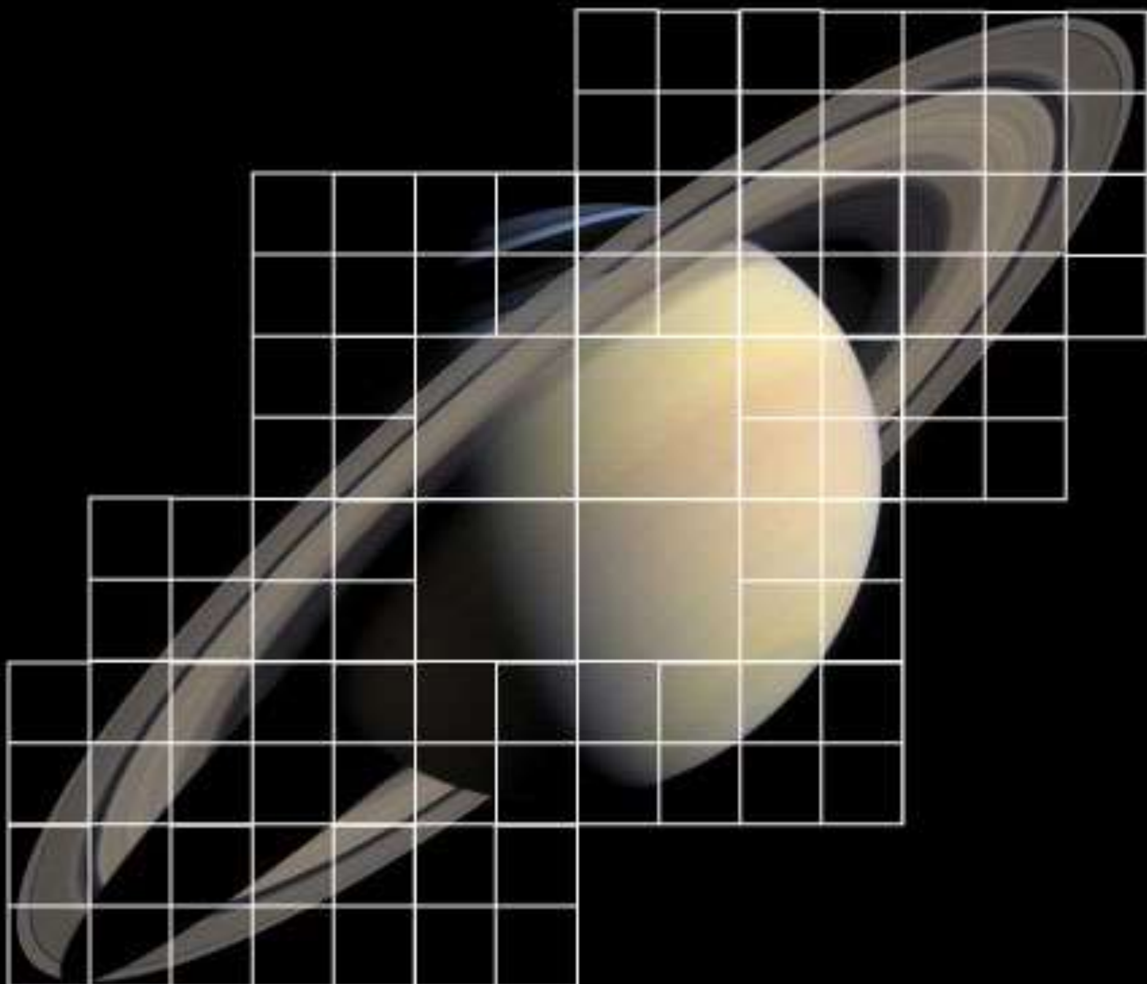
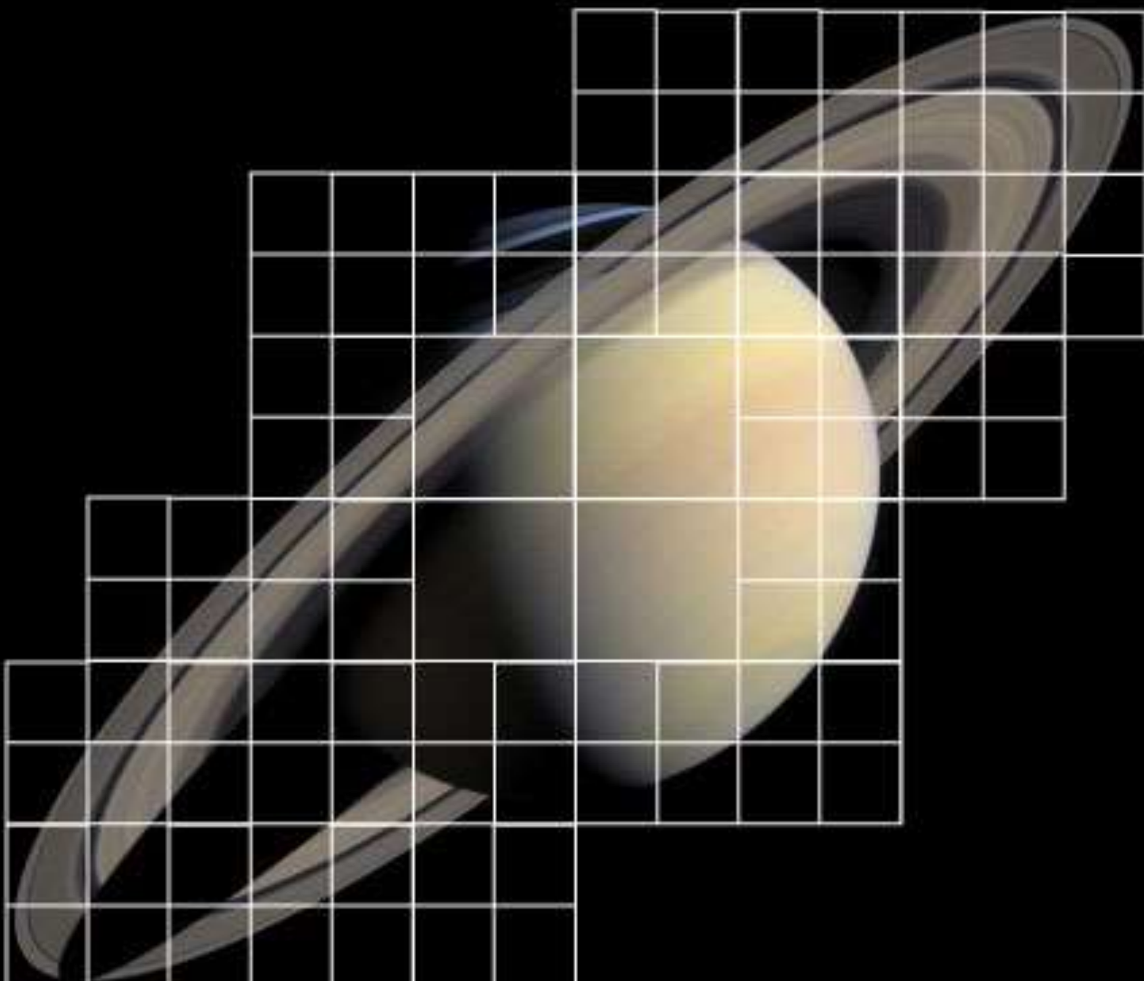
MODELING OF LARGE-SCALE SYSTEMS



K.C. Hansen
University of Michigan
Center for Space Environment Modeling

MODELING OF LARGE-SCALE SYSTEMS
(WHAT DOES THE COMMITTEE REALLY WANT FROM ME?)



