Fellowship Search Committee
Carnegie DTM

Members of the Search Committee,

I am writing to apply for the Postdoctoral Fellowship in Astronomy and Planetary Science at Carnegie DTM. I am currently a Ph. D. candidate at the University of Maryland, Baltimore County and am conducting my graduate research on numerical modeling of circumstellar debris disks at NASA/Goddard Space Flight Center.

For my thesis project, I have developed a 3D model of debris disks that includes fragmenting collisions between bodies. My model allows me to simulate the collisional and dynamical evolution of a debris disk in the presence of one or more planets, and simulate images of disks at submillimeter wavelengths. In my next position, I plan to extend the model's capabilities to simulate images at optical and infrared wavelengths, and to study the interaction between the populations of large parent bodies and small dust grains in disks. The morphological features observed in disks at both short and long wavelengths can act as signposts for the presence of unseen exoplanets, and even allow us to constrain the planets' masses and orbits.

Carnegie DTM hosts experienced debris disk theorists who would provide valuable expertise during my research project, as well as debris disk observers who would benefit from my modeling techniques and software. In particular, I hope to work with Dr. John Chambers, a staff scientist at DTM with research interests including the dynamics of exoplanets and disks. His expertise in numerical simulations of disk dynamics will be a valuable resource as I upgrade my model, test new versions of the code, and apply new versions to study various problems in debris disk physics. Carnegie DTM also employs several other staff scientists with related interests involving circumstellar disks and exoplanets, as well as researchers studying relevant Solar System topics. Interactions with these researchers will introduce me to a variety of possible applications of my simulations and other techniques for improving the model.

I have enclosed my curriculum vitae, a publication list, and a statement describing my research plans. Three letters of recommendation from Drs. Aki Roberge, Hanno Rein, and Marc Kuchner have been sent directly. I look forward to hearing from the committee.

Thank you for your consideration,

Erika Nesvold

Erika R. Nesvold

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RESEARCH INTERESTS

Debris disk morphology, planet-disk interactions, planetary system dynamics, submillimeter imaging

EDUCATION

Ph.D., Physics
expected May 2015, University of Maryland, Baltimore County (UMBC)
Advisor: Dr. Marc Kuchner, NASA Goddard Space Flight Center

M.S., Applied Physics
May 2011, UMBC

B.S., Mathematics
May 2009, UMBC
Magna Cum Laude

GRANTS, AWARDS, AND HONORS

ALMA Student Observing Support Grant 2014
National Radio Astronomy Observatory
Student funding associated with ALMA observations ($27 K)

ALMA Observing Proposal 2014
Co-I, *Confirming the recent collisional destruction of an extra-solar Pluto*

HST Theory Grant 2013
Co-I, *SMACK: A New Tool for Modeling Images of Debris Disks* ($110 K)

Student Stipend Award 2012
Division of Dynamical Astronomy (DDA)
Travel grant to present at the 2012 DDA Meeting

Graduate Assistantships in Areas of National Need 2009-2011
Department of Education
Graduate fellowship providing full tuition and student stipend

Loughran Regents Scholarship 2005-2009
UMBC
Merit scholarship providing full undergraduate tuition, fees, and stipend

INVITED TALKS AND SEMINARS

Planet and Star Formation Seminar October 2014
University of California Berkeley

Astrophysics Colloquium October 2014
NASA Jet Propulsion Laboratory

Infrared Processing and Analysis Center Seminar October 2014
California Institute of Technology

Journal Club Talk October 2014
University of California Los Angeles

Astro Seminar October 2014
Carnegie Department of Terrestrial Magnetism

Planetary Astronomy Seminar October 2014
University of Maryland College Park

Radio and Geoastronomy Lunch Talk September 2014
Harvard-Smithsonian Center for Astrophysics

Exoplanet Seminar Series November 2013
NASA/GSFC

STScI Star and Planet Formation Seminar Series October 2013
Space Telescope Science Institute

RESEARCH EXPERIENCE

Graduate Researcher 2010-Present
NASA Goddard Space Flight Center (GSFC)
Developed a new collisional model of debris disks using parallelized C code. Applied model to observations of debris disks to analyze effects of collisions on planet-disk interactions.
Advisor: Dr. Marc Kuchner

