The “birth” of exoplanets’ gaseous envelopes

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Planets are now known to be ubiquitous around other stars. These extra-solar planets (exoplanets) are more diverse in their compositions and orbital architectures than we could have possibly imagined a decade ago and their physical properties are proving challenging to reproduce using the standard paradigm of planet formation.

One of the most surprising discoveries by recent observational searches for exoplanets is a population of short-period (< 100 days), small (< 4 Earth radii) planets (e.g., Batalha 2013). These exoplanets are so common that on average most stars host at least one (e.g., Fressin et al. 2013). Our standard models of planet formation cannot predict this population of common planets, and their origin remains a mystery.

The presence of voluminous H/He gaseous envelopes on many of these planets (e.g., Jontof-Hutter et al. 2016) indicates that they must have formed before the gas disc dispersed. In previous work, I have demonstrated that these exoplanets’ proximity to their parent star results in vigorous atmospheric escape, driven by high-energy radiation, that is sufficiently strong to have sculpted the exoplanet population from the one formed after several million years to the one we see today after billions of years of evolution. In some cases, atmospheric escape is vigorous enough to remove massive (1-10 % of the planet’s mass) natal H/He envelopes (Owen & Wu 2013). The inference that the majority of close-in exoplanets formed in the gaseous discs, but were then subsequently “photoevaporated” into the planets we see today led to a prediction of a bimodal radius distribution for close-in exoplanets. The bimodal nature of the radius distribution separates planets that have lost their natal envelopes from those that retain it (Owen & Wu 2013, Lopez & Fortney 2013). Such a bimodal nature has recently been observed (Fulton et al. 2017) and is indicative that most close-in planets were born in the gaseous discs and had short period orbits when the disc dispersed (Owen & Wu 2017).

My URF project is to understand precisely how these close-in exoplanets evolve under the influence of mass-loss arising from UV/X-ray driven atmospheric escape. In doing so, I will be able to evolve the observed population of planets back in time to the point where the gas disc has finished dispersing. Using these results, I will be able to make inferences about how these ubiquitous, yet unexplained planets formed.

The “birth” of exoplanets – the boil-off phase

In previous work, I demonstrated that the properties of young planets after the disc dispersed is not the same as the properties of these planets before the dispersal phase began (Owen & Wu 2016). We know from observations that the inner regions of protoplanetary discs disperse rapidly, on a timescale of $\sim 10^5$ years, significantly shorter than the disc’s total lifetime ($\sim 3 \times 10^6$ years, Koperferl et al. 2013). This rapid removal of the inner disc occurs exactly where the common close-in, small exoplanets are observed today.

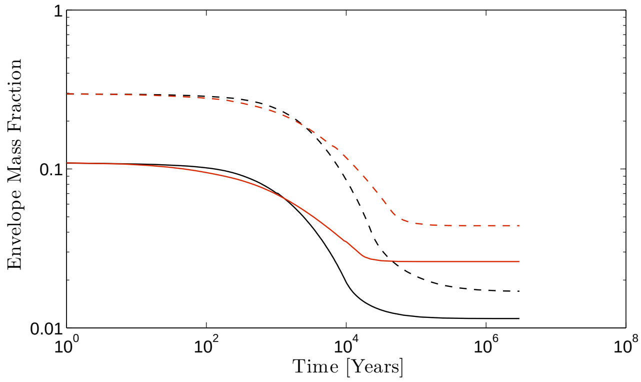

Figure 1: *Evolution of the envelope mass fraction (mass in gaseous envelope/mass in solid core) as a function of time for a planet evolving during disc dispersal. The red lines show planets with orbital periods of ∼10 days, the black lines show planets with orbital periods of ∼100 days. Taken from calculations performed by Owen & Wu (2016).*

I have shown that the rapid (on a timescale shorter than the thermal timescale of the envelope) decompression that a planet’s gaseous envelope experiences during disc dispersal can have some dramatic consequences, leading to mass-loss and cooling (Owen & Wu 2016 – see Figure 1). Put simply, as the pressure confining gas disc is removed the outer region of the planet’s envelope expands to try to maintain hydrostatic balance. As the envelope cannot cool on this short timescale, the outer layers become thermally unbound and escape in a thermal wind. In Owen & Wu (2016) we called this process “boil-off”. Since this “boil-off” phase of evolution can lead to dramatic mass-loss and cooling, we cannot directly link the properties of forming exoplanets embedded in a pressure confining gaseous disc, with those that are evolving in a vacuum. Therefore, outputs of planet formation calculations cannot be directly linked to exoplanet evolutionary calculations (such as those I will produce during my URF).

