Exploring the Formation and Evolution of Planetary Systems
Proceedings IAU Symposium No. 299, 2013
M. Booth, B. C. Matthews & J. R. Graham, eds.

doi:10.1017/S1743921313008090

The Story of Planets: Anchoring Numerics in Reality

Zoë M. Leinhardt

School of Physics, University of Bristol
H.H. Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
email: zoe.leinhardt@bristol.ac.uk

Abstract. Building a complete coherent model of planet formation has proven difficult. There are gaps in the observational record, difficult physical processes that we have yet to fully understand, such as planetesimal formation, and an extensive list of observationally determined constraints that the model must fulfil. For example, the diversity of extrasolar planets detected to date is staggering – from single hot-Jupiters to multiple planet systems with several tightly packed super-Earths. In addition, the characteristics of the host stars are broad from single solar-mass stars to tight binaries and low mass, low metalicity stars. Even more surprising, perhaps, is the frequency of detection and thus, the implied efficiency of the planet formation process. Any theoretical model must not just be able to explain how planets form but must also explain the frequency and diversity of planetary systems. So why is planet formation so prolific? What parameters determine the type of planetary system that will result? How important are the initial parameters of the protoplanetary disk, such as composition, versus stochastic effects, such as gravitational scattering events, that occur during the evolution of the planetary system?

Current observations of extrasolar planets provide snapshots in time of the earliest and latest stages of planet formation but do not show the evolution between the two. It is at this point that we must rely on numerical models to evolve proto-planetary disks into planets. But how can we validate the results of our numerical simulations if the middle stages of planet formation are effectively invisible? Collisions are a core component of planet formation. Planetesimals, the building blocks of planets, collide with one another as they grow and evolve into planets or planetary cores and are viscously stirred by larger protoplanets and fully-formed planets. The range of impact parameters encountered during growth from planetesimals to planets span multiple collision outcome regimes: cratering, merging, disruption, and hit-and-run events. Most of these collisions produce significant debris and dust. If we have a good understanding of the production of collisional debris we can use it as an indirect tracer of on-going planetary evolution even if the planets themselves are not directly detectable.

In this paper I will show how numerical simulations of planet formation including realistic collision modelling can be used to predict, and be constrained by, observations.

Keywords. methods: numerical, solar system: formation, planetary systems: formation, protoplanetary disks

---

1. Introduction

Planet formation is seemingly common around main sequence stars as evidenced by the continual increase in the number of observed planets (889 on 02.06.2013). The sheer number and diversity of the planets drives planet formation theory. Observations of planetary systems provide snapshots of protoplanetary disks or stable planetary systems but they do not provide all the steps in between. A complete self-consistent model of planet formation has eluded astronomers because of gaps in the observational record, incomplete physics in the numerical simulations, and computational constraints. In addition, observations of the earliest phase of planet formation are often indirect. We are not observing the material or objects that we would like to observe, for example, the presence of gas or planets must often be inferred. Thus, the evolution from one state to the other is not fully understood, however, the gaps are being filled in with a combination of observations, numerical simulations, and laboratory experiments.

2. Current Status on our Understanding of Planet Formation

Let us begin by considering where the field stands at the moment both from an observational view point and from a numerical and experimental viewpoint.

2.1. *The Earliest Evidence of Planet Formation: Proplyds, Pre-Transitional, and Transitional Disks*

The Hubble Space Telescope Orion Nebula Proplyd Atlas provides a plethora of beautiful images of protoplanetary disks. These disks are diverse in size, shape, and local environment. In addition, there are an increasing number of resolved pre-transitional and transitional disks that have specific features that indicate planet formation in progress. For example, MWC 758 and SAO 206462 have two clearly identifiable spiral arms (Grady *et al.* 2013, Muto *et al.* 2012). The spiral arms could be caused by perturbing planets. LkCa 15 and SAO 206462 have large dust holes between 10s and 100s of AU wide (Kraus & Ireland 2012). Holes of this size could suggest more than one planet (Dodson-Robinson & Salyk 2011, Zhu *et al.* 2011). LkCa 15 actually shows evidence of an object in the gap, which could be a very young, hot planet.

