Computational Methods for Kinetic Processes in Plasma Physics

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Context

- History of Tristan code
- Major differences with other PIC codes
- Applications of Tristan code
- Structure of Tristan code

  Subroutines
- Initial settings

  Jet simulations

  Reconnections

History of Tristan code

1989: working on the old code written by the assembler language for Cray 1 by Oscar Buneman (failed)

1990: Tri-dimensional Stanford (Tristan) code is developed for solar wind-magnetosphere interaction

1993: Oscar Buneman passed away on January 24 and ***Computer Space Plasma Physics: Simulation Techniques and Software*** was published April

1993 – 2001: Global solar wind-magnetosphere interaction was investigated with interstellar magnetic fields (IMFs)

1995: thin jet simulations have been performed

2002 – present: Weibel (filamentation) instability has been investigated

2006 – present: reconnection simulations have been performed

2008: The TristanMPI has been developed by Jacek Niemiec when he was at Iowa State University first used for the investigation of Cosmic ray acceleration

2008 – present: Synthetic radiation has been investigated

Major differences with other PIC codes

UPIC: spectral method

in general good for avoiding numerical Cherenkov radiation

Tristan: conserving current deposit

good for MPI and non-periodic boundary conditions

Applications of Tristan code

Global solar wind-magnetosphere interaction

Relativistic jets

Kinetic Kelvin-Helmholtz instability (kKHI)

Outline of talk

- **Space Weather research**
- **Reconnection in magnetosphere with IMF**
  - *** southward IMF**
  - *** duskward IMF**
- **Reconnection in astrophysics**
  - *** Mini-jets in Relativistic jets**
  - *** Pulsar Nebula**
- **New aspects of reconnection in astrophysical jets**
  - *** additional acceleration mechanism**
  - *** radiation mechanism for gamma-ray burst?**
- **Summary**

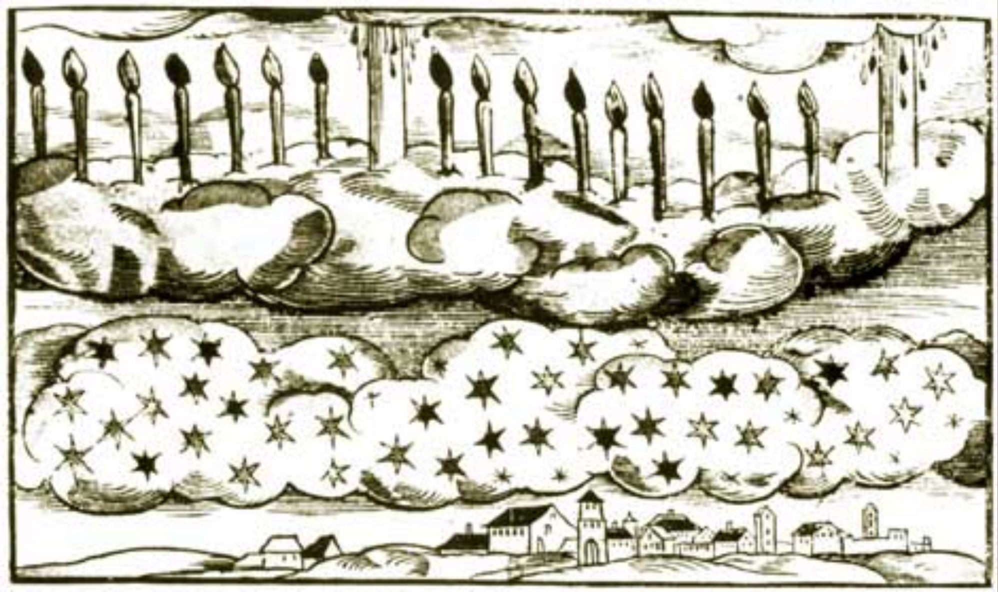
(Courtesy of J. Raeder for some slides)

play yellowknife-combined.mov

Aurora

- Hard to sell space physics: there is not much to see, unlike astronomy!
- Only at high latitudes: aurora: the TV screen of the magnetosphere.
- Rarely at low latitudes: geomagnetic storms (1989, 2003). Quite frightening for people in ancient times.
- Even many scientists who study space physics have not seen aurorae! Thankfully, we have conferences:

- 1994: ICS2, Fairbanks, AK: very active.
- 2007: ESA/CLUSTER workshop, Saariselka, Lapland: solar minimum, dooh!
- 2011: Chapman conference, Fairbanks, AK: better now!
- Always: cold (-30C) because you can't see them in daylight.

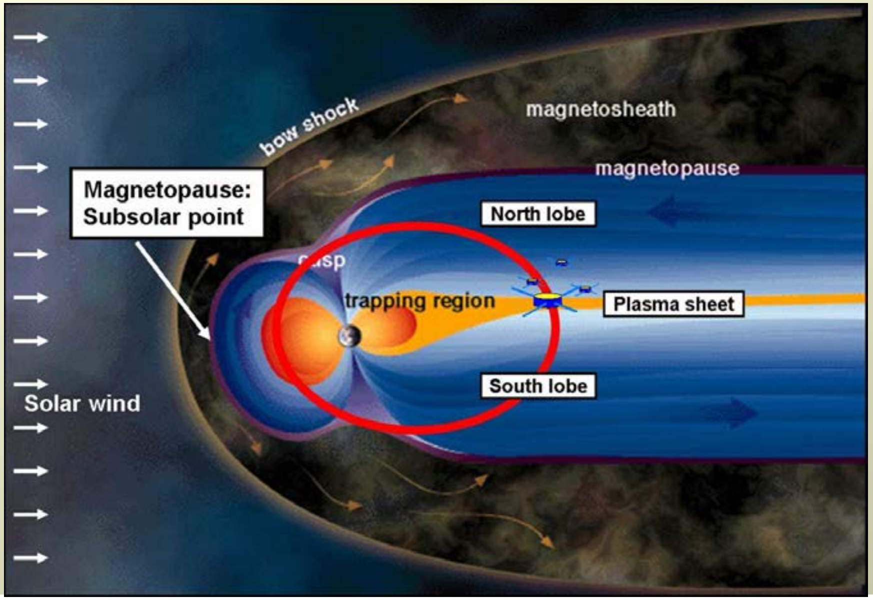


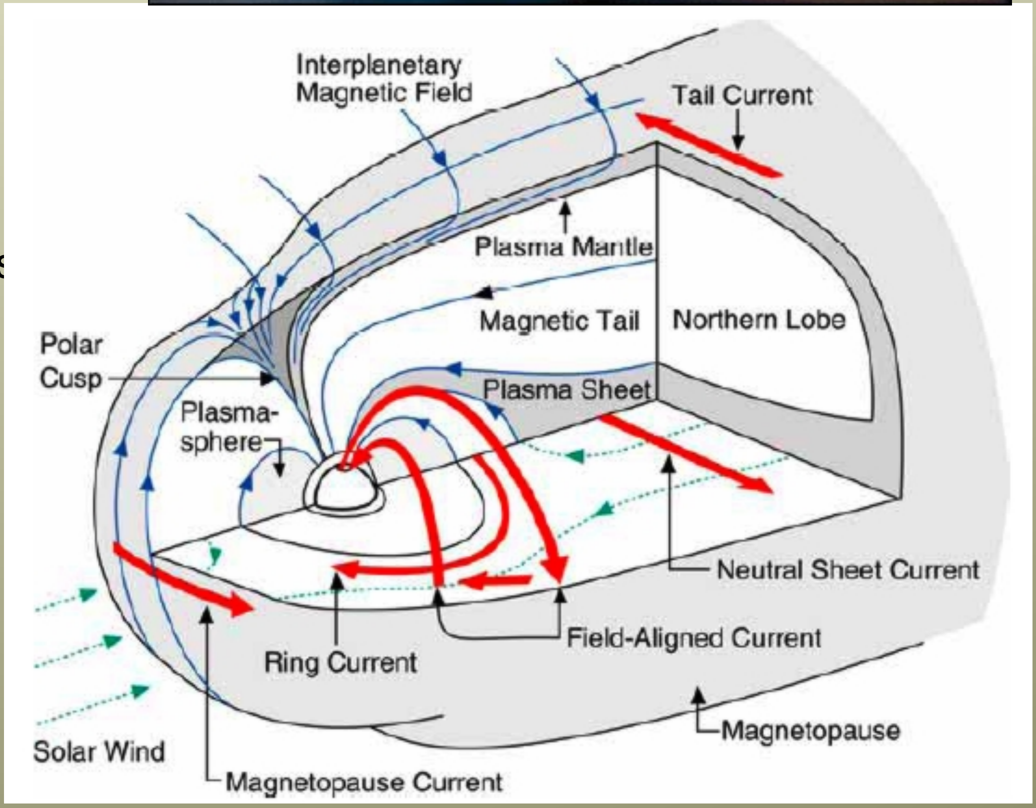
Geospace

After 50+ years of space research and ~100 satellite missions we can draw some pictures and name features and processes:

Solar Wind / IMF, bow shock, magnetosheath, magnetopause, reconnection, cusps, boundary layers, tail lobes, plasma sheet, neutral sheet, ring current, radiation belts, field aligned currents, auroral particle precipitation, ionosphere convection, ionosphere layers, TEC, ionosphere currents, ion outflow, thermosphere/density, thermosphere composition, thermosphere winds and tides …..

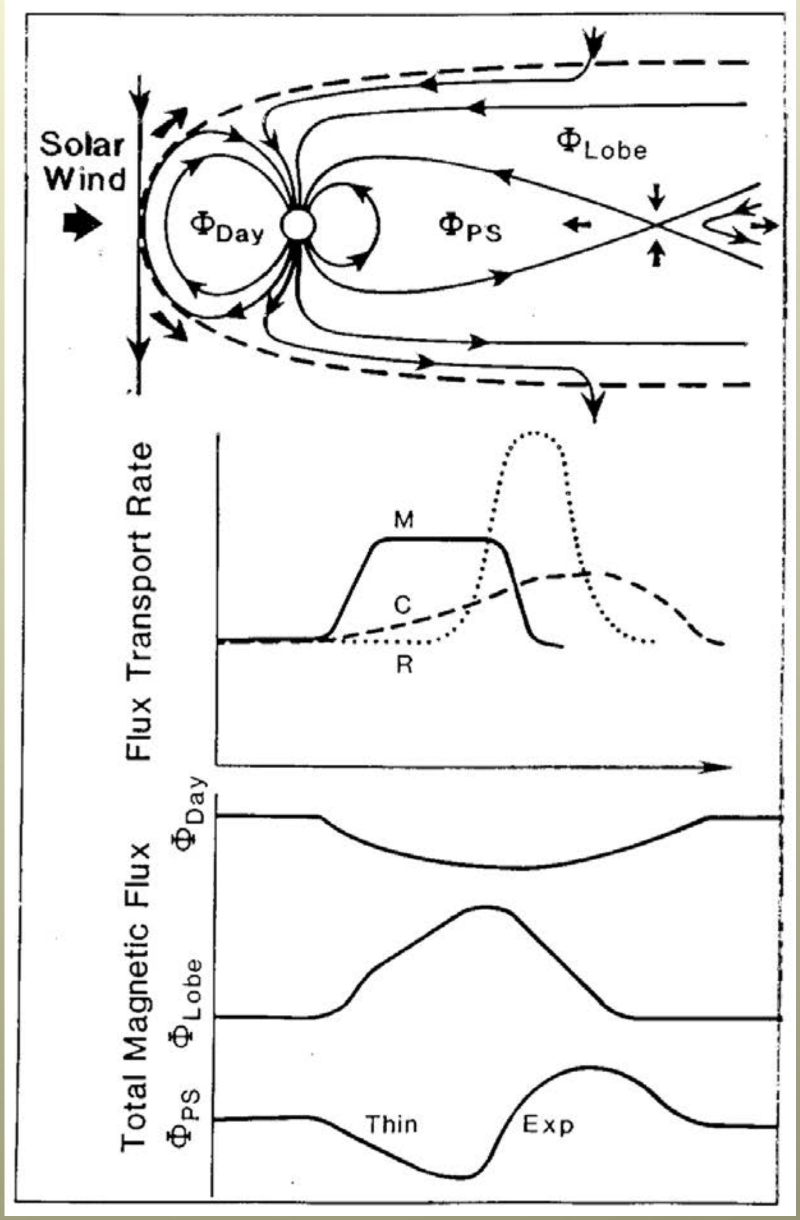
Lots of features and processes. Our understanding of how everything works together is still mostly at the cartoon level. We can not claim understanding until we have predictive models.





So, why does the aurora light up: Substorms

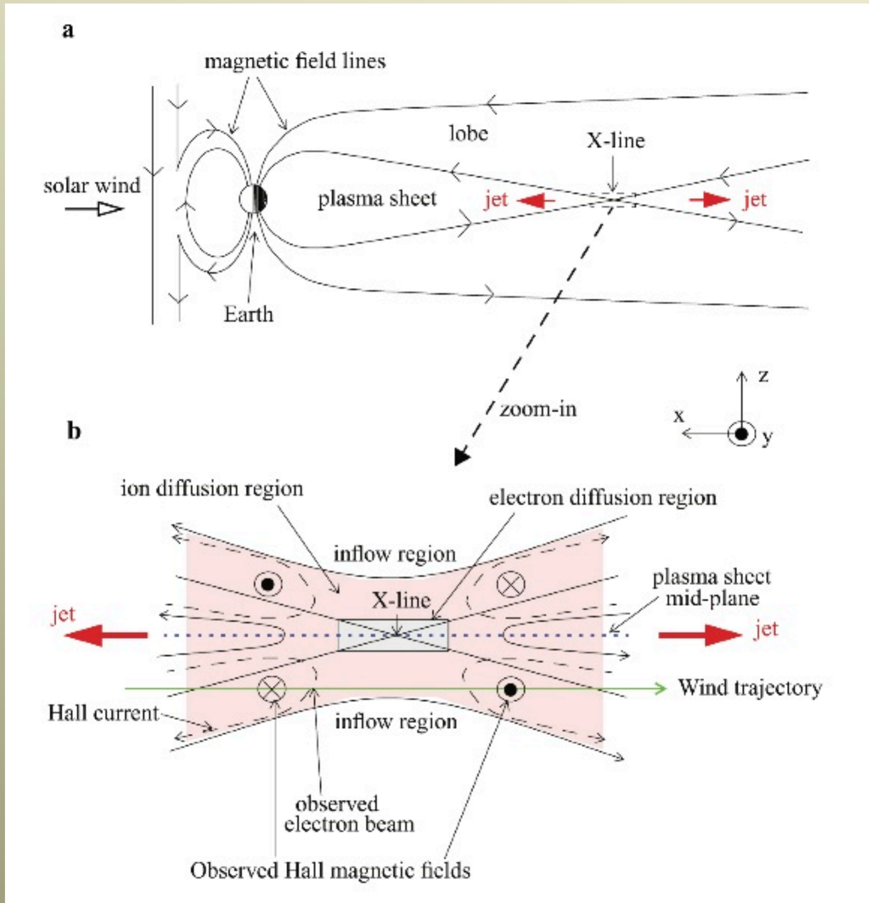
- Substorms are a consequence of reconnection rate imbalance: the nightside rate must balance dayside rate, at least on long scales (>1h) to return flux back to the dayside.
- During a substorm, first the dayside reconnection rate exceeds the nightside rate: growth phase.
- Explosive reconnection in the nightside signals the expansion phase with auroral brightening and westward traveling surge.
- It remains an open question what triggers the expansion phase onset: 2 minute question.
- If rates balance: steady magnetospheric convection (SMC).

