Solar Magnetogram Synthesis:
A Vital Data Analysis Component of A Space Weather Prediction Infrastructure

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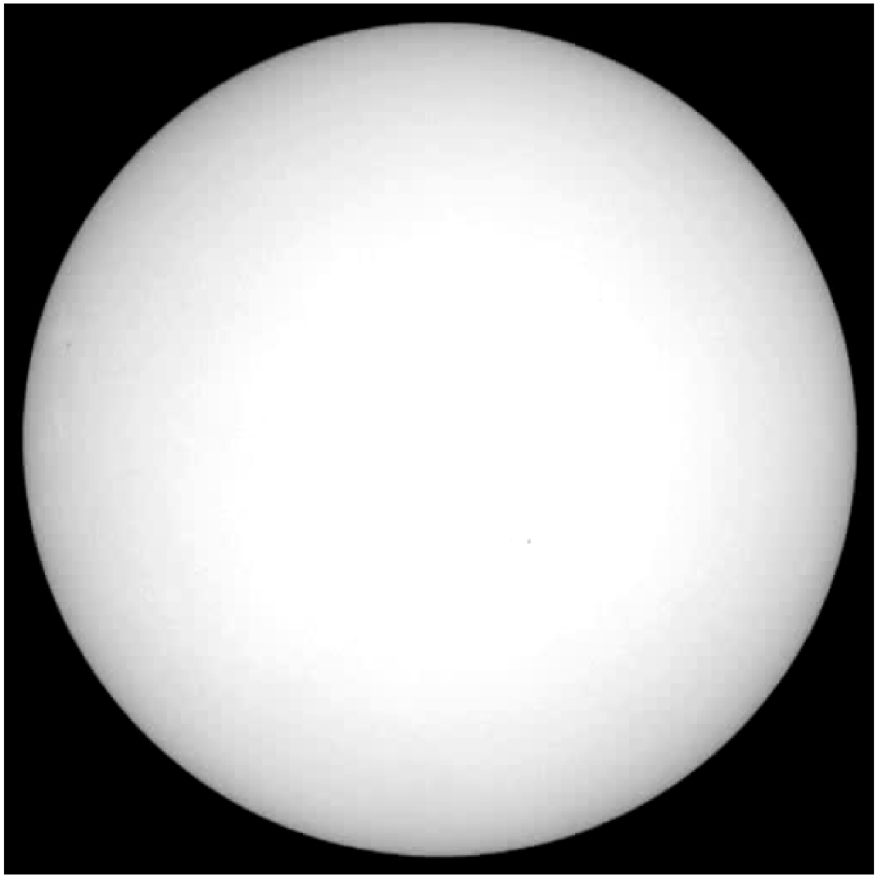
Space Weather Primer

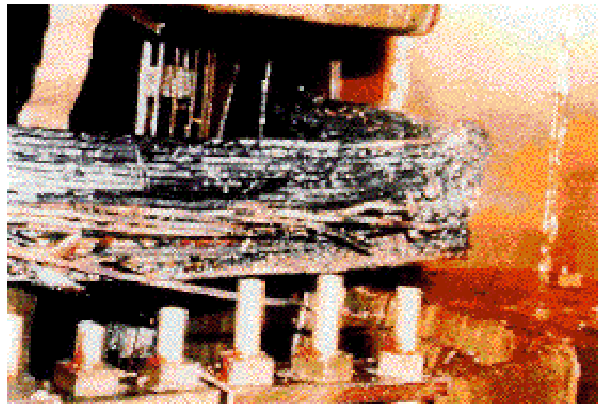
- Sun is the source of all transients driving space weather
- Most severe cases - Highly stressed coronal magnetic fields relax explosively – Flares/Coronal mass ejection

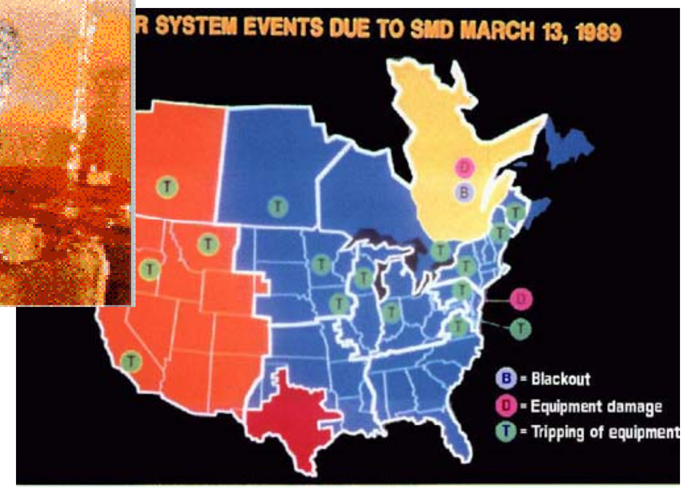


Credit : SOHO Project

- Resulting hazards
  - Prompt radiation (8 minutes)
  - Fast particles (e^- > 30 mins, p^+ > 60mins)
  - CME shock driven particles (> 12 hours)
  - Mass Ejecta (>18 hours)
  - Resulting magnetic storm

