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Research Proposal

Can you make figure that shows smooth disk vs planet-carved disk? remember broad audience and you want to emphasize what YOU do.

what kinds of feedback?

Constraining how giant planets influence planet formation through self-consistent chemical and dynamic models

1 Overview

Good but a bit vague – be a bit stronger in your assertions/goals.

1st part of sentence doesn't really match 2nd part

Despite the discovery of over 6,000 exoplanets[1] and numerous surveys of protoplanetary disks (PPDs) [e.g., 1, 5, 6, 9], we still lack a clear picture of how to connect these disks, both their molecular composition and their global structure, to the planets that form within. As a 51 Pegasi b Fellow, I will study in a self-consistent manner the feedback processes between disks and the planets that form there, shedding light on the origin of the diverse planetary systems we observe around other stars and how they can inform us about the formation of our own Solar System.

2 Background and Significance

Need a statement of your goals as they fit into bigger picture. – state your goals clearly very early to capture reader's attention.

As giant planets form within disks, they naturally create ring and gap substructures in the dust via gravitational interactions with the surrounding gas, concentrating dust exterior to the planet's orbit [3, 7]. Such substructures have been observed to be common in both dust [1] and molecular line emission [5]. Combined with JWST IR spectroscopy of the inner disk, we are now able to see a ~~more clear~~ Clearer picture of the composition of the gas, ice, and dust that make up planet forming environments. Despite these advances in observational techniques, we still lack a clear, self-consistent framework for connecting the observed population of exoplanets with specific disk conditions.

Are there specific conditions to link to or do they evolve over time? what do you mean by "conditions" here?

As they form, planets drastically alter the disk environment both locally and globally. Planet induced gaps concentrate dust at pressure bumps, possibly triggering the streaming instability and the subsequent formation of later planets. At the same time, collision between dust and pebbles may lead to fragmentation, resupplying small dust which can leak past the planet via filtering. This effect may have particular consequences when accounting for 3D meridional flows expected around embedded planets [4], which stir dust and gas vertically away from the midplane. **While previous models have made different assumptions regarding grain growth and fragmentation, a self-consistent dust growth model accounting for planet-induced dust stirring has not yet been developed.** Understanding this dust evolution near the planet is necessary for interpreting emission from the inner disk, as the efficiency of dust trapping at these gaps sets the inventory of solids and volatiles that may be delivered to the inner disk via pebble drift.

Awkward. Gaps don't concentrate dust.

refs?

s

I have shown

why "leak"? You haven't really introduced dust trap idea – just said dust can concentrate.

pebble-pebble collisions are what's important

ref?

There is a lot here that one has to process by reading in between lines.

Because these planets sculpt the dust in their disk, they will also control the chemistry throughout the disk. As small dust is the primary source of opacity in the disk, understanding its distribution is necessary for accurate chemical modeling. **Despite observations of molecular and dust emission, there is no clear correlation between these substructures in the current disk population.** Consistently modeling the dust and chemical evolution of these disks is necessary for interpreting current observations and identifying possible signatures of planet formation.

This is good

How does 2nd sentence relate to 1st?

What do you mean by this?

refs?

feel you should make point that planets are common as are structures in disk, so these relationships need to be understood.

3 Proposed Research and Research Plan

How giant planet formation impacts subsequent planet formation, as well as its own formation environment, is necessary for connecting disk and planet compositions and constraining the current population of giant planets in observed disks. These planets will have important

[1] https://exoplanetarchive.ipac.caltech.edu

THIS IS GREAT! EARLIER! Build off of this.