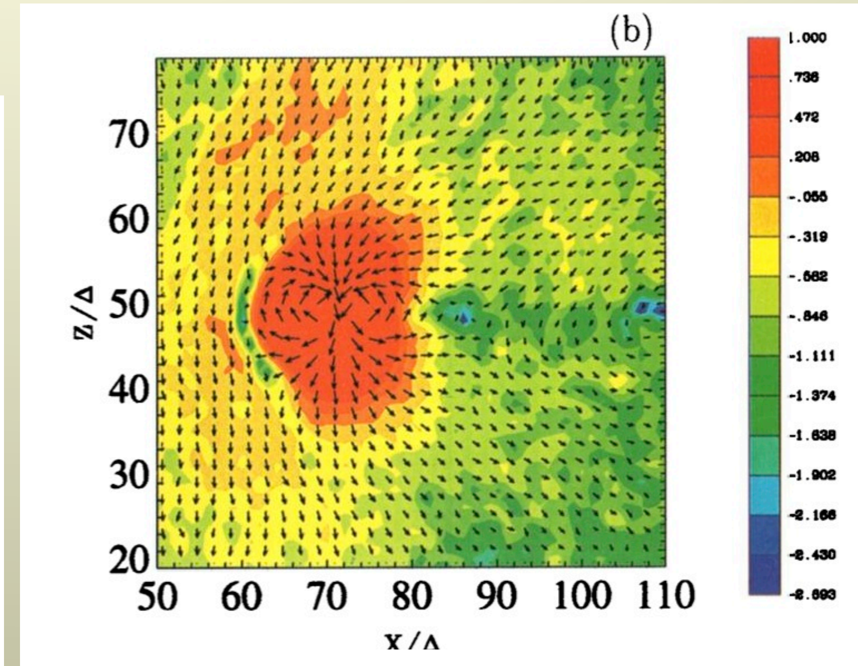


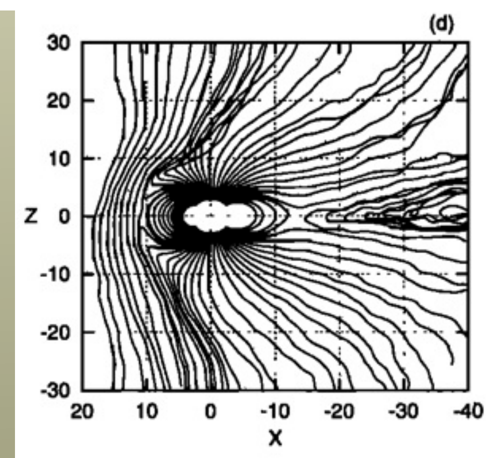
Russell, 1993

Reconnection with southward IMF

schematic reconnection







from *Report of the Workshop on Opportunities in Plasma Astrophysics*

(Nishikawa, JGR, 1997)

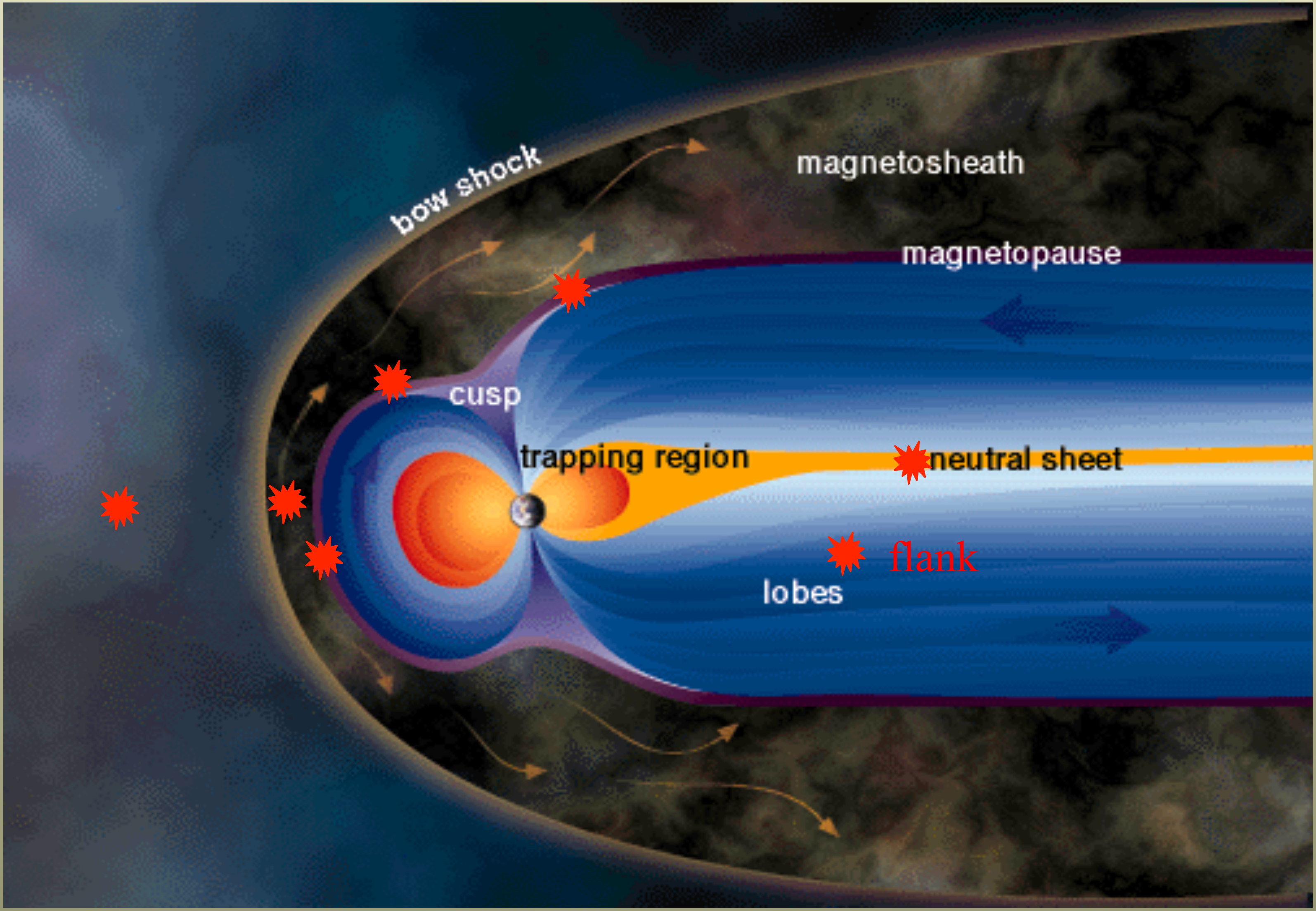
Space Physics According to NASA EPO

Schematic view of solar wind – magnetosphere interaction

play SOHO5_CME_ANIM_EARTHA.mov

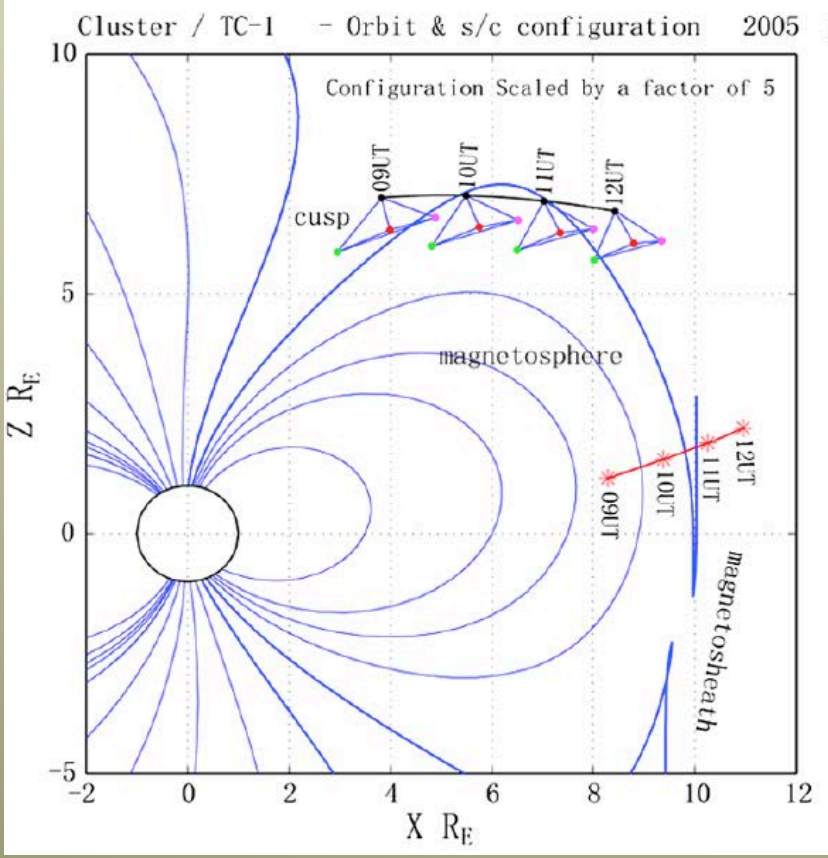
Locations of reconnection in magnetosphere observed by Cluster

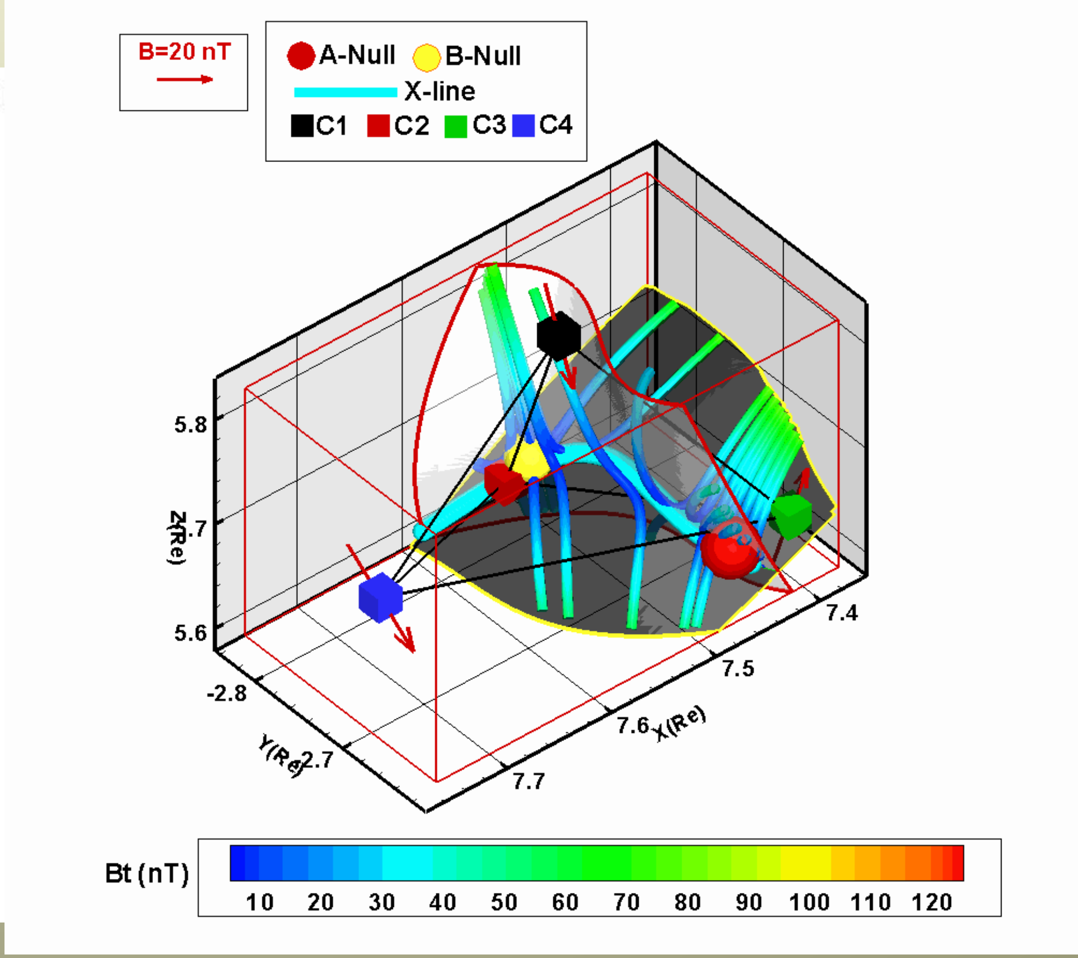
Courtesy of **C. P. Escoubet**



B null near the cusp

3D Magnetic reconnection



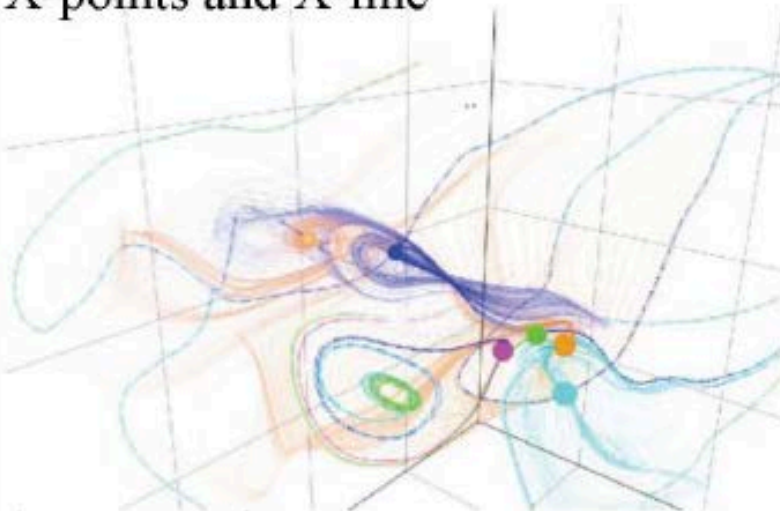


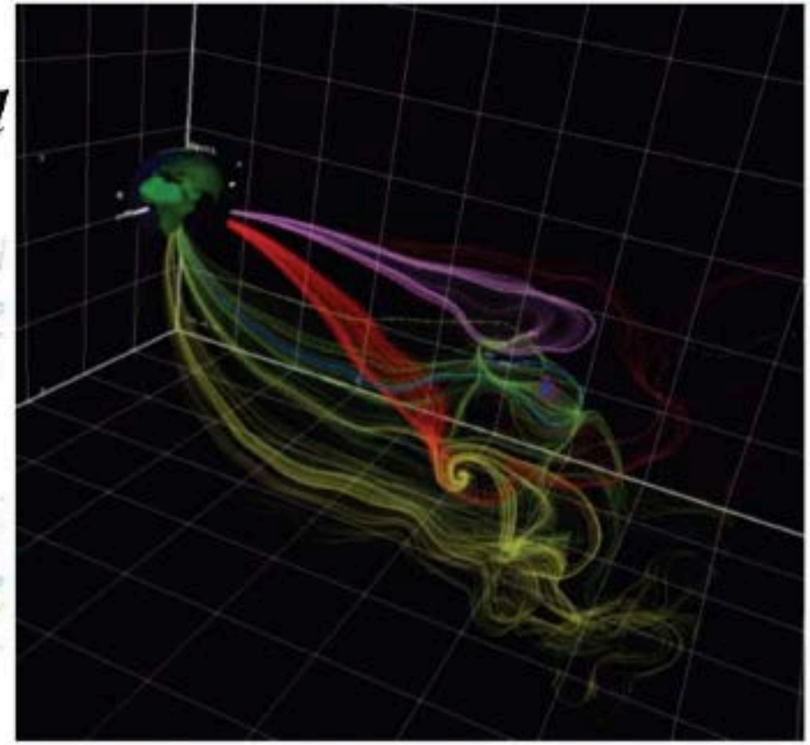
Courtesy of **C. P. Escoubet**

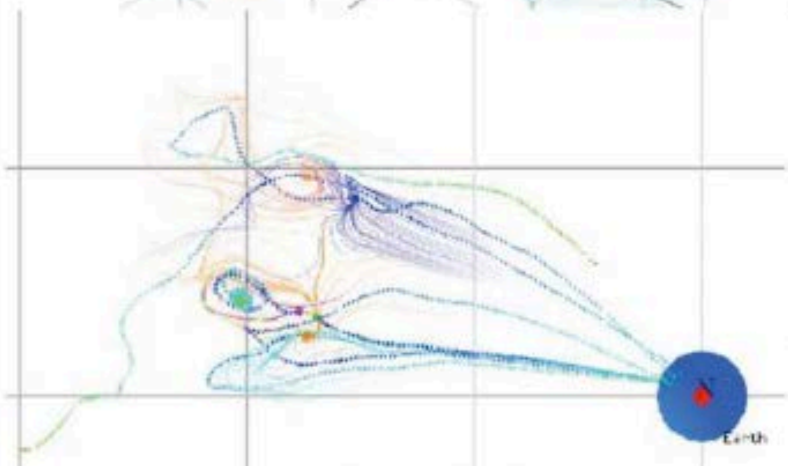
[Dunlop et al, PRL, 2009]