Societal Impact of Space Weather

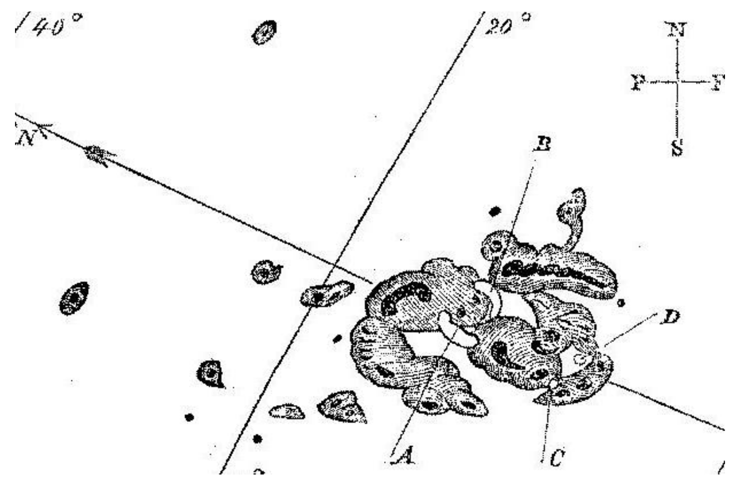


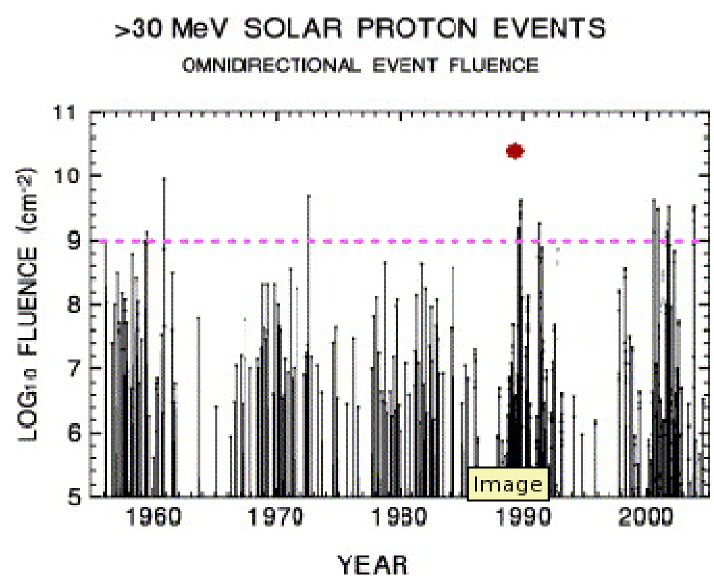


- Power Grid failures
  - Blackouts (eg Quebec, Mar 13 1989)
  - long term, if high voltage transformers damaged
- Satellite failures (and over long term, reduced lifetimes)
- Communication and GPS blackouts
- Particle hazards to astronauts and polar flight passengers

Space Weather Primer (contd)

- Worst Case Scenario – Carrington event, Sept 1,1859
  - Aurora in Havana
  - No solar event of comparable magnitude in the technological era, by factor of 4 !
  - Ice core records suggest one ‘Carrington like’ event or bigger impacts Earth every 500 years.
  - Estimates ~$70 billion impact on satellite industry (Odenwald et al 2006)
    - more than 80 satellites would be disabled
    - Approx 100 LEO would reenter prematurely