put axes on this to make clear it is a plot

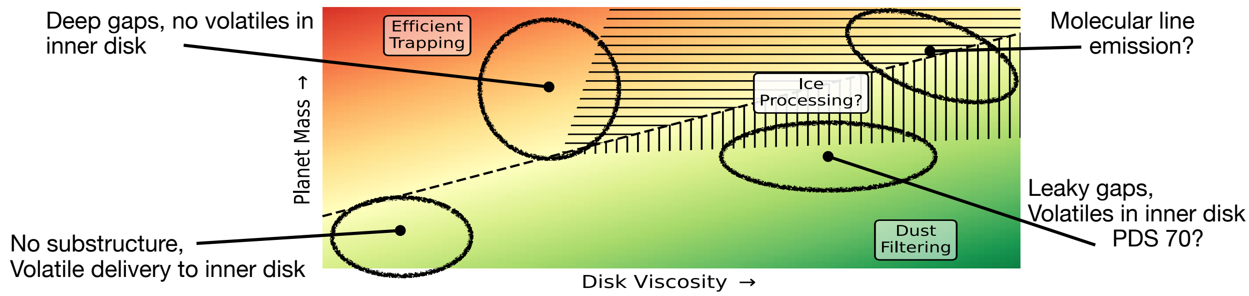

Figure 1: Examples of possible disk observations in the proposed parameter space. As disk viscosity increases, small grain are able to leaky past more massive planets and deeper gaps. Thus the combination of inner disk volatiles and outer disk substructure allows for self-consistent constraints on both planet and disk parameters. The hatched region represents regions where exposure to increased temperatures in the bump or gap may lead to the processing of ices on the grains.

get what your saying, but perhaps to be a bit more specific — "leave observational signatures"?

implications on the composition of the surrounding disk, both the refractory and volatile reservoirs, that should be reflected in the disk, other planets, and the giant planet itself.

Project 1: Constraining leaky disks

have you explained what this means?

While models and observations have shown at least some disks are leaky (Recently, Sierra et al. [8] inferred the PDS 70 disk to have a leaky gap, explaining water ice present in the JWST MIRI spectra), it is still unclear how many disks contain leaky gaps. As JWST continues to observe emission from the hot inner disk, the presence of emission from volatile ices will help to constrain the leakiness of these gaps. Interpreting these results, however, requires a self-consistent understanding of 1) the degree of leakiness for different planet and disk parameters and 2) the processing of grains as they cross the gap.

won't ices sublimate in hot, inner disk?

is it the number of disks that are leaky that matter or conditions that set whether leaks happen?

As the first part of this project, I will model the dust size distribution for a suite of 3D hydrodynamic simulations of varying disk viscosities and embedded planet masses. By post-processing these HD simulations with my Monte Carlo particle tracking techniques (~~following the methodology of Van Clepper et al.~~ [11]), I will determine relative velocities and residence times in the dust trap exterior to the planet. Thus I can directly test the competing growth, fragmentation, and leaking timescales for a variety of disk viscosities and planet masses.

3D never done before, but you have shown 3D effects are critical!
· why is particle tracking better than fluid approach here?

of?

At the same time, in disks where solids are filtering past the planet, I will track the exposure to heating and radiation in the gap. The high radiation environment of the gap may processes these ices, either creating more complex molecules on the ice or resulting in photodesorption of ices, limiting their delivery to the inner disk. Alternatively, vertical cycling of dust in the pressure bump as a result of planetary meridional flows may expose ice to irradiative environments even without filtering past the planet.

thermal desorption too?

The results of these models can be directly compared to JWST infrared and ALMA millimeter emission. While these observations may be used separately to tell us about the inner and outer disk respectively, detailed modeling of the gap is required to tell us under what conditions we expect these two reservoirs to be connected. In low viscosity disks or gaps containing high mass planets, these reservoirs should be separate, with minimal leaking across the gap and efficient growth in the pebble trap. Alternatively,

but function of dust evolution + sizes, too which you are going to explore.

you start paragraph with this but don't return to observational data.

Connection to meteorites?

What observations will you use to constrain models?

high viscosity disks will lead to leakier gaps, but chemical processing of ices may limit the delivery of volatiles to the inner disk. A schematic of possible results from my models in the disk viscosity and planet mass parameter space is outlined in Figure 1, with connections to observable emission highlighted for a number of different possible outcomes.

contrast w/ stammler?

