Exoplanets around stars of different masses as empirical constraints for planet formation models

Gijs Mulders
(University of Chicago)

w/ Ilaria Pascucci, Daniel Apai (University of Arizona)
Fred Ciesla (University of Chicago)
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Planets occur more frequently around low-mass stars...

Conclusion

Discussion

...but we do not understand the implications for planet formation
Expectations
(Planet Formation)
Disk Mass correlated with stellar mass

Pascucci+ 2016, also Ansdell+ 2017
Giant Planet Occurrence increases with stellar mass

Johnson+ 2010
sub-Neptune occurrence decreases with stellar mass
Mulders 2018, Handbook of Exoplanets
Kepler
Planet occurrence rates are corrected for detection biases

talks by Andrew Howard, Darin Ragozine
Planet occurrence decreases with effective temperature

Howard+ 2012
Maybe low-mass stars have planets that are closer in?
Spatial Distribution of Planets

Mulders et al. 2015a
Spatial Distribution of Planets

Mulders et al. 2015a
Same Spatial Distribution of Planets for different spectral types

Mulders et al. 2015a
Planet Population Inner Edge

Mulders et al. 2015a
Break in exoplanet population

Mulders et al. 2015a
Protoplanetary disk inner edge

Mulders+ 2015a, see also Lee+ 2017
Maybe low-mass stars have planets that are smaller?
Planet Radius Distribution: Low-mass stars have more sub-Neptunes!
Mulders et al. 2015b
Planet Radius Distribution: Low-mass stars have more sub-Neptunes!

Mulders et al. 2015b
Dispersion in disk mass

Pascucci+ 2016
The implications of both of these results in Section 2. Planet occurrence rate vs planet mass ratio (hereafter, Mass Ratio). The planet occurrence rate divided by the square root of the planet period and planet-to-star radius are the parameters that are best determined by the transiting technique. For the median host-star mass, the occurrence rate has a break at \( q \approx 0.5 \), for the median host-star mass, \( q \approx 0.5 \). The break can be well described by a power law with a period longer than 100 days. In addition, this period excess is mitigated when using EPOS and per spectral type as in Mulders et al. 2015a. The past decade has seen an exponential increase in the number of discovered exoplanets (e.g., Pascucci et al. 2017). It has also established among the many interesting discoveries, the location beyond which water vapor condenses onto ice. At the snowline the surface density in solids increases by a factor of a few to several. This radial distance is of particular interest as it is close to and beyond the snowline (e.g., Chen & Kipping 2017). The planet occurrence rate divided by the square root of the planet period and planet-to-star radius are the parameters that are best determined by the transiting technique. We limit the plot and following analysis to planets inside the snowline (e.g., Min et al. 2013b). The region beyond, an expectation that is fulfilled in the Solar System.

This radial distance is of particular interest as it is close to and beyond the snowline (e.g., Min et al. 2013b). The region beyond, an expectation that is fulfilled in the Solar System. 

The past decade has seen an exponential increase in the number of discovered exoplanets (e.g., Pascucci et al. 2017). It has also established among the many interesting discoveries, the location beyond which water vapor condenses onto ice. At the snowline the surface density in solids increases by a factor of a few to several. This radial distance is of particular interest as it is close to and beyond the snowline (e.g., Min et al. 2013b). The region beyond, an expectation that is fulfilled in the Solar System.

We start from the new DR25 catalogue. As uncertainty we take the upper end. Both issues are mitigated when using EPOS and degeneracy between planet mass and radius at the upper end. The region beyond, an expectation that is fulfilled in the Solar System.

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Planet Mass Dependence?
Pascucci+ 2018, also Wu 2019
Heavy Elements Mass, P<50 days (mass-radius relation)

Mulders et al. 2015b
Comparison with disk solids
Mulders 2018, Handbook of Exoplanets
Why?
How to explain elevated occurrence rate for M dwarfs planets

- Detection biases
- Spatial or size distribution
- Trade-off with giant planets?
- Binary fraction?
- Cluster Interactions? (talk by Cai and others)
- Planet Formation?
ALMA: Constraints on radial drift

Ansdell+ 2018
Low-mass disks are more compact

Tripathi+ 2017 (also Andrews+ 2015, 2018)
The exoplanet population around stars of different masses

• Giant planets more common around more massive stars
• Sub-Neptunes are more common around low-mass stars
• Inconsistent with protoplanetary disk mass scaling laws
• Efficient radial drift or planet migration?
Occurrence Rate

vs.

