EVOLUTION OF CIRCUMSTELLAR AND CIRCUMPLANETARY DISKS. P. R. Estrada[1,2], O. M. Umurhan[1,2] and U. Gorti[1], [1] Carl Sagan Center, SETI Institute, Mountain View, CA, USA; [2] NASA Ames Research Center, Moffett Field, CA, USA; (Paul.R.Estrada@nasa.gov).

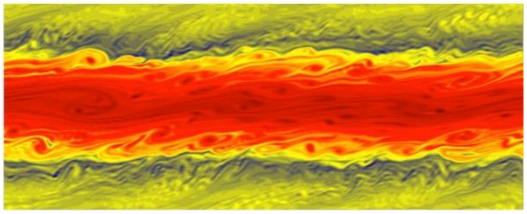

Figure 1: *Vortex field from a fully-developed Vertical Shear Instability in a secondary transition [11-12].*

Introduction: Planet formation appears to be extremely robust and moreover lead to a very diverse set of outcomes [1]. Our understanding of how planetary systems form and their resulting architectures and compositions is severely limited by the complexity of their natal environments. Planet formation is concurrent with star formation, a process where gravity, magnetic fields, radiation, chemistry and dynamics, all play significant roles, making this a highly coupled and non-linear problem that appears almost intractable. The disks that result after gravitational collapse during star formation and build the star at early stages, ultimately provide the raw material out of which planets form; they are therefore the ideal targets of study to help us provide the insights we need. Furthermore, the fact that all of the giant planets of our own solar system harbor “mini-solar systems” of their own suggests that satellite formation is an inevitable consequence of giant planet formation, and the structure, diversity and apparent order we see in these systems may also be informative to their circumstellar analogs. It is then essential to address these two promising avenues of study together in going forward – circumstellar or protoplanetary disks (PPD, hereafter), and their analogs, circumplanetary disks (CPD).

The dynamical state of PPDs (as well as CPDs) directly influences the manner and location of planetesimal (satellitesimal) formation. Indeed, the concept of planets forming in a static minimum mass nebula where the local temperature uniquely determines the chemistry through some invariable cosmic abundance has been replaced in favor of a continuously active disk in which structure and composition evolves both on local and global scales. This is because our understanding of the dynamical state of PPDs has undergone profound revision based on exciting new observations alongside theoretical and numerical advances over the last decade. This talk aims to broadly discuss theoretical understanding of PPD (CPD) structure, review new developments in the understanding of disk turbulence and its influence on particle growth, and examine the issues that confront the question of disk evolution and its pertinence to planetesimal (satellitesimal) growth.

Planetesimal formation in evolving disks: Herschel, Spitzer and now ALMA have demonstrated that PPDs are very diverse. Since the bulk of the mass in the disk is contained in the gas component, and since growth from small dust particles into planets depends on the gas surface density profile, understanding the evolution of gas is paramount in understanding planetesimal formation. Gas disks evolve primarily through accretion over most of their lifetime. Accretion transports mass onto the central star, and angular momentum outwards. Material at the disk surface can be launched into a wind, thermal and magnetically driven, which results in the disk eventually losing its gas. The availability of gas as a function of radius and time, in turn, affects ongoing planet formation in the disk. Some of the key questions facing our understanding PPD evolution include: (a) Quantifying the efficiency of angular momentum transport which, in turn, involves identifying and constraining the spatio-temporal sources and intensities of turbulence in PPD which influences (b) the gas mass in disks as a function of r and time. Our current estimates of the gas content are uncertain by orders of magnitude [2]. Data derived from future far-infrared facilities (e.g., SOFIA, SPICA, OST) will inform us, but this issue will remain a challenge for decades to come. On the other hand, the gas mass in CPDs at the time of satellite formation may be easier to infer [8,9], and given the inevitability of detecting satellites around giant exoplanets, this is sure to be an area of study ripe for exploration.

Turbulence: PPDs are generally classed into regions that are sufficiently ionized to merit a magnetohydrodynamic description or those that are sufficiently neutral to be considered as a hydrodynamic flow. Magnetized disks are known to support dramatic dynamical activity in the form of jets and MRI turbulence [5-7]. However, the zones supporting MHD processes are either too close to the parent star (<1-5 AU) or too far out (>100 AU) [10] leaving out the bulk of the disk where the majority of planet construction is thought to take place -- this has remained an outstanding theoretical issue for almost a decade.