Graduate Summer Researcher Summer 2013
NASA/GSFC
Updated Python code for generating spectral image cubes of Solar System planets and dust for use with instrument simulators. Integrated simulated and observed planet spectra with empirical and model dust distributions.
Advisor: Dr. Aki Roberge

Graduate Summer Researcher Summer 2010
NASA/GSFC
Developed IDL code to reduce optical and infrared data for two circumstellar disks. Analyzed the morphology of both disks to identify indications of the presence of exoplanets and to constrain the mass of any possible planets.
Advisor: Dr. Mark Clampin

Undergraduate Summer Intern Summer 2008
NASA/GSFC
Reduced submillimeter data for several extragalactic sources using a C-based software package. Performed temperature and spectral analysis on the reduced data using IDL routines.
Advisors: Dr. Dominic Benford & Dr. Johannes Staughan

PUBLICATIONS

Nesvold, E. R., Kuchner, M. J., Rein, H., Pan, M., 2013, *SMACK: A New Algorithm for Modeling Collisions and Dynamics of Planetesimals in Debris Disks*, ApJ, 777, 144

Nesvold, E. R., Kuchner, M. J., 2014, *Gap Clearing by Planets in a Collisional Debris Disk*, ApJ, in press

Pan, M., **Nesvold, E. R.**, Kuchner, M. J., 2014, *Collisional Pericenter Glow: Re-Interpreting Submillimeter Images of Debris Disks*, in prep

Roberge, A., Wilkins, A. N., Rizzo, M. J., **Nesvold, E. R.**, Stark, C. C., Lincowski, A. P., McElwain, M. W., Kuchner, M. J., Robinson, T., Meadows, V. S., Straughn, A. N., Wikland, T., Turnbull, M. C., 2014, *Finding the Needle in the Haystack: A High-Fidelity Model of the Solar System for Simulating Exoplanet Observations*, in prep

Jang-Condell, H., Chen, C. H., Mittal, T., Puravankara, M., Watson, D., Lisse, C., Kuchner, M., **Nesvold, E.**, 2014, Spitzer *IRS Spectra of Debris Disks in the Scorpius-Centaurus OB Association III*, in prep

OTHER SUBMITTED PROPOSALS

ALMA Observing Proposal 2014
Co-I, *Measuring the gap width in a bright, planet-sculpted debris disk*

ALMA Observing Proposal 2014
Co-I, *Resolving Millimeter Emission in the HD 10647 Debris Disk*

NASA Internal Research and Development Grant 2014
Co-I, *EcHELLE: Exoplanet Habitability and stELLar Evolution – A systematic interdisciplinary study of the impact of stellar evolution on the habitability of other worlds*

NASA Astrobiology Institute Program 2014
Co-I, *EcHELLE: Exoplanet Habitability and stELLar Evolution – A systematic interdisciplinary study of the impact of stellar evolution on the habitability of other worlds*

NASA Astrophysics Theory Program 2012
Co-I, *SMACK: Superparticle Model/Algorithm for Collisions in Kuiper belts and debris disks*

CONFERENCE POSTERS AND PRESENTATIONS

5th National Capital Area Disks (NCAD) Meeting July 2014
Presentation · Carnegie DTM
“Gap-Opening by Planets in Debris Disks”

223rd American Astronomical Society (AAS) Meeting January 2014
Presentation · National Harbor, Maryland
“Modeling Eccentric Debris Rings with SMACK: Collisions Change Everything”

5th Subaru International Conference December 2013
Presentation · Kona, Hawaii
“SMACK: A New Algorithm for Modeling Collisions and Dynamics of Debris Disks”

45th Division for Planetary Sciences (DPS) Meeting October 2013
Presentation · Denver, Colorado
“SMACK: A New Collisional Algorithm for Modeling Collisions and Dynamics in Debris Disks”

DC/MD/VA Astrophysics Summer Meeting for Grad Students July 2013
Presentation · University of Maryland, College Park
"A New Collisional Algorithm for Modeling Collisions and Dynamics in Debris Disks"

2013 Rocks! ALMA Conference April 2013
Poster · Kona, Hawaii
"SMACK – A New Method for Modeling How Collisions and Planets Affect Debris Disks"

4th NCAD Meeting July 2012
Presentation · STScI
"Debris Disks: Modeling Collisions and Dynamics Together"

