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Leaking Exoplanets: Understanding how Stars affect Atmospheric Escape in Exoplanets

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Introduction

One of the biggest surprises in the discovery of nearly 4,000 exoplanets (planets outside our solar system) is that the majority of known exoplanetary systems have a very different architecture than that of the solar system. Many exoplanets orbit very close to their host stars, with distances that can be more than 10 times smaller the Sun-Mercury distance.

This extreme proximity causes exoplanets to receive a larger dosage of high-energy radiation from their host stars. This radiation heats exoplanetary atmospheres, which expand and more than likely 'leak'. The escaping atmosphere then interacts with stellar winds, which can act to confine this escaping atmosphere, like a fan blowing steam back into a cup of tea!

Equations Governing Atmospheric Escape

Momentum Conservation Equation[1]

$$v\frac{\partial v}{\partial r} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM_{pl}}{r^2} + \frac{3GM_* r}{a^3}$$

Left term is $\frac{dv}{dt}$ and right hand side is pressure acceleration plus gravitational acceleration plus tidal acceleration.

Energy Conservation Equation[1]

$$\rho v\frac{\partial}{\partial r}\left(\frac{k_B T}{(\gamma-1)m}\right) = \frac{k_B T}{m} v\frac{\partial \rho}{\partial r} + Q - P_r$$

Left term is the enthalpy of system, right hand side is the sum of all the energy terms.

Ionisation Balance Equation[1]

$$\frac{\eta_0 F_{xuv} e^{-\tau}\sigma_{\nu_0}}{h\nu_0} = \eta_+^2\alpha_{rec} + \frac{1}{r^2}\frac{\partial(r^2\eta_+ v)}{\partial r}$$

$Q = \epsilon F_{XUV}\sigma_{\nu_0}\eta_0 e^{-\tau}$

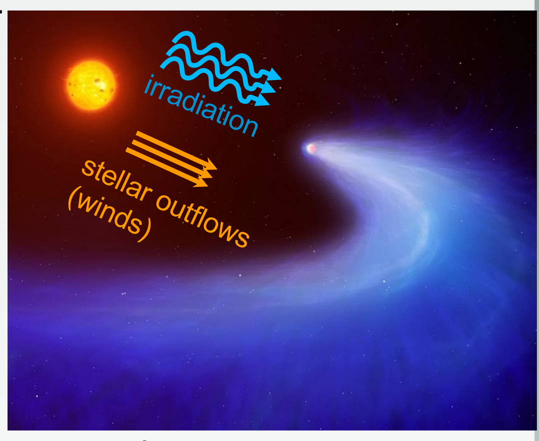
$P_r = 7.5\times10^{-19}\eta_e\eta_0 e^{-\frac{118348}{T}}$

α_{rec} = radiative recombination coefficient for hydrogen ions

ϵ = fraction of energy deposited as heat

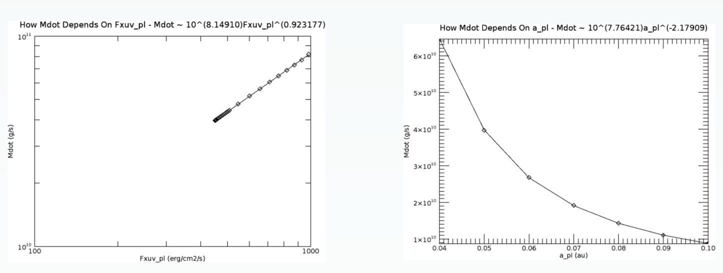
σ_{ν_0} = cross section for photoionization of H