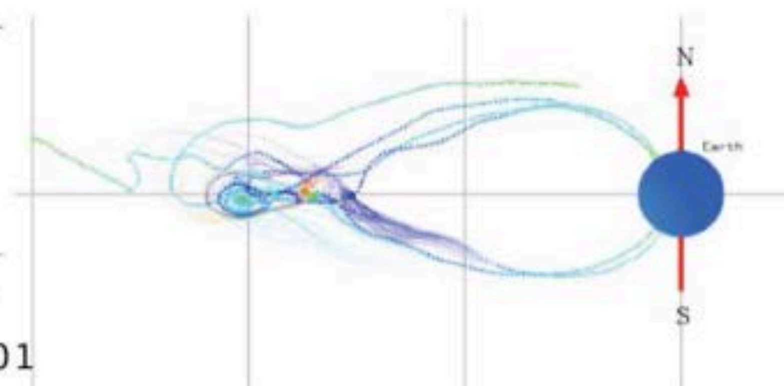
Three-dimensional topology of magnetic fields in the magnetotail

X-points and X-line





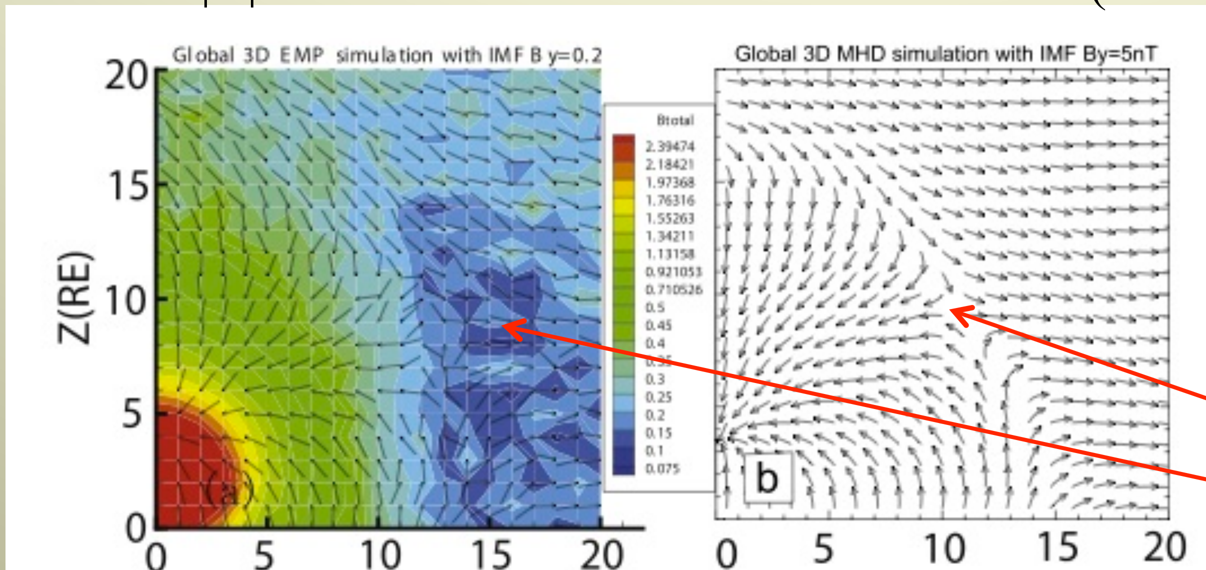




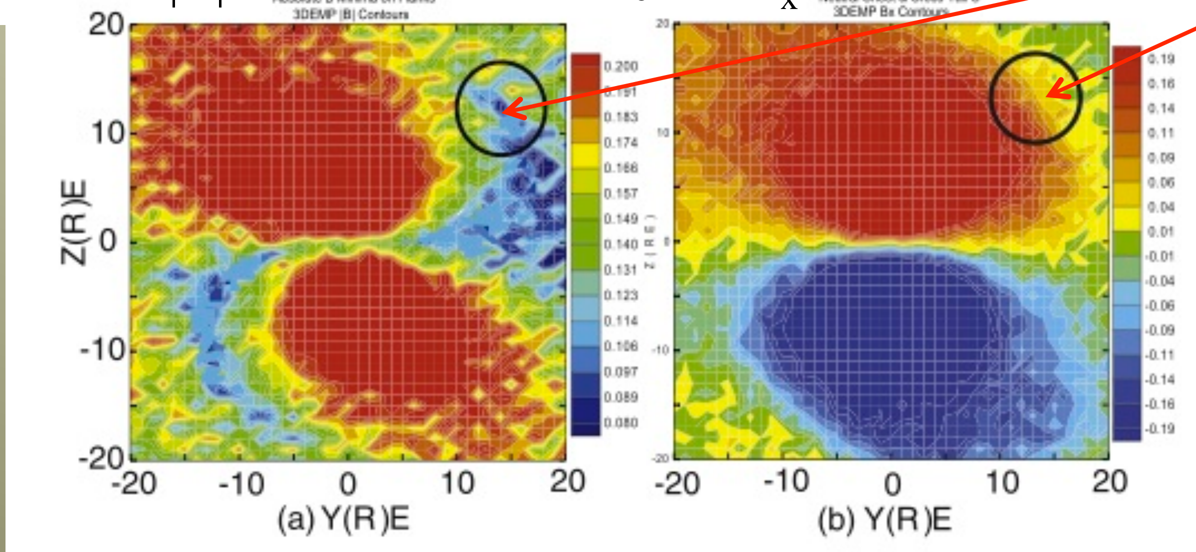
Cai et al. EPS. 2001

Duskward IMF component reconnection (viewed from the Sunward)

|B| X = -5RE 3D MHD (White et al. 1998)



|B| X = -10RE B_x

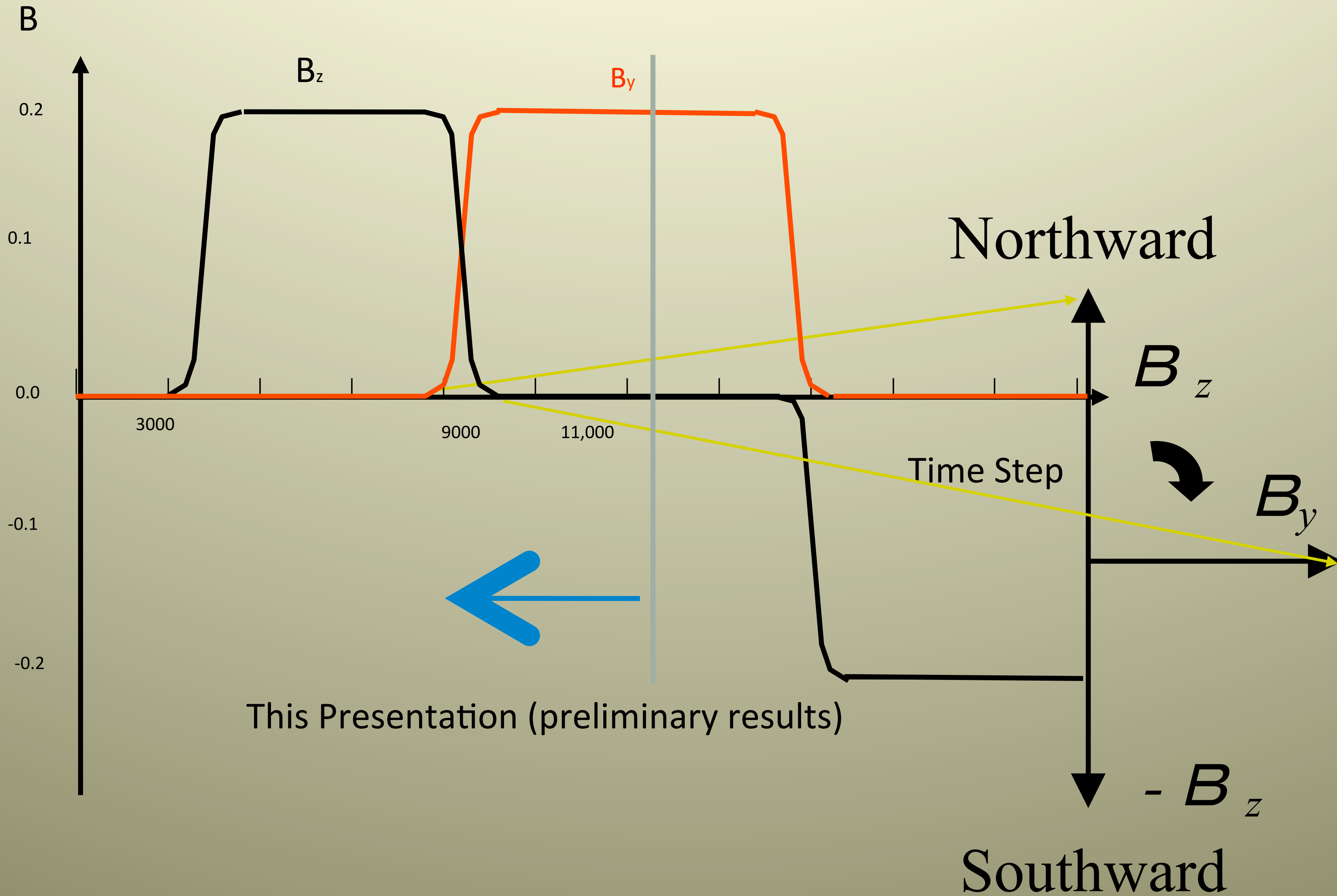


Crosstail-S is formed with duskward IMF

"sash"

(Cai et al. GRL, 2006)

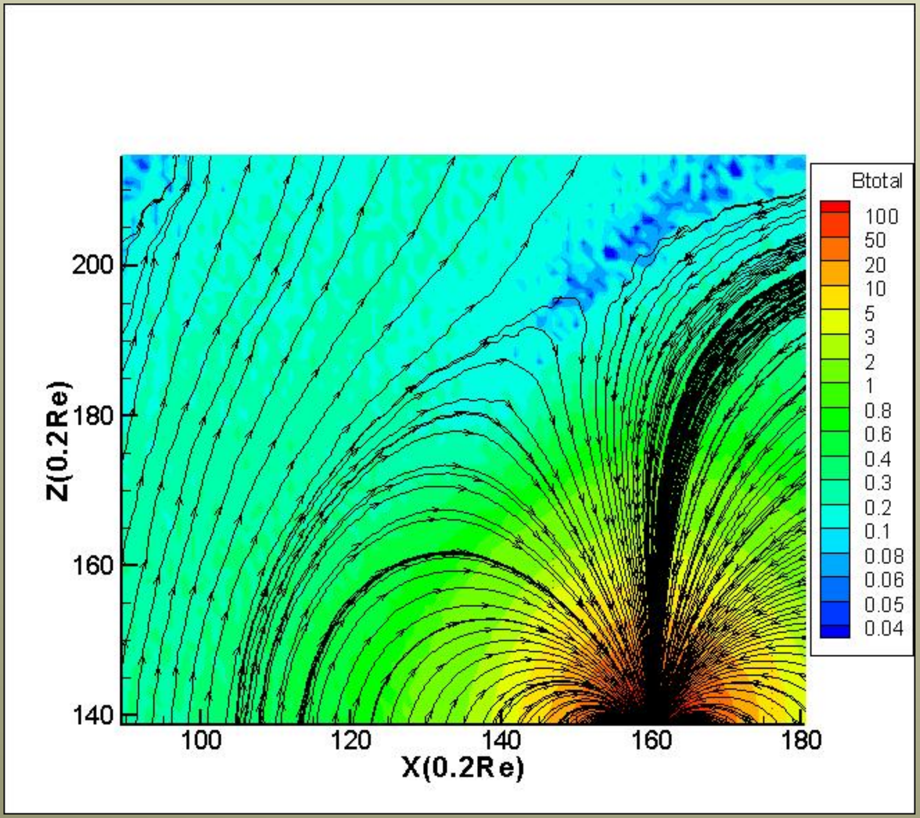
Time Sequence of IMF Rotation from B_z to B_y



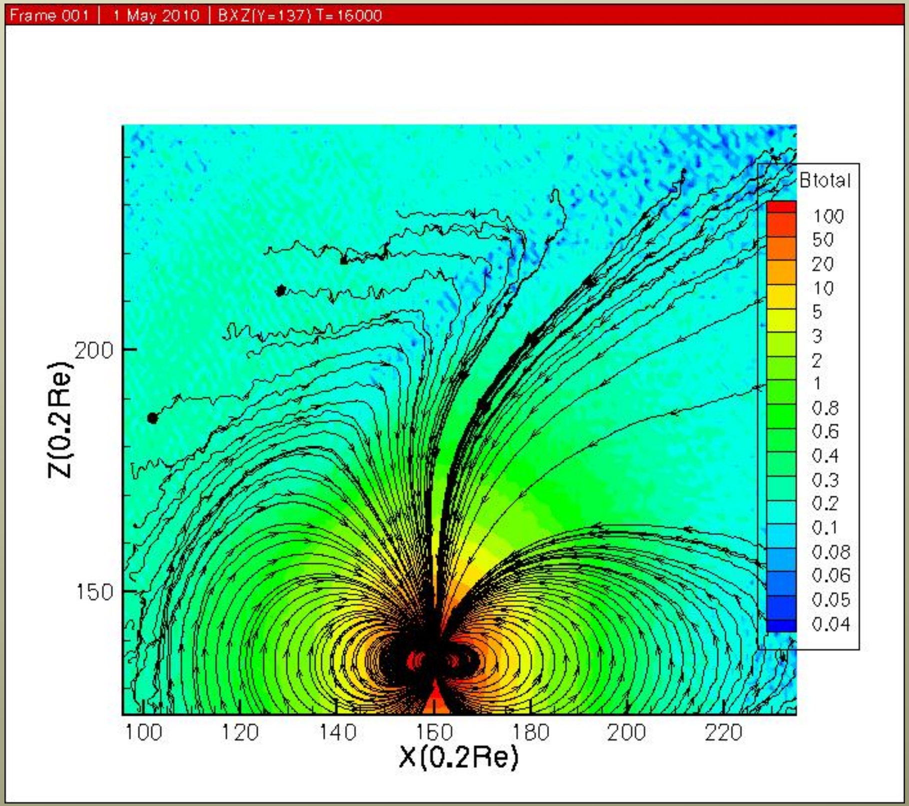
Cusp Region (Enlarged View)

B slicing (meridian plane Z-X)