Division of Dynamical Astronomy (DDA) Meeting May 2012
Presentation · Mt. Hood, Oregon
"A New Algorithm for Modeling Collisions in Debris Disks"

Signposts of Planet Conference October 2011
Poster · NASA/GSFC
"A New Algorithm for Modeling Collisional Evolution of Debris Disks in 3-D"

SERVICE AND OUTREACH

Member of **Disk Detective** science team January 2014-present
Participated in social media outreach program for the NASA-funded Zooniverse Disk Detective citizen science program.
www.diskdetective.org

Writer for **Astrobites** blog December 2012-present
Contributed monthly posts to the Astrobites blog, summarizing recent astrophysics publications. Edited other contributors' posts. Represented Astrobites at the 2014 Winter AAS meeting.
www.astrobites.org

Organizer, NASA/GSFC Disks/Planet Group Meetings 2011-present

Referee, Astronomy & Astrophysics 2014

Executive Secretary, NASA PATM Review Panel 2012

President, UMBC Physics Graduate Student Associaiton 2010-2011

Publication List
Erika Nesvold

1. **Nesvold, E. R.**, Kuchner, M. J., Rein, H., Pan, M., 2013, *SMACK: A New Algorithm for Modeling Collisions and Dynamics of Planetesimals in Debris Disks*, ApJ, 777, 144
2. **Nesvold, E. R.**, Kuchner, M. J., 2014, *Gap Clearing by Planets in a Collisional Debris Disk*, ApJ, in press
3. Pan, M., **Nesvold, E. R.**, Kuchner, M. J., 2014, *Collisional Pericenter Glow: Re-Interpreting Submillimeter Images of Debris Disks*, in prep
4. Roberge, A., Wilkins, A. N., Rizzo, M. J., **Nesvold, E. R.**, Stark, C. C., Lincowski, A. P., McElwain, M. W., Kuchner, M. J., Robinson, T., Meadows, V. S., Straughn, A. N., Wikland, T., Turnbull, M. C., 2014, *Finding the Needle in the Haystack: A High-Fidelity Model of the Solar System for Simulating Exoplanet Observations*, in prep
5. Jang-Condell, H., Chen, C. H., Mittal, T., Puravankara, M., Watson, D., Lisse, C., Kuchner, M., **Nesvold, E.**, 2014, Spitzer *IRS Spectra of Debris Disks in the Scorpius-Centaurus OB Association III*, in prep

Research Plan

Background

Spatially resolved debris disk images from HST, *Spitzer*, and Herschel show spectacular patterns and sub-structures including inclined[1] and eccentric rings[2,3,4,5], warps or sub-disks[6,7] and a variety of other morphologies[8,9]. Hidden exoplanets could create many of these features via gravitational perturbations; many authors have argued that when a debris disk shows a warp or ring or other asymmetry, we can use it to constrain the location, orbit, and physical properties of an unseen perturbing planet. In the last few years, direct images of (a very few) exoplanets combined with numerical models[10,11] have demonstrated the power and necessity of this astrophysical detective work. In fact, interpreting images of debris disks is currently the only repeatable way to find true exo-Neptune analogs, orbiting at > 20 AU.

But even the most advanced models used to infer the connection between the debris disks and hidden exoplanetary perturbers are still primitive; crucially, they do not correctly model the dust sources. Most current models tacitly assume a hidden population of colliding mm-km sized parent bodies that produce the observed dust and, as an oversimplification, assume this population to have the same dynamics as non-colliding dwarf planets, despite its rapid collisional evolution.

Recently, ALMA has begun delivering images of resolved debris disks at submillimeter wavelengths, which probe the parent body distributions directly[12,13,14]. Understanding the complex interaction between collisions and dynamics is essential for interpreting these ALMA images correctly, and for connecting the parent body distributions observed with ALMA to the dust distributions imaged at shorter wavelengths, including future disk observations with JWST.

SMACK: A New Collisional Model

Though some advanced models now include the effects of grain-grain collisions[15] or the 2D effects of parent body collisions[16], I have developed the only fully 3-D debris disk model that can directly track the collisions of the mm-km size bodies that produce the dust, and predict how these asymmetrical sources of dust affect debris disk morphologies probed by high spatial resolution images. My new code, the Superparticle-Method Algorithm for Collisions in Kuiper belts and debris disks (SMACK) is a set of new modules added to the REBOUND code[17], a highly modular open-source N-body integrator.