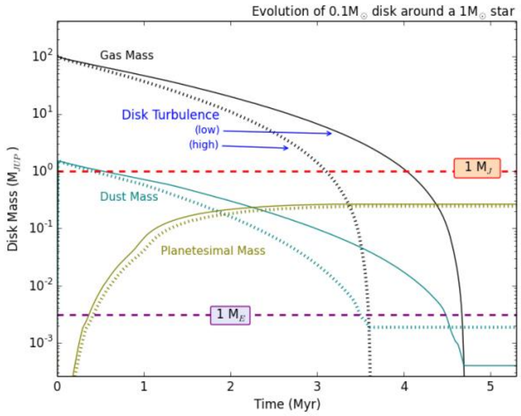

Figure 2: *Evolution of disks with different levels of turbulence, incorporating dust collisional processes, gas photoevaporation and plannetesimal formation by the streaming instability.*

Non-ionized zones of PPDs, once considered "Dead Zones" [6] because no turbulence inducing instabilities had been theoretically identified to robustly operate in Keplerian sheared stratified environments, have recently been shown to be susceptible to three new linear instability mechanisms and demonstrated to lead to a moderate degree of turbulence. The mechanisms involved will be reviewed [12-14] and a picture of their secondary cascade to turbulence in a PPD environment will be discussed (see Fig. 1). Additionally, we examine settings and locations where these processes are thought to occur and discuss their dependence on the thermodynamic properties of the disk, including opacity and temperature structure.

Particles in turbulent environments: [15] have recently published models following the growth and fate of particles in quasi-two dimensional PPD models following the growth of various species of grains under the influence of turbulent viscosity, and other environmental factors affecting the mean Rosseland opacities, temperature structure and density distribution of the disk. The turbulent mixing of grains of a given size influence the effective gas opacities of the disk material which, in turn, affect the continuance or abatement of the aforementioned linear instabilities that lead to turbulence. We discuss the physics of this process and highlight its importance in understanding how planetesimals lead to asteroid scale bodies.

Evolution of gaseous and dusty disks: Recent disk evolutionary models [3-4] show that planetesimal formation occurs in a very dynamic environment. While our knowledge of how gas in the disk is dispersed and how small sub-micron sized dust particles accumulate to form planets remains incomplete, these results highlight the importance of turbulence in the disk not just in how it influences particle growth, but also global transport of solids and condensables; gas disk dispersal times depend on the level of turbulence, as does the rate at which particles grow and drift radially with time (see Fig. 2). Once planets have formed, the available mass reservoir dictates the likelihood of gas accretion to form Jovian analogs, their final mass, that of the CPD and ultimately the total mass of satellites and perhaps even their structure (see Fig. 3).

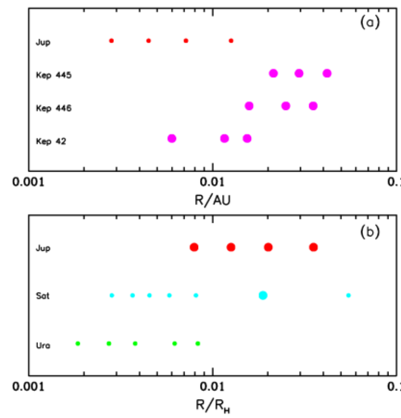

Figure 3: *(a) Architecture of selected Kepler systems. Jovian system included for comparison. Adapted from [16]. (b) Giant planet systems in terms of Hill sphere.*

Dynamical structure of exoplanet systems: Exoplanetary system discoveries will continue to revolutionize our understanding of planet and satellite formation. Most systems discovered to date are observationally biased in the sense that the lion's share of systems discovered are compact (see Fig. 3a). It is still not clear whether exoplanet system architectures like our own are common or not, but future observations should fill in the gaps between these compact systems and those (some directly imaged) with giant planets very far from their parent star. But there is potentially much to learn from within our own solar system because CPDs have produced compact systems that perhaps display a "progression" of structure which may be linked to CPD gas mass, and the amount of gas in the nebula at the time of their formation (see Fig. 3b). Understanding more about the Uranian system at the same level as Jupiter and Saturn would be an important step.

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