Northward IMF



Dusk-Dawn IMF

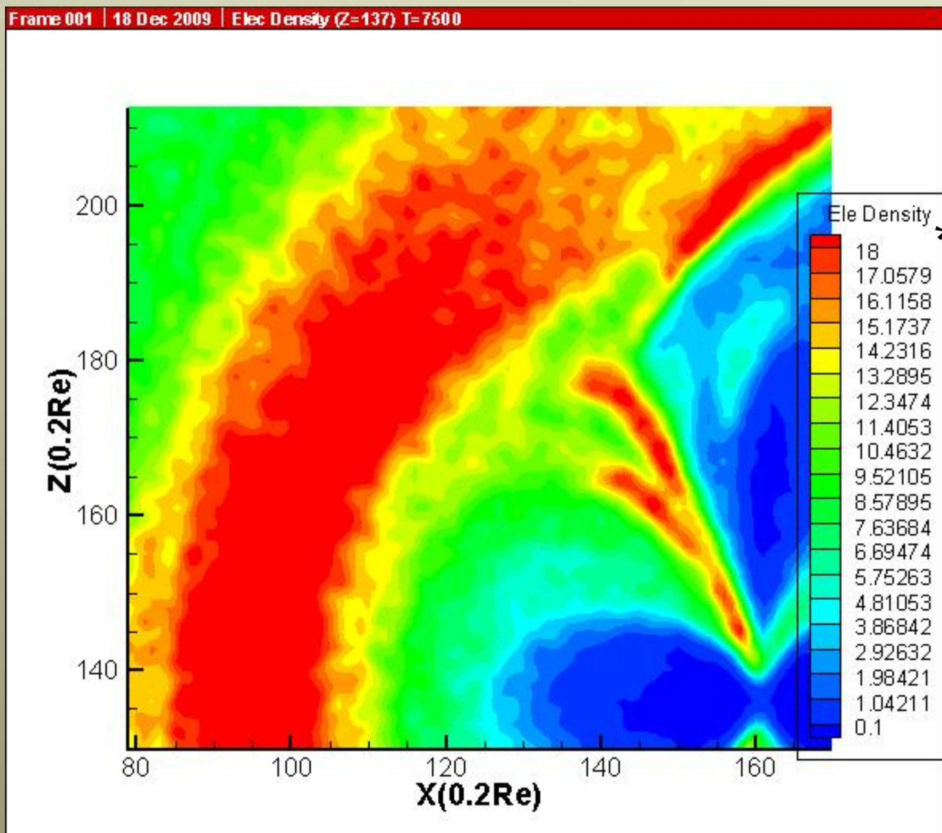


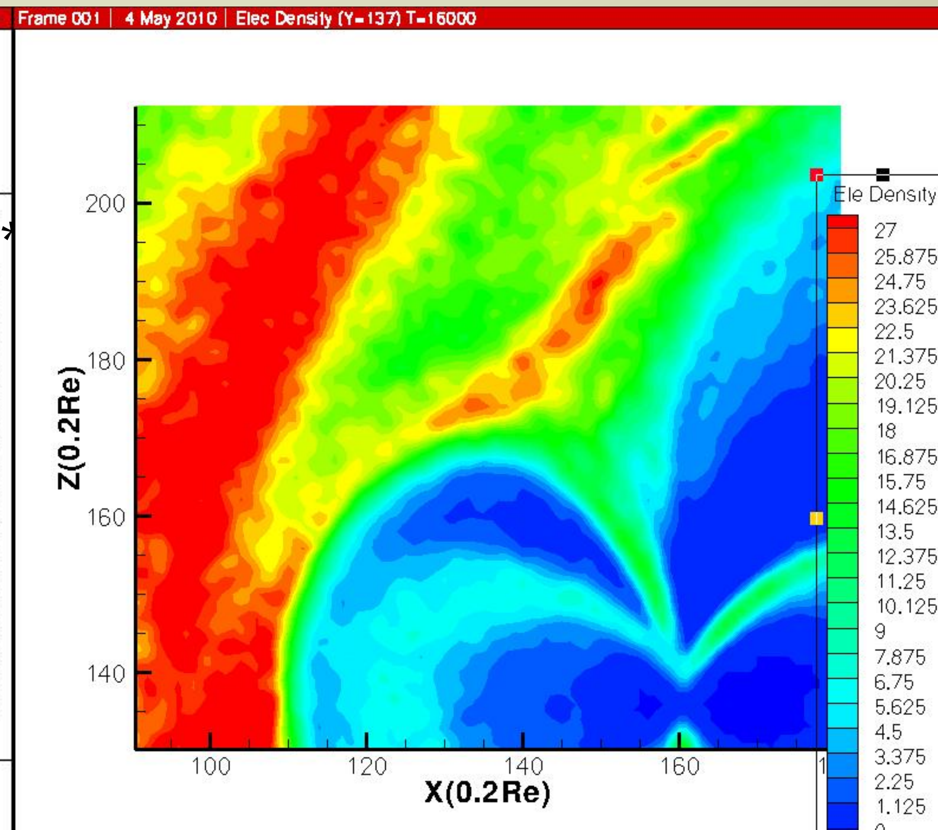
Cusp Region (Enlarged View)

Electron density slicing (meridian plane Z-X)

Northward IMF

Dawn-Dusk IMF





Cusp Region (Enlarged View)

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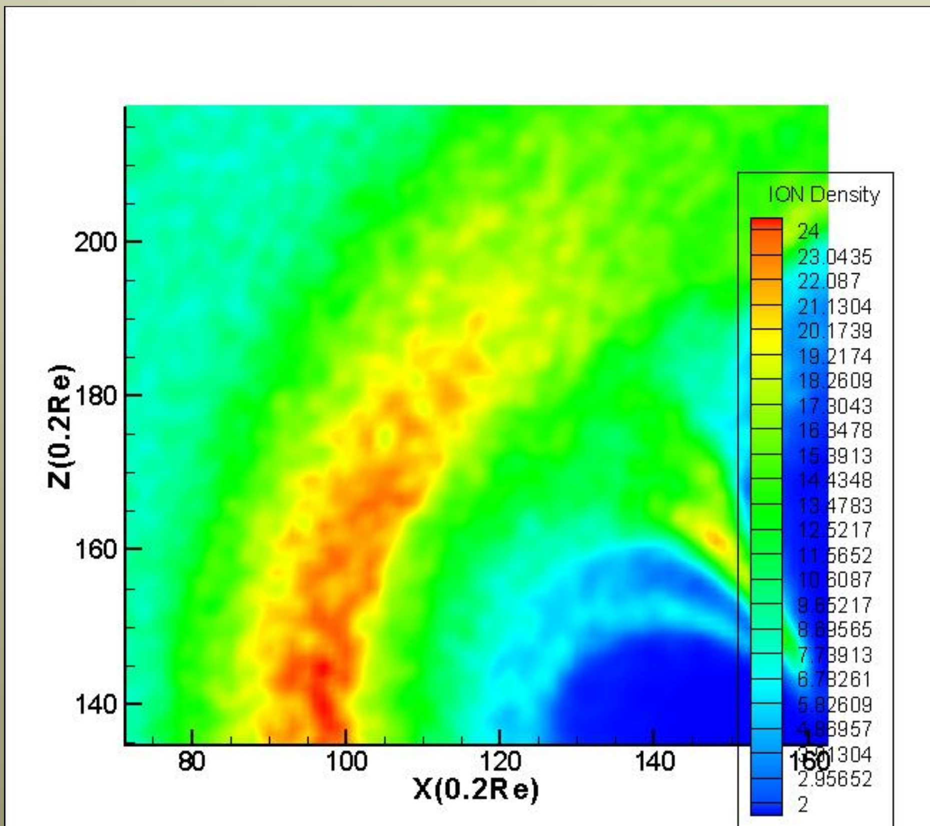
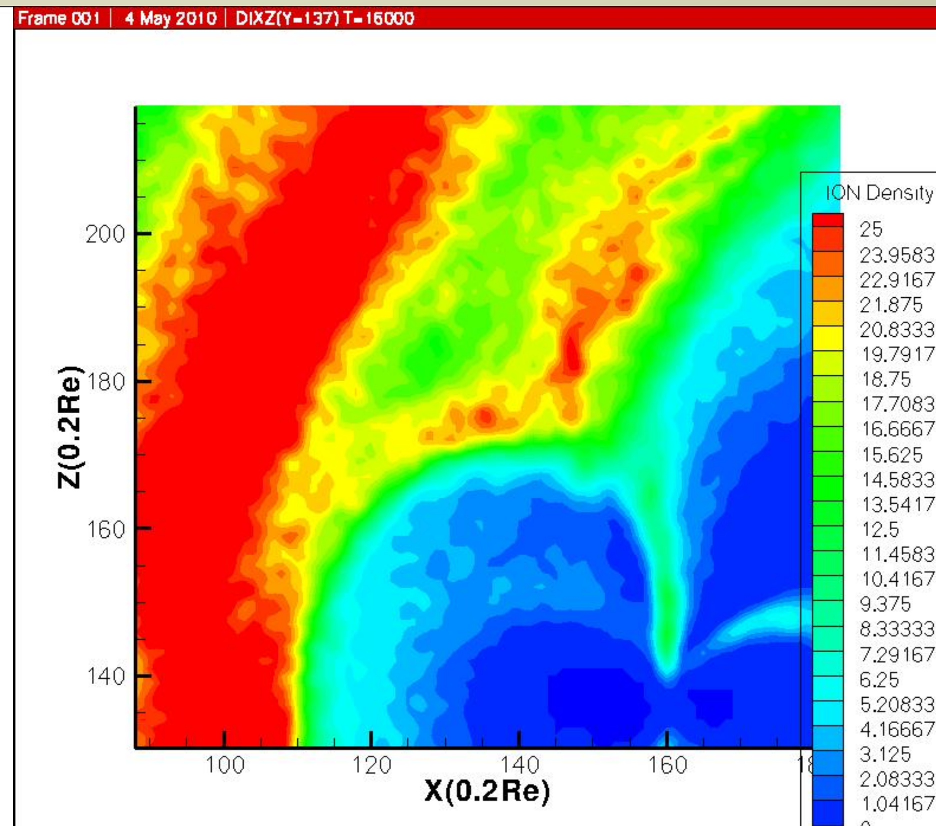
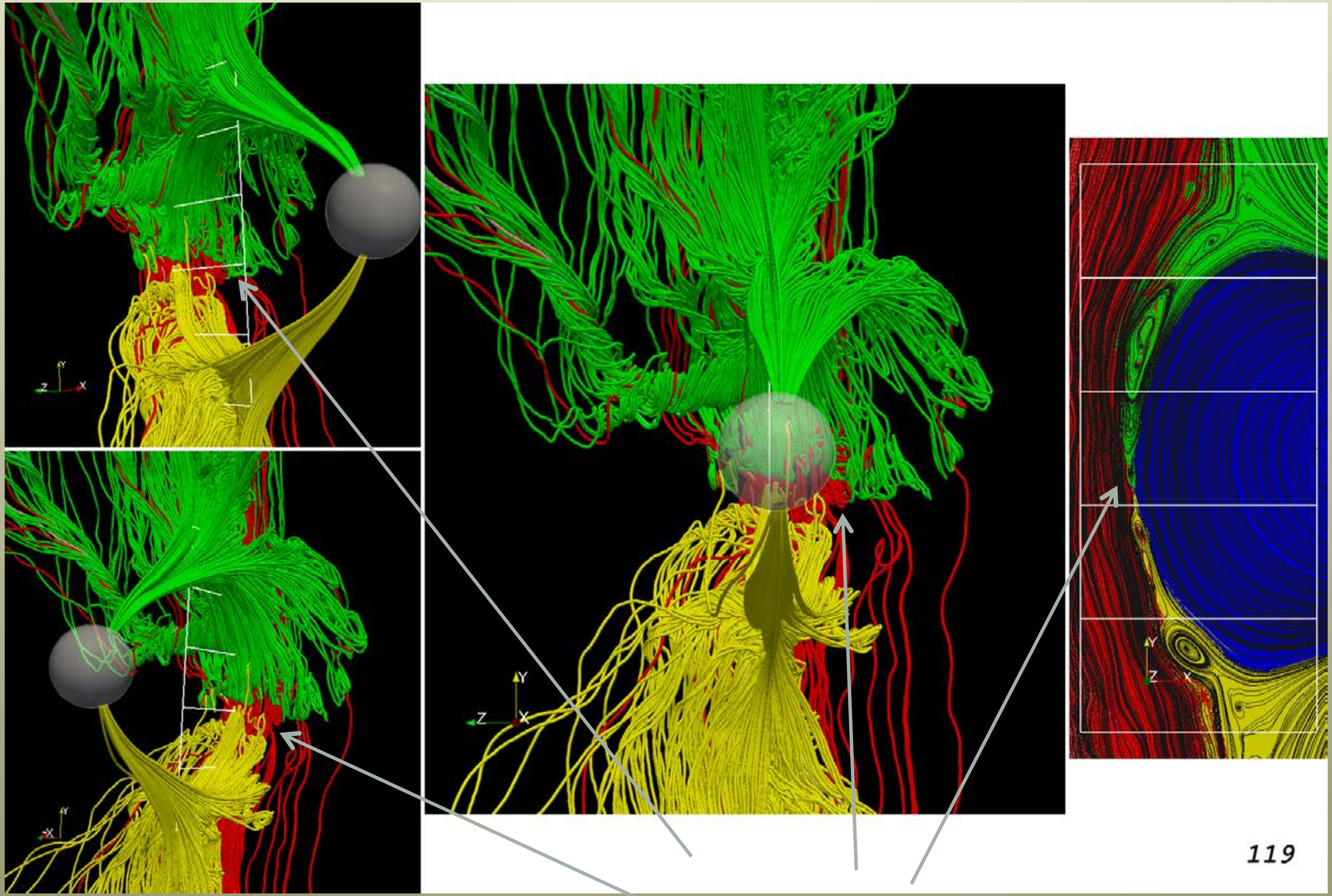


Dawn-Dusk IMF



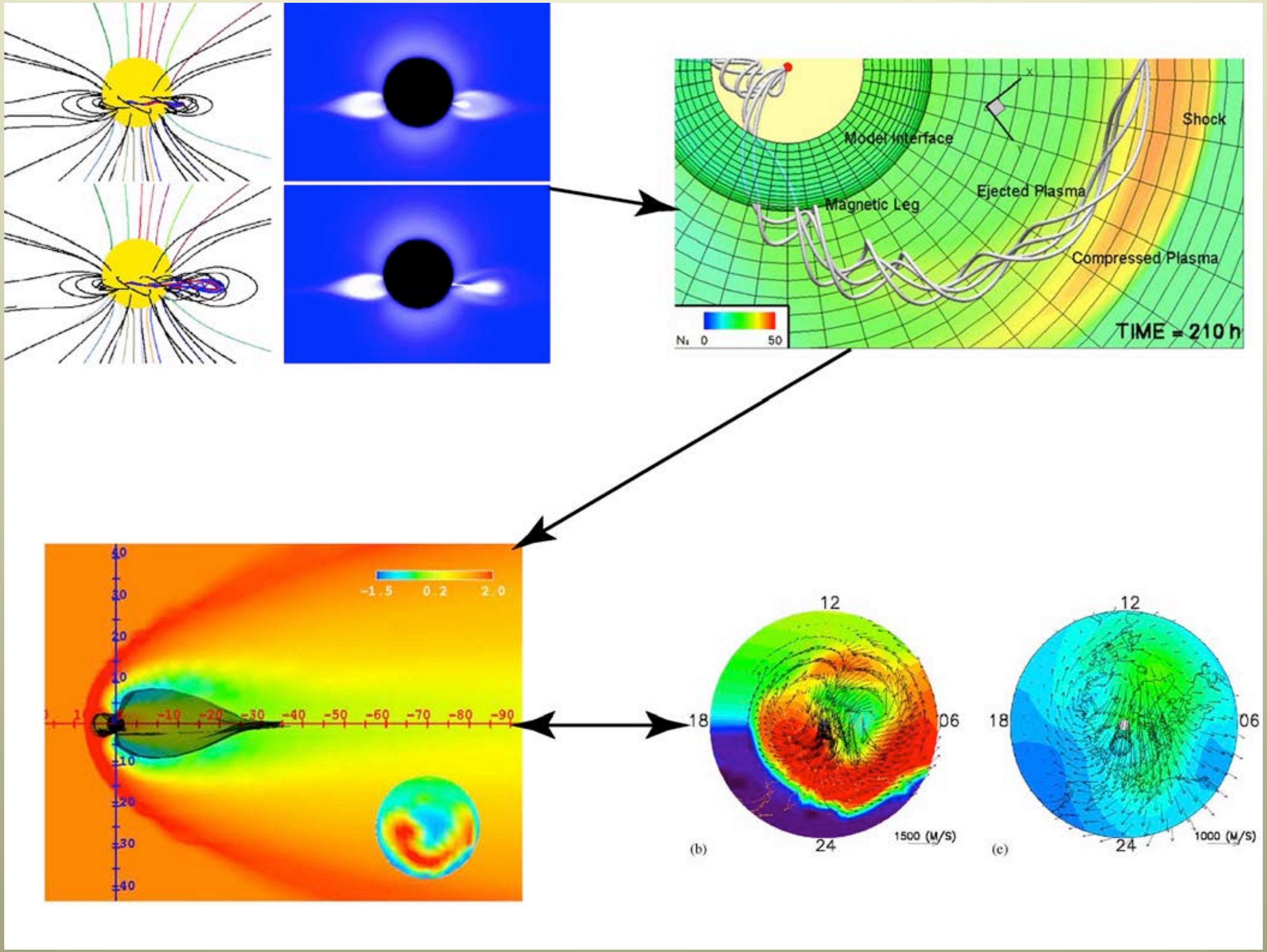
Peta-Scale 3D Global Hybrid Simulations

(Karimabadi, et al., GRL, to be submitted, 2010)



reconnection (courtesy of H. Karimabadi)