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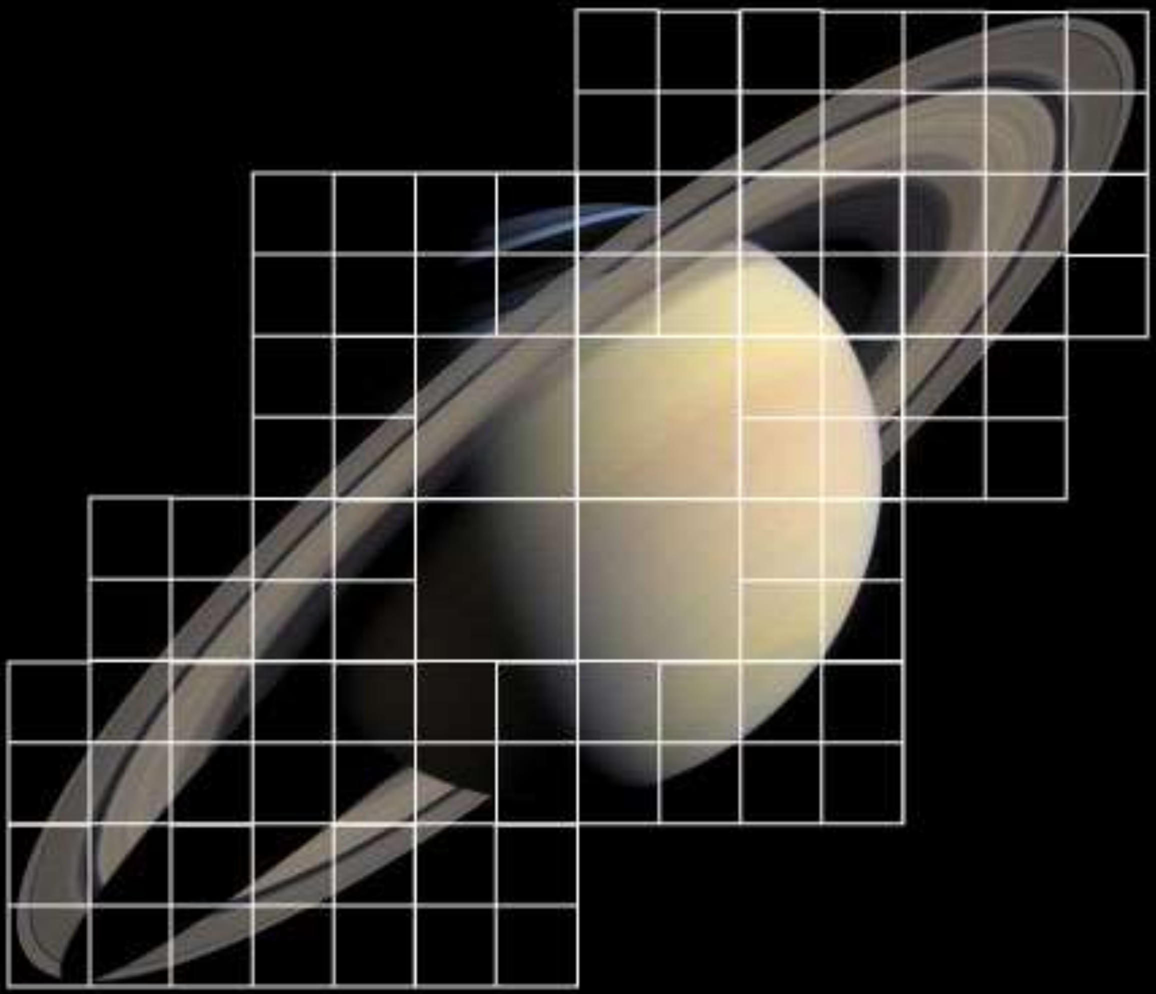
MODELING OF LARGE-SCALE SYSTEMS

(OOPS ... MARGY IS GIVING THAT TALK)



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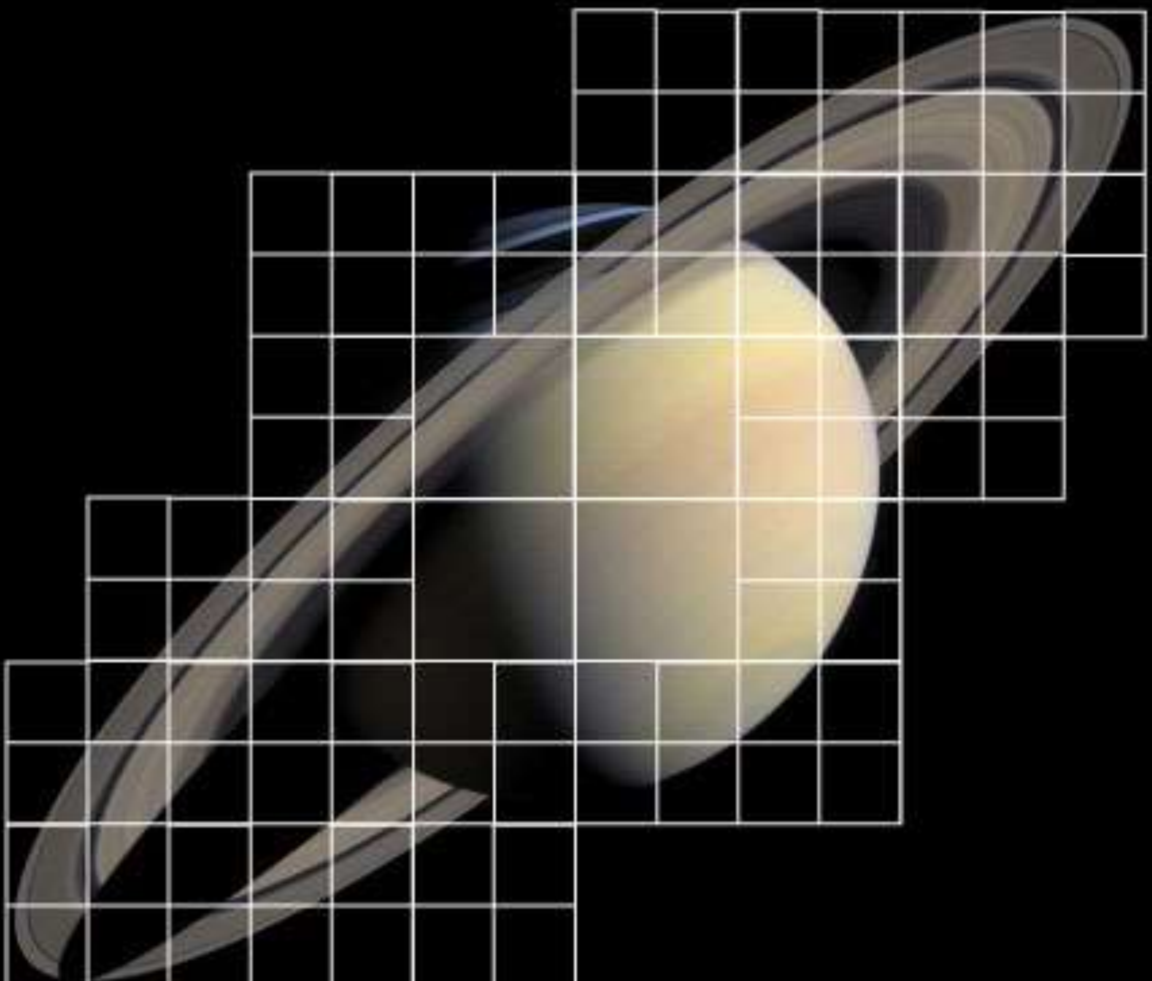
MODELING OF LARGE-SCALE SYSTEMS

(NO ... XIANZHE IS GIVING THAT TALK ...
AND HIS WILL BE BETTER ANYWAY)



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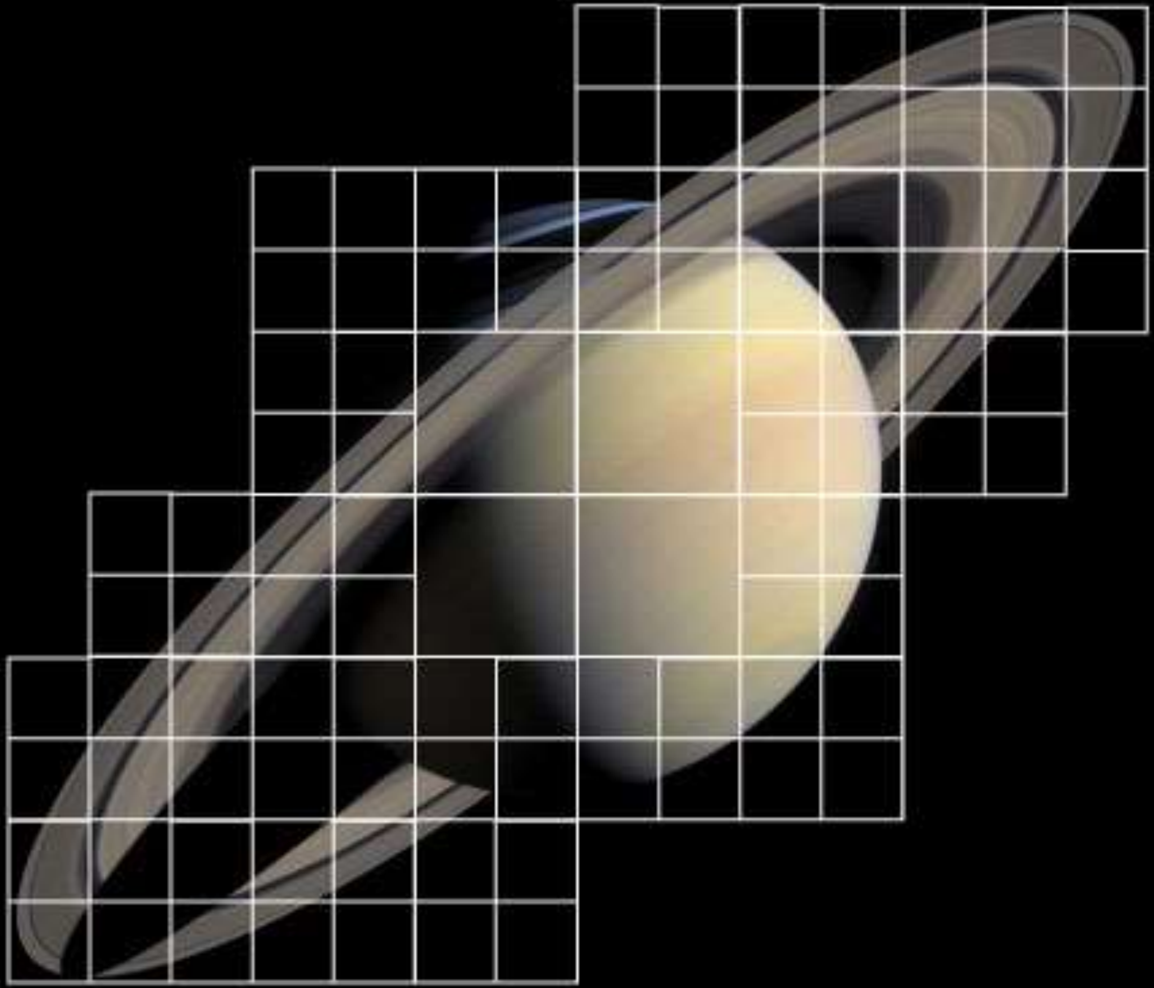
MODELING OF LARGE-SCALE SYSTEMS