REBOUND contains Barnes-Hut tree modules to calculate self-gravity and detect collisions. In the original version, collisions were resolved using an instantaneous collision model with a normal coefficient of restitution. But collision speeds in debris disks are in the fragmentation regime (~km/s). These fragmenting collisions would rapidly increase the number of bodies to be tracked in a conventional N-body integrator, making such a model prohibitively computationally expensive.

To handle this computational challenge, I use the particles in REBOUND to statistically represent the distribution of actual planetesimals in the space of orbital elements and planetesimal sizes. Each particle in the SMACK version of REBOUND is a "superparticle", representing an ensemble of planetesimals with a range of sizes (e.g., from 1-1000 mm). The algorithm keeps track of the size–frequency distributions for each swarm, allowing the model to simulate the orbits and collisions of a changing number of planetesimals without overloading the N-body integrator. When the algorithm detects an encounter between swarms, two daughter superparticles are produced with new size distributions and trajectories representing the outcomes of the fragmenting collisions between planetesimals in the parent superparticles. A few particles are set aside to model massive bodies: the star and the planets. In this way, SMACK models both the cloud dynamics and the evolving planetesimal size distribution.

SMACK is fully parallelized and can simulate the evolution of a disk over 10 Myr in 12-24 hours on 48 CPUs. SMACK has passed a series of numerical tests to validate the code's ability to reproduce basic debris disk physics while constraining sources of numerical noise, viscosity, and angular momentum growth[18]. SMACK is ideal for creating simulated images of resolved debris disks at millimeter and submillimeter wavelengths directly. I have used SMACK to create figures for ALMA proposals to observe HD 181327, HD 10747, and HD 107146, to demonstrate not only that disk asymmetries can be observed at submillimeter wavelengths, but also that we can use the observed morphology of debris disks in the submillimeter to constrain the mass and orbits of unseen planets (Fig. 1).

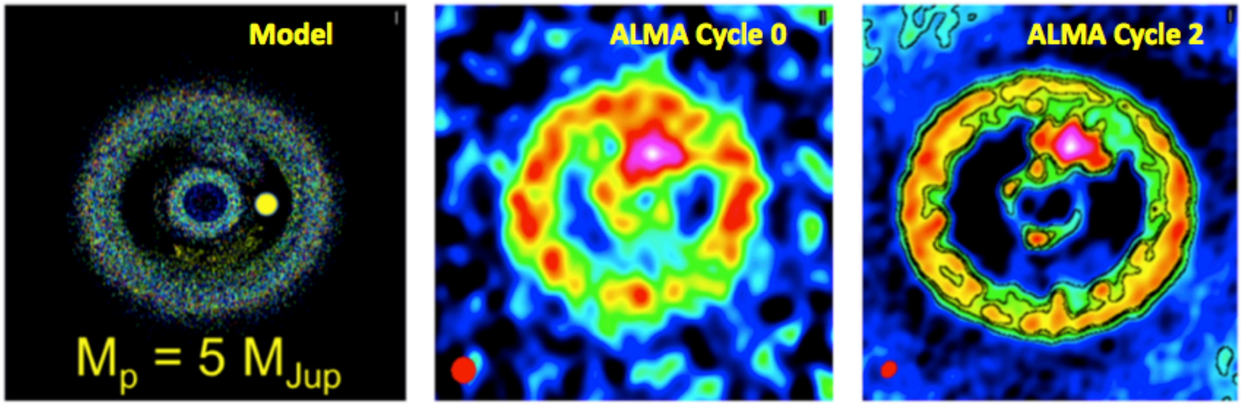

Fig. 1: Images of HD 107146 with an embedded planet simulated by SMACK, with corresponding ALMA maps simulated at 1.3 mm (center) and 0.87 mm (right) for 345 GHz. SMACK models the evolution of the parent bodies directly, which are the particle sizes probed at submillimeter wavelengths.

Previous Applications of SMACK

I have applied SMACK to model a system of one eccentric planet orbiting interior to a wide circular ring of parent bodies. After 10 Myr, the ring became eccentric and apsidally aligned to the planet due to the forced eccentricity imposed by the planet, as collision-free Laplace-Lagrange evolution predicts. However, in the process collisional damping narrowed the ring by a factor of 25% and destroyed the spiral structure that would have been created by differential precession[18]. These results indicate that the narrow eccentric rings we observe, e.g., Fomalhaut and HR 4796 A, are collisionally relaxed and the reason that they are so narrow may be the collisional damping combined with gravitational sculpting by a nearby planet.