Coupled-Model Simulation from Sun to Earth



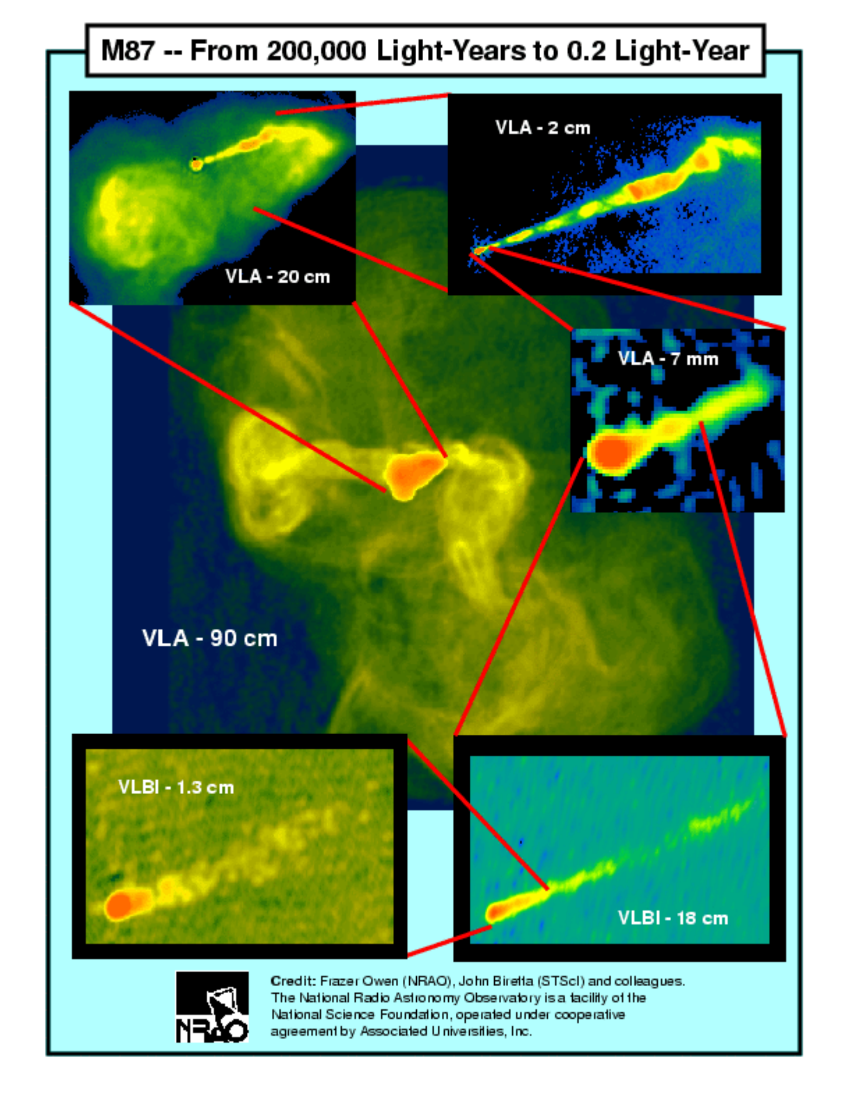
https://www.bu.edu/cism/News/highlights.html

Astrophysical Jets

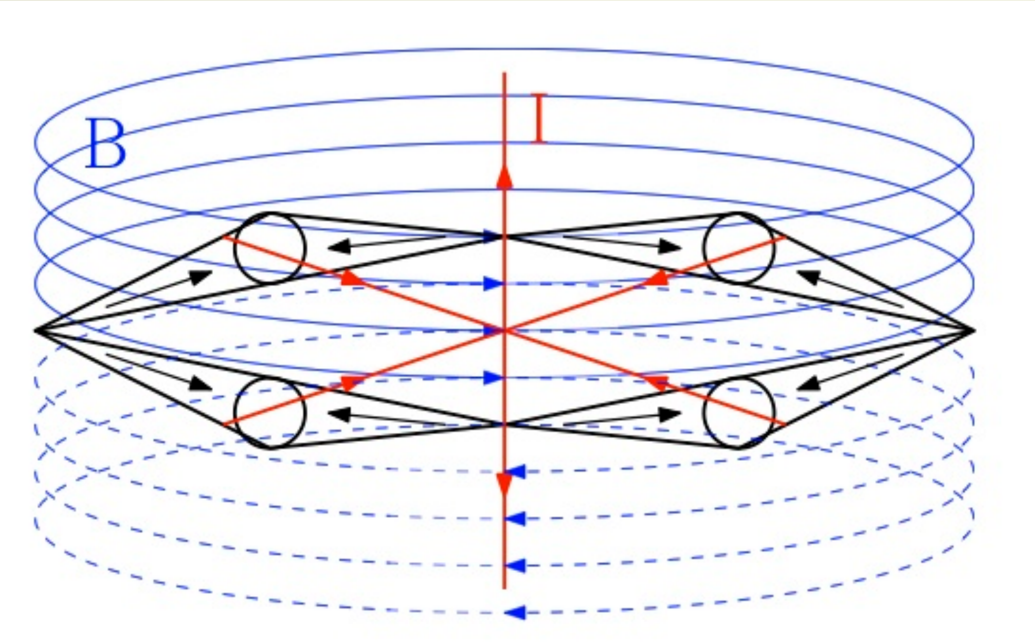
- *Astrophysical jets: outflow of highly collimated plasma*
  - Microquasars, Active Galactic Nuclei, Gamma-Ray Bursts, Jet velocity ～c, Relativistic Jets.
  - Generic systems: Compact object（White Dwarf, Neutron Star, Black Hole）+ Accretion Disk

- *Key Problems of Astrophysical Jets*
  - Acceleration mechanism and radiation processes
  - Collimation
  - Long term stability

M87



Reconnection-Powered Minijets in Blazars



Schematic representation of a toroidal current sheet at the boundary of two magnetic domains of opposite polarity, showing orientations of magnetic fields (*blue*), currents (*red*) and minijet flows (*black arrows*) from X-points to O-points.

(Nalewajko et al. MNRAS, 413, 333, 2011)

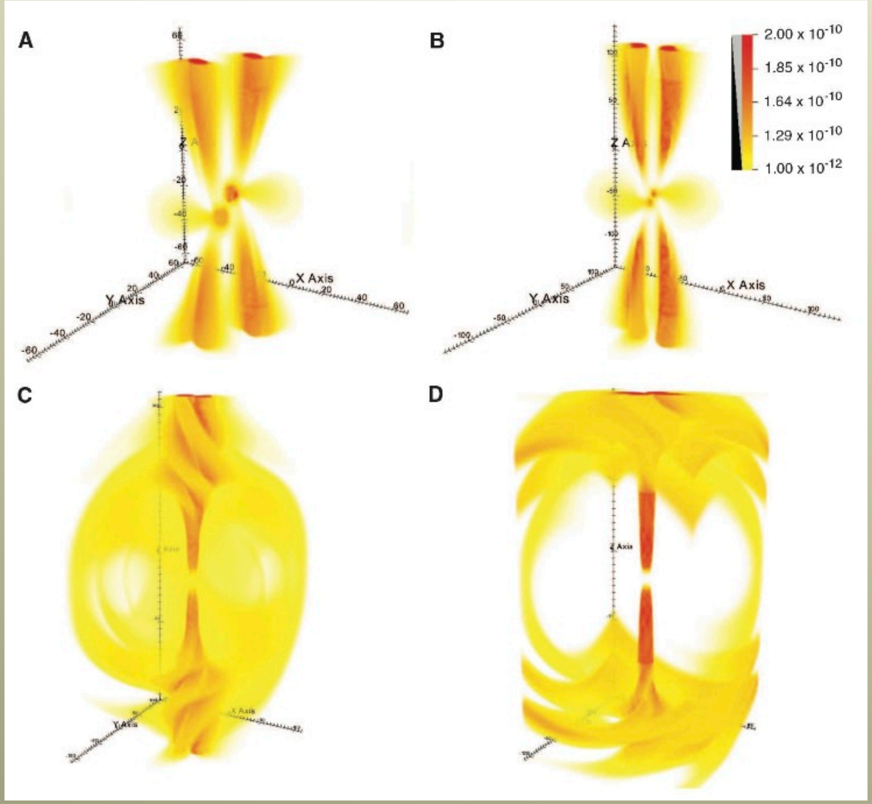
Recent Work for Relativistic Jets

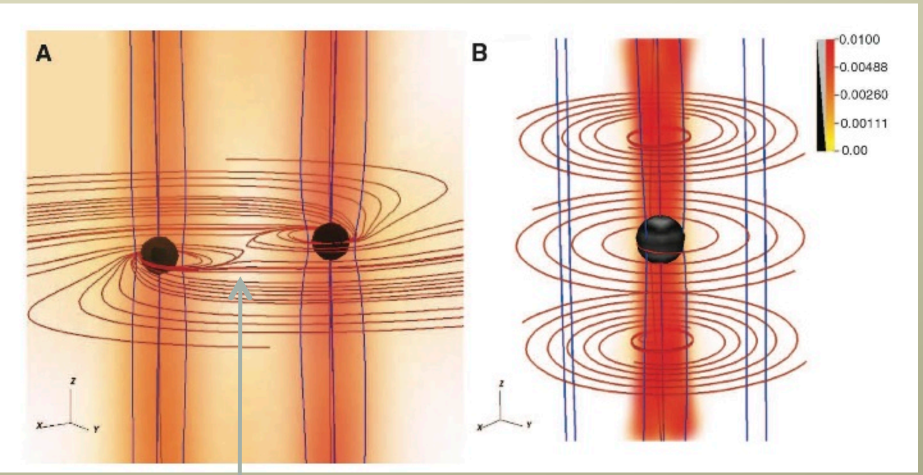
- Investigate the role of magnetic fields in relativistic jets against three key problems
  - Jet formation
  - Jet acceleration and radiation process
    - Acceleration of particles to very high energy
  - Jet stability
    - Kelvin-Helmholtz instability
    - Current-Driven instability

- **Recent research topics**
  - Development of 3D general relativistic MHD (GRMHD) code "RAISHIN"
  - GRMHD simulations of jet formation and radiation from Black Hole magnetosphere
  - A relativistic MHD boost mechanism for relativistic jets
  - Stability analysis of magnetized spine-sheath relativistic jets
  - Particle-In-Cell (PIC) simulations of relativistic jets

play 3Dprej5b_1.mov for kink instability

Reconnection during merging black hole binary?



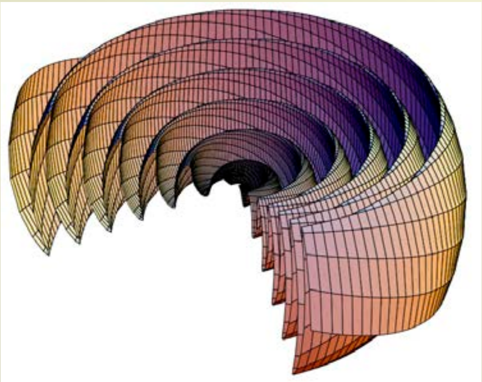


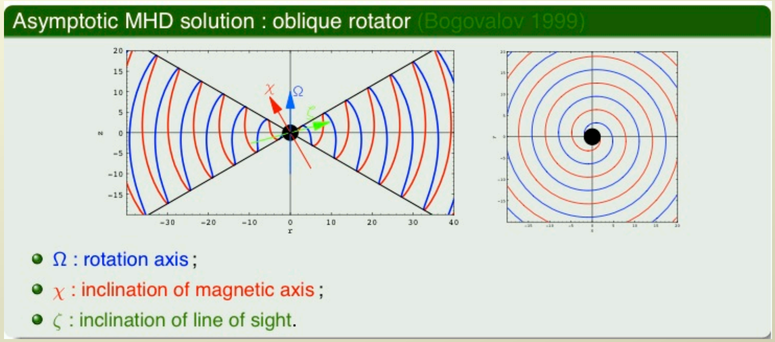
reconnection?