(CRAP ... THE ABSTRACT DEADLINE IS TODAY)



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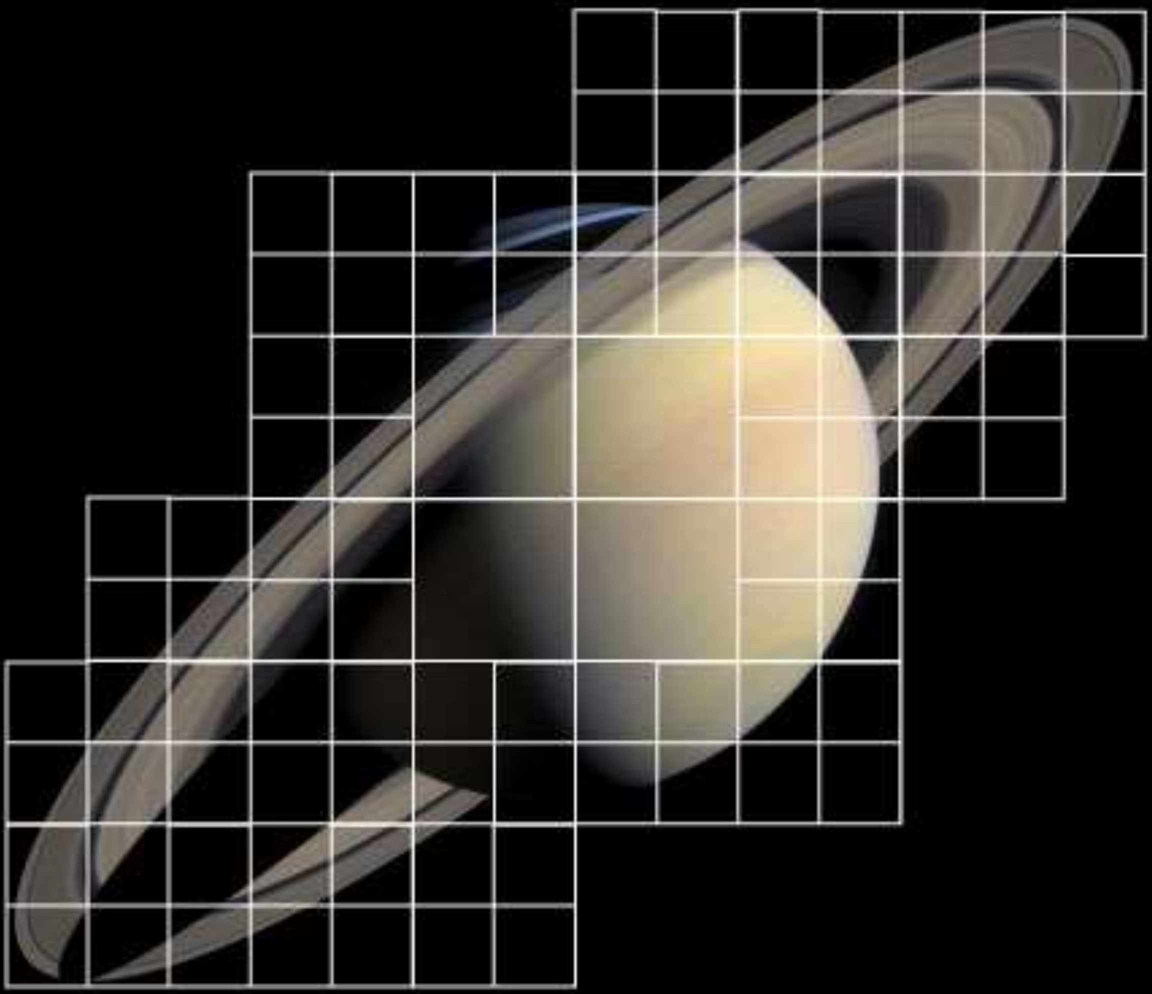
MODELING OF LARGE-SCALE SYSTEMS

(MODELING CHALLENGES AND COMPARISON TO BUILDING AN INSTRUMENT)



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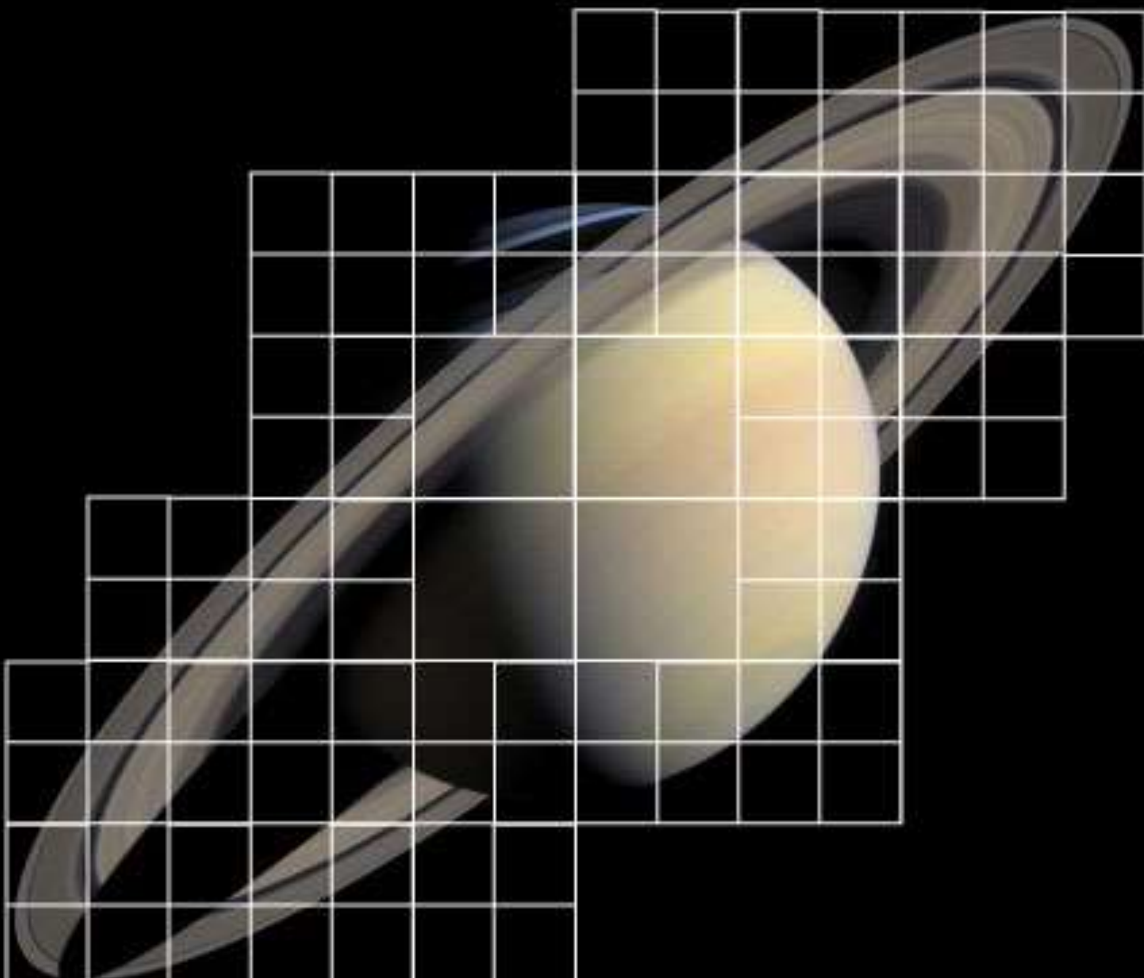
MODELING OF LARGE-SCALE SYSTEMS