To investigate the effects of collisions on planetary sculpting of debris rings, I re-examined the resonance overlap criteria for gaps in debris disks[19]. Resonance overlap near a planet's orbit creates a zone of chaotic orbits, which eject parent bodies on short timescales. Analytic derivations find a power law relationship between the width of the chaotic zone and the planet mass[20], with an index of 2/7. The chaotic zone has been invoked to explain observed gaps in debris disks, and collisionless numerical simulations reproduce the 2/7 law[21,10]. I used SMACK to simulate the opening of a gap in a debris disk with fragmenting collisions, varying planet mass and disk optical depth, and derived a new collisional gap law. I found that the width of a gap depends on both the age and optical depth of the disk, and that collisions allow smaller planets to open wider gaps by eroding the inner edge of the debris ring. My new collisional gap law is a power law with a time-dependent index, and it can infer planet masses up to 5 times smaller than the collisionless, time-independent gap law would predict.

Proposed Research Plan

My work so far has demonstrated that SMACK can directly simulate submillimeter images and predict the significant effects of collisions on the parent body distributions in debris disks. SMACK also records the location and amount of dust produced in every collision, yielding a time-evolving 3D map of the dust production rate in the disk. However, the current version of SMACK does not trace the orbits of the smaller dust grains after they are produced by collisions. Further work is needed to adapt SMACK to model the final dust grain distribution and simulate images in the optical and near-infrared.

I propose to upgrade SMACK to include the dynamical and collisional evolution of the small (μm-mm size) dust grains produced during each simulation. This upgrade is non-trivial, as the size-dependent forces of radiation pressure and Poynting-Robertson drag that affect small grains cannot be modeled using SMACK's superparticle approximation, which dynamically couples parent bodies of different sizes into the same orbits. I will therefore address this problem in two stages.

First, I will use the dust production data output by SMACK as input in a separate dust grain model to trace the orbits of the dust grains after they are produced. This step is relatively straightforward, as SMACK already calculates the dust production, and several dust grain models are already available. I will use this combined SMACK+dust model to study systems that exhibit narrow eccentric rings.

Next, I will adapt SMACK to model the evolution of the dust grains directly. This will require significant alterations to the SMACK algorithm, but it will allow me to study the interaction between parent bodies and dust grains down to ~1 μm, and to simulate state-of-the art debris disk images at wavelengths from the submicron to the submillimeter.

Phase One: SMACK+dust

In Phase 1, I will use the dust production data output by SMACK as input in a separate dust grain model to trace the orbits of the dust grains after they are produced. This step is relatively straightforward, as SMACK already calculates the 3D dust production, and several dust grain models are already available. Each of my simulations will have two steps. First, I will model the collisional evolution of the parent bodies with SMACK and, if submillimeter images are available, ensure that I can reproduce these images of the parent body distribution. I will then use the size and spatial distributions of the dust calculated by SMACK as the initial conditions for a dust model. Early in the project, I will use a non-collisional REBOUND simulation to calculate the dust trajectories under the influence of radiative forces. This two-step "SMACK+dust" model is the fastest way to produce dust distributions from SMACK simulations, but also the simplest, as it will neglect collisions between the dust grains themselves.

As a next step, I will upgrade the collisionless dust dynamics model to the Collisional Grooming Algorithm (CGA), which simultaneously models the dynamics of grains (PR drag, solar gravity, planet gravity, radiation pressure, etc.) and grain-grain collisions[15]. The CGA iteratively solves the mass flux equation to calculate the density distribution of the dust after grain-grain collisions. To synthesize images of the dust to compare with short-wavelength images of real debris disks, I will use the ZODIPIC and DUSTMAP software[22], which include scattering phase functions measured for zodiacal light[23] and simple Henyey-Greenstein functions informed by spatially resolved images. I will convolve each synthetic disk image with a point-spread function (PSF) for the observing instrument.

Eccentric Rings

Many of the resolved debris disks observed so far show narrow eccentric rings with cleared inner regions (e.g., Fomalhaut, HR 4796 A, HD 181327). Several features of these systems act as signposts for the presence of unseen planets and can be used to constrain the planet's mass and eccentricity.