Pre-transitional objects PDS 70 and UX Tau A also have large gaps 10s of AU wide with inner disks (Hashimoto *et al.* 2012, Tanii *et al.* 2012). Again one of the most convincing ways to create a large gap while maintaining both an inner and outer disk is to evoke at least one embedded planet. A large number of transitional and pre-transitional disks also show evidence of grain growth either large grains have been observed and/or disk size is significantly different when observed at different wavelengths suggesting grain growth or filtration both of which indicate ongoing planet formation and/or the presence of a young planet.

2.2. *Grain Growth*

Protoplanetary disks often show evidence of grain growth. Some disks show the presence of very large grains, for example, UX Tau A has large 30 μm grains and disks in Lupus and Chamaeleon have cm-sized grains (Ubach *et al.* 2012). While other disks seem to have a radial dependence on grain size – the protoplanetary disk AS 209 has a strong radial dependence on maximum grain size. Beyond 70AU sub-mm grains are the largest grains found in the disk while within 70 AU larger mm and cm-sized grains were observed (Perez *et al.* 2012).

Numerical simulations predict disk and gap size should vary with dust size in a transitional disk with an embedded planet (Fouchet *et al.* 2012). In addition, it is often not enough to explain a transitional disk observation by just envoking one embedded planet. GM Aur, for example, an embedded planet plus grain growth are required to explain the large gap and small grain depletion. Small grains should be able to filter through the gap created by the planet although the large grains pile-up at the gap edge (Zhu *et al.* 2012) but the abundance of small grains in the gap is too low, thus, it is possible that the small grains do filter through but also grow over time in the gap.

In evoking grain growth one should also consider how straight forward it is to grow in the local environment. If the environment is strongly perturbed by an embedded object such as a planet, grain growth may be significantly suppressed. Laboratory experiments such as those presented in Jankowski *et al.* (2012) show that aggregates do not always continue to increase in mass and instead may bounce or be disrupted if the impact energy is too high. It is also possible that embedded planets may enhance grain growth in certain locations by concentrating grains at pressure maxima where the increased surface density can lead to more grain collisions.

2.3. *Planetesimal Formation*

Growing grains must eventually make it into the larger building blocks of planets, planetesimals. Planetesimals outside of our own solar system are effectively invisible to observational techniques because they are too small to be directly observable as individual objects. Within our own solar system it is generally assumed that Kuiper Belt Objects (KBOs) are left over planetesimals from our own Solar System's evolution. With the sparse constraints this offers, theorists have come up with many hypotheses to explain planetesimal formation. The three most popular are: 1) *pair-wise accretion* - two planetesimals hit each other and stick. The major argument against this process is that the mean impact speed in a protoplanetary disk can be very high above the disruption threshold. In addition, the aerodynamic drag on metre-sized bodies would cause fast inward migration (Weidenshilling 1977). In recent work by Garaud *et al.* (2013) pair-wise accretion has been shown to work well even in a high-velocity environment as long as there is a distribution of impact speeds amongst the colliders and sweep-up of small material is efficient; 2) *gravitational instability* - direct collapse of dust into planetesimal-mass objects. This process requires a cold, dense environment that does not occur globally in a protoplanetary disk except potentially at very large semi-major axes. Gravitational instability seems to be more successful when used in combination with another instabilities such as the steaming instability or vortices which can collect the solid material to create a locally dense region (for example, Johansen *et al.* 2007); and 3) *dust trapping* - generic term for mechanisms such as vortices and pressure bumps that can collect solid material and increase the local dust density which can then lead to gravitational instability (Dittrich *et al.* 2013, Meheut *et al.* 2012).

Planetesimal formation is particularly difficult to constrain at the moment and the astronomy community has yet to reach a consensus as no planetesimal formation method seems to work well in all conditions. For a more detailed discussion of planetesimal formation please see the review by Eugene Chiang in these proceedings.

2.4. *Planetary Systems*

To date there are about 1000 confirmed planetary systems and thousands of candidates but the astronomy community is still missing a clear observational picture of how planets form, why the formation process is so common, and what parameters determine the type of planetary system will be formed. One of the most surprising characteristics of observed planets is their diversity. There are small planets, large planets, planets in multiple planet systems that are widely spaced, multiple planet systems that are tightly packed, planets that are close to their parent star, planets that are very far away from their parent star, planets around single stars, planets orbiting binary stars, planets orbiting young stars and planets orbiting highly evolved stars. Planet formation is not just common, it is prolific and the process produces objects that are so diverse they stretch the imagination of the most enthusiastic sci-fi follower.