(CRAP … I'M THE VERY LAST TALK … THEY MUST HAVE HATED MY ABSTRACT)



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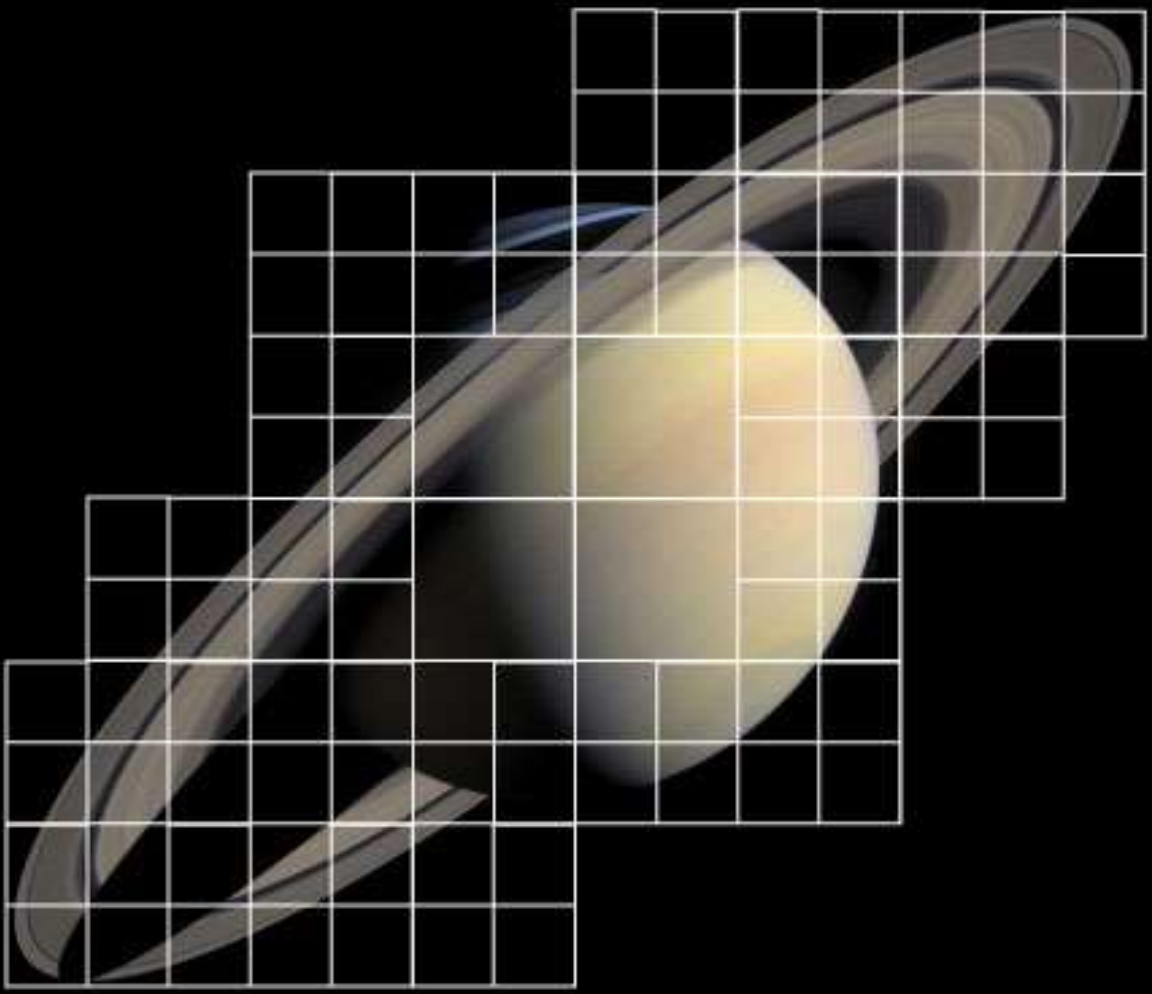
MODELING OF LARGE-SCALE SYSTEMS

(FRAN SAYS … I PUT YOU THERE BECAUSE YOU SHOW ENTERTAINING MOVIES TO KEEP PEOPLE INTERESTED SO THAT THEY WILL STAY UNTIL THE END)



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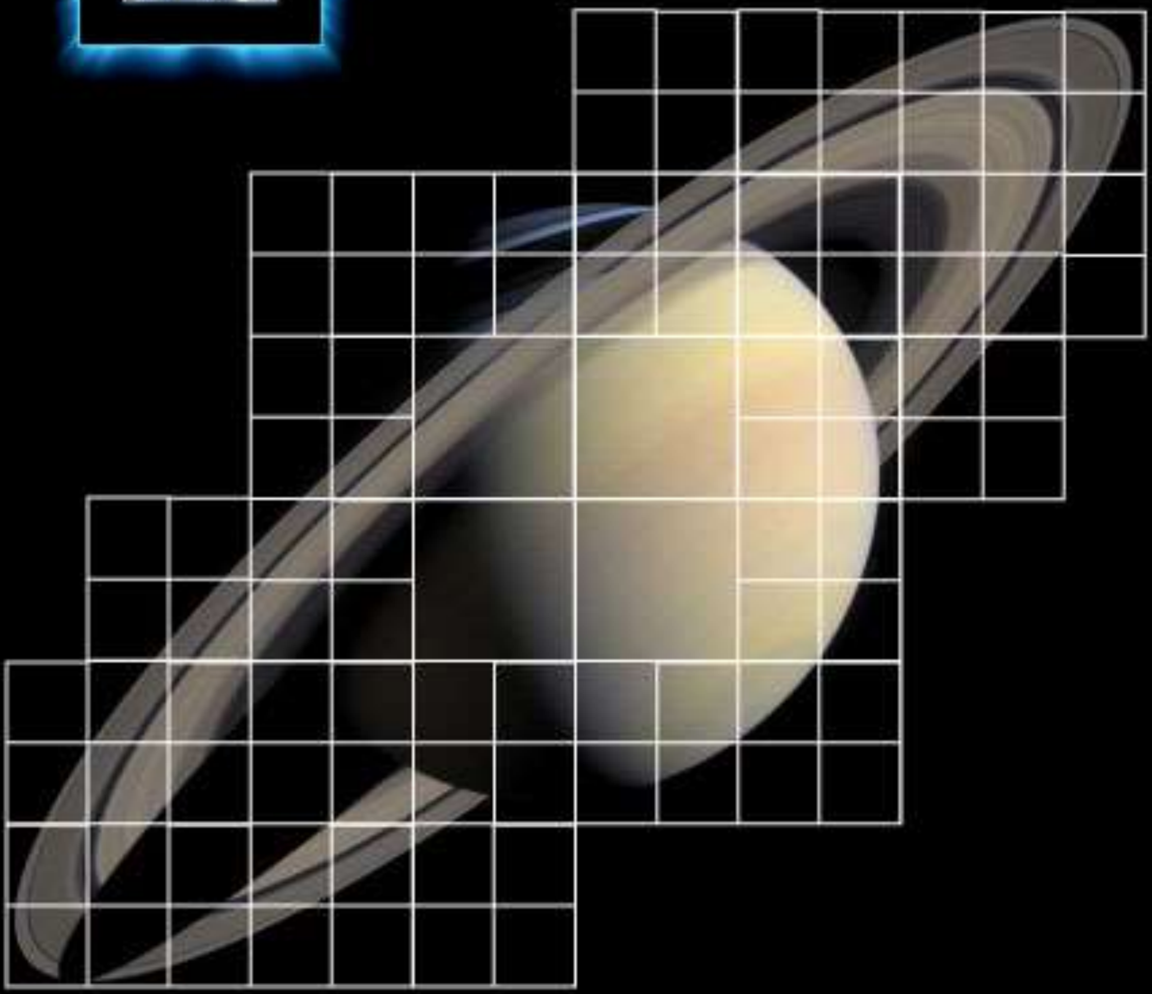
CENTER FOR SPACE ENVIRONMENT MODELING

CSEM

MODELING OF LARGE-SCALE SYSTEMS

(MODELING CHALLENGES AND COMPARISON TO BUILDING AN INSTRUMENT)



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University of Michigan

Center for Space Environment Modeling

- and –

Modelers Everywhere

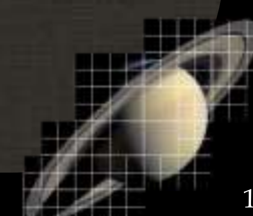
Take Home Message

- Developing a high quality, large-scale simulation model is comparable in scope to designing and building a spacecraft instrument

- Using these models is similar in complexity to using and interpreting spacecraft data

- There are many challenges that must be overcome when developing and running these models

Yes … I did get contacts?



