publications of the Astronomical Society of Japan,	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/pasj/psy011	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Shima, Kazuhiro; Tasker, Elizabeth J.; Federrath, Christoph; Habe, Asao	4．巻 -
2．論文標題 The effect of photoionizing feedback on star formation in isolated and colliding clouds	5．発行年 2017年
3．雑誌名 Publications of the Astronomical Society of Japan	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/pasj/psx124	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Jin, Keitaro; Salim, Diane M.; Federrath, Christoph; Tasker, Elizabeth J.; Habe, Asao; Kainulainen, Jouni T.	4．巻 469
2．論文標題 On the effective turbulence driving mode of molecular clouds formed in disc galaxies	5．発行年 2017年
3．雑誌名 Monthly Notices of the Royal Astronomical Society	6．最初と最後の頁 383-393
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stx737	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Pettitt, Alex R.; Tasker, Elizabeth J.; Wadsley, James W.; Keller, Ben W.; Benincasa, Samantha M.	4．巻 468
2．論文標題 Star formation and ISM morphology in tidally induced spiral structures	5．発行年 2017年
3．雑誌名 Monthly Notices of the Royal Astronomical Society	6．最初と最後の頁 4189-4204
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stx736	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Shima, Kazuhiro; Tasker, Elizabeth J.; Habe, Asao	4．巻 467
2．論文標題 Does feedback help or hinder star formation? The effect of photoionization on star formation in giant molecular clouds	5．発行年 2017年
3．雑誌名 Monthly Notices of the Royal Astronomical Society	6．最初と最後の頁 512-523
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stw3279	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Tasker, Elizabeth; Tan, Joshua; Heng, Kevin; Kane, Stephen; Spiegel, David; Brasser, Ramon; Casey, Andrew; Desch, Steven; Dorn, Caroline; Hernlund, John; Houser, Christine; Laneuville, Matthieu; Lasbleis, Marine; Libert, Anne-Sophie; Noack, Lena; Unterborn, Cayman; Wicks, June	4．巻 1
2．論文標題 The language of exoplanet ranking metrics needs to change	5．発行年 2017年
3．雑誌名 Nature Astronomy	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41550-017-0042	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 DeLatte, Danielle; Crites, Sarah; Guttenberg, Nicholas; Tasker, Elizabeth; Yairi, Takehisa	4．巻 12
2．論文標題 Segmentation Convolutional Neural Networks for Automatic Crater Detection on Mars	5．発行年 2019年
3．雑誌名 IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/jstars.2019.2918302	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

1．著者名 Tasker, Elizabeth; Laneuville, Matthieu; Guttenberg Nicholas	4．巻 159
2．論文標題 Estimating Planetary Mass with Deep Learning	5．発行年 2020年
3．雑誌名 The Astronomical Journal	6．最初と最後の頁 41
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-3881/ab5b9e	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

1．著者名 Tasker, Elizabeth; Ishimaru, Kana; Guttenberg Nicholas; Foriel, Julien	4．巻 19
2．論文標題 Earth-Like: an education & outreach tool for exploring the diversity of planets like our own	5．発行年 2020年
3．雑誌名 International Journal of Astrobiology	6．最初と最後の頁 264-275
掲載論文のDOI（デジタルオブジェクト識別子） 10.1017/S1473550419000326	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

〔学会発表〕　計19件（うち招待講演　10件／うち国際学会　6件）

１．発表者名 Tasker
２．発表標題 Alien Landscapes
３．学会等名 European AstroFest (outreach conference)（招待講演）
４．発表年 2019年

１．発表者名 Tasker
２．発表標題 Weighing planets with deep learning
３．学会等名 Arizona State University Colloquium（招待講演）
４．発表年 2018年

１．発表者名 Tasker
２．発表標題 Exploring the exoplanet archive with neural networks (poster presentation)
３．学会等名 Exoplanets II
４．発表年 2018年

１．発表者名 Tasker
２．発表標題 Weighing planets with deep learning
３．学会等名 Nature Astronomy Colloquium（招待講演）
４．発表年 2018年