Any coherent, self-consistent planet formation model most be able to explain the observed diversity of extrasolar planets. As mentioned earlier it is observations that are currently driving the field of exoplanet research but often the observations are indirect while numerical and experimental investigations are direct. For significant progress to be made we must now focus on connecting direct numerical simulations with the indirect or inferred results from observational programs. In the next section I will focus on using collisions and the debris produced by collisions as a tracer for planet formation.

3. Collisions within the Solar System

Collisions are fundamental to the evolution of solar systems. Within our own Solar System we see evidence of the final giant impacts that occurred in the last stages of solar system evolution. The Earth-Moon system and Pluto-Charon could have been formed by large impacts (Cuk & Stewart 2012, Canup 2005). In the asteroid belt there are many dynamical families with similar orbital and spectral parameters. Objects within one dynamical family are believed to have originated from the same parent body which was disrupted by a high speed impact (Nesvorny *et al.* 2006). There is also one dynamical family in the Kuiper Belt which appears to be the result of a collision event (Leinhardt *et al.* 2010).

Regardless of how the building blocks of planets formed, it is generally understood that in order for planetesimals to grow into planets they must grow via collisions (gravitational instability may indeed avoid this process for large giant planets at large semi-major axis). Thus, the evolution of planetesimals is dominated by a series of individual collisions with other planetesimals. The collision outcome: merging, erosion, cratering, hit-and-run, depends on the specific impact conditions and although the planetesimals may be observationally undetectable the debris that is produced as a result of collisions may indeed be the key to connecting numerical simulations of early planetary growth with observations of evolving protoplanetary disks.

Interpreting the collisional evidence requires that we understand the collisions and have a model to describe them. Previous collision models were not developed to be able to determine the underlying parent population. Now we need a model that can be used to do just that. The work that I am going to present here is motivated by explaining the diversity of extrasolar planets and identifying tracers of the formation process that have to date been unobservable.

3.1. *Numerical Simulations of Collisions*

In order to develop the model we constructed a series of numerical simulations of planetesimal collisions in isolation and fit scaling-laws to the results. The collisions ranged from slow sub-sonic impacts to fast shock generating super-sonic impacts. Using results from previous studies and our own simulations we investigated collisions with a range of impact parameters and bulk compositions (Leinhardt & Stewart 2012).

In this work we found that there is no one velocity that will determine disruption of a particular target. In other words the catastrophic disruption threshold for gravity dominated objects,

$$Q^{\star}_{RD\,grav} = q_g (\rho_1 G)^{3\bar{\mu}/2} R_{C1} V^{\star(2-3\bar{\mu})}, \tag{3.1}$$

where ρ_1 is 1 g cm^{-3}, G is the gravitational constant, q_g and $\bar{\mu}$ are material parameters fit to the empirical results, R_{C1} is the radius of the combined mass of the target and projectile with a bulk density of ρ_1, and $V^{\star}$ is the critical impact speed, is velocity dependent. It is the momentum of the impact that determines the outcome not the impact energy as has often been assumed in the literature. The catastrophic disruption threshold in the gravity regime has a velocity dependence that scales with momentum, $\bar{\mu} \sim 0.35$. Equation 3.1 fits the empirical data well over five orders of magnitude even though the data is very diverse and includes multiple numerical techniques including an