Fraction of stars w/ Planets
\[ \eta = \eta_s \eta_p \]

(talk by Darin Ragozine)
FGK stars: $\eta \sim 0.3$

(Mulders+ 2018, Wei Zhu+ 2018)

M dwarfs: $\eta \sim 0.7$

(Ballard+ 2016)

$$\eta = \eta_s \eta_p$$
Higher fraction of M dwarf disks form planets

Pascucci+ 2016
What planet formation mechanism can explain the stellar mass dependency?
Which planet formation processes has right stellar mass dependence?

image credit: Kees Dullemond
## Stellar Mass Dependency

<table>
<thead>
<tr>
<th>Grain Growth</th>
<th>Stellar Mass Dependency</th>
<th>Comments</th>
<th>Eq</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverse Timescale</td>
<td>0.5</td>
<td>fixed sma</td>
<td>gtd/Omega</td>
<td>Pinilla+ 2011, eq 19</td>
</tr>
<tr>
<td>Fragmentation Size</td>
<td>0.5</td>
<td>(disk=1, PMS)</td>
<td>sd_gas/c_s^2</td>
<td>Testi+2014, eq 8</td>
</tr>
<tr>
<td>Drift Size</td>
<td>1.5</td>
<td>(disk=1, PMS)</td>
<td>sd_dust*(v_k/c_s)^2</td>
<td>Testi+2014, eq 9</td>
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</table>

<table>
<thead>
<tr>
<th>Pebbles</th>
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<tbody>
<tr>
<td>Mass flux</td>
<td>4/3</td>
<td>(disk=1)</td>
<td></td>
<td>Lambrechts &amp; Johansen 2014, eq 14</td>
</tr>
<tr>
<td>Mass reservoir</td>
<td>1?</td>
<td></td>
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<tr>
<td>Streaming Unstable</td>
<td>?</td>
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<tr>
<td>Accretion efficiency</td>
<td>2/3</td>
<td>(pebbles=disk=1)</td>
<td></td>
<td>Johansen &amp; Lambrechts 2017, eq 27+31</td>
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<tr>
<th>Planet Growth</th>
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<tbody>
<tr>
<td>Pits accretion</td>
<td>1.5</td>
<td>(disk=1)</td>
<td>dm/dt= sd_p omega</td>
<td>Armitage, eq 190</td>
</tr>
<tr>
<td>Type-I Migration</td>
<td>0</td>
<td>(disk=1, Mp fixed)</td>
<td>tau=</td>
<td>Armitage, eq 265, Johansen &amp; Lambrechts 2017 eq 40</td>
</tr>
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<tr>
<th>Planet Mass</th>
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<tbody>
<tr>
<td>Feeding zone</td>
<td>1</td>
<td>(disk=1)</td>
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<tr>
<td>Hill radius</td>
<td>2/3</td>
<td>(disk=1)</td>
<td>2 pi a sd_dust a hill</td>
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<tr>
<td>Isolation</td>
<td>1</td>
<td>(disk=1)</td>
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<tr>
<td>Type-I Migration</td>
<td>9/8</td>
<td>two growth modes</td>
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<td>Pebble Isolation</td>
<td>1/4</td>
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<td>Bondi limit</td>
<td>1/4</td>
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[Armitage, eq 190]  
[Johansen & Lambrechts 2017, eq 40]  
[Wu 2019]  
[Kuwahara+ 2019, eq 1 & abstract]
Planets occur more frequently around low-mass stars...

**Conclusion**

**Discussion**

...but we do not understand the implications for planet formation
Backup Slides
The Astronomical Journal, in their paper, as it is not specified.

Massive stars of types OBA are the rarest, accounting for fewer of the brown dwarf population is not well constrained. Purposely left blank, as they are not stars, and in fact, the size ison. The percentage of stars that they comprise has been main-sequence objects, they have been included for compar-
of all stars by that spectral type. While brown dwarfs are not other main-sequence spectral types, along with the percentages.

Because we measured a number of advantages over studies conducted by others. All accurate trigonometric parallaxes, the study presented here has.

accurate distances to draw conclusions from their data. We were also able to calculate projected separations that were more accurate than those of others, as our sample has trigonometric distances. Most other surveys were forced to use less accurate types of companions using other methods.

Our results also agree with the earlier studies of MR than the 23.5 ± 3.65.

MR of Ward-Duong et al. did not include any late-M dwarfs. We searched to 8 pc. Fischer & Marcy searched the 5 pc sample of M dwarfs, while Bergfors sample studied here reveals an additional 308 M dwarfs with low statistical errors.

The open green and orange points are the blue and red subsamples from Table 16.4.2. Comparison to More Massive Stars

<table>
<thead>
<tr>
<th>Type</th>
<th>Stars Rate</th>
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are the uncorrected MRs for the three mass bins explored throughout this paper, that each spectral type comprises, along with the reference.

Next, the Table provides an anchor for the statistics at the low end of the color diagram in Figure 21.

References.


The clear decrease in multiplicity with decreasing mass bins explored throughout this paper, taken from the literature for the more massive main-sequence stars. The references are listed.

Winters et al. 2016.
The Kepler Exoplanet Population Around Different Types of Stars
Mulders 2018 (Handbook of Exoplanets)