η_e, η_+, η_0 = number density of electrons protons and neutral H respectively

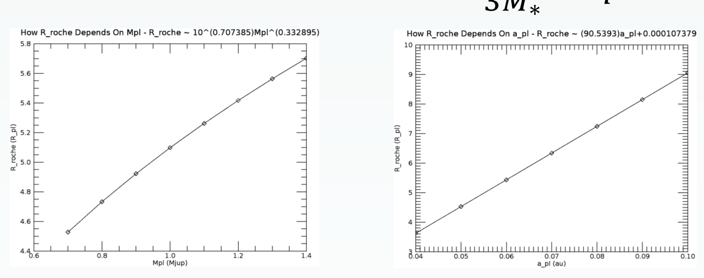


Relationships Between Input Parameters and Key Outputs

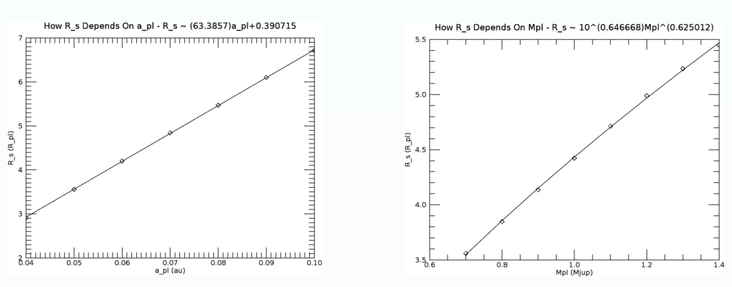
Mass Loss Rate



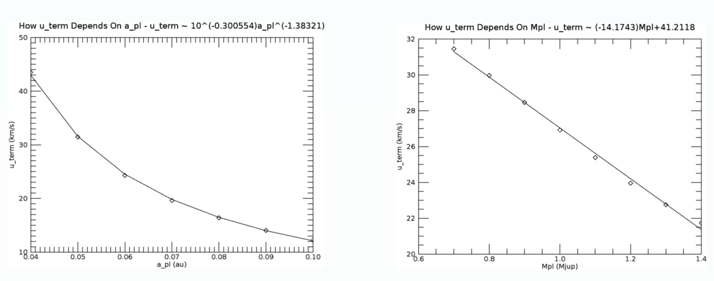
Roche Lobe - $R_{roche} = \left(\frac{M_{pl}}{3M_*}\right)^{\frac{1}{3}} a_{pl}$



Sonic Point



Terminal Velocity



Found that the model does not depend on the atmospheric density at the base of the atmosphere. This shows that the model is robust as this is not an observable quantity.

Containment of Planetary Wind

Theory

If the ram pressure of the planetary wind is smaller than the ram pressure of the stellar wind at the sonic point, then the planetary wind will be confined.

Ram Pressure: $p_{ram} = \rho u^2$ $\quad\quad$ $p_{ram_{planet}} < p_{ram_{star}} \Rightarrow$ Confinement

This is because the sonic point is the maximum distance at which information can be "passed back" to the planet.

Method

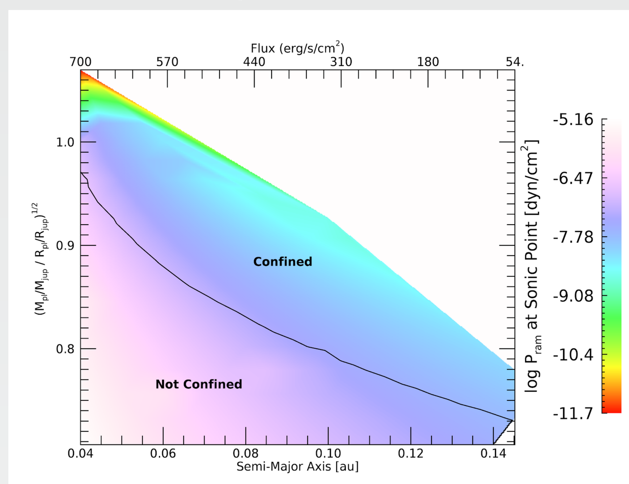
Ran many simulations of models, varying both the escape velocity and the semi-major axis of the planet.