Shea et al 2006

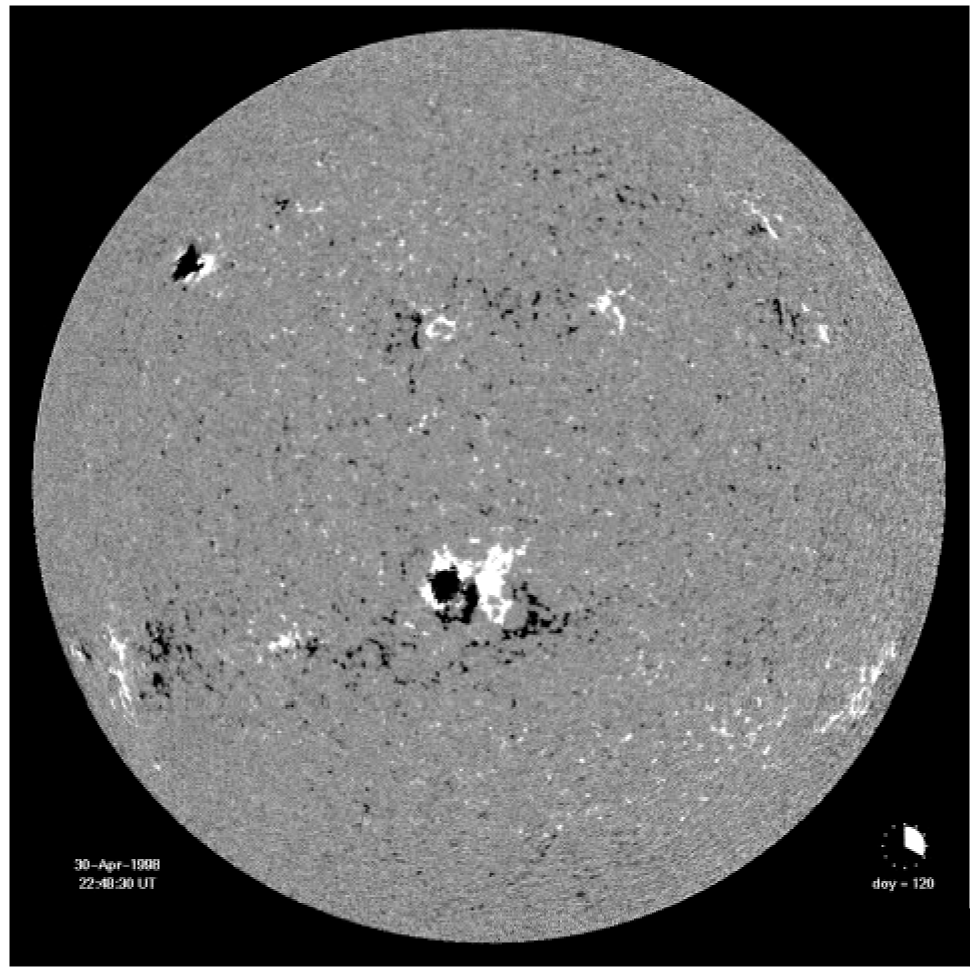
Next Generation Space Weather Models

- Coronal models will be
  - Global
  - Time dependent
  - 3D MHD with adaptive mesh refinement
  - Driven by observed surface flows
- Models will need to support both forecasting and research
  - Function with latest data and archived data regardless of data limitations
- Models will define spatial resolution and cadence of magnetogram data at inner boundary
  - eg global vector fields with maximum resolution of $\sim 1''$, cadence of 1 second

Where will these models get their data ?

Magnetograms

- Images of the Sun's magnetic field.
- Measured in photosphere
- LOS and vector
- Full disk tend to only be LOS



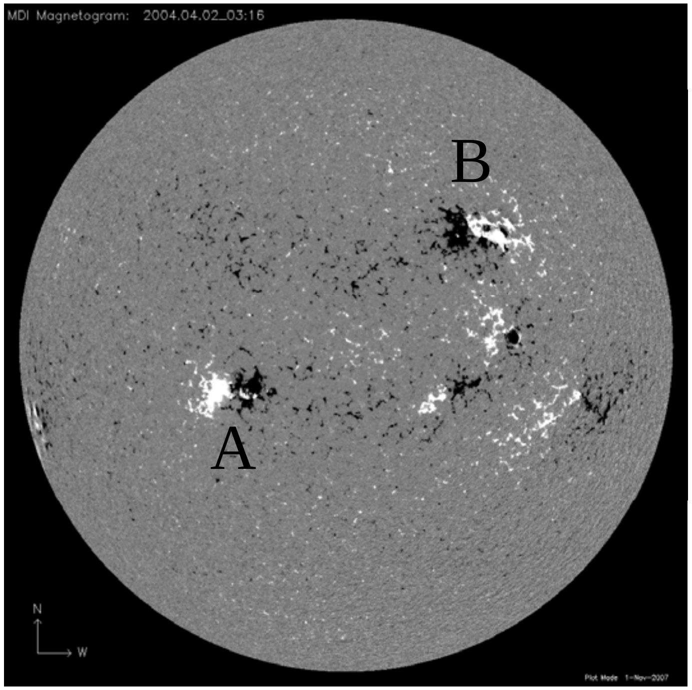
Magnetogram Limitations

- Magnetogram source limitations include
  - Cadence and duty cycle
  - Resolution
  - Field of view
  - Quality, particularly horizontal components of vector data
  - Systematic errors associated with line fittings
  - No coverage of far side
  - Very poor polar fields
- No single source provides enough coverage!
  - eg SDO – 0.5″ resolution data
    - Limited FOV Vector data every 10 minutes
    - Full Disk Line of Sight data every 10 minutes
    - Full disk vector data every 6 hours

How do we provide global surface vector fields and flow fields to an active region model at the spatial and temporal resolution required by the model?