I have already used SMACK to develop a time-dependent gap law to include the widening of the planet-induced gap by erosive collisions[19]. However, this gap law is based on simulations of a planet on a circular orbit. Planets on eccentric orbits may create wider gaps as their orbits cover a larger radial distance from the star, changing the index of the gap law[24], and they may excite collisions in the inner edge of the disk and widen the gap further. I will build upon this work to examine the relationship between planet mass and gap size in systems with eccentric planets. Radiation pressure may push small dust grains into the gap create by a planet from interior regions of the disk[25], which would smear out the gap signature in short-wavelength images. I will investigate this phenomenon with SMACK+dust to determine whether submillimeter images could recover gap signature of planets that are undetectable at shorter wavelengths.

The shapes of the inner and outer edges of a debris ring have also been used to predict the presence of unseen planets. Observers measured a sharp outer edge for the parent body ring in the Fomalhaut system with ALMA and argued that a second planet must be orbiting exterior to the ring, truncating the outer edge[12]. However, my SMACK simulations have already shown that collisional damping can narrow a ring without the need for a second, exterior planet[18]. Images of the Fomalhaut dust ring with HST show a much smoother outer edge in the dust distribution, which could indicate that dust created in the narrow parent body ring is being pushed outwards by radiation pressure. I will use my SMACK+dust model to simulate images of the Fomalhaut ring at ALMA and HST wavelengths to demonstrate whether a single eccentric planet orbiting interior to the ring could be responsible for the dust and parent body distributions.

My simulated images of disks with gaps also predicted clumps of emission orbiting ahead of and behind the planet in each system (Fig. 2). The source of this emission was planetesimals trapped in resonant orbits at the planet’s semi-major axis, analogous to the Trojan asteroids that orbit with Jupiter in the Solar System. After further analysis I discovered that the brightness of these Trojan-like clumps relative to the debris disk increased with planet mass up to a certain point, beyond which the relative brightness dropped off rapidly, as the resonances became unstable at higher planet masses. I also discovered that the planet mass where the brightness peaked is a function of disk optical depth. I will run more simulations to study the evolution of the Trojan analogues in more detail and determine whether they are enhanced or destroyed by planets on eccentric orbits. Radiation pressure and P-R drag may smear out the distribution of the dust born in these clumps, so I will use SMACK+dust to determine whether these clumps are observable at submillimeter and/or submicron wavelengths, and whether they could be used to place constraints on planet mass or eccentricity.

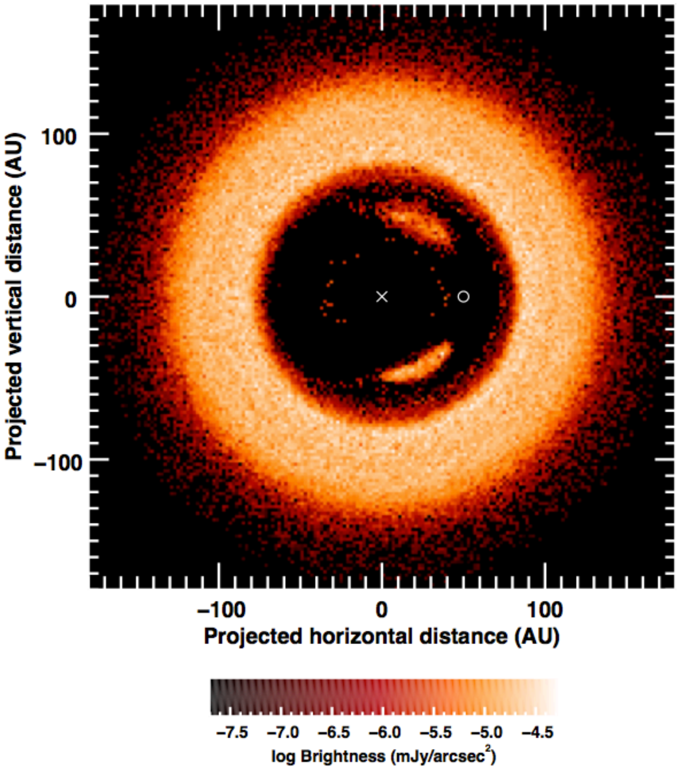

Fig. 2: Simulated image at 850 μm of a 10 M_{Jup} planet on a circular orbit (circle) interior to a disk. After 10 Myr, the planet opens a gap between its orbit and the inner edge of the disk[19].