The work I propose to do here will be the first of its kind to combine dust growth and mixing across the gap in a self-consistent manner. These results will help to drastically reduce the parameter space for planets in gaps in observed PPDs, or if results do not match they may be evidence to rule out planets entirely. While dust growth and coagulation has been done in 1 and 2D using prescribed relative velocities, this has never been approached using a full 3D simulation. This 3D approach not only accounts for the 3D flow created by planets, but the use of Monte Carlo tracer particles also allows for simultaneous modeling of ice processing, providing for the first time a self-consistent constraint on expected volatile delivery past giant planets. These results are necessary to interpret not only the solar system record but also to interpret observations of PPDs and the exoplanet systems that form within.

move this to earlier to emphasize the points

Project 2: Chemical fingerprints of planet formation

Dust evolution sets the conditions for chemistry in the disk, controlling not only grain surface chemistry – such as adsorption, (photo)desorption, and hydrogenation – but also the temperature and irradiation in the disk. Because of this, **understanding the small grain distribution in the disk, both radially and vertically, is necessary for accurate modeling of the chemical environment of the disk.** As I previously showed in Van Clepper et al. [10], dust growth settling to the midplane removes volatile ices from the gas via the cold finger effect, but also increases the local radiation field, accelerating UV driven chemistry. It is natural, then, to ask: how will dust fragmentation and lofting near an embedded planets be reflected in the gas phase chemistry?

As my second project, I propose to combine my 3D dust simulations from project 1 with chemical models to identify the chemical implications of planet formation. By using the Monte Carlo particle tracking methods of project 1, I will be able to 1) use particle residence times throughout the disk to determine disk optical depths, temperature, and irradiation in a self-consistent manner and 2) track individual trajectories of grains,

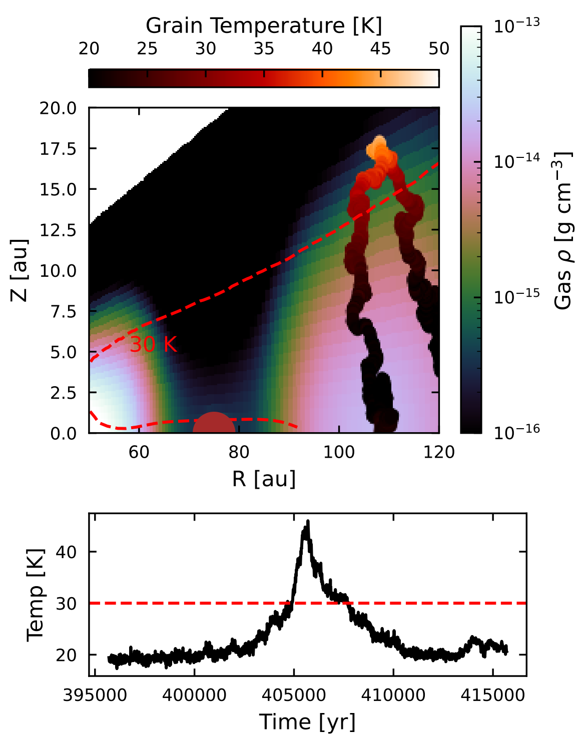

Figure 2: An example of a small grain being lofted near the surface of the disk in a simulation containing a Jupiter mass embedded planet. This example particle is transported from the midplane to the surface of the disk, reaching temperatures well above where CO should sublimate off the grain.

determining where ice processing may occur
throughout the entire disk. In Van Clepper et al. [11] I showed that not only are disks leaky, but that they can create global structure, creating multiple dust rings and gaps depending on disk and planet parameters. Understanding not only the dust morphology of these separate rings, but also the chemical consequences of planet formation will allow observers to place constraints on the types of planets that may be forming, or point to alternative explanations besides planets for the observed substructures.