１．発表者名 Tasker
２．発表標題 A planet not our own
３．学会等名 Royal Institution public lecture
４．発表年 2018年

１．発表者名 Elizabeth Tasker
２．発表標題 Following the Water
３．学会等名 International SETI conference #2, Indonesia Space Science Society（招待講演）
４．発表年 2017年

１．発表者名 Elizabeth Tasker
２．発表標題 A Statistical Approach to Characterizing Exoplanets: Neural Networks
３．学会等名 Habitable Worlds 2017（国際学会）
４．発表年 2017年

１．発表者名 Elizabeth Tasker
２．発表標題 Stop Pretending we can Measure Exoplanet Habitability
３．学会等名 Japan Geoscience Union Meeting (JpGU)（国際学会）
４．発表年 2017年

１．発表者名 Elizabeth Tasker
２．発表標題 Finding Patterns in Planets: A neural network approach to the exoplanet dataset
３．学会等名 10th RESCEU/Planet2 Symposium, Planet Formation around the Snowline（国際学会）
４．発表年 2017年

１．発表者名 Elizabeth Tasker
２．発表標題 Finding Patterns in Planets
３．学会等名 DTA Symposium VIII Challenge to Super-Earths and their Atmospheres（国際学会）
４．発表年 2017年

１．発表者名 Elizabeth Tasker
２．発表標題 We have not found Earth 2.0
３．学会等名 Communicating Astronomy to the Public（国際学会）
４．発表年 2018年

１．発表者名 Elizabeth Tasker
２．発表標題 Hunting Habitable Shadows
３．学会等名 National Academies Astrobiology Science Strategy for the Search for Life in the Universe（招待講演）（国際学会）
４．発表年 2018年

１．発表者名
Elizabeth Tasker

２．発表標題
Finding Patterns in Planets

３．学会等名
Department Seminar: American Museum of Natural History (AMNH)（招待講演）

４．発表年
2018年

１．発表者名
Elizabeth Tasker

２．発表標題
Finding Patterns in Planets

３．学会等名
Department Seminar: California Institute of Technology (CALTECH)（招待講演）

４．発表年
2018年

１．発表者名
Elizabeth Tasker

２．発表標題
Finding Patterns in Planets

３．学会等名
Department Seminar: University of California, Riverside（招待講演）

４．発表年
2018年

１．発表者名
Elizabeth Tasker

２．発表標題
Finding Patterns in Planets

３．学会等名
Department Seminar: University of Washington（招待講演）

４．発表年
2018年

1．発表者名 Tasker, Elizabeth
2．発表標題 Can Habitability be Measured?
3．学会等名 EON/ELSI Planet Diversity Workshop
4．発表年 2016年

1．発表者名 Tasker, Elizabeth
2．発表標題 Habitability Cannot be Measured
3．学会等名 AbSciCon 2017
4．発表年 2017年

1．発表者名 Tasker, Elizabeth
2．発表標題 From Galaxies to Planets
3．学会等名 Invited seminar（招待講演）
4．発表年 2016年

〔図書〕　計1件

1．著者名 Elizabeth Tasker	**4．発行年** 2017年
2．出版社 Bloomsbury Sigma	**5．総ページ数** 336
3．書名 The Planet Factory	

〔産業財産権〕

〔その他〕

Outreach media:
1. Earth-Like website: earthlike.world
2. Mind the Gap: filling in the gaps in our knowledge of exoplanets using neural networks: https://www.youtube.com/watch?v=cQygpmYwKw4&t=14s

Media coverage:
1. Earth-Like Planet? Not So Fast
https://www.space.com/39075-habitable-alien-planet-watch-your-words.html
2. Tool Helps Track a Planet's Habitable Zone
https://www.space.com/39676-alien-planets-habitable-zone-animation-tool.html
3. You can build your own Earth 2.0 with the awesome website 'Earth-like'
https://www.space.com/build-an-earth-like-planet-with-website.html
4. Neural networks filling the gaps
https://www.nature.com/articles/s41550-019-1004-8

６．研究組織

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