Small-Scale Substructures in Protoplanetary Disks

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strong "feedback" between disk structures and planets



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two perspectives on the *substructures* / planets link

1) indirect

fluid instabilities; steep ∇ in materials





Bai 15

Dipierro+14

M. Flock

perturbations concentrate solids, promoting planetesimal formation



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Dipierro+14

M. Flock

perturbations concentrate solids, promoting planetesimal formation

2) direct

dynamical sculpting (+ instabilities)





Bae+ 17

C. Baruteau Zhu+ 14

perturbations reveal masses and architectures of planetary systems

substructures control the evolution of disk solids



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key tracer is high-resolution microwave continuum emission



ESO / C. Malin

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ALMA can access ~30 mas (4 au) scales emission (optical depth) contrasts ~few %

ESO / C. Malin

to date, ALMA data for only 2 disks at <5 au resolution

(published; more coming...)

HL Tau (290 GHz)



ALMA Partnership+ 15; Akiyama+ 16

TW Hya (290 GHz)



Andrews+ 16; Huang+ 18

these substructures are small, and ~optically thick



ALMA Partnership+ 15; Carrasco-González+ 16

Andrews+ 16; Tsukagoshi+ 16; Huang+ 18

hints of pervasive *substructures* at ~10-20 au resolution

e.g., Zhang+ 16



van der Plas+ 17



Pérez+16



Cieza+ 16



Loomis+ 17



Isella+ 16



Fedele+ 17

A Survey of Protoplanetary Disk Substructures

an ALMA "Large Program" (~70 hours)

co-Pls: Dullemond, Isella, Pérez co-Is: Bai, Benisty, Birnstiel, Carpenter, Guzmán, *Huang*, Hughes, Öberg, Ricci, Wilner, Zhu

<u>goals</u>: prevalence, forms, scales, spacings, symmetry, amplitudes of substructures in a representative sample of "normal" disks

plan: 240 GHz observations of 20 disks at ~5 au resolution, ~17 μ Jy/beam 20 disks at ~3-5 au resolution, ~12-15 μ Jy/beam



Andrews+ 2018, in preparation

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(look for first papers, and the data product release, in fall 2018)









Andrews+ 2018, in preparation

concentric rings / gaps are most common substructures

Huang+ 2018b, in preparation

a few (spectacular) cases of spiral pattern substructures

Huang+ 2018c, in preparation

azimuthally asymmetric *substructures* are rare (~10%)

Pérez+ 2018, in preparation Benisty+ 2018, in preparation Isella+ 2018, in preparation ...and many other related issues to be explored...

geometric constraints on turbulence

Weaver+ 2018, in preparation

multiples: dynamical perturbations at high q

Troncoso+ 2018, in preparation

additional features accessible in gas tracers

Guzmán+ 2018, in preparation

some things to consider:

existential

(probably) all disks have substructures; is there really a "smooth" (large-scale) component at all?

is there an evolutionary sequence, or a higher dimensional behavior explaining diversity?

practical

are the substructures generally optically thick?

can we associate features we trace in solids with gas?