Therefore, I am applying for a four year Ph.D. studentship at Imperial College London and the associated necessary computational equipment. The student will be under my direct supervision to support my research on the formation and evolution of close-in exoplanets. The student will study the interaction between a forming close-in planet’s gaseous envelope and a dispersing protoplanetary disc. The student will build on the boil-off model I recently proposed (Owen & Wu 2016) and work motivated by it (Ginzburg et al. 2016, 2017). Much of this early work is analytical, thus one of the main accomplishments of this studentship will be to perform realistic numerical simulations of the interaction between the dispersing disc and embedded planets. These new calculations will allow a comprehensive assessment of the boil-off process' impact on the evolution of exoplanets. Results on the initial cooling time of exoplanets from my URF project should also lead to direct quantitative tests for this proposed project by the end of the studentship.

Objectives

The key objectives of this project are listed below and detailed in the following proposal:

- Identify the dominant driving energy source(s) of the boil-off process.
- Use realistic numerical calculations to model the entire boil-off process.
- Understand how the rate at which the disc disperses impacts the final properties of the formed planets.

Part I: identifying the dominant driving energy source – *Timeline, Year 0 → Year 1*

The weakly bound material that escapes the planet during the boil-off phase must gain a small amount of energy to finally escape the planet's potential. For large envelopes, this primarily arises from the internal energy of the envelope itself, and as such, cools the remaining bound material (Owen & Wu 2016). Therefore, the planet suffers premature aging and has a much lower entropy than one would ordinarily expect. Since a lower entropy results in a smaller radius, this will affect the planet's subsequent evolution; for example, photoevaporative atmospheric escape is strongly sensitive to the planet's radius.

Ikoma & Hori (2012) and subsequently Ginzburg et al. (2016) suggested that residual heat in the solid core, left over from its formation, could also provide a source of luminosity for young planets, perhaps dominating over that arising from the gravitational contraction of the envelope. Ginzburg et al. (2017) provided rough analytic arguments that suggested the solid core's luminosity was relevant to low-mass envelopes (envelopes with mass fractions less than a few percent). However, Lee & Chiang (2014) indicated that the rate of removal of internal energy from the solid core assumed by Ikoma & Hori (2012) and therefore Ginzburg et al. (2017) exceed any known transport mechanisms within solid bodies. Finally, there are a couple of other possible energy sources. First, there may still be solids accreting onto the planet during the disc dispersal phase, providing an accretion luminosity. Second, radioactive decay of unstable isotopes in the solid core could provide a source of core luminosity. These additional energy sources may be critical during the boil-off phase.

The student will initially combine the analytic framework of Owen & Wu (2016), which considers the internal energy of the envelope itself, with the analytic framework of Ginzburg et al. (2017) for core luminosity into a semi-analytical model for boil-off. This new semi-analytical model will allow the student to determine which energy source dominates in different regions of the parameter space such as core mass, envelope mass fraction, and distance from the star.

The student will then include a solid core luminosity into the numerical planetary evolution MESA model (Owen & Wu 2013). The numerical models will not only allow the amount of the envelope lost to be calculated but will also allow the final entropy of the remaining material to be studied. The numerical model will also allow the student to test whether the rate of energy leakage from the solid core affects the evolution, as suggested is important by Lee & Chiang (2014), although without any calculation.

Part II: realistic numerical calculations – *Timeline, Year 1 → Year 2.5*

The weakness of current work is its simplicity, so much so that the current models are of limited use in comparing to the observations. The overall goal of this project is for the student to advance the models of boil-off to the point where they are realistic enough to be compared to the properties of observed exoplanets, such as those that will be obtained during my URF project.

All previous models of the boil-off process assume that the outflow is isothermal, as such an outflow can be treated analytically. This approximation will certainly break down when the outflow is optically thick, and the mechanical luminosity of the outflow is comparable to the driving luminosity. Both these situations are likely to occur during the boil-off phase. The student will use hydrodynamical numerical simulations to self-consistently solve for the temperature in the outflow.

Since the flow time-scale (∼days to weeks) is much shorter than the evolutionary timescale for the planet's envelope ($\sim 10^5$ years), the outflow can be considered in steady-state on the evolutionary timescale. This separation of timescales will allow the student to separately compute steady-state flow profiles of the upper envelope and use these as input boundary conditions in the longer term evolutionary calculations. To calculate the outflow profiles, the student will use the modern PLUTO astrophysical fluid dynamics code with the public radiative transfer module. These simulations will be done in 1D to allow the full parameter space to be mapped out, as well as the fact the problem is essentially 1D, although any interesting parameters can be explored in 2D/3D if necessary.

The student's hydrodynamic simulations will allow the outflow properties, including the the mass-loss and energy-loss rates to be computed. The outflow properties can then be tabulated as a function of input boundary conditions to be used in the long-term evolutionary calculations with the MESA stellar/planetary evolution code. These will allow the student to follow the evolution of a planet's envelope from the start of the disc dispersal phase until the point at which boil-off finishes and the planet's envelope finally becomes stable. Such an approach has been successfully applied to the formation of giant planets (e.g., Marleau et al. 2017), and it should be simple for the student to implement this coupling within the MESA code. MESA is specifically designed to be modular and easy to modify to include new physics. During the first summer of the student's Ph.D. program, they will attend the annual MESA summer school, where they will become proficient at such modifications, as well as interacting with a wider group within the astrophysical community.