Model vs Instrument Development

How much ?

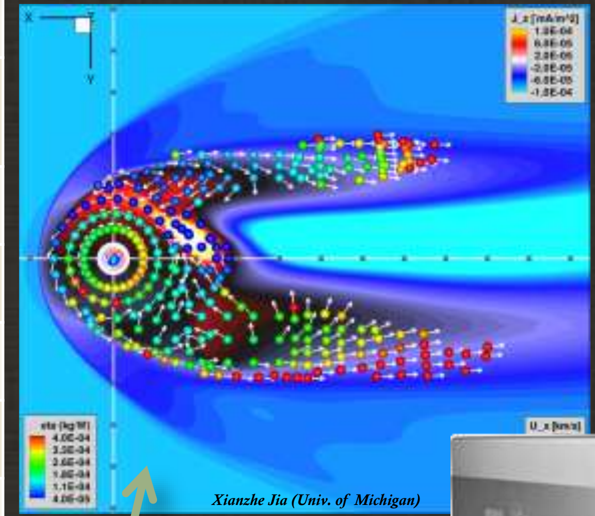
	Michigan MHD Model BATSRUS/SWMF	MIMI Instrument/Cassini Huygens
Years (Development)	15	7+7
Years (Science)	15	9
Cost (Development/Operations)	~$20 M	~$30 M
Cost (Science)	~$15 M	~$10 M
Development /Operations FTEs	~10	~15
Objects studied	21	7
	Sun, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Io, Europa, Enceladus, Titan, 6+ comets, Heliosphere, Extra-solar star-planet interaction	Jupiter, Saturn, Enceladus, Rhea, Dione, Titan, Heliosphere
Funded by	NASA/DOD/NSF – Mostly space weather applications	NASA-Cassini/Huygens mission
Mass	400,000 Lines of code	16 kg
Wow …	~$50/Line	~$1.5 M/kg
Required!	Validation	Calibration

Xianzhe Jia – Profile of a Modeler

Metric	Value
CPU Hours Used (2010)	~ 1,000,000
Equiv. number of full time processors	128
Annual value of those processors	~$500,000
For a Typical run	
Number of cores	256 – 512
CPU Hours	50,000
Wall time	12-24 hr
Time in queue	2-48 hr
Preparation time	Days
Times to try each run before success	2-4
Size of output files	1GB per hour simulated
Typical number of hours simulated	1000-2000 hr

★ The Modeler

★ The Stats



★ The Model

★ The REALLY large hard drives on the modeler's desk

Multiple Length Scales

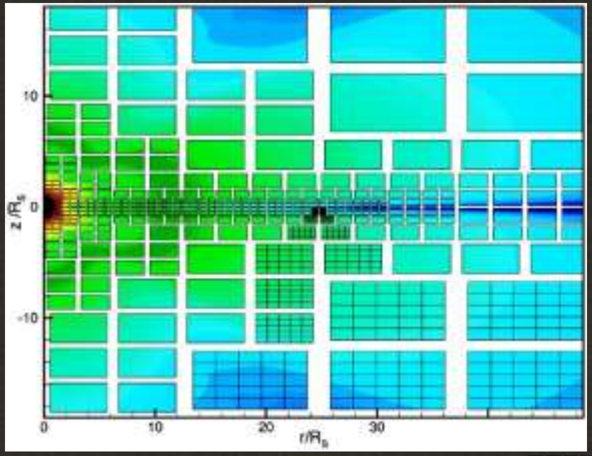
- 2000 R_J Jupiter's magnetotail (> 4AU)
- 100 R_J Jupiter's bow shock
- 1 R_J Boundary Conditions
- 0.5 R_J Current sheet thickness
- .025 R_J Io's radius

$$2000\ R_J\ /\ 0.\ 025\ R_J\ =\ 80{,}000\ \approx\ 2^{16}\ !!!$$

Options?

☒ Use 2^{16} cells and wait a lifetime for the run to finish

☑ Develop some kind of non-uniform grid

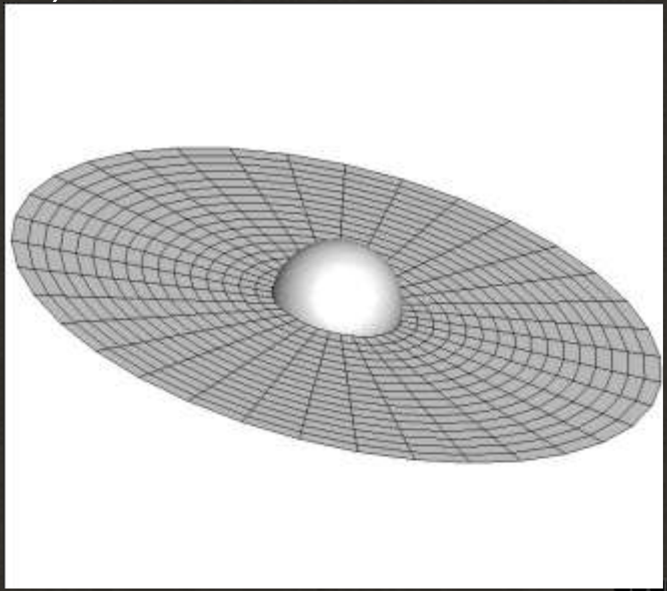


- CFL condition (Courant–Friedrichs–Lewy)

$$\frac{u \cdot \Delta t}{\Delta x} \leq C$$ → What speed is u? → The fastest wave speed

- Run time in 3D simulations
  - ≈ #of cells and Δt
  - ½ the cell size (double the resolution)
    - 8x more cells
    - ½ the time step
    - Run takes 16 times longer!

- Square peg in a round hole
  - Spherical planets on square grids
  - Obvious mismatch
  - Hard to get boundaries right
  - Hard to resolve scale heights



Canadian Football League?

Under-resolved Features and Numerical Errors

- Numerical discretization results in deviations which mimic physical attributes
  - Resistivity
  - Viscosity
  - Diffusion
- These may not be "wrong" but they are not well characterized and generally cannot be quantified and/or controlled

- Under-resolved Features
  - Are not necessarily "wrong"
  - But … understanding what is valid and what might not be requires significant experience
  - Will expand until they are resolved (3-5 grid points)
  - Can result in increased transport rates, diffusion rates, …

Strong magnetic fields

Steep gradients → Very hard to resolve

*Separate intrinsic field from the perturbation field
*Grid that matches field line shape

High wave speeds → Very small time steps

*Boundaries at 2-5 R_p instead of 1 R_p
*Semi-relativistic MHD

- MHD has unbounded wave speeds

$$V_A = \frac{B}{\sqrt{\mu_0 \rho}}$$


"I visited a scientist who had a helmet with magnetic fields controlled by computer sequences that could profoundly affect your mood and your perceptions."
-Douglas Trumbull

Overheard at a MOP meeting
"What are your boundary conditions?"

