A. C. Quillen – Research Narrative (2024)

Contents

1 Celestial Mechanics – multiple exoplanet and satellite systems

In 2006 I worked on general theory on orbital resonance capture [1] to cover the non-adiabatic regime, extending Peter Goldreich and Nicole Borderie's work that was restricted to adiabatic drift only. A dimensional analysis argument facilitates estimating whether pairs of drifting bodies can capture into orbital resonance. My estimate has since been applied to interpret migrating multiple exo-planet systems, orbital dust dynamics, satellite systems and early evolution of planetary embryos.

In 2011 I developed a theory, based on a three-body resonance overlap condition for chaotic behavior, to predict numerically measured scaling relations for stability times in closely packed satellite or planetary systems [2]. This is a first attempt to theoretically explain numerically measured scaling relations and establish a theoretical foundation for predicting planetary system stability. I and Rob French corrected and extended the theory [3] to cover more types of three-body resonances with a study of the inner Uranian satellite system in 2014, where I have tried to better understand the chaotic evolution and stability of resonant chains or consecutive pairs of bodies in first order resonances. My work has recently been built upon and extended by Antoine Petit, Jeremy Rath and Dan Tamayo who have confirmed the importance of three-body resonances in influencing planetary system stability.

A body of our work [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16], in collaboration with students and colleagues at U. Rochester and postdocs Richard Edgar and Peggy Varnière, focuses on relating properties of dusty circumstellar disks to underlying and unseen planetary architecture. This work includes proposing (with Math Holman in 2000) a new mechanism [17] for creating star grazing comets via planet migration. We related the structure of dusty and gaseous disk edges to the masses of planets residing just interior to or within them and made predictions for unseen planets in three systems [4, 5, 10], including in 2006 the prediction of a planet in the Fomalhaut system, just interior to its dusty disk edge, and where an orbiting object was later found in 2008, though subsequent observations imply that it is unlikely to be a planet.

The associated computational efforts motivated us (with graduate student Alex Moore) to develop the first GPU (graphics processing unit) accelerated symplectic integrator (QYMSYM)[18] capable of resolving collisions between planetesimals and planets and integrating all force pairs in a celestial mechanics setting. Using our code (and running on home-built gaming computers that housed graphics cards given to us by NVidia), we wrote a series of papers [19, 20, 21, 22, 23] relating multiple planet architecture to evolution of combined planet and planetesimal systems, including placing constraints on how much orbital debris could have crossed the orbits of multiple planet HR8799 and KOI730 systems and how impacts with embryos could help explain both the proximity and different densities of the Kepler 36 planets.

Working with resolved bodies (see section 2) led to our discovery of a new type of spin resonance, involving mean motion resonant perturbations, [24, 25] that can affect satellite obliquity in migrating systems. In the context of migrating satellites that are embedded in ring systems, I recently explored scenarios for accretion of ornamental equatorial ridges on moons such as Pan [26].

Much of this work has been supported with 2 National Science Foundation grants and 2 NASA astrophysics grants, each giving 3 years of support, primarily to support a single graduate student at a time and with me as a PI.

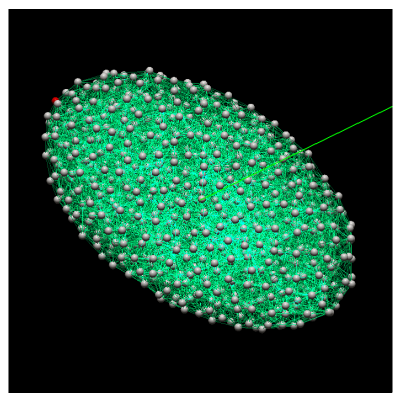

Figure 1: A screen snap of a spinning triaxial body that is resolved with masses and springs.