(Palenzuela, Lehner, & Liebling, Science, 329, 927, 2010)

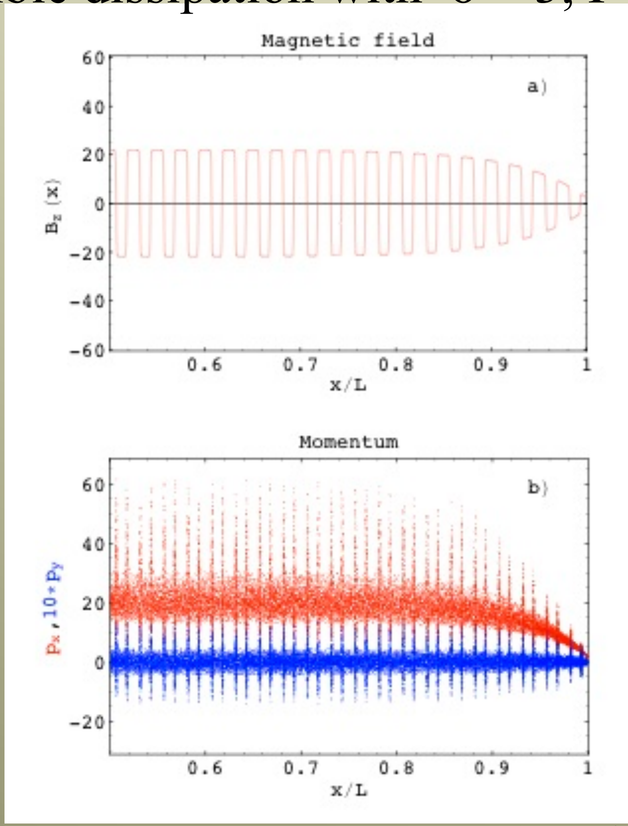
PIC simulation

play combinedmovie.mov

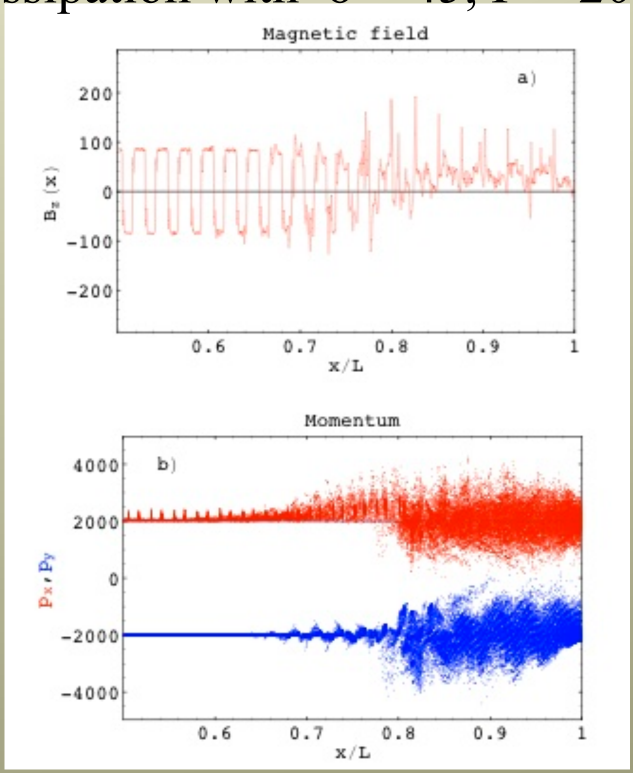




negligible dissipation with σ = 3, Γ = 20

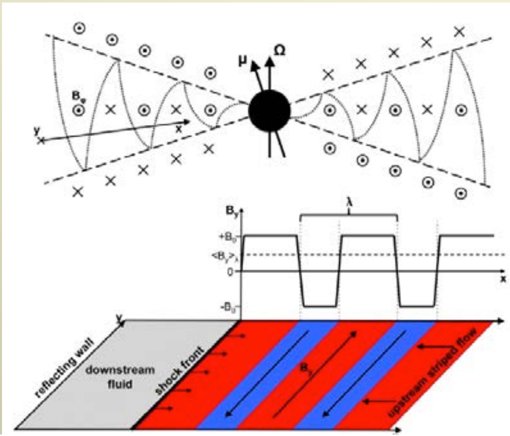


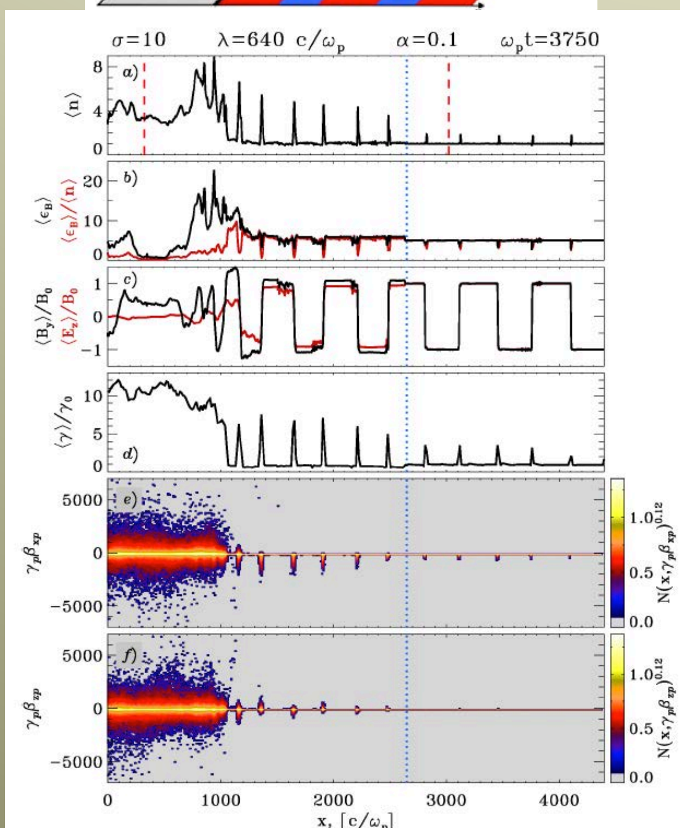
dissipation with σ = 45, Γ = 20

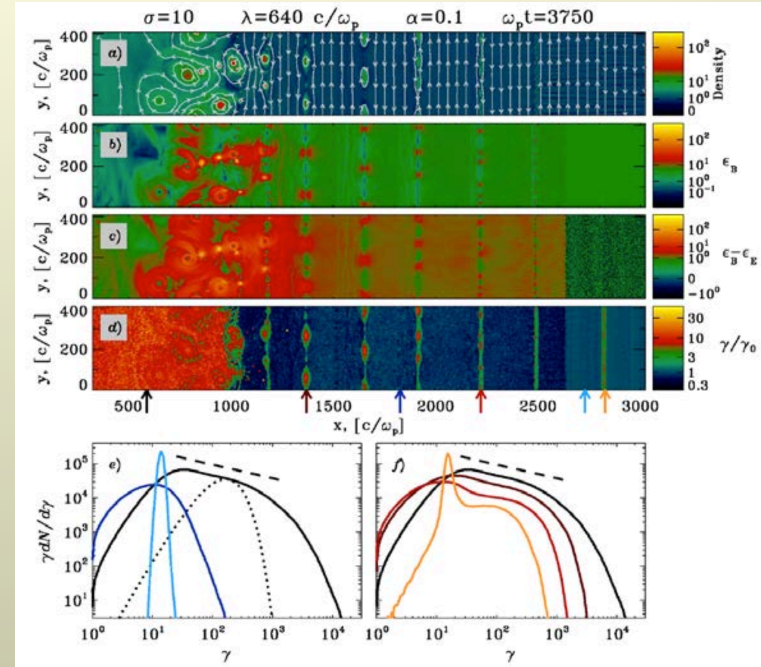


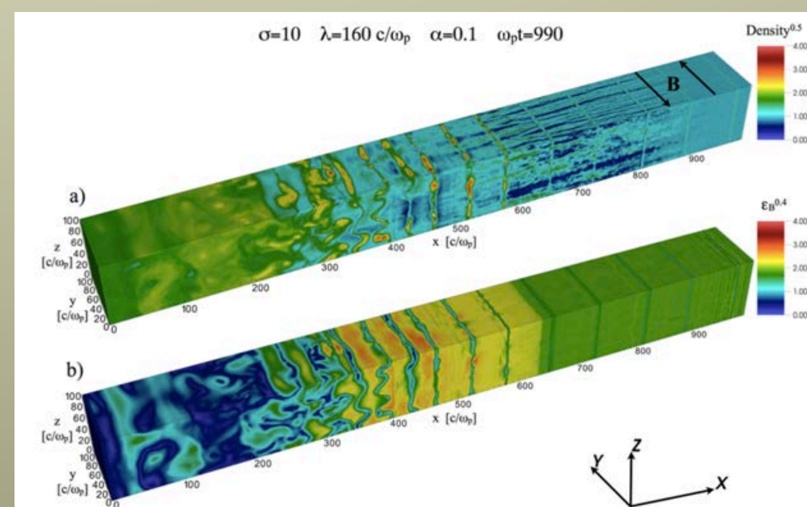
(Pétri & Lyubarsky, A&A, 2007)

2-D Striped wind simulation





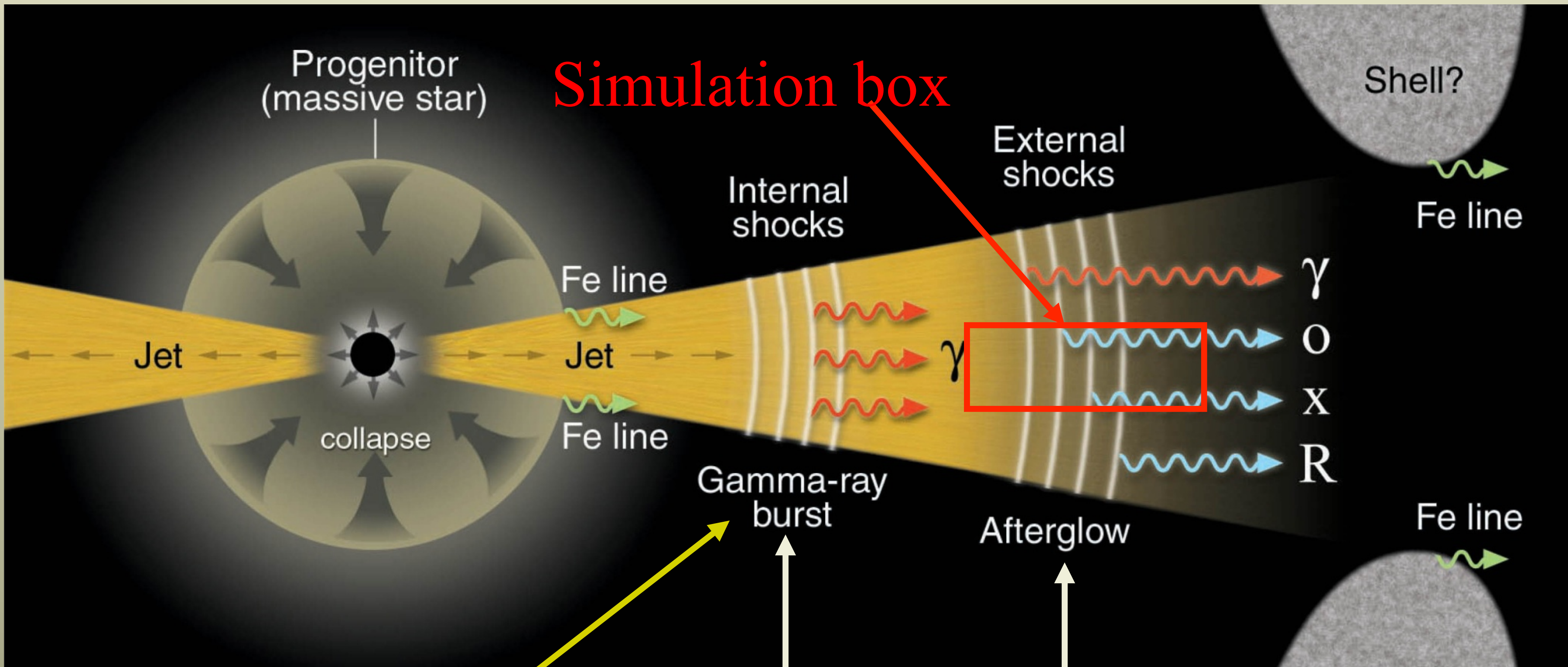




Sironi & Spitkovsky, ApJ, 2011

Schematic GRB from a massive stellar progenitor

(Meszaros, Science 2001)



Prompt emission

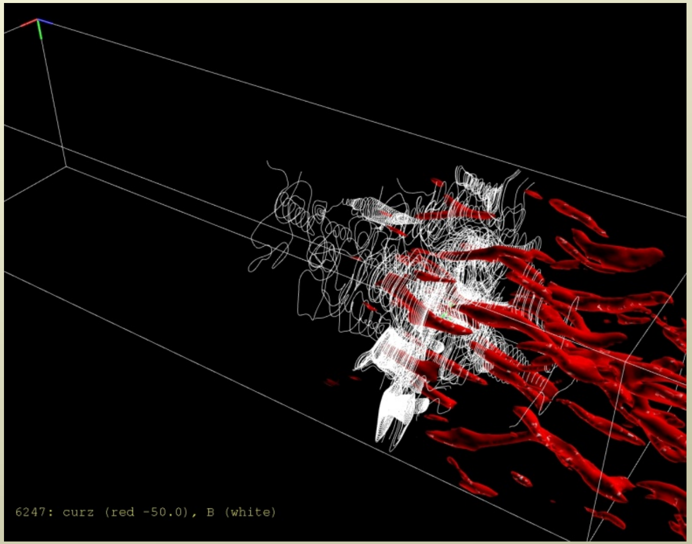
Polarization ?

Accelerated particles emit waves at shocks

3-D isosurfaces of z-component of current J_z for narrow jet ($\gamma v_{||}=12.57$)

electron-ion ambient $t = 59.8\omega_e^{-1}$

$-J_z$ (red), $+J_z$ (blue), magnetic field lines (white)

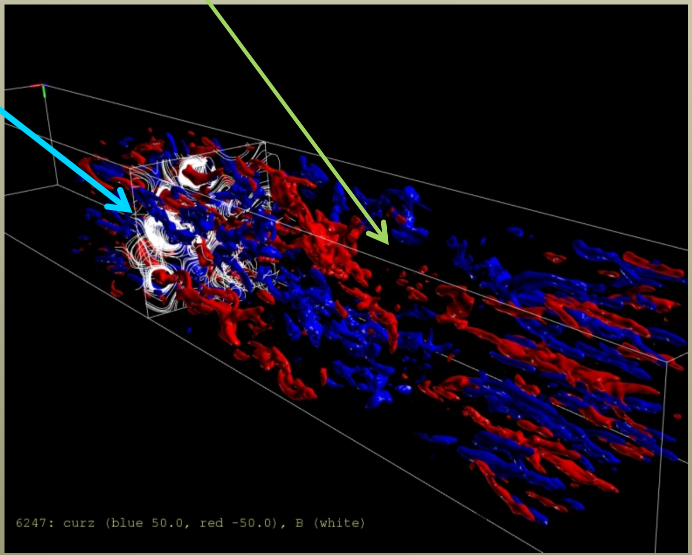


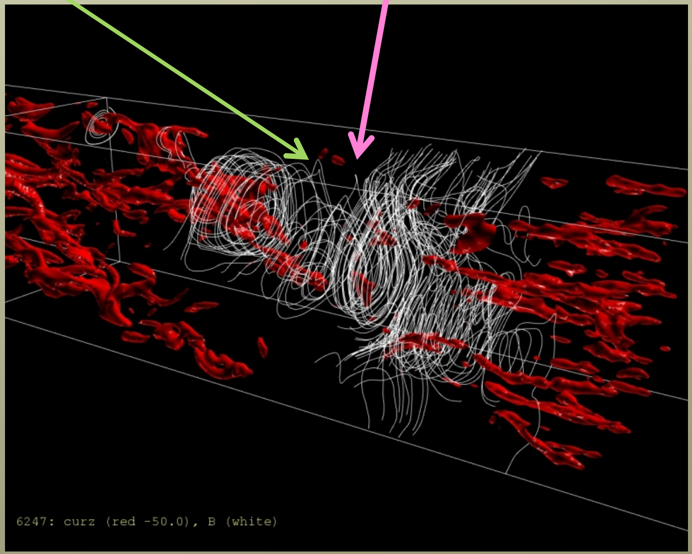
Particle acceleration due to the local reconnections during merging current filaments at the nonlinear stage

play apf62jzB.avi

thin filaments

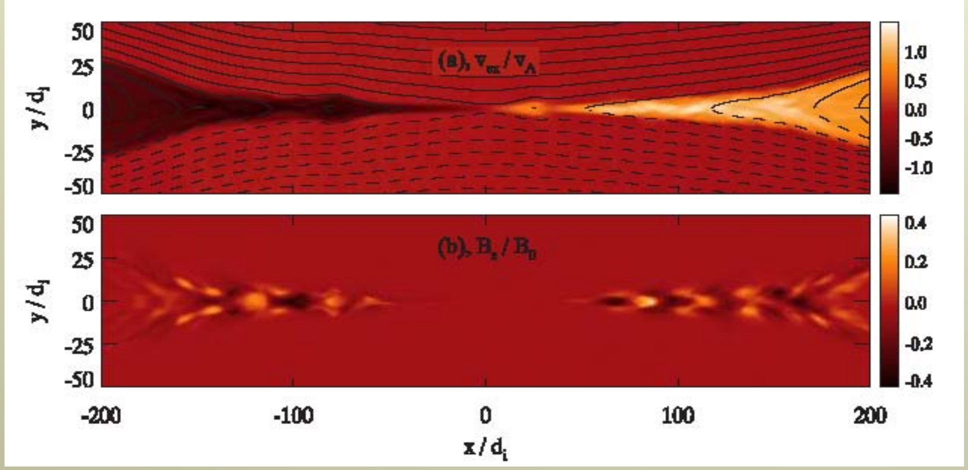
merged filaments





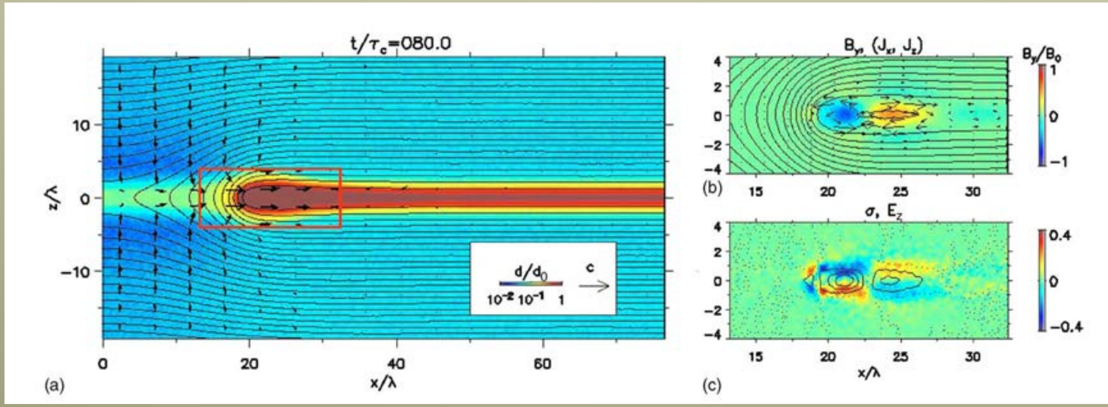
Weibel instability in reconnections

Electron beam excite the Weibel instability



nonrelativistic reconnection

(Swisdak, Liu, & Drake ApJ, 2008)



relativistic reconnection

(Zenitania & Hesse, PoP, 2008)