- Boundary conditions can control everything in a simulation!
- Wave reflections
- Whether or not magnetic field penetrates a body
- How plasma behaves at a surface
- Including and ionosphere

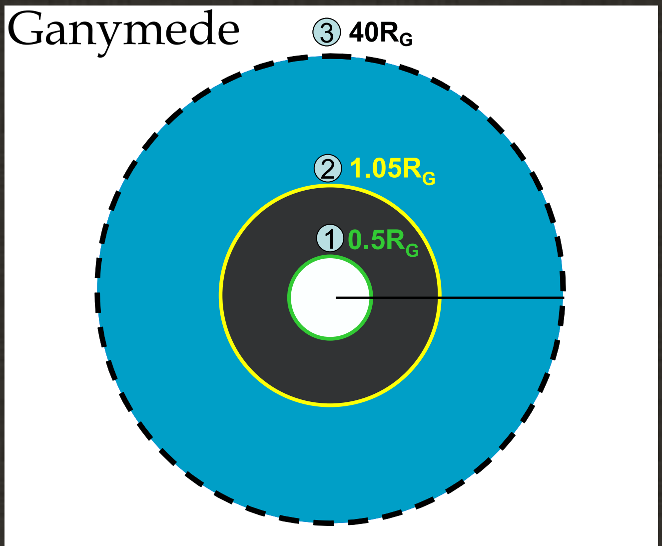
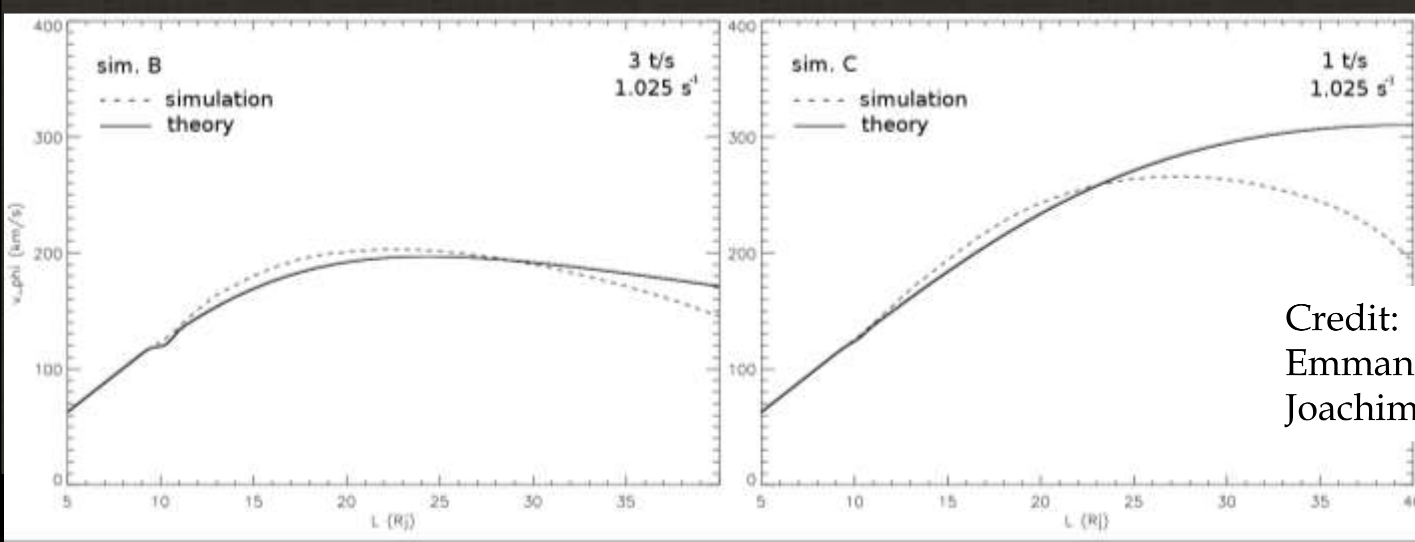


Figure 1. A cartoon showing the three boundaries in the simulation: (1) the core boundary (green circle), (2) the inner boundary (yellow circle), and (3) the outer boundary (black circle).

Credit: Jia, 2009

Physics (the good, the bad and the missing) - I

- The reality is that ALL models do some things CORRECT and some things with LIMITED or NO fidelity. A realistic consequence of this is:
  - Run the model, see what happens
  - Be realistic – under resolving the system, numerical limits, or leaving out some physics doesn't necessarily invalidate the results. However, you must understand the model's limitation and put results in the proper context
  - Just like with data – don't misuse, over interpret, ignore limits
- MHD
  - Does better than is should in most applications
  - Numerical resistivity, viscosity and diffusion mimic physical features, but are very difficult to quantify and/or control
- Source terms
  - A simple way to include non-MHD effects
    - Mass loading, momentum loading, charge-exchange, heating, "friction", …
  - Not described by CFL condition so can make solutions "stiff" – meaning more difficult to solve and require smaller time steps
  - Can be hugely important - but do not really solve the problem of missing physics

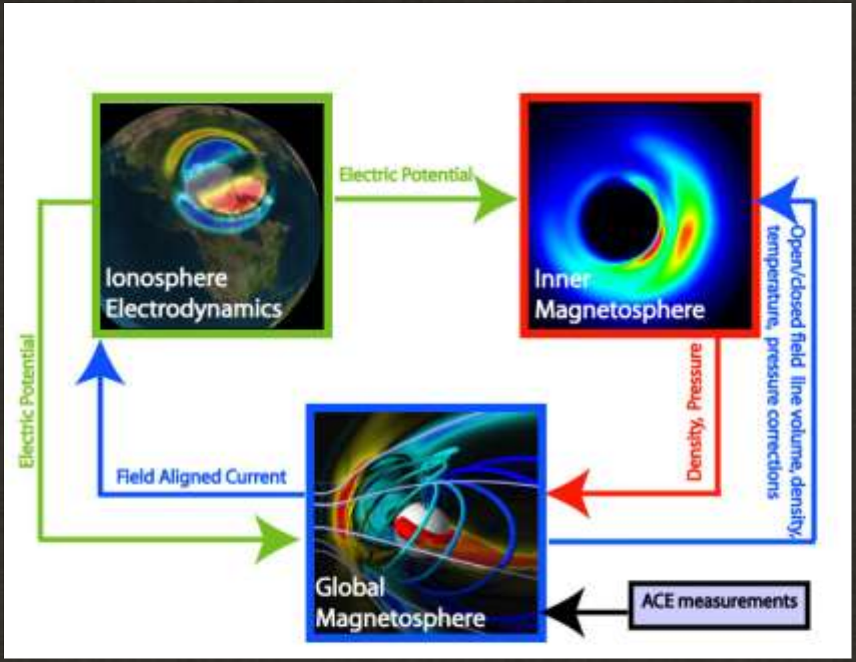


Credit:
Emmanuel Chané,
Joachim Saur

Physics (the good, the bad and the missing) - II

- MHD extensions
  - Including physics resistivity, viscosity, diffusion
  - Multi-species, Multi-fluid (electrons, ions, dust, …)
  - Hall-MHD, conductance models
- Hybrid
- Coupled Models