Title: Detection of Outer ExtraSolar Planets and Characterization of Disk Properties from Circumstellar Gas and Dust Morphology, Award Period: 06/01/04-05/31/08, Source of Support: NASA, Award Amount: $265,000

Title: Collaborative Proposal: Holding Footpoints to the Fire: Planet Disk Theory Confronts Observations, Award Period: 08/15/04-07/31/08 Source of Support: NSF, Award Amount: $464,945, Additional REU Supplement: + $26,125

Title: The dynamics of disk clearing, late stage planetesimal disk and planetary system evolution Award Period: 09/01/2009-08/31/2012 Source of Support: NSF, Award Amount: $289,134

Title: Stability and Evolution of Multiple Planet and Satellite Systems Award Period: 6/01/13-5/31/16, Source of Support: NASA, Award Amount: $322,460

2 Soft-astronomy: Spin dynamics using viscoelastic mass-spring model simulations

Mass spring models had not been used in astrophysics, possibly because most known asteroids are well approximated by rubble piles rather than solid elastic bodies. However, our attempt to simulate tidal deformation during close encounters [27] spurred us to improve numerical measurements of deformation and this led to the development of our mass-spring model for simulating soft viscoelastic bodies [27, 28]. The model conserves angular momentum and the simulated bodies can accurately and self-consistently respond to small tidal deformations. With this new types of simulation, I, Cindy Ebinger and John Shaw proposed a new geophysical process: that tensile stress associated with strong tidal encounters could cause crustal failure and large chasmata on icy moons (and perhaps accounting for Valles Marineris on Mars) [27]. We proposed that surface features associated with tensile failure might be evidence for predicted strong grazing encounters in the early Solar system. With Julien Frouard and Michael Efroimsky at the Naval Observatory, I carried out the first direct simulation of tidal spin down and tidal lock with a simulation that self-consistently takes into account the viscoelastic behavior of a tidally deformed body [28]. Subsequent work explores tidal spin down of non-round, non-homogeneous triaxial bodies [29], viscoelastic relaxation of non-principal axis rotation [30], chaotic excitation and evolution of tumbling for Phobos and Deimos [31], asymmetric tidal heating in the early Moon (with Miki Nakajima; [32]) and excitation of normal modes in small asteroids by strong impacts (with Yuhui Zhao) [33]. With YuanYuan Chen, I explored the obliquity evolution of Pluto and Charon's minor satellites, [24, 25] and found a mechanism that could account for their high obliquity.

Most recently with a study of the evolution of binary asteroids, we infer that non-principal axis rotation is long lived for asteroid binary secondaries [34]. We predict that binary asteroid secondaries should be in non-principal axis rotation states. Prior computations of radiation driven torque (BYORP) either assume that the secondary is tumbling, giving zero torque, or that it is tidally locked, giving a large torque that would cause the binary to rapidly disrupt. By tracking body orientation in our spin dynamics simulations we compute radiation driven torque on the secondary and find a continuum of intermediate states. We reconcile estimates for binary material properties with those of single asteroids and increase estimates for asteroid binary lifetimes by showing that non-principal axis rotation can reduce BYORP.

This work was supported by the following grants with me as PI:
Title: Astro-elastodynamics, Measuring Tidally generated heat and torque Amount: $366,498, Period Covered: 12/01/2017 - 11/30/2020, Source of support: NASA
Title: Dynamics of Tides, the Milky Way, and Multiple-Planet Systems Amount: $121,870 Period Covered: 07/01/2017 - 06/30/2018 Source of Support: Simons Foundation

3 Collective phenomena, biophysics, active matter and robotic locomotion

We explored simple concepts for robotic locomotion that are not necessarily biologically motivated. Summer 2016, motived by the problems associated with tidal oscillations of fluid/solid boundaries I made a small 1cm long robotic swimmer from a vibrational motor. It swims at low Reynolds number in glycerin, has no external moving parts and only costs $1.20, so provides a low-cost way of making robust and small robotic swimmers [35]. Randal Nelson and I constructed a light-weight low-cost hopper, weighing only a few grams, that can traverse granular media [36]. Surprisingly we found that the permeativity of the granular media to air affected the locomotion. These two mechanisms move without any external moving parts, and are *recoil locomotors*. Recoil locomotion is attractive for mechanisms that need to traverse hostile environments, such as an asteroid or planetary surface. We (with Randal Nelson and undergraduate John Liu) have constructed small (few cm long) and low-cost (less than $20) autonomous solar-powered boats, also using a vibrational motor. These move via a flexible flipper but are not particularly efficient because the motor itself is not efficient.