Current chemical models of planet formation tend to assume a single bump and gap, a prescribed dust distribution, and a static disk, with chemistry taking place over the disk lifetime with no evolution of the dust or planet-induced gap. As a result, is it impossible to account for the dynamic and evolving nature of the disk, including transport of dust and gas via advection and diffusion, and how the growth and fragmentation of dust grains can transport volatile ices throughout the disk. One consequence of this is the difficulty in differentiating between chemical and dynamic effects in disks. CO gas, for example, is often used as a tracer for disk mass assuming a constant CO abundance. If CO is depleted onto grains via freeze-out, then inward pebble drift may deliver that CO to the pebble trap near the planet. Fragmentation of these large pebbles can result in the smaller dust lofting to warmer regions of the disk, sublimating the ice CO back into the gas phase. As a result, while one would expect in a static disk for all gas, including CO, to be depleted in the gas phase, this local enhancement in CO as a result of the *dynamic* transport of icy grains may reduce this observational signature. Figure 2 shows an example of one such micron sized grain, that is transported from the midplane to the surface of the disk following the planetary meridional flows. This grain experiences over 10 K of warming, sufficient to sublimate any CO that may have been present as ice. The chemical models I propose here will address this effect and provide insights into observational signatures of planet formation.

These methods can be combined with 2D gas phase chemistry models to track the chemistry and chemical evolution throughout the disk. Given that molecular line substructures do not always align with dust continuum substructures, it is clear that the dust and gas are interacting in currently unexplained ways to produce these observable chemical signatures. Modeling dust and chemical evolution simultaneously is challenging, but my experience modeling the connections between dust evolution and chemistry [10] and the dust dynamics in structured disks [11] prepares me to tackle this issue to provide a self-consistent framework for the interplay of dust and chemical evolution.

Project 3: Planetary inheritance of disk chemistry

While it is typically believed that planets reflect the composition of the disk they formed within, planet formation is an ongoing process with dynamic and chemical consequences, as explored in projects 1 and 2. Given that planets can drastically alter the disk environment, to what extent do planets reflect the disk composition and to what extent do disks reflect the chemical consequences of planet formation?

Observations of disk chemistry show that they tend to be carbon rich, with hydrocarbon emission indicating C/O>1 in some disks. Giant planet atmospheres, on the other hand, tend to have C/O closer to stellar values [2]. While this may be explained by the planets preferentially accreting oxygen and leaving behind carbon in the gas, this does not adequately explain the observed planet metallicities given current theories of planet formation.

To address this inconsistency, I will combine the dynamic and chemical models of projects 1 and 2 to self-consistently model the evolution of not only the disk, but the planets that form within. In a recently submitted paper currently in review, I proposed a novel mechanism by which fragmentation in the pressure bump can lead to dust lofting and sublimation of ice, which can then be accreted onto the growing planetary embryo. If volatile ice is sublimated from the grains via photodesorption as a result of this process, then this may lead to a natural transfer of volatiles from the disk to the planetary atmosphere, leaving behind refractory carbon in the disk explaining these observations.

This is a promising avenue of research, highlighting the dynamic environment of planet formation and the need to better understand how processing of grains in the disk may affect planetary compositions. This effect must be explored in more detail and in a self-consistent manner to constrain under what conditions we might expect this volatile enhancement in giant planets. Understanding this formation mechanism will allow us to better constrain planet formation environments and locations in disks, connecting the observed exoplanets to their formation histories and evolutionary pathways.

4 Expected Research Impact

The projects proposed here build upon techniques and methods that I have developed throughout my PhD, with clear relevance to upcoming ALMA and JWST observations. The results of these projects will not only address the questions posed above, but also lay the groundwork for more broadly interpreting chemical signatures in the context of substructured and evolving disks. As we enter the phase of large disk surveys using multi-wavelength approaches, a cohesive framework for understanding these disk observations will allow us to better understand the population of young planets forming in these regions.

As the majority of the methodological approach is completed, I anticipate the first year of my fellowship to involve performing a suite of hydrodynamic simulations while incorporating dust evolution into the Monte Carlo dust evolution simulations. These results on dust evolution and leaky gaps will be able to be published within the first year of my fellowship, setting the stage for subsequent publications for the implications for planetary and disk chemistry.

Beyond these publications, this work will highlight the chemical effects of considering planet formation in a dynamic disk, allowing observers and theorists to account for these secondary effects in further research on planet formation.

References

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Cite these early!