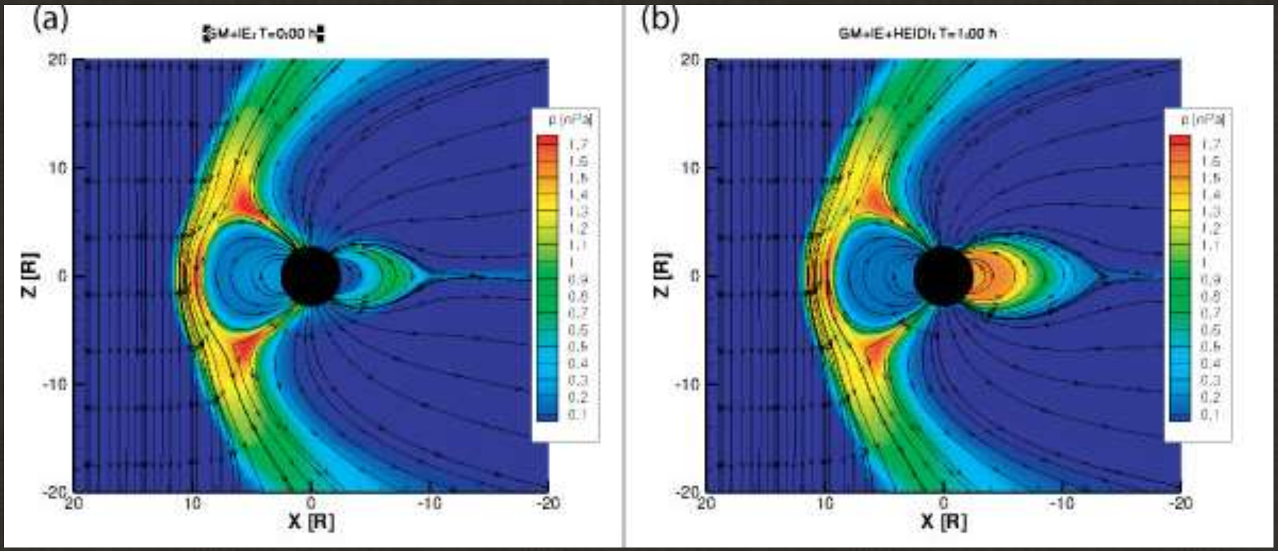
Coupling a Ring Current Model to MHD

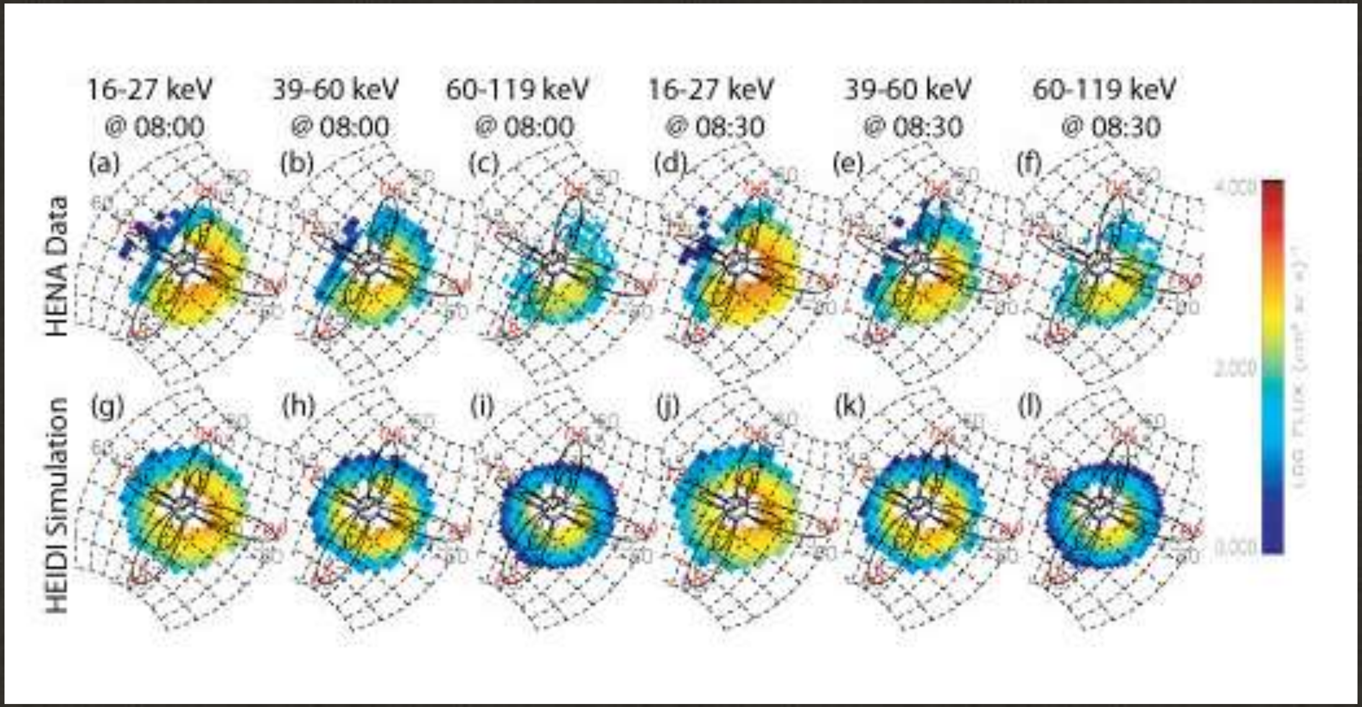


- For Earth: The SWMF already couples MHD with Ring Current (RCM or HEIDI)
- HEIDI solves the time-dependent, gyration- and bounce-averaged kinetic equation for the phase- space density f(t, R, φ, E, μ_0)
- Collisionless drifts, energy loss and pitch angle scattering due to Coulomb collisions with the thermal plasma, charge exchange loss with the hydrogen geocorona, and precipitative loss to the upper atmosphere.
- For Earth, the source term for the phase space density calculated by HEIDI is the outer simulation boundary, where particle fluxes must be specified. These fluxes are specified from GM.
- The numerical work was done to make the coupling work for the Earth. For Saturn we need to modify the source and loss terms and the boundary conditions followed by extensive validation.

Coupled HEIDI-MHD Results: Earth

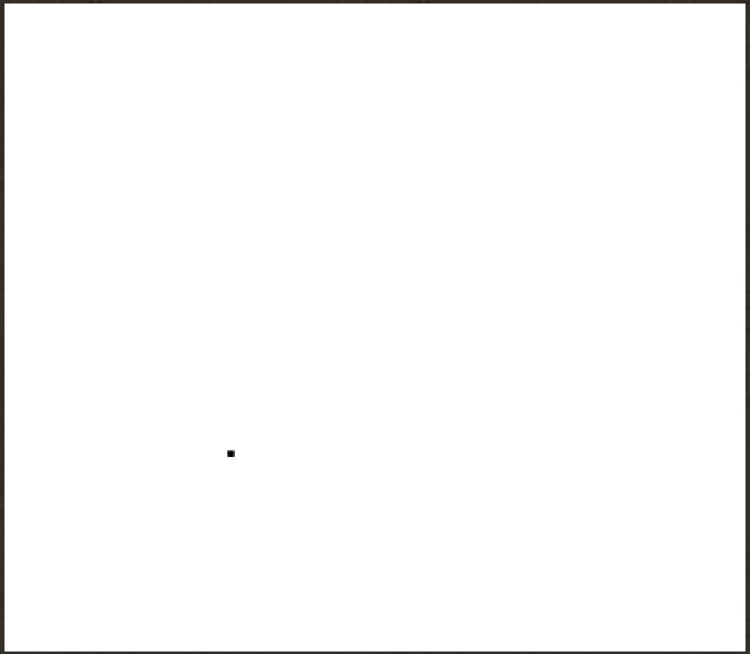
Affect of HEIDI in our MHD model





Comparison of HEIDI and HENA ENA images

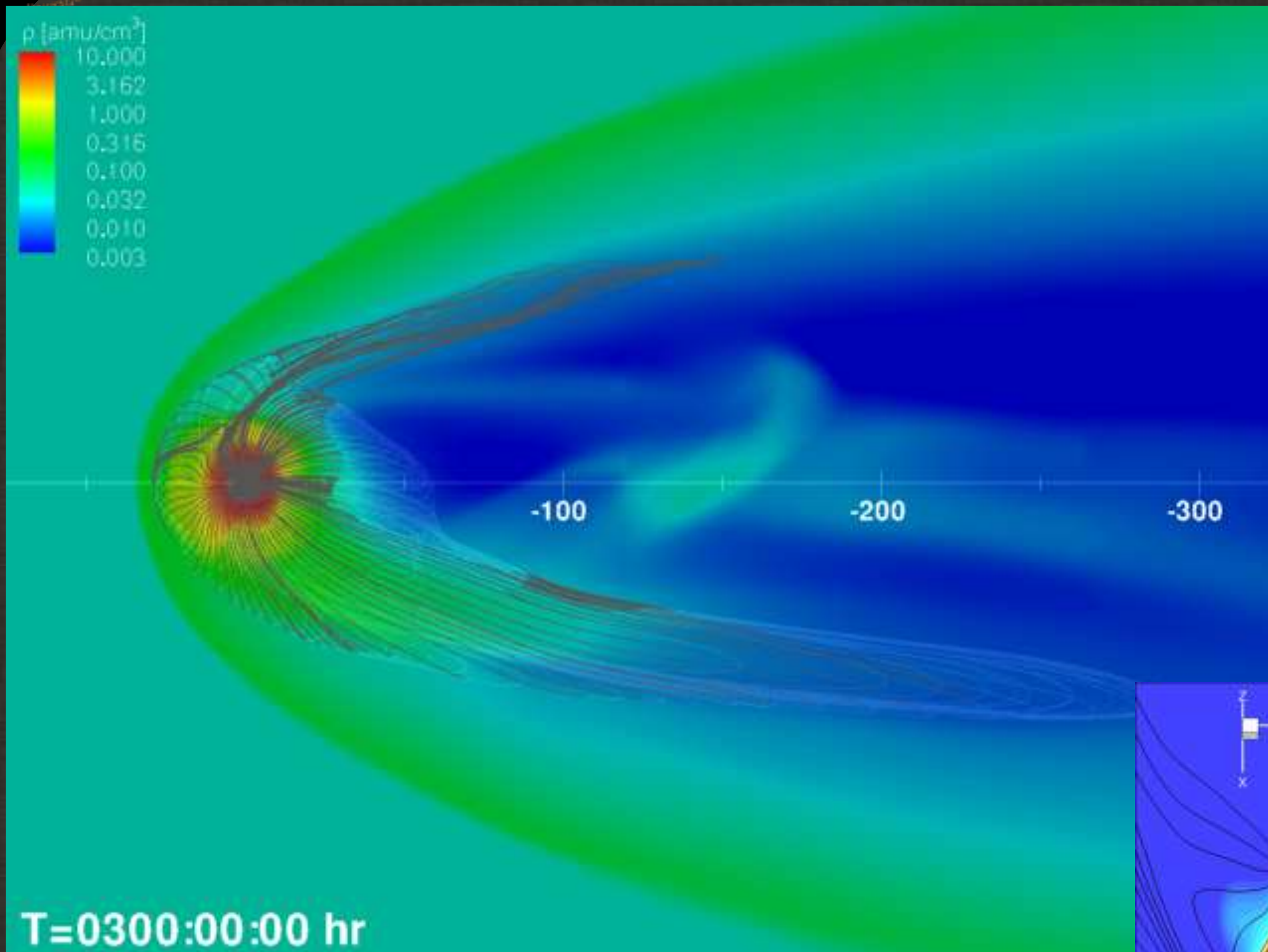
- Porting a code to a supercomputer to run in parallel is a time-consuming task requiring detailed analysis of the codes features
- Fluid based models, as well as any model calculating a self-consistent magnetic field, requires frequent communication between processors
- Distribution of cells to processors needs to be carefully optimized in order to minimize message passing time