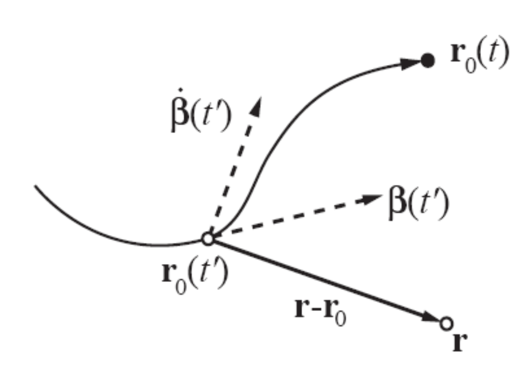
Cracow 2008 conference presentations
http://www.oa.uj.edu.pl/cracow2008/Program.html

Radiation from particles in collisionless shock

To obtain a spectrum, "just" integrate:

$$\frac{d^2W}{d\Omega d\omega} = \frac{\mu_0 c q^2}{16\pi^3}\left|\int_{-\infty}^{\infty} \frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^2}\, e^{i\omega(t'-\mathbf{n}\cdot\mathbf{r}_0(t')/c)}dt'\right|^2$$

where $\mathbf{r}_0$ is the position, β the velocity and $\dot{\beta}$ the acceleration



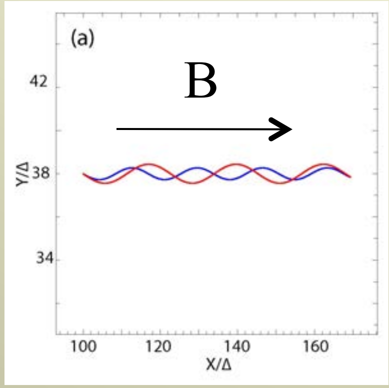
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

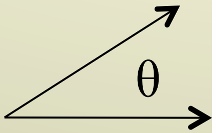
Hededal, Thesis 2005 (astro-ph/0506559)
Nishikawa et al. 2008 (astro-ph/0802.2558)
Sironi & Spitkovsky, 2009, ApJ
Martins et al. 2009, Proc. of SPIE Vol. 7359
Nishikawa et al. 2011, ASR

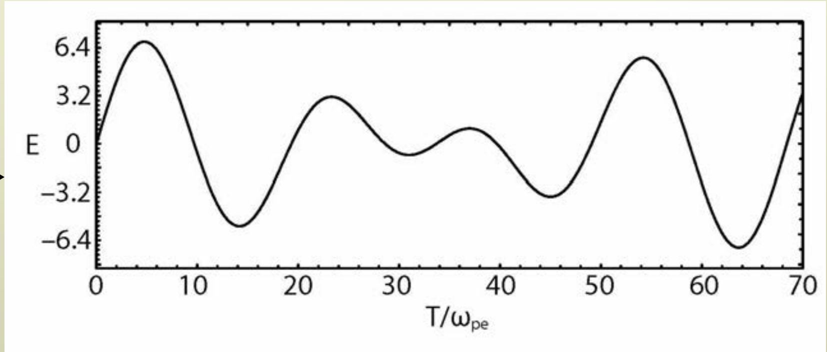
Synchrotron radiation from propagating electrons in a uniform magnetic field

electron trajectories

radiation electric field observed at long distance





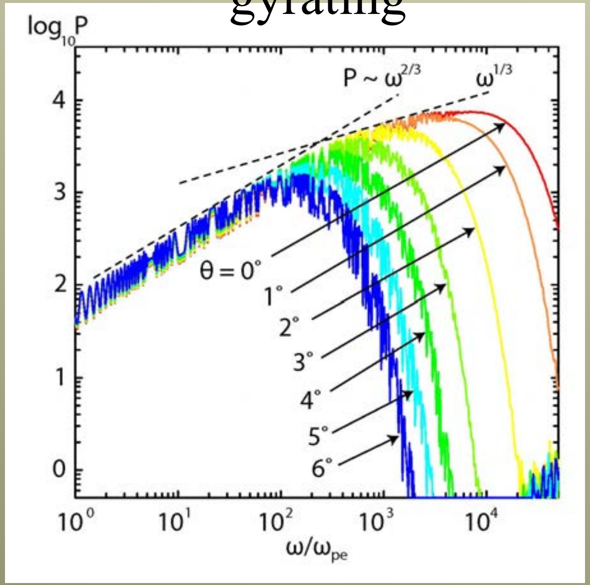


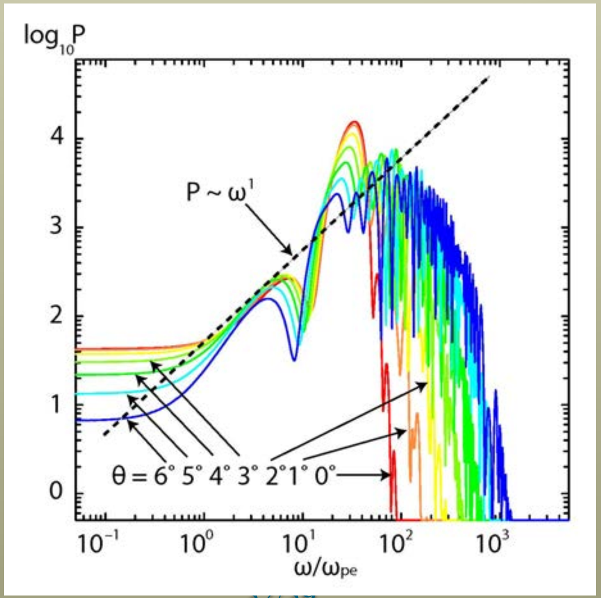
observer

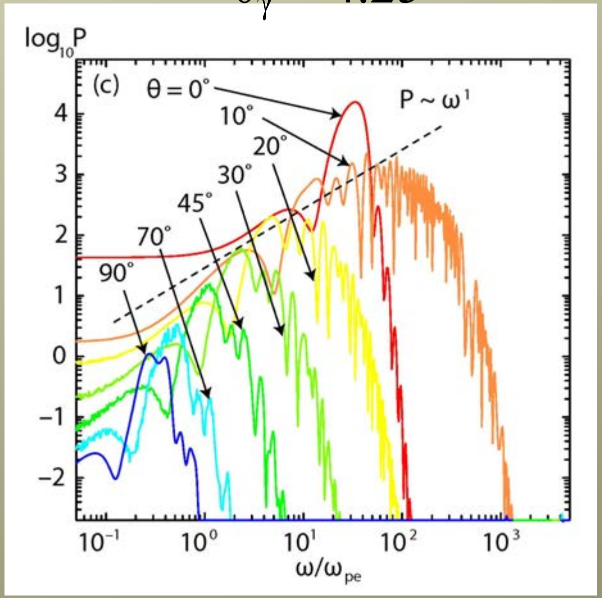
spectra with different viewing angles (helical)

gyrating

$\theta_\gamma = 4.25°$



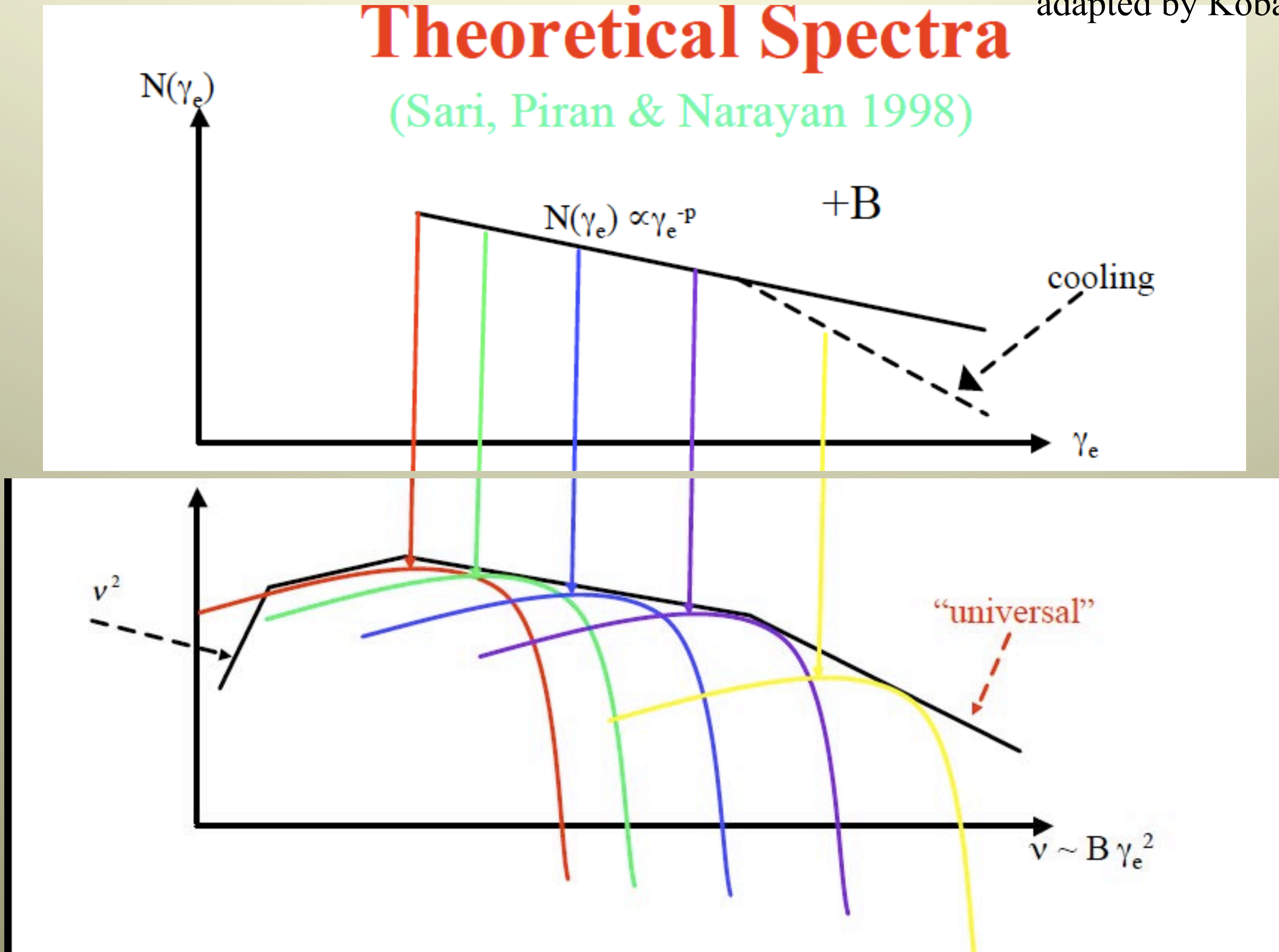




Nishikawa et al. astro-ph/0809.5067

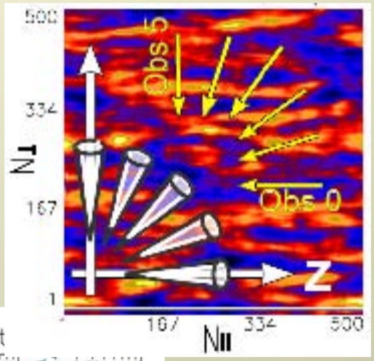
Synchrotron Emission: radiation from accelerated

adapted by Kobayashi



Importance of Synchrotron radiation calculated in 3-D system

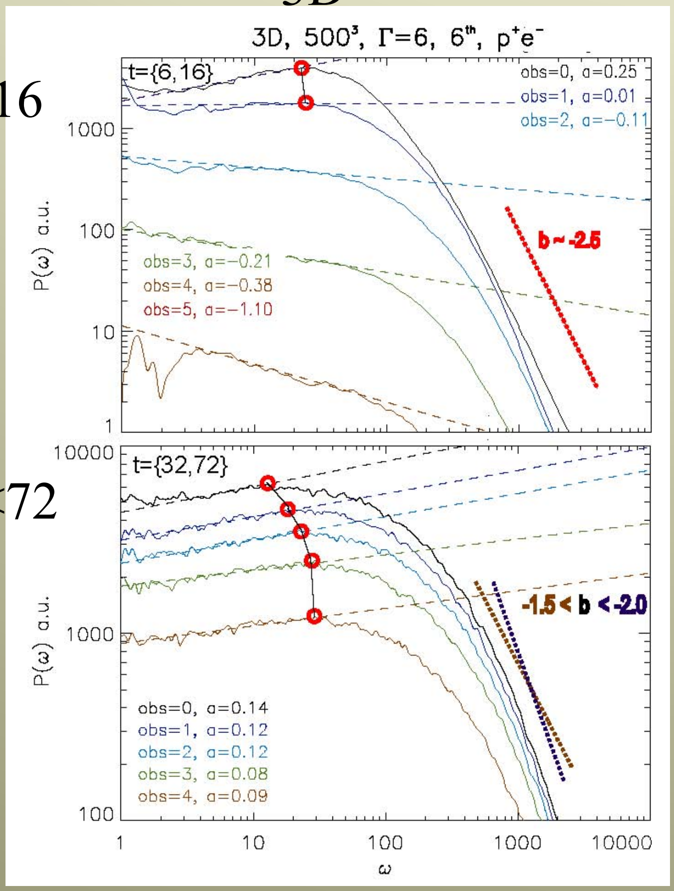
$\gamma = 6$, $P^+ e^-$ counter-streaming jet, no shock generated



