CCMC: A Code Provider's View

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What Does it Take to Develop a Major Code?

	SWMF/BATS-R-US	Cassini MIMI
Years of development	7 (from concept to HP code) + 7 (full development)	7 (pre-selection) + 7 (development)
Years of Science Apps	10	9
Development cost	~$20M	~$30M
Science operations/ applications cost	~$10M	~$10M
Application areas	Sun, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Io, Europa, Enceladus, Titan, 10+ comets, Outer Heliosphere, Extra-solar star-planet interaction	Solar wind, Solar Energetic Particles, Jupiter, Saturn, Enceladus, Rhea, Dione, Titan, Outer Heliosphere
"Mass"	~400,000 lines of code	16 kg
Unit cost	~$50/line	~$1,875/g
Funding Agencies	NASA, NSF, DoD, DoE	NASA

Developing/maintaining a major simulation code takes very similar resources than developing/operating a major space instrument.

Code Developer's Paranoia

- I am not getting any funding to support CCMC and its learning curve…
- My competitors will never give their code to CCMC, so why would I?
- Source code is like technology and my code is better, so why would I give up the source code?
- My code is my livelihood, what will I do if I lose control over its usage?
- Those guys at CCMC do not understand the sensitivities of the code and they will misuse it…
  - Run with inconsistent control/input parameters…
  - Will misinterpret the result…
  - I will be blamed for the stupid mistakes of others…
- …any other reason you can think of

Paranoia vs. Reality

- No code was stolen or “mined”
- CCMC acted professionally and responsively with all codes
  - They did not publicly endorse or criticize any code
  - They quietly worked out all the issues with the code developers
  - There was no code or proprietary information leakage
  - CCMC tried to minimize the developers support time
- The broader community actually used the codes at CCMC and some good science was accomplished
  - All codes were misused by some users and the sky did not fall
  - All codes were properly used by many users and everybody benefited
- Students took advantage of code availability
  - Several dissertations/class projects were based on CCMC runs
  - The next generation of space scientists is trained to use large simulation codes responsibly
- Overall, CCMC is a win-win for the community and the code developers

Emerging Community View

- Global simulations are useful community tools
  - They capture the big picture
  - They help to guide data analysis/interpretation
  - More than one code is needed for each simulation domain
  - Physics limitations/missing physics must be recognized and taken into account
    - Do not over-interpret results
- Global simulation tools must be maintained and improved
  - Add better physics
  - Development should be only funded if it addresses well documented needs
    - Relevant new results must come during the development starting from the early stages
- Try to share the cost with other agencies

How Many Codes are Needed?

- There is no single answer
- Possible analogies (none is really good)
  - DoE has 3 major weapons labs
  - There are ~25 major Earth System models in the IPCC analysis
    - Leading US models are at NOAA GFDL, NOAA NCEP, NCAR, DoE
    - None of these have major university participation. Is this the nature of high end models, or is this a consequence of "not invented here" syndrome?
- My personal guess: At least 2, but not more than 5.
  - Answer is somewhat simulation region dependent
  - Solar/heliosphere: from the tachocline to 10 AU
  - Magnetosphere/ionosphere/atmosphere: from GICs to the bow shock
  - Today we have components, but no complete model systems
- Annual cost of supporting these efforts would be ~$10M
  - Where will the money come from?
  - How can new groups break into the system, or old groups gracefully wind down?

Modelers of the World, Unite!

- The winds are shifting and modeling is becoming mainstream
- Code wars are not useful for anyone
  - Everyone understands that no code is perfect
    - All codes have advantages and disadvantages
    - For sanity check we need at least two codes for each problem
    - Ensemble simulations are an important part of uncertainty quantifications that is needed for progress
  - Instead of criticizing each other we should focus on the positive
    - Global models are becoming important tools of space space physics
    - Emphasize the new physics and improved understand your simulation enables
- Remember, we want to expand the pie by $10M/year and not redistribute the morsels
- With a united front we can expect much more support from the community
  - … but we need to SERVE them and listen to the needs of the community
  - CCMC is a critical link in this process

Model Use at CCMC

Solar Corona		Inner Heliosphere		Global Magnetosphere		Inner Magnetosphere		Ionosphere & Thermosphere	
ANMHD	6	MAS+ENLIL	488	BATS-R-US	1123	Fock RC	290	AbbyNormal	27
MAS	62	WSA+ENLIL	868	BATS-R-US+RCM	503			CTIP	368
PFSS	155	EXO	25	GUMICS	39			SAMI 2/3	135
SWMF	44	IPS/SMEI	61	LFM	83			TIE-GCM	66
WSA	50	SWMF	43	OPEN GGCM	512			USU-GAIM	169
Total	272	Total	1485	Total	2260	Total	290	Total	765

- SC models are least used
  - Too much missing physics
  - Difficult to simulate eruptions
- ENLIL dominates IH simulations
- GM is the most widely used model element
  - Most runs are made with SWMF and OPEN-GGCM
- IT simulations are split between CTIP, USU-GAIM and SAMI 2/3