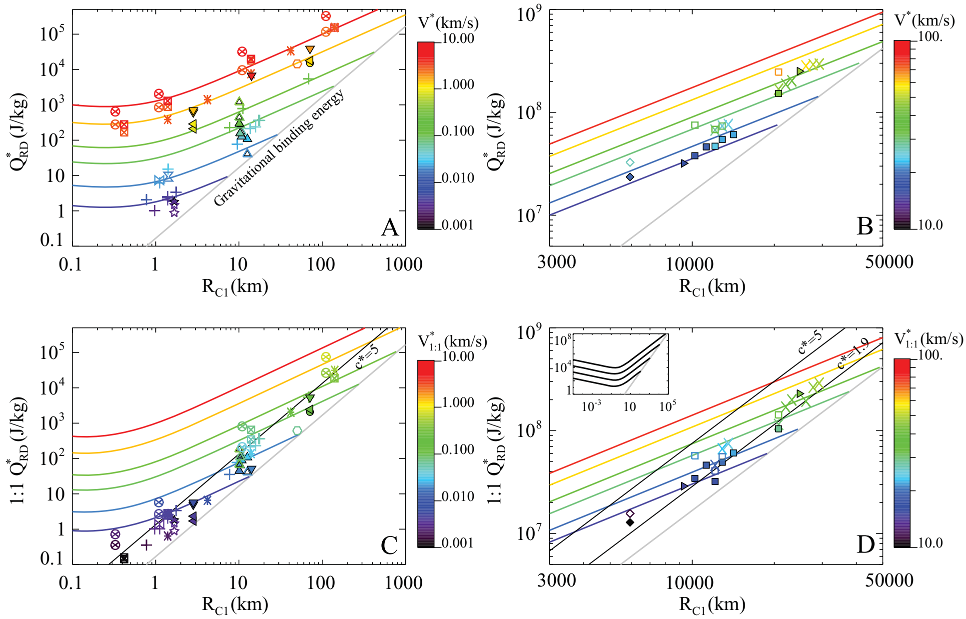

Figure 1. Collision outcome maps from Leinhardt & Stewart (2012). Each region indicates the type of collision outcome from a two body collision given the impact parameter and impact speed for four example mass ratios. The solid curves indicate the transition between different collision outcomes. The thick solid black curve identifies the catastrophic disruption threshold where 50% of the total system mass is permanently removed. The dashed and dotted lines indicate other interesting transitions such as projectile erosion and projectile disruption.

N-body gravity code, Eulerian grid codes, and Lagrangian smoothed particle hydrocode techniques from multiple authors (for example, Benz & Asphaug 1999, Leinhardt *et al.* 2000, Leinhardt & Stewart 2009, and Jutzi *et al.* 2010). In addition to the catastrophic disruption threshold we have also fit the data with scaling laws for the mass of the largest remnant, the size distribution of the remnant tail, and the velocity dispersion of the remnants. The mass of the largest remnant scales linearly with $Q^{\star}_{RD}$ for impacts within the disruption regime (impact energy less than twice $Q^{\star}_{RD}$) but is fit better with a power law for more energetic super-catastrophic impacts ($Q_{RD} > 2Q^{\star}_{RD}$). The results give us detailed collision outcome maps which identify the type of collision that will occur for a given mass ratio, impact parameter, and impact speed (Fig. 1). The collision outcome maps have several interesting characteristics - as projectile and target reach similar masses hit-and-run impacts become more prevalent. Hit-and-run impacts could be an efficient mechanism for stripping mantle material from projectiles and increase the diversity of densities within one planetary system. Satellite forming giant impacts such as the Earth-Moon or Pluto-Charon tend to occur on the transition between accretion and hit-and-run suggesting that hit-and-run impacts occurred within our solar system.

The final result is a model that can predict the collision outcome taking into account most parameters including impact parameter, mass ratio, and impact speed. For a more detailed discussion of this collision model see Leinhardt & Stewart (2012) and Stewart & Leinhardt (2012).

3.2. *Implications of Collision Model*

To check the long term implications of our collision model we retrospectively applied our new model to the N-body simulations of the last stage of planet formation. The original

https://doi.org/10.1017/S1743921313008090 Published online by Cambridge University Press