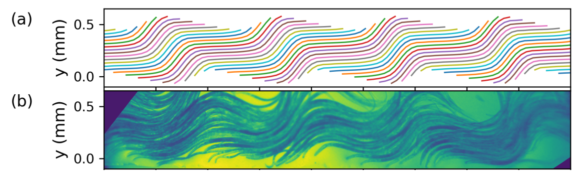

Figure 2: a) A synchronization model based on coupled oscillators for the collectively organized metachronal wave seen in swimming *Turbatrix aceiti* nematodes shown in b).

With the goal of creating biodegradable robotics parts, I have became interested in how active matter interacts with flexible boundaries. We numerically explored how collective motion in concentrations of self-propelled particles (aka *boids*) could induce ruffles in a confining flexible boundary [37].

Postdoc Anton Peshkov and I searched for collective behavior in concentrations of small swimming microorganisms commonly used in aquaculture (briny shrimp and nematodes known as vinegar eels). This led to Anton's discovery of collective metachronal wave formation in concentrations of vinegar eels [38]. The vinegar eels are a nice mesoscale (meaning not microscopic as they are about 1 mm in length) system of self-propelled organisms that also oscillator ('swarmalators'). To model the collective behavior I created an interacting oscillator model that suppresses motion via steric interactions [39]. Strong fluid circulation is driven by the metachronal wave, involves hydrodynamic screening and large excursions by the tails of the nematodes involved in the wave [40]. Applications of the collective behavior could include a biodegradable pump.

Robust formation of metachronal waves are critically important in many biological systems. However, many interacting oscillator models tend to exhibit long-lived synchronous rather than wave-like states. I find that instabilities that are present in directional models (these do not obey reflection symmetry) can cause a synchronous state to be unstable, facilitating metachronal wave formation [41].

Our work on robotics was supported by the following multi-disciplinary grant with me as PI:

Title: Robotic Physics of Miniature Crawlers, Swimmers and Burrowers — Non-biological Locomotion Strategies in Complex Media, Award Period: 07/01/2017- 07/01/2019, Amount: $40,000 Source of Support: University of Rochester University Research Award.

We are lucky to receive some funds for biophysics research!

Title: Controlling active oscillating materials with container boundaries and working toward the design of a biodegradable pump, Amount: $14,000, Award date: July 2023, Source of Support: Feinberg Research award

4 Laboratory investigations of impacts into granular materials

Many laboratory based studies related to astrophysical impact processes focus on high velocity impacts (a few km/s) because this velocity scale is typical of the relative velocities of asteroids. However, impact ejecta, spin out events and re-accumulation events after disruption can give a population of bound objects that can return to impact a rubble-pile asteroid at low velocity. The low velocity impact regime is relevant for the design of successful sample return missions which must interact with asteroid surface material in low surface gravity. The low velocity impact regime may have been particularly important during the era of planetesimal formation [42].

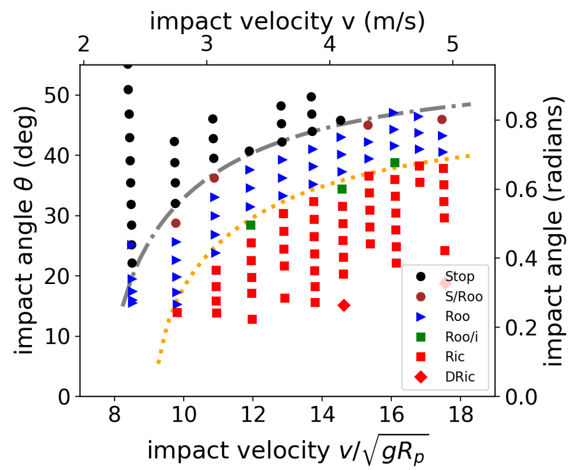

Figure 3: Experiments of low velocity grazing angle impactors into sand either **ricochet** (red), **stop** within their impact craters (black) or **roll-out** of their impact craters (blue). Experiments of 1 cm diameter marbles on Earth are matched or scaled to impacts on an asteroid and at low surface gravity via the acceleration or Froude number which is shown on the bottom axis. The dotted and dashed lines show empirical models.