What is Needed in Global MHD

- None of the model runs are grid converged
  - Grid convergence studies should be carried out
  - As a minimum we should understand the issues
- Reconnection should be handled better
  - In ideal MHD we need to develop estimates for reconnection rates due to numerical resistivity
  - Resistive (including anomalous resistivity) effects need to better understood
  - Need good algorithms to find reconnection sites in 3D
  - Use 2 fluid Hall MHD, that is the lowest-order self consistent fluid approximation that can describe physical reconnection
    - Use appropriate resolution so that physical reconnection dominates
- Multifluid, anisotropic pressure, drift physics improvements

Multi-Ion, Two-Fluid Hall MHD

- Lowest order self-consistent set of MHD equations beyond ideal MHD
- Accounts for electron-ion velocity difference
- Physical description of reconnection

$$\frac{D\rho_i}{Dt} + \rho_i(\nabla\cdot\mathbf{u}_i) = \dot{\rho}_i$$

$$\rho_i\frac{D\mathbf{u}_i}{Dt} + \nabla p_i - en_e\left[\mathbf{E} + \mathbf{u}_+ \times \mathbf{B}\right] = \rho_i\mathbf{g} + \rho_i\dot{\mathbf{u}}_i$$

$$\frac{Dp_i}{Dt} + \frac{5}{3}p_i(\nabla\cdot\mathbf{u}_i) + \frac{2}{3}(\nabla\cdot\mathbf{h}_i) = \dot{p}_i$$

$$\frac{Dp_e}{Dt} + \frac{5}{3}p_e(\nabla\cdot\mathbf{u}_e) + \frac{2}{3}(\nabla\cdot\mathbf{h}_e) = \dot{p}_e$$

$$\frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{B}$$

$$n_e = \sum_{\alpha=ions} Z_\alpha n_\alpha \qquad \rho_i = \sum_{\alpha=ions} m_i n_i$$

$$\mathbf{u}_e = \mathbf{u}_+ - \frac{\mathbf{j}}{en_e}$$

$$\mathbf{u}_+ = \sum_{\alpha=ions}\frac{Z_\alpha n_\alpha}{n_e}\mathbf{u}_\alpha$$

$$\mathbf{E} = -\mathbf{u}_+ \times \mathbf{B} - \frac{1}{en_e}\mathbf{j}\times\mathbf{B} + \eta_e\mathbf{j}$$

$$\mu_0\mathbf{j} = \nabla\times\mathbf{B}$$

Multifluid Anisotropic MHD

Ion continuity equation: $\frac{D\rho_\alpha}{Dt} + \rho_\alpha(\nabla\cdot\mathbf{u}_\alpha) = \dot{\rho}_\alpha$

Ion momentum equation:

$$\mathbf{w}_\alpha = \mathbf{u}_\alpha - \sum_{s=ions}\frac{Z_s n_s}{n_e}\mathbf{u}_s$$

gyration around bulk velocity of positive charges

charge density weighted ambipolar & Lorentz force

$$\rho_\alpha\frac{\partial\mathbf{u}_\alpha}{\partial t} + \rho_\alpha(\mathbf{u}_\alpha\cdot\nabla)\mathbf{u}_\alpha + \nabla p_{\alpha_\perp} - eZ_\alpha n_\alpha\mathbf{w}_\alpha\times\mathbf{B} + \frac{Z_\alpha n_\alpha}{n_e}(\nabla p_{e_\perp} - \mathbf{j}\times\mathbf{B}) =$$

perpendicular pressure

perpendicular pressure

$$\rho_\alpha\dot{\mathbf{u}}_\alpha + \rho_\alpha\mathbf{g} + eZ_\alpha n_\alpha\eta_e\mathbf{j} - B\nabla_\parallel\left[\left(\frac{p_{\alpha_\parallel} - p_{\alpha_\perp}}{B} + \frac{Z_\alpha n_\alpha}{n_e}\frac{p_{e_\parallel} - p_{e_\perp}}{B}\right)\mathbf{b}\right]$$

adiabatic focusing

Ion energy equations:

$$\frac{\partial p_{\alpha_\parallel}}{\partial t} + (\mathbf{u}_\alpha\cdot\nabla)p_{\alpha_\parallel} + p_{\alpha_\parallel}(\nabla\cdot\mathbf{u}_\alpha) + 2p_{\alpha_\parallel}\mathbf{b}\cdot\nabla_\parallel\mathbf{u}_\alpha + \frac{4}{5}\mathbf{b}\cdot\nabla_\parallel\mathbf{h}_\alpha + \frac{2}{5}(\nabla\cdot\mathbf{h}_\alpha) = \dot{p}_{\alpha_\parallel}$$

$$\frac{\partial p_{\alpha_\perp}}{\partial t} + (\mathbf{u}_\alpha\cdot\nabla)p_{\alpha_\perp} + 2p_{\alpha_\perp}(\nabla\cdot\mathbf{u}_\alpha) - p_{\alpha_\perp}\mathbf{b}\cdot\nabla_\parallel\mathbf{u}_\alpha - \frac{2}{5}\mathbf{b}\cdot\nabla_\parallel\mathbf{h}_\alpha + \frac{4}{5}(\nabla\cdot\mathbf{h}_\alpha) = \dot{p}_{\alpha_\perp}$$