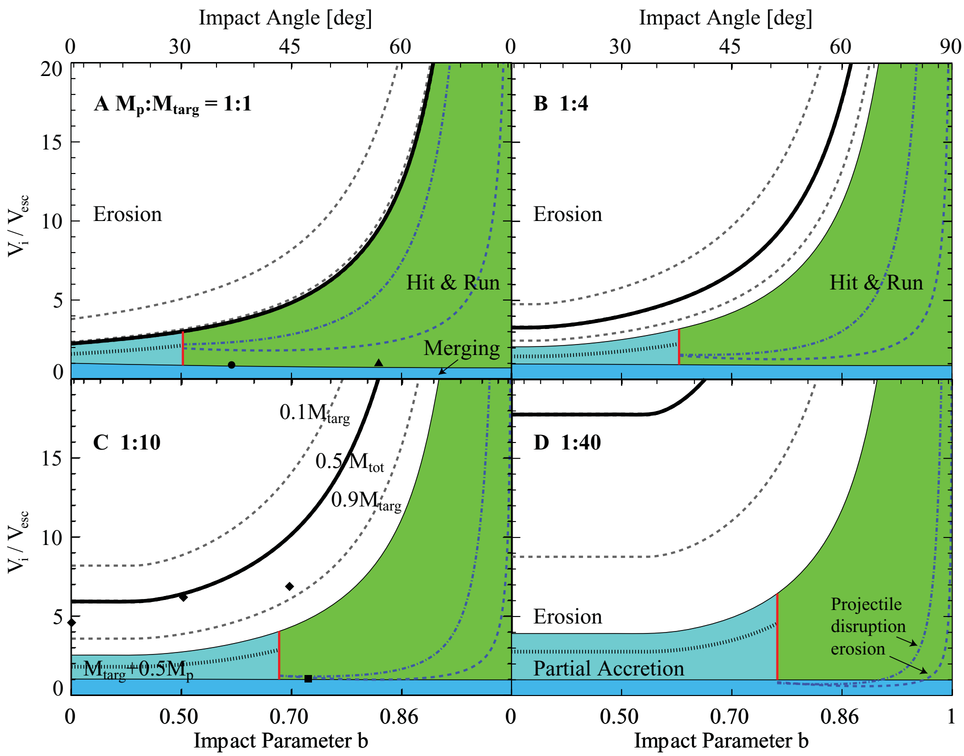

Figure 2. Synthetic dust images of pre-transitional disks with embedded Jupiter-mass planet. Figure 3 from Dobinson *et al.* (submitted) reprinted here with permission from the author. The first row shows the instantaneous surface density of dust calculated from direct N-body simulations of a protoplanetary gas-free disk with an embedded Jupiter-mass planet. The second row shows the flux density using RADMC-3D (Dullemond 2012) to calculate the full radiative transfer. The first column shows the results from circular embedded planet using the rubble collision model from Leinhardt & Richardson (2005), which allows planetesimals to both grow and erode do to collisions. The next three columns show results from merging simulations in which the underlying planetesimal population is forced to merge as the result of a collision. These three columns have embedded planets with varying degrees of eccentricity: 0.0, 0.1, and 0.2, respectively.

simulations (O'Brien *et al.* 2006, Raymond *et al.* 2009) assumed that all collisions resulted in perfect merging events. We reanalysed these simulations in Stewart & Leinhardt (2012) and found that outcomes of giant impacts span all possible collision regimes including hit-and-run, accretion, erosion and catastrophic disruption. Fragmentation during giant impacts is also significant. The majority of the ejected material is mantle from partial accretion events or energetic hit-and-runs that result in the disruption of the projectile. If the ejected material is not totally re-accreted giant impacts can create planets depleted in volatiles and mantle (including water and atmosphere) compared to initial embryos.

In summary, we found less than 10% of the collisions between protoplanets would result in perfect merging events and a large fraction (1/5 to 1/3) would result in hit-and-run events. Depending on the assumptions made about the reaccretion of mantle material the high fraction of stripping events could lead to a significant increase in the range of densities of the final planetary embryos.

4. Current Work on Early Indications of Planet Formation

4.1. *Transitional Disks: Collisional Dust from an Embedded Planet*

Let us now return to early indications of planet formation. With the ever increasing observational capabilities of ground and space based facilities such as ALMA and Kepler there is no time better than the present to definitively link the dynamic process of planet formation which is simulated numerically with a young system protoplanetary disk in the midst of planetary formation. As a result, we have begun focusing our numerical efforts on transitional and pre-transitional disks. Assuming that some transitional and pre-transitional disks are the result of embedded planets we have constructed a series of numerical simulations with 10^6 self-interacting planetesimals and one embedded Jupiter-mass planet. Assuming that the planet formed via core accretion there should be planetesimals that have evolved on the same timescale. These planetesimals will collide with each other due to perturbations from the planet and the planetesimals themselves. The collisions will generate observable dust (see Fig. 2 from Dobinson *et al.* submitted). When considered in isolation this second generation dust looks remarkably similar to primordial dust trapped in the gas disk of a transitional disk with an embedded planet (Gonzalez *et al.* 2012). However, it is clear that collisions are fundamentally important to the evolution of planetary systems and cannot be ignored. We hope that as this work progresses, multiple planets will be embedded in the planetesimal disk, and the primordial dust signature will also be taken into account. We will then be more confident about identifying young systems that are likely to be in the midst of planet formation from the dust signatures.