I and graduate student Esteban Wright have been exploring the behavior of granular materials (sand and rubble) in the lab. We use fluorescent markers and high speed video to track ejecta and the center of mass and spin of projectiles. We have proposed a scaling relation so we can match our 1g experiments to low gravity environments. We are designing and will be constructing a projectile launch mechanism so that we can launch non-round projectiles and adjust their spin rate and angle. The design is compact because we hope to transport it next year to a drop tower (in collaboration with Naomi Murdoch in Toulouse). Drop tower experiments would help us improve our ability to predict impact behavior at low gravity.

We have proposed a new mechanism for stranding boulders on the surface of a rubble asteroid via collisional sorting of material ejected off the surface following a strong impact [43]. A spherical projectile impacting a horizontal surface of granular material at grazing angle is likely to ricochet and our scaling relation suggests that ricochets are common in low gravity environments [44].

With experiments of impacts into media with different mean grain sizes, we find that ricochets are sensitive to substrate grain size [45]. Using coefficients of restitution measured from our impactor trajectories we characterize lift and drag coefficients from interactions with the granular media. The impacts span behavior from ballistic, where particle and projectile have similar sizes, to fluid like, when projectile is much larger than the mean grain size.

Using an accelerometer array, we find that pulses excited by impacts decay rapidly, supporting a seismic jolt model for how impact generated seismic energy propagates through a rubble asteroid [46] (with Max, and Bingcheng and Lucas!). We also explored how a granular surface is disturbed outside the crater radius by tracking particle motions [47]. Subsurface pulses are strongly asymmetric for oblique impacts into a granular system, even if craters are round [48]. These studies are relevant for interpretation of the DART mission impact. We (led by Bingcheng Suo) have recently completed a study of oblique impacts, showing that subsurface seismic pulses are remarkably asymmetric, even when craters are nearly round [49].

We have begun experiments on alignment of particles on the surface by landslides and plowed flows that could take place in low-g environments.

With thermophysical models, Dannielle Bovie and I estimated how far particles move due to thermal cycling on asteroid surfaces [50].

Particle rich headwinds may have sculpted and exchanged material with small planetesimals [42]. We proposed that the Transneptunian object Arrokoth was sandblasted by the snow storm in which it coalesced.

Our laboratory work is funded via a grant with me as PI: Title: Ricochet and Roll-out of Low Velocity Impactors into Granular Media, Amount: $712,945, Period Covered: 10/26/2020 - 10/25/2023, Source of Support: NASA

5 The interface between quantum and classical complexity

I am interested in the connection between classical complexity and quantum systems.

I find [51] that quantum channel can display some of the complexity of dynamical systems, such as period doubling, but often at the expense of removing information, which can be done via initializing subspaces. Channels that are derived from discrete functions, sound simple, be even these can display complexity! Error correction can be in the class of channels that can be implemented with resets. It was amusing to find a way to implement a 2300 year old algorithm on a quantum computer.

Inspired by classical methods developed to estimate the width of chaotic regions, we succeeded in estimating the energy width of an ergodic region for a quantum analog to the sinusoidally perturbed Harper model. The estimate required averaging the perturbation within the interaction picture. See [52].