3D

6<t<16

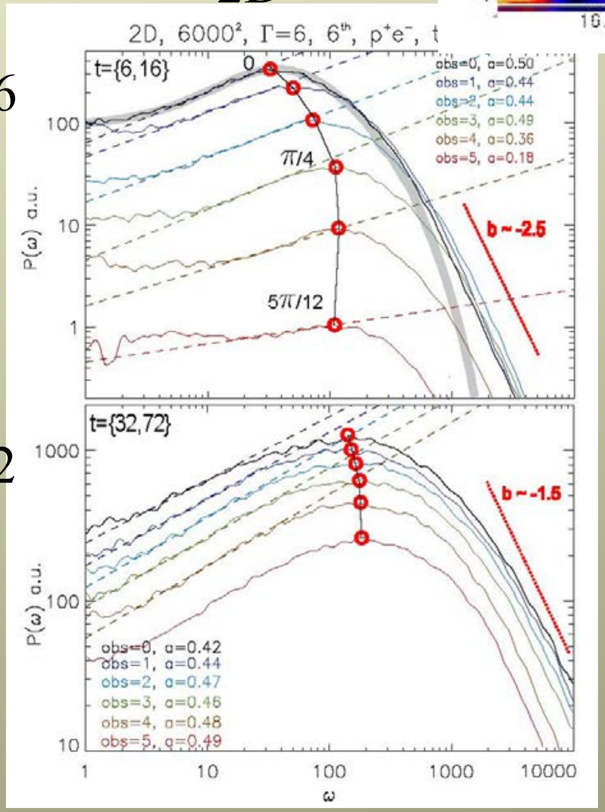
32<t<72



2D

6<t<16

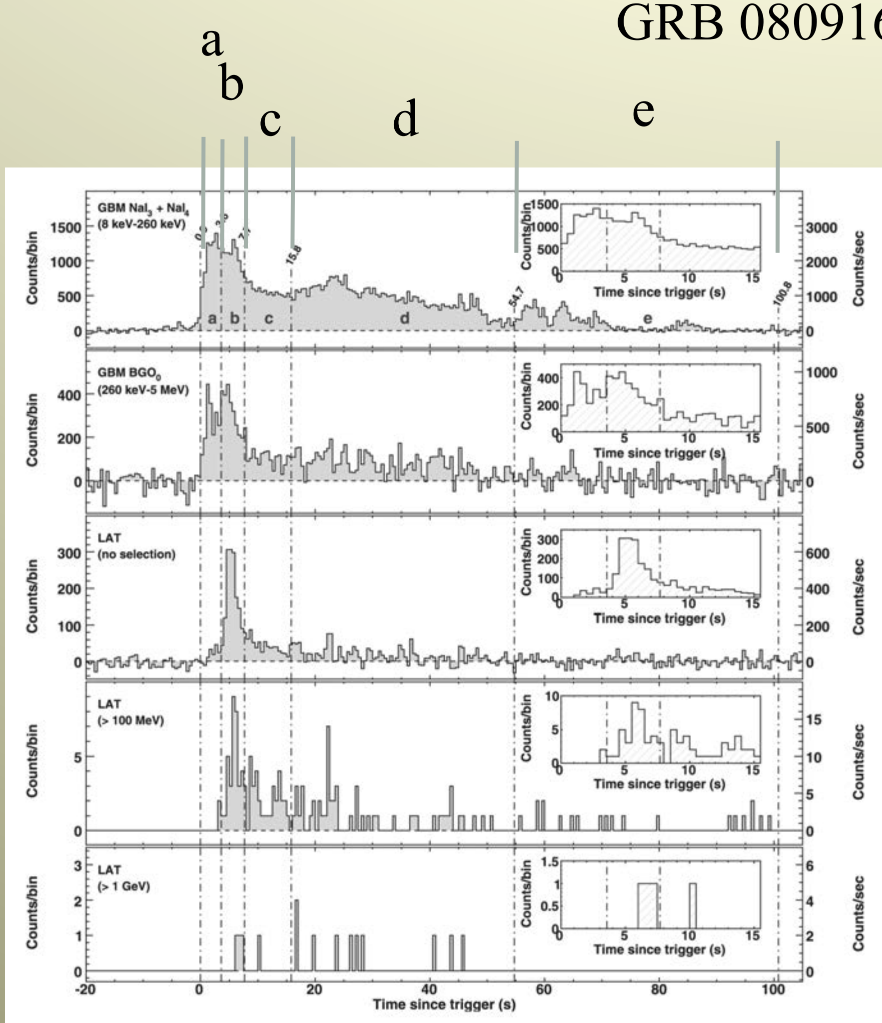
32<t<72

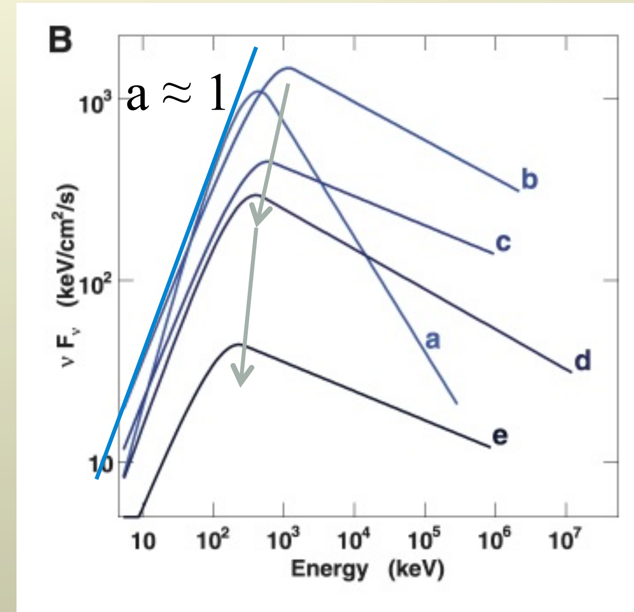


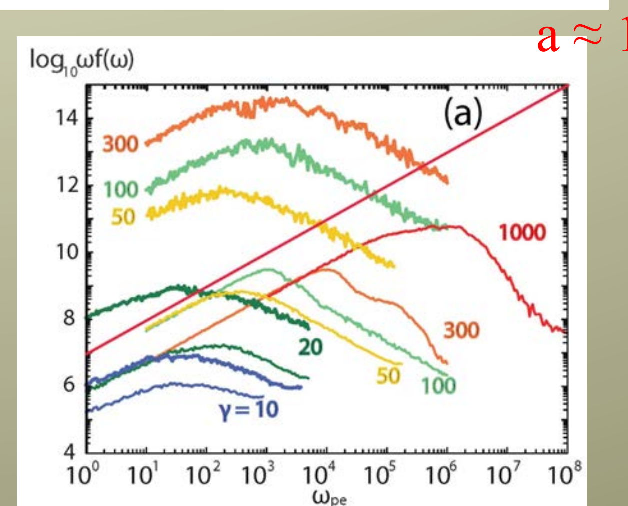
Frederiksen et al. ApJL, 2010

Observations and numerical spectrum

GRB 080916C







Abdo et al. 2009, Science

Nishikawa et al. 2010

Summary

- Reconnection is ubiquitous in magnetosphere, solar, and astrophysical plasmas
- Reconnection release Poynting flux to kinetic energy
- Particles are accelerated by reconnection
- Reconnection may provide additional time variability in radiation and involve in spectrum evolution and its structure
- Reconnection near compact objects may contribute to particle acceleration

Gamma-Ray Large Area Space Telescope (*FERMI)*

(launched on June 11, 2008) ***http://fermi.gsfc.nasa.gov/***

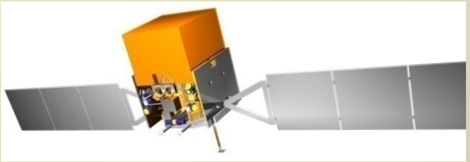
Compton Gamma-Ray Observatory (CGRO)

Burst And Transient Source Experiment

(BATSE) (1991-2000)

PI: Jerry Fishman

→



Fermi (GLAST)

All sky monitor

- **Large Area Telescope (LAT) PI: Peter Michaelson: gamma-ray energies between 20 MeV to about 300 GeV**

- **Fermi Gamma-ray Burst Monitor (GBM) PI: Bill Paciaas (UAH) (Chip Meegan (Retired;USRA)): X-rays and gamma rays with energies between 8 keV and 25 MeV**

(http://gammaray.nsstc.nasa.gov/gbm/)

The combination of the GBM and the LAT provides a powerful tool for studying radiation from relativistic jets and gamma-ray bursts, particularly for time-resolved spectral studies over very large energy band.

Structure of Tristan code: Subroutines

Main program

- main loop
- dump data for rerun and diagnostics
- accumulate data for radiation

input program (include)

- set parameters for simulations (density, jet velocity, magnetic field, etc)
- load particles as initial conditions

diagnostic program (include) (not active)

Initial settings

Jet simulations

```
c number of processors
      parameter (Nproc=4)
      parameter (Npx=1,Npy=2,Npz=2)

c  VIRTUAL PARTICLE array is distributed among processes so that each process
c  works on nFx*nFy*nFz cells (its subdomain);

c !!! y and z domain size MUST BE EQUAL in the present setup: nFy=nFz !!!

c  FIELD arrays have mFi (mFx,mFy,mFz) elements in each dimension:
c  nFi plus 3 ghost cells on the "Right" and 2 ghost cells on the "Left"
      parameter (mx=645,my=11,mz=11)

      parameter (nFx=(mx-5)/Npx,mFx=nFx+5)
      parameter (nFy=(my-5)/Npy,mFy=nFy+5)
      parameter (nFz=(mz-5)/Npz,mFz=nFz+5)
```

```
c depending the size of domain in a processor
      parameter (nptl=2000000)
      parameter (mb=nptl,mj=1800000)

c  size of particle communication buffer arrays
c ** size is set as for ambient particles that move in one general direction  **
c !! check for particle number moving perpendicular to jet flow in Left proc. !!
c **       mpass = nFy*nFz*c*DT*adens + 10%-20%                               **
c ** must be reset for different particle densities                          **

      parameter (mpass=500000)

      parameter (mdiag=2500)

c  2**15-1
      parameter (imax=32767)

      integer size,myid,ierror
      integer lgrp,comm3d
```

```
      integer topol

      integer dims(3),coords(3)
      logical isperiodic(3),reorder

      integer FBDRx,FBDRy,FBDRz
      integer FBDLx,FBDLy,FBDLz
      integer FBDRxe,FBDLxe
      integer FBDRxp,FBDLxp
      integer FBD_BRx,FBD_BRy,FBD_BRz
      integer FBD_BLx,FBD_BLy,FBD_BLz
      integer FBD_ERx,FBD_ERy,FBD_ERz
      integer FBD_ELx,FBD_ELy,FBD_ELz

c  temporary arrays in 16-bit integers for data dump
      integer*2 irho,ifx,ify,ifz,ixx,iyy,izz

      real mi,me
```

```
      character strb1*6,strb2*6,strb3*6,strb4*6,strb5*6,strb6*6
      character strj1*6,strj2*6,strj3*6,strj4*6,strj5*6,strj6*6
      character strfb*5,strfe*5
      character strin*8
      character dir*28,num*3,st01,st02,st03,st0*3,st*4,hyph
      character step*6,step1,step2,step3,step4,step5
      character soutb*3,soute*3,soutd*5,soutv*4
      character ndiag*6,nfield*7
      character num1,num2,num3
      character strpd*6

c  electric and magnetic field arrays
      dimension ex(mFx,mFy,mFz),ey(mFx,mFy,mFz),ez(mFx,mFy,mFz)
      dimension bx(mFx,mFy,mFz),by(mFx,mFy,mFz),bz(mFx,mFy,mFz)

c  electric field longitudinal increaments (currents) arrays
      dimension dex(mFx,mFy,mFz),dey(mFx,mFy,mFz),dez(mFx,mFy,mFz)

c  ambient ions and electrons positions and velocities arrays
      dimension xi(mb),yi(mb),zi(mb),ui(mb),vi(mb),wi(mb)
      dimension xe(mb),ye(mb),ze(mb),ue(mb),ve(mb),we(mb)
```

```
c  jet ions and electrons positions and velocities arrays
      dimension xij(mj),yij(mj),zij(mj),uij(mj),vij(mj),wij(mj)
      dimension xej(mj),yej(mj),zej(mj),uej(mj),vej(mj),wej(mj)

c  diagnostic arrays (for quantities recorded on the grid)
cWR      dimension flx(mFx,mFy,mFz),fly(mFx,mFy,mFz),flz(mFx,mFy,mFz)
cWR      dimension rho(mFx,mFy,mFz)

c  diagnostic arrays for velocity distribution
      dimension Cvpar(mdiag),Cvper(mdiag),xpos(mdiag)

c  integer*2 arrays
      dimension ifx(mFx,mFy,mFz),ify(mFx,mFy,mFz),ifz(mFx,mFy,mFz)
      dimension irho(mFx,mFy,mFz)
      dimension ixx(mb),iyy(mb),izz(mb)

c  temporary arrays for jet injection
c       dimension Cseli(msel),Csele(msel)

      dimension ipsend(4),iprecv(Nproc*4)
```

```
 cCOL embed "topology" calculation
      dimension itops(3),itopr(Nproc*3)
      dimension topol(0:(Nproc-1),3)

c  smoother array
      dimension sm(-1:1,-1:1,-1:1)
c  smoother arrays for combined digital filtering
      dimension sm1(-1:1,-1:1,-1:1),sm2(-1:1,-1:1,-1:1)
      dimension sm3(-1:1,-1:1,-1:1)
      dimension nfilt(16)

c  initialize MPI
c ** "size" must be equal "Nproc"; "myid" is a ID for each process **
      common /pparms/ lgrp,comm3d

      lgrp = MPI_COMM_WORLD

      call MPI_INIT(ierror)
      call MPI_COMM_SIZE(lgrp,size,ierror)
      call MPI_COMM_RANK(lgrp,myid,ierror)
```

```
c  define virtual topology - assign processes to the domains
c  3D Cartesian decomposition
c  number of processes in each direction
      dims(1)=Npx
      dims(2)=Npy
      dims(3)=Npz
c  indicate whether the processes at the "ends" are connected
c ** y and z directions are periodic **
cJET
      isperiodic(1)=.false.
      isperiodic(2)=.true.
      isperiodic(3)=.true.
c  changing "reorder" to .true. allows MPI to reorder processes for better
c  performance - in accordance to the underlying hardware topology
      reorder      =.false.
c  number of dimensions
      ndim=3
```

```
c  create Cartesian decomposition
c  new communicator "comm3d" created - it must be used for communication
c ** in test simulations processes in "comm3d" have the same rank as in **
c ** MPI_COMM_WORLD (is this feature portable to different computers?)  **
      call MPI_CART_CREATE(lgrp,ndim,dims,isperiodic,reorder,
     &                                    comm3d,ierror)

c  find Cartesian coordinates of the process (one can use also "MPI_CART_GET")
c ** coordinates run from 0 to Npi-1 **
      call MPI_CART_COORDS(comm3d,myid,3,coords,ierror)
c     call MPI_CART_GET(comm3d,3,dims,isperiodic,coords,ierror)

c  find ID of the (6) neighbors to the process (through the surfaces)
c ** communication is set up in the way that it requires contacting 6 closest **
c ** neighbors only                                                            **
c ** second argument in "MPI_CART_SHIFT" is direction, third is shift=1 **
      call MPI_CART_SHIFT(comm3d,0,1,nleft,nright,ierror)
      call MPI_CART_SHIFT(comm3d,1,1,nfront,nrear,ierror)
      call MPI_CART_SHIFT(comm3d,2,1,nbottom,ntop,ierror)
```

```
      if (nFy.ne.nFz) then
       if (myid.eq.1) print *,'Y and Z DOMAIN SIZES MUST BE EQUAL !!!'
       goto 9999
      end if

      call smoother(sm)

c  defining the characters for filenames
      strfb = 'fldb_'
      strfe = 'flde_'

      strb1 = 'pambx_'
      strb2 = 'pamby_'
      strb3 = 'pambz_'
      strb4 = 'pambu_'
      strb5 = 'pambv_'
      strb6 = 'pambw_'
```

```
      strj1 = 'pamjx_'
      strj2 = 'pamjy_'
      strj3 = 'pamjz_'
      strj4 = 'pamju_'
      strj5 = 'pamjv_'
      strj6 = 'pamjw_'

      strin = 'inparam_'

c  diagnostics and partial output files
      soutb = 'bf_'
      soute = 'ef_'
c       soutd = 'dens_'
      soutd = 'diag_'
      soutv = 'vel_'

c continued
```