5. Summary and Conclusions

Planet formation seems to occur around most stars producing a large diversity of objects and systems. There are large gaps in our observational record and numerical methods are not powerful enough to fill in all of the gaps. Progress is being made observationally, numerically, and experimentally but we are at a point where these methods must now be used together and not in isolation in order for significant progress to be made. Interpretation of observations is difficult and often non-unique. For example, in most cases the presence of planets must be inferred. The planets are not directly observed.

Collisions are important in the formation of planets and should produce observable signatures, however, the signature from the collisions is complicated by the presence of primordial and growing dust grains. In order to interpret the observational results from young protoplanetary systems more work needs to be done including collisional evolution and grain growth in the presence of a gas disk. However, it is clear that planets within planetesimal disks do produce clear observational signatures and with a bit more work the community should be able to confidently identify unique signatures of planet formation within transitional and pre-transitional disks.

References

Benz, W. & Asphaug E. 1999, *Icarus*, 142, 5
Canup, R. 2005, *Science*, 307, 546
Ćuk, M. & Stewart S. T. 2012, *Science*, 338, 1047
Dittrich, K., Klahr, H., & Johansen, A. 2013, *ApJ*, 763, 117
Dodson-Robinson, S. E., Salyk, C. 2011, *ApJ*, 738, 131
Dullemond, C. P. 2012, *ASCL*, 1202.015
Fouchet, L., Gonzalez, J.-F., & Maddison, S. T. 2010, *A&A*, 518, A16

Garaud, P., Meru, F., Galvagni, M., & Olczak, C. 2013, *ApJ*, 764, 146
Gonzalez, J.-F., Pinte, C., Maddison, S. T., Ménard, F. & Fouchet, L. 2012, *A&A*, 547, A58
Grady, C. A., *et al.* 2013, *ApJ*, 762, 48
Hashimoto, J., *et al.* 2012, *ApJL*, 758, L19
Jankowski, T., Wurm, G., Kelling, T., Teiser, J., Sabolo, W., Gutiérrez, P. J. & Bertini, I. 2012, *A&A*, 542, A80
Johansen, A., Oishi, J. S., Mac Low, M.-M., Klahr, H., Henning, T. & Youdin, A. 2007, *Nature*, 448, 1022
Jutzi, M., Michel, P., Benz, W., Richardson, D. C. 2010, *Icarus*, 207, 54
Kraus, A. L. & Ireland, M. J. 2012, *ApJ*, 745, 5
Leinhardt, Z. M., Richardson, D. C., Quinn, T. 2000, *Icarus*, 146, 133
Leinhardt, Z. M., Richardson, D. C. 2005, *ApJ*, 625, 427
Leinhardt, Z. M. & Stewart, S. T. 2009, *MNRAS*, 199, 542
Leinhardt, Z. M., Marcus, R. A. & Stewart, S. T. 2010, *ApJ*, 714, 1789
Leinhardt, Z. M. & Stewart, S. T. 2012, *ApJ*, 745, 79
Meheut, H., Meliani, Z., Varniere, P. & Benz, W. 2012, *A&A*, 545, A134
Muto, T., *et al.* 2012, *ApJL*, 748, L22
Nesvorný, D., Enke, B. L., Bottke, W. F., Durda, D. D., Asphaug, E. & Richardson, D. C. 2006, *Icarus*, 183, 296
Pérez, L. M., *et al.* 2012, *ApJL*, 760, L17
Stewart, S. T. & Leinhardt, Z. M. 2012, *ApJ*, 751, 32
Tanii, R., *et al.* 2012, *PASJ*, 64, 124
Ubach, C., Maddison, S. T., Wright, C. M., Wilner, D. J., Lommen, D. J. P., & Koribalski, B. 2012, *MNRAS*, 425, 3137
Weidenschilling, S. J. 1977, *MNRAS*, 180, 57
Zhu, Z., Nelson, R. P., Hartmann, L., Espaillat, C., Calvet, N. 2011, *ApJ*, 729, 47
Zhu, Z., Nelson, R. P., Dong, R., Espaillat, C. & Hartmann, L. 2012, 755, 6

https://doi.org/10.1017/S1743921313008090 Published online by Cambridge University Press