Part III: the role of the rate of disc dispersal – *Timeline, Year 2.5 → Year 3.5*

As the disc dispersal timescale is much shorter than the thermal time (set by the radiative diffusion timescale at the radiative-convective boundary) for the planet's envelope, previous calculations assumed that the disc dispersed instantaneously and then followed the subsequent evolution of the planet's envelope. However, the exploratory numerical simulations by Owen & Wu (2016) showed that advective transport of energy by the outflow itself, through the radiative-convective boundary, removed the radiative bottleneck in the planet's cooling. This advective transport results in dramatically increased cooling while the planet is losing mass, lowering the planetary envelope's internal entropy. Once the boil-off process finishes and the radiative bottleneck is re-established the planet's subsequent cooling time is an order of magnitude longer than if it did not undergo boil-off since its internal entropy has been lowered.

The advective transport of heat means the thermal time of the envelope during the most vigorous parts of the boil-off phase is set by the mass-loss time-scale, which can be comparable to the disc dispersal timescale (see Figure 1). This means that exactly how and on what time-scale the disc disperses is going to affect the planets evolution. I have heavily studied protoplanetary disc dispersal and have built a model for how a population of discs evolve and disperse (Owen et al. 2011).

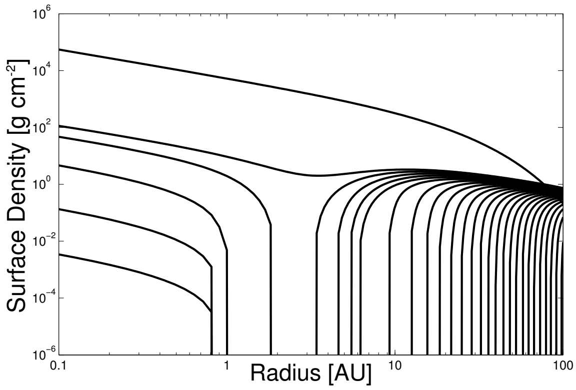

Figure 2: *Snapshots of a protoplanetary disc's evolution taken from Owen et al. (2011). The initial surface density is shown, and then again at every 1% of the disc's lifetime once clearing begins. For this case the total disc lifetime is* 3 *Myr, making the inner disc clearing timescale* 1.5×10^5 *years.*

In the final part of the project, the student will use the numerical model they developed in part II to vary the disc dispersal timescale. These disc dispersal timescales will be calibrated against the latest observational results, as well as theoretical models. The student will then use their models to predict the planetary properties at the end of the disc dispersal phase. These predicted planetary populations will then be compared to the properties of the observed exoplanets, such as those derived from my URF project, where we will specifically focus on the mass and initial entropies of the envelope. Towards the end of this project future observational studies (e.g., K2, TESS, and NGTS) will be detecting young planets; the properties of these observationally detected young planets can be compared to the planet population predicted by the student's simulations. By combining the results from the student's project, the results on the initial properties of exoplanets from my URF and the observed planets we will be able to draw inferences as to how the abundant, yet unexplained, close-in small exoplanets formed. The final six months of the project is allotted to the student's thesis preparations and any overrun if necessary.

Summary

I'm applying for funding to support a four-year Ph.D. student and to purchase the necessary computer equipment. Under my supervision, the student will study the evolution of a close-in planet's envelope during the disc dispersal phase. I have shown in previous work this "birth" phase of a planet's evolution to be important in setting its final mass and entropy; however, realistic calculations have not been performed. The student will use numerical simulations to model this phase and compare their results with the observed exoplanets. This project has been designed with the student's development in mind. As well as working in a dynamic and rapidly expanding area of astrophysics, the student will also gain practical skills in numerical astrophysical fluid dynamics, high-performance computing, and numerical stellar/planetary evolution.

References: Batalha et al., 2013, ApJS 204 24 ■ Fressin et al., 2013, ApJ 766 81 ■ Ginzburg et al., 2016, ApJ 825 29 ■ Ginzburg et al. 2017, arXiv:1708.01621 ■ Ikoma & Hori, 2012, ApJ 753 63 ■ Jontof-Hutter et al., 2016, ApJ 820 39 ■ Koepferl et al., 2013, MNRAS 428 3327 ■ Lopez & Fortney, 2013, ApJ 776 2 ■ Marleau et al., 2017, ApJ 836 221 ■ Owen et al., 2011, MNRAS 411 1104 ■ Owen & Wu, 2013, ApJ 775 105 ■ Owen & Wu, 2016, ApJ 817 107 ■ Owen & Wu, 2017, arXiv:1705.10810