6 Galaxy Dynamics

In 2011, I, graduate student Justin Comparetta and undergrad Michaela Bagley ran 3 extra million massless particle tracers in a N-body Galactic simulation (accelerated on the GPU and modeled after the Milky Way) so that we could resolve and search for structure in local velocity distributions (phase space)[53]. We made a series of predictions, some of which are supported by recent studies with GAIA observations and other more recent Galactic surveys. We predicted structure (gaps in the local velocity distributions) everywhere in the Galaxy (and this seems to have been confirmed!). We suggested that gaps are associated with changes in spiral pattern speed rather than resonances. We predicted a three-arm structure near the Solar neighborhood that would be coupled to lopsided motion at larger radii. We predicted localized bursts of star formation (and with age gradients

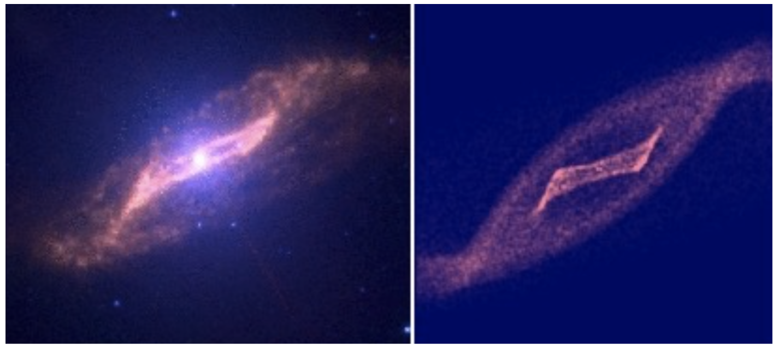

Figure 4: Shown below on the left is a multi-color mid-infrared image of Centaurus A from Spitzer images and on the right is the model with warp seen in emission. The model is based on the model in my thesis that I used to match sub-millimeter kinematics and ground based near-infrared images.

moving across the Galaxy) caused by peaks from interference between spiral patterns (and building on our previous study of M51 [54]). Previous work had not carried out such a detailed study using an N-body simulation possibly because many particles are needed to resolve structure in both spatial and velocity dimensions.

Our recent work includes the discovery of vertical asymmetry in the Galactic disk velocity distribution (with the Galah survey team; [55] and then confirmed with GAIA data by Giacomo Monari [56]), a measurement of Galactic acceleration using binary pulsars ([57]; with Sukanya Chakrabarti), a new proposed mechanism associated with spiral arms for causing structure in the local velocity distribution [58], and a study of the birth recent locations of moving groups including their vertical motions ([59] with John Gagné and Alex Pettitt).

In 2015 I, with visiting undergraduate student Alex de la Vega, investigated epicyclic phase wrapping [60] associated with external perturbations as a possible explanation for the vertical gradients detected in the outer Galaxy. This work offers a simpler and alternative explanation (compared to breathing and bending modes) for these recently detected gradients and builds on our previous work searching for disk structures in the outer galaxy using stellar number counts [61], our proposal that stirring in the outer galaxy is more likely induced by perturbations from dwarf galaxy encounters [62] rather than migration associated with spiral density waves [63], and our proposal, led by Ivan Minchev, that there could remain kinematic evidence of these past structures in the velocity field [64]. This last prediction was recently confirmed with GAIA observations. I found that spiral perturbations could cause chaotic behavior near a bar's resonance (leading to a paper entitled *Chaos in the solar neighborhood* [65]). I proposed a resonant heating model to account for peanut shaped bulges [66], following the discovery of such a bulge in our Galaxy and using N-body simulations to test the model.

7 Infrared extragalactic studies and warped disks

My graduate thesis focused on ground based observations in sub-millimeter and near-infrared wavelengths of the nearest radio galaxy Centaurus A [67, 68]. With a dark and curved dust-lane across its center, the elliptical galaxy hosts a warped star forming disk that is dark at visible wavelengths, but emitting in the mid-infrared and sub-millimeter. My warped disk model was predictive. Shown below on the left is a multi-color mid-infrared image of Centaurus A from Spitzer images and on the right the model with warp seen in emission, modified from that used to match the sub-millimeter kinematics and the ground based near-infrared imaging (with warp seen in absorption) developed in my thesis. Centaurus A was one of the first targets observed by the Spitzer Space Telescope and the earliest science demonstrations of its success also presented my model [69].