Also varied the age of the host star of the planet, for a range of incident stellar irradiance. These models of stars mimic the Sun throughout its early years up to its current state[2]:

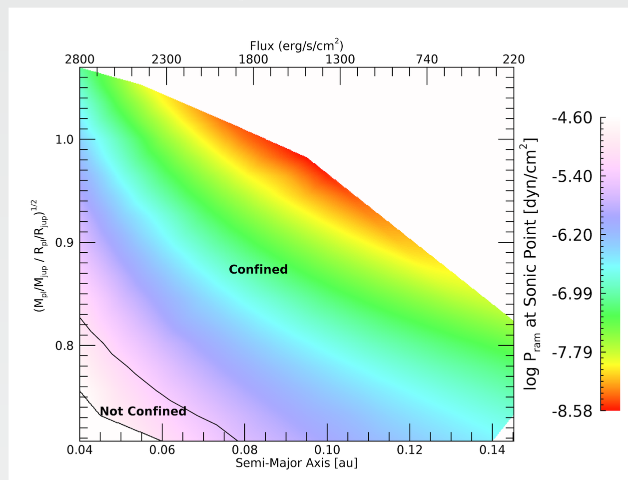
Results

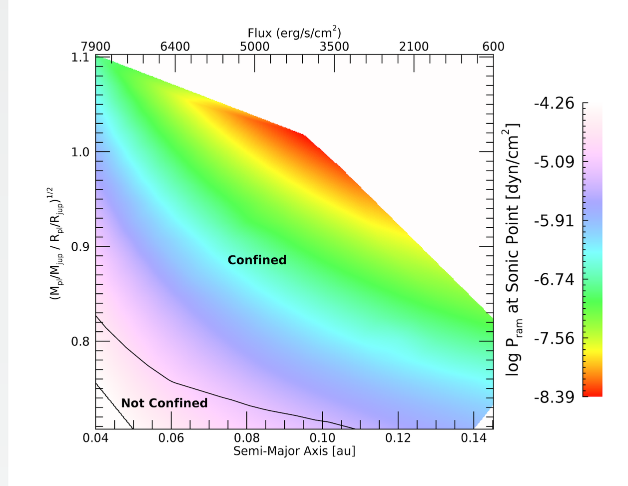
Ram Pressure

4.6 Gyr Solar-Like Star

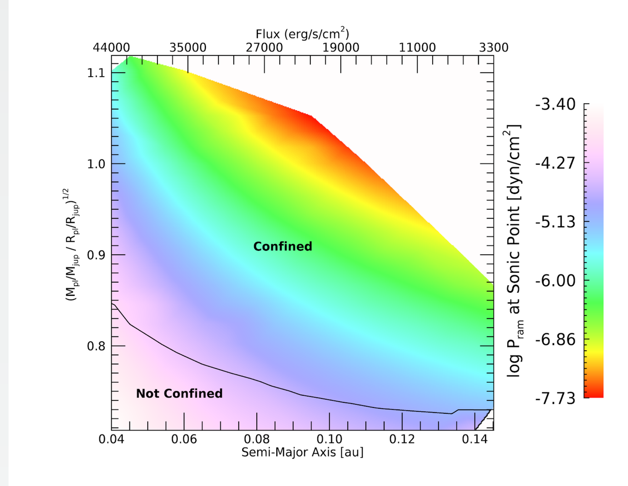


1.4 Gyr Solar-Like Star





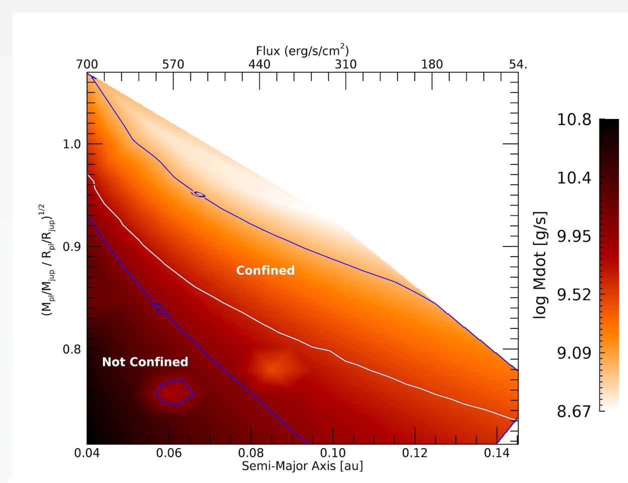
0.6 Gyr Solar-Like Star



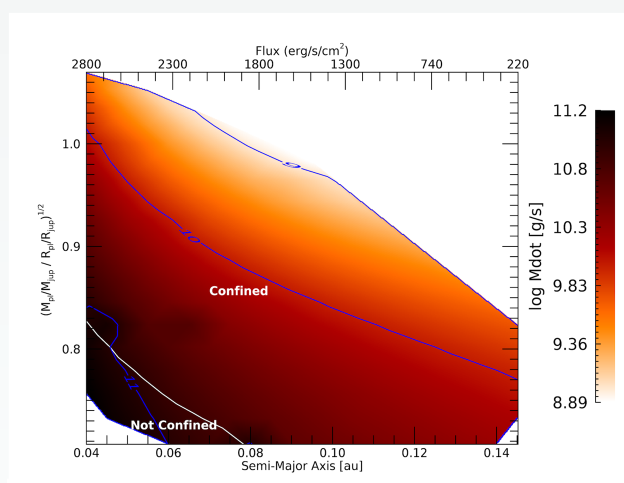
0.14 Gyr Solar-Like Star

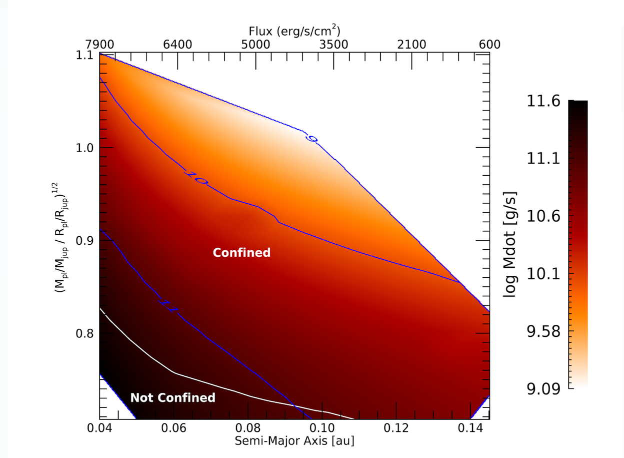
Mass Loss Rate

4.6 Gyr Solar-Like Star

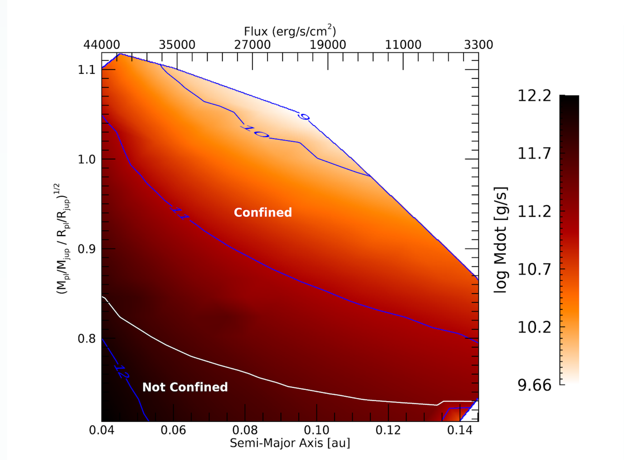


1.4 Gyr Solar-Like Star





0.6 Gyr Solar-Like Star



0.14 Gyr Solar-Like Star

Conclusion and Summary

Host stars heat their planets, which causes their atmospheres to evaporate. However, at the same time, the star's stellar wind, incident on the planet, can act to confine this evaporating atmosphere. Thus, we have a trade off between these mechanisms, which the above equations describe. We modelled the combined effects of these mechanisms for a variety of planets and host stars.

We found that the planetary atmosphere is not confined by the stellar wind if both the semi-major axis and the escape velocity of the planet are sufficiently small. Otherwise, the ram pressure of the stellar wind is larger than the ram pressure of the exoplanetary wind, and the planetary atmosphere is confined. Furthermore, we found that for young stars, there isn't a strong dependence on age. However, we see a higher mass loss rate, terminal velocity and ram pressure of the escaping atmosphere for younger systems as that is caused by the higher stellar irradiance.

References

1. Murray-Clay et al. 2009, APJ, 693:23-42
2. Ribas et al. 2005, APJ, 622:680-694

Acknowledgments

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