Many eccentric rings were first observed as brightness asymmetries in the disk emission. In an eccentric ring with uniform density, bodies near pericenter are closer to the star and receive more flux, so the pericenter side of the ring appears brighter. This phenomenon was named “pericenter glow”[26], and is sufficient to explain observed brightness excesses at pericenter in images at visible and near-infrared wavelengths. However, ALMA and other submillimeter instruments have observed brightness excess at apocenter in eccentric rings like Fomalhaut[27,28,29,12] (Fig. 3). These apocentric excesses cannot be explained by the pericenter glow model, which does not include the significant effects of collisions and resonances on the azimuthal density variations of the parent bodies.

I will investigate this problem with SMACK+dust by modeling the evolution of eccentric rings, simulating images at submillimeter and submicron wavelengths, and comparing the ratios of the simulated flux at apocenter and pericenter for different planet masses and eccentricities. Preliminary SMACK results indicate that both the collision rate and the mass of dust produced in collisions peak at apocenter, which causing a peak in emission from mm-sized bodies produced in excess at apocenter, but whose distribution is not smeared azimuthally by radiative forces. I will use SMACK+dust to model the distribution of the smaller grains, which are also produced in excess at apocenter but are quickly moved by radiation pressure and P-R drag. Understanding this apocenter glow phenomenon is crucial for interpreting millimeter and submillimeter images of resolved eccentric debris rings, and may reveal new methods for constraining planet masses and eccentricities by combining short and long-wavelength images of eccentric debris rings.

Phase Two: SMACK Dust Model

My proposed SMACK+dust model will allow me to study the effects of the time-dependent distribution of parent bodies on the final distribution of the dust grains, but it will not simulate the effects of dust grains on the parent bodies, since the simulations of parent body and dust dynamics are run in sequence, not simultaneously. Fully modeling the interaction between parent bodies and dust grains is crucial for producing state-of-the art models of the spatial and size distributions of particles from 1 μm to 1 km in size. Time permitting, for Phase 2 I will adapt SMACK to model the evolution of the dust grains directly. This will require significant alterations to the SMACK algorithm, which will likely increase the computation time of SMACK. However, the potential benefits of a full micron-to-kilometer SMACK model justify moderate increases in computation time. The full SMACK model will allow me to study the interaction between parent bodies and dust grains, and to simulate state-of-the art debris disk images at wavelengths from the submicron to the millimeter.

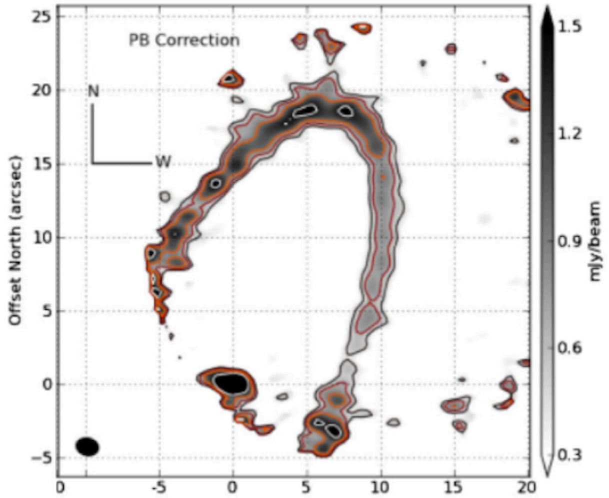

Fig. 3: 350 GHz ALMA image of Fomalhaut's ring[12]. The enhancement at the ansa can be explained by project effects, but the excess at apocenter (~30° counterclockwise form the ansa) cannot be explained by projection effects or the collisionless pericenter glow model.

I will experiment with several different possible approximations to add dust grains directly to the SMACK algorithm. For example, I will explore the use of separate populations of superparticle, each representing a smaller range of particle sizes. Superparticles representing smaller grains would be subjected to radiative forces. Depending on the level my success and the time remaining on the project, I will apply the completed μm-km SMACK model to at least one disk that has been resolved at both short and long wavelengths (e.g., Fomalhaut) to study the interactions between the parent bodies and dust grains.

References

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