What is Needed in Solar

- There is only one subsurface solar model at CCMC
  - Anelastic MHD (ANMHD) solves for the evolution of **v** and **B** together with linearized thermodynamic perturbations (s_1, p_1, ρ_1, T_1) in a stratified hydrostatic background (given by $s_0(z)$, $p_0(z)$, $\rho_0(z)$, $T_0(z)$)
  - Rempel and Manchester flux emergence/sunspot models are not available.
  - No solar dynamo model at CCMC
  - No radiative transfer model is available at CCMC to simulate ionization states and line emissions
- CCMC needs buy-in from the solar physics community
  - Part of the problem is that solar interior funding sources (NASA, NSF AST) do not participate in CCMC activities

What is Needed in Corona Models

- More realistic chromosphere to corona models have been developed but are not yet available at CCMC for runs
  - PSI
    - At lower boundary T=20,000K, $n_e=2\times10^{18}$ m^{-3}, B=2G ($\beta\approx35$) (chromosphere)
    - Heat conduction, radiative energy loss, exponential coronal heating, equation for Alfvén wave energy, wave pressure acceleration and heating
  - Michigan
    - Lower boundary T=20,000K, $n_e=2\times10^{16}$ m^{-3}, B=1G ($\beta\approx1$), outgoing Alfvén wave amplitude 15km/s (chromosphere)
    - Heat conduction, radiative energy loss, separate equations for ± Alfvén wave energy, wave pressure acceleration and heating, Kolmogorov and counter-propagating wave dissipation
- The complexity of physics in these models are comparable to the global magnetosphere models
- Next step:
  - Quantitative predictions of solar wind parameters in the corona and at 1AU
  - Quantitative prediction of white light and EUV/X-ray line intensities and charge states

What is Needed in SEP

- There are no SEP models at CCMC
  - EMMREM (Earth-Moon-Mars Radiation Environment Model) is listed among the CCMC model suite, but…
  - EMMREM is not available for “Runs on Request”
  - No EMMREM results are in the CCMC public archives
- There is a need for an SEP model
  - SEP transport along IMF flux tubes
  - SEP acceleration by flares
  - Energetic particle acceleration by CMEs, CIRs and other discontinuities
- Is such a code available?

What is Needed in Magnetosphere

- Reconnection, reconnection, reconnection…
  - With MMS on the horizon being able to simulate physical reconnection is critical
  - Major issues
    - Finding reconnection sites
    - Applying physical reconnection process
      - Embedded kinetic code
      - Hall MHD
      - Anomalous resistivity
      - Any other idea…
- Drift Physics
  - Radiation belts
  - Ring current
  - Connection between tail and inner magnetosphere
- In my opinion, improving reconnection and drift physics are the highest priorities

What is Needed in M-I Coupling

- Inner boundary conditions are oversimplified
  - Gap region (1.1 – 2.5 R_E) is missing
  - Ionospheric electrodynamics is in effect electrostatics (potential field)
  - Mass coupling is usually poorly handled
- A decade ago the MRC tried to model the gap region
  - Extend the thermosphere and ionosphere to 3 R_E
  - Include self-consistent plasmasphere
  - ...but the code never really worked and now the group is out of the global space plasma simulation business
- There is a need to revisit the entire M-I coupling area!

What is Needed in Ionosphere-Atmosphere

- This are tightly interconnected domains with vastly different physics
- What is really needed: a whole atmosphere model extending from the troposphere to 3 R_E, including
  - Non-hydrostatic approximation
  - Gravity wave and other momentum/energy transport in ALL directions
  - Radiation transfer with photochemistry
  - Proper neutral and ion chemistry at all altitudes
  - Ionization sources and losses
  - Plasma dynamics from the D region to the plasmasphere and polar wind
  - GIC generation
- Anyone interested?

Changes in a Decade: The Big Picture
(or Science Progresses One Funeral at a Time)

- Most younger scientists consider numerical simulations to be a pillar of space physics
  - Measurements/data analysis
  - Theoretical/conceptual models
  - Numerical simulations
- However, there are influential voices still advocating:
  - Fluid simulations are fundamentally flawed
  - In MHD simulations numerical resistivity dominates over physical resistivity, so no result is believable
  - Most large space physics simulation codes were developed with support from other agencies/programs, and we should keep it that way
    - We should not waste our sparse resources on code development/maintenance

Summary

- CCMC is a great success for the code development community
- The present arrangement is a win-win for the space science community and code providers
- We need a range of code/model improvements to become a third pillar of space science
- There is a need for about $10M/year stable funding source for large code development/support
- This investment can be justified only if code providers and CCMC listen to the community's needs and work closely with the community
- New paradigm: it is not degrading to be useful for others and provide services to the community

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