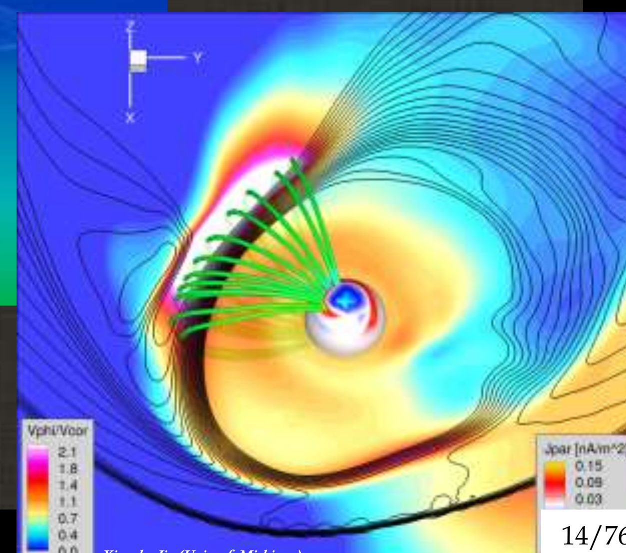


Hilbert space filling curve. BATSRUS uses this to optimize the cell distribution and message passing

Plasmoids at Saturn

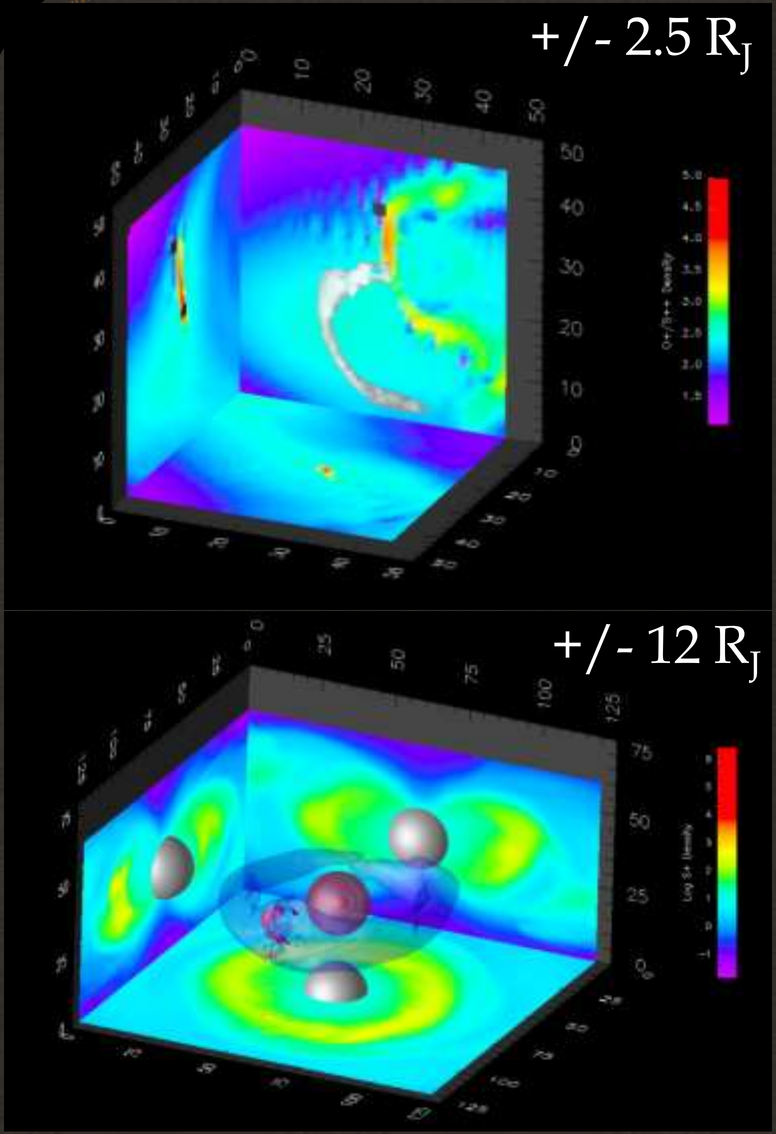
To make Tamas and Fran happy … token 3D image and movie …





Xianzhe Jia (Univ. of Michigan)

Visualization



Credit: Winglee, this meeting.

- Terabytes of information
- Inherently 3D data
- Qualitative and visually appealing vs. quantitative
  - Color vs. lines
  - General vs. extracted along spacecraft track
  - "MHD variables" vs. "instrument"
- Time dependence
- The ability to slice and dice

Can you see me now …

So you have a code …

- Can you find a big enough computer?
  - How long will it take to get an account?
  - Will I have to be fingerprinted?
  - Will my non-US-resident graduate student be able to get an account?
- The machine has a different compiler, will the code even run?
- How long are you willing to wait for the run to finish? A nearly universal constant!
- The typical trade-offs
  - Resolution vs. time
  - Physics vs. time

“Data” Requires “Modeling” Also

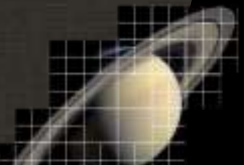
- Forward modeling of CAPS singles data by Rob Wilson
- Data: 2004-2009
  - 3-4 minute intervals
  - 13,513 intervals
  - 2k – 20k iterations of the model for each moment calculation
  - ~1000 hours of data
- ~5000 processor hours to compute the moments
- Take home message: some data is highly processed and dependent on the processing method and its built in assumptions

Models vs Instruments

	Models	Instruments
Unknowns	Discretization effects Missing physics	System "drivers" "time" vs. "spatial"
It's NEW, but is it REAL?	Numerical artifacts Interpretation takes skill	Instrumental artifacts Interpretation takes skill
Assumptions	Physics Parameters (knobs)	Outside FOV Instrument behavior Raw vs. processed
Basic unit → processing → desired unit (as an example)	Moments → Counts	Counts → Moments
It all boils down to!	Tightly control inputs Ability to "Experiment"	"Ground truth" Motivation

We all need each other!

- Developing a high quality, large-scale simulation model is comparable in scope to designing and building a spacecraft instrument
- Using these models is similar in complexity to using and interpreting spacecraft data
- There are many challenges that must be overcome when developing and running these models



Credits:

Saturn

Jupiter

Uranus

Titan

Enceladus

Ganymede

Io

Go MOP!

Go MOP!

Modeling Issues

- Multiple Length Scales <> Grid requirements
- Resolution <> time step + compute time
- Round planets <> square grids
- What happens when you under-resolve
  - Example from Peter Delemere
- Source Terms <> CFL condition issues
- Alfven speed <> time step
  - Strong magnetic fields cause all kinds of problems
  - Hybrid … whistler … even worse!
- Conservation! (of density, energy, …)
- Boundary conditions!!!
- Visualization
  - Example from Robert Winglee
- Physics (The good, the bad and the missing)
  - MHD/Fluid
    - Straight up MHD
    - Multi species
    - Multi fluid
    - Hall
    - Plasma + neutrals
    - Semi-relativistic
    - …
  - Hybrid
  - Coupling to include additional physics
  - Assumptions
    - Neutral densities
    - Sources
- Doing Runs
  - Finding a big enough computer
  - How long are you willing to wait
  - Beating the queuing system
  - $ Cost
  - Compromises
    - Resolution <> time

Model <> Instrument Development

- Heritage (family trees)
  - Where did the code/instruments start
  - Branches – how many versions are there now
  - Version control
- Development
  - Time
  - Manpower
  - Cost
- Validation <> Calibration
- Algorithm <> Technology development
- Unknowns
  - Drivers
  - Instruments
    - Internal vs. external
    - Time variation vs. spatial variation
    - Calibration / other instrument parameters
  - Models
    - Missing physics
    - Effect of grids, method, …
- What you do when you get the data
  - Is it real?
    - Numerical artifact vs. physics
    - Instrument artifact vs. physics
  - Processing and assumptions
    - MHD (moments) -> instrument
    - Instrument (counts) -> distributions -> moments
- What it all boils down to
  - Instruments: "ground truth"
  - Models: the ability to tightly control drivers and to "experiment"
  - We all need each other