I proposed a new mechanism for generating a warp from feedback, the *wind driven warp instability* [70] (an alternative to the radiative warp instability) and applied a warped disk model to the radio galaxy M84 but on a much smaller scale [71] (the central few hundred parsecs rather than a kilo parsec). The dynamics of a galactic warp is a set of circular rings that precess slowly in a background potential. Deviations from this in M84 suggested in 2000, prior to the Chandra era, (and later on in the nucleus of Cen A, [72]) that feedback from ambient hot gas could push and reorient dusty disks [71]. In Centaurus A if you look closely near the center on the left, there is a faint elliptical feature, a shell, that is not present in the model on the right (first seen in these images) [73]. Subsequent Spitzer spectroscopic observations demonstrated that the shell has different spectral characteristics than the star forming disks [74], so it could be a counterpart to expanding hot bubbles that have been seen in active galaxies and recently discovered in our Galaxy (the Fermi bubble). It would be interesting to reexamine models for dusty disks in galaxy centers in a more modern context of active galaxy feedback.

8 Infrared imaging and constraints on dark matter in galaxies

At Ohio State, in 1994 as a postdoc, I joined a near-infrared survey of nearby galaxies, using one of the early large format near-infrared arrays and writing a series of papers on the structure of nearby galaxies as seen in the near-infrared [75, 76, 77, 78, 79, 80, 81, 82, 83]. I carried out a substantial fraction of the survey observations and data reduction. I developed an efficient convolution technique for estimating the mid plane gravitational potential using an image [83], and used that to estimate the torque on gas inflowing along a galactic bar [82] (fueling a nuclear starburst). I discovered a peanut shaped bulge in an inclined barred galaxy [78] where both peanut and bar could be seen simultaneously in the near-infrared. Using the gravitational potential models produced directly from the images I wrote a series of papers looking at integrated stellar orbits, and placed constraints on the dark matter distribution in galaxies [76, 84, 85]. I used non-axisymmetric structures such as galactic bars and spiral arms to measure the mass to light ratio and then estimated the dark matter fraction by subtracting out the baryonic disk component. The series of papers supported a relationship between surface brightness and dark matter concentration `http://arxiv.org/abs/astro-ph/9811024v1` where brighter galaxies contain little central dark matter. The paucity of dark matter in the centers of high surface brightness galaxies continues to present challenges for models of galaxy formation.

9 Observations of Active Galaxies

Using high angular resolution near-infrared imaging by the Hubble Space Telescope, and while at Steward Observatory, I wrote a series of papers studying ionization cones and emission line morphology in active galaxies [86, 87, 71]. With Almudena Alonso-Herrero and others, we discovered that most Seyfert galaxies host unresolved nuclear point sources, more easily detectable in the near-infrared, and demonstrated through their variability and with correlations with other activity indicators that these unresolved sources were associated with accretion onto a black hole [88, 89]. Subsequent spectral energy distributions (with Almudena Alonso-Herrero) showed that spectral energy distributions were inconsistent with a sharped edged torus model (there are too many intermediate Seyferts) and so requires a dusty torus that is clumpy [90]. I carried out a survey of elliptical galaxy cores [91], and placed constraints on extinction in galaxy centers using Pa-α emission, giving early evidence that most H-α radiation escapes, even in starburst galaxies [92].

With graduate student Alex Hubbard, I proposed a new mechanism for formation of a lopsided or eccentric disk near a massive black hole [93]. Andy Gould and I proposed a mechanism for capture of stars such as SO2 on highly eccentric orbits near the black hole at the Galactic center [94]. During a visit to the Technion in 2001, I proposed with Avi Laor that the intermediate mass black hole in NGC 4395 could be measured in only a few days with UV observations on HST and using reverberation mapping techniques [95] (unfortunately my coordinated ground based infrared photometric variability campaign at the IRTF was clouded out).

I was funded in observational astronomy via observing proposals to the Hubble Space and Spitzer Telescopes. The following are those for which I was principal investigator.

Title: IRS mapping of the 500pc nuclear dust shell in Centaurus A Award Period Covered: 08/10/06 -08/31/09 Source of Support: JPL/Spitzer Science Center, Total Award Amount: $86,305

HST Cycle 7 proposal 7868: Near-IR Cores of Radio Galaxies, Are the AGN's Moving in the Galaxy?

HST Cycle 7 proposal 7869: The Morphology of Dense Gas in Seyferts, Obscuration and Fueling of AGNs

HST Cycle 7 proposal 7886: NICMOS Snap Shot Survey of Early-Type Galaxies

HST Cycle 15 proposal 10972: The structure of HD100546's self-shadowed circumstellar disk

HST Cycle 7 proposals received funding in 1998 and HST Cycle 15 proposals in 2006.

10 Light curves and the transient dimming sky

Transient sky surveys or optical monitoring programs that measure light curves of many stars focus on finding objects that brighten (novae, gamma ray bursts) or are periodic (planet transits) and they do not systematically search for stars that dim infrequently. Stars that host eclipsing circumsecondary disks have only been found through serendipity. Dippers (young stars with dips in the light curve) in the Kepler K2 mission archive and Boyajian's star (all stars that dimmed) were found via a citizen science program – *the planet hunters* (people looking by eye and flagging weird regions in the millions of light curves). To address this problem I wrote in 2011 the section in the J1407 discovery paper (with Eric Mamajek) estimating the likelihood that a survey would find a circumsecondary or circumplanetary disk in occultation and showing that the probability is not necessarily low [96]. I carried out the first systematic survey (of 40000 stars and using the 2MASS calibration database) blindly looking for stars that dim [97]. With visitor Zeyang Meng we developed an automated way of identifying eclipses from disks that were present in eclipsing binary catalogs [98].

With graduate student Eva Bodman, we developed a comet evaporation model for Boyajian's star [99] (publishing the first scientific paper on interpretation of dips in its light curve and following Jason Wright's alien megastructure proposal). We proposed a magnetospheric truncation *unification* model for the K2 dippers, offering an explanation for why so many low mass stars exhibit this phenomena [100] (truncation radius must be below dust sublimation temperature and the magnetosphere lifts dust letting us see it passing in front of the star). We have also proposed a new mechanism for infrared light curve variability involving heating the edge of a circumbinary disk [101]. I encourage searches in photometric surveys for objects that dim, with the goal of making it possible for novel and rare dimming objects to be followed up right away spectroscopically, rather than only being identified after they happened (via serendipity) and when it's too late to observe them during the occultation. Occultations could be exciting and powerful as they would allow measurements on milli-AU structures of disk material (ring structures, gaps in disks) and measurements of composition (through spectroscopic studies as material passes in front of and absorbs light from the star). I would like to propose for exploratory time-sensitive observing of some known young stars with occulting material to see if spectroscopic follow up will be interesting. I expect more exotic phenomena will be discovered via synoptic surveys and these will become increasingly exciting in the next decade.

11 Turbulence, Winds and Feedback

In 2005, motivated by Spitzer imaging of young clusters, we tested the idea that jets and winds from young stellar objects are responsible for turbulence in the molecular cloud associated with star formation region NGC 1333. Lacking any direct association between young stars and motions in the molecular cloud, but finding many slow moving and large cavities in the molecular cloud, we proposed that cavities, or remnants of past outflow activity, are an important and necessary intermediary between young stellar outflows and molecular cloud turbulence [102]. This led to a series of papers in collaboration with Adam Frank and graduate students in his group on simulations of stellar outflows and how they disturb molecular clouds. Graduate student Adam Rubinstein discovered a protostar jet that we suspect is locally and rapidly dissipated possibly due to its wide precession angle. Jets that vary their propagation angle are unlikely to puncture a molecular cloud but instead could cause local disturbances [103].

With graduate student David Trilling I proposed that planets would drive outflows during accretion, though this phenomena has yet to be detected [104]. With an analogy to the Yarkovsky effect, graduate student Jean Teyssandier and I proposed the outflows from planets could cause exoplanet orbital drifts [105]. Joss Bland-Hawthorn and I proposed that star formation can be episodic due to feedback delay and using a delay-differential equation model [106].

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