A Hypothetical Modeling Challenge

- Active Region evolution Model
  - Suppose we need a model for slow evolution of Active Region A
- There is a second active region B on disk
- Synoptic vector magnetogram data is available from Kitt Peak along with individual vector magnetograms taken 3 times per day. However data for region B is poorly sampled due to instrument problems.
- Marshall Vector Magnetogram has data for B but at different times and resolution than Kitt Peak.
- Also have LOS magnetograms at selected times from Kitt Peak, Mt Wilson and MDI.



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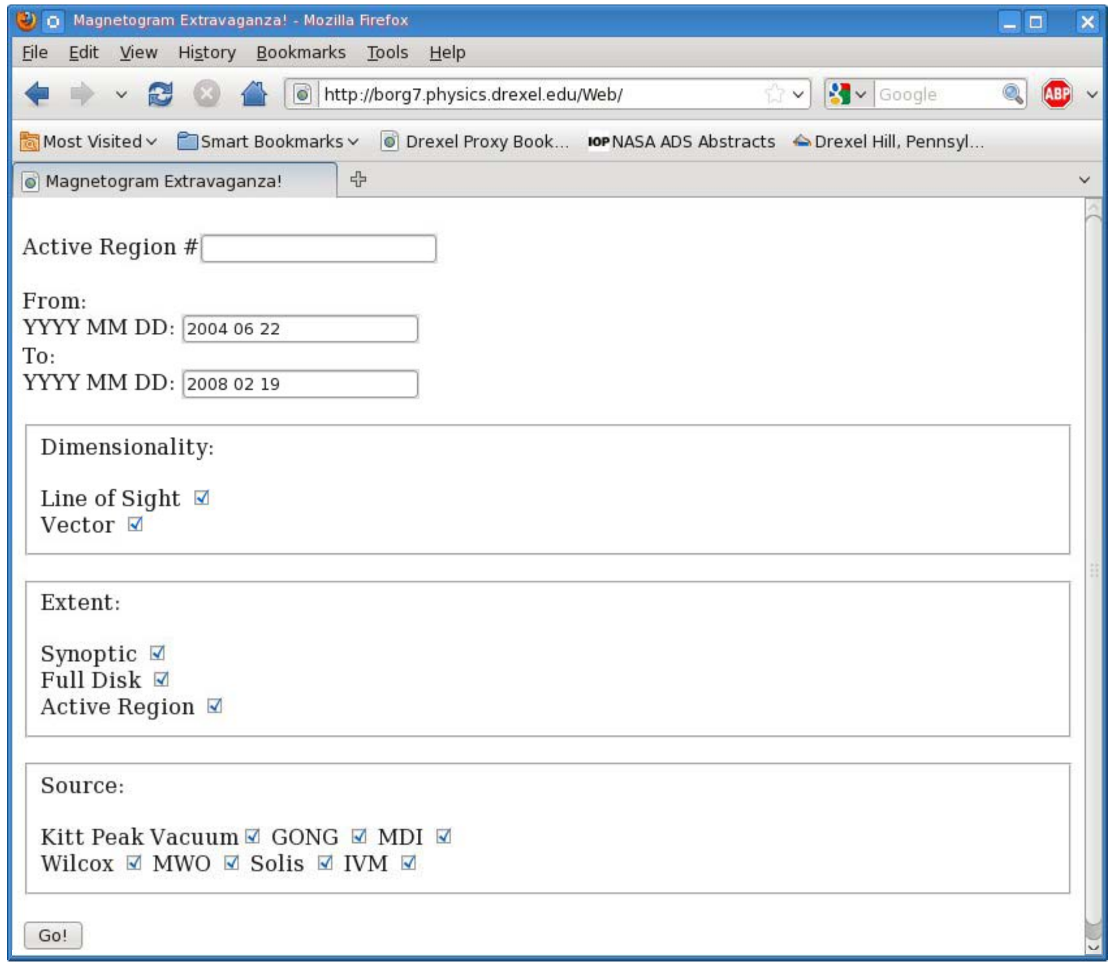
Our Solution: MAGIC

- MAGIC (MAGnetogram Interpolation and Composition) consists of:
- Active Region and Magnetogram Database
  - Find magnetograms
  - Download and convert to Kameleon format (Maddox 2007)
- Lightweight Processing Layer
  - Interpolation in space and time
  - Monopole Subtraction
  - LOS-to-Radial projection
  - Combine Magnetograms
  - Others to be defined
- Heavyweight Processing Layer
  - Interface to 3rd party tools such as DAVE4VM and NLFFF extrapolation

Active Region/Magnetogram Database

- Database tools scans instrument archives looking for new magnetograms.
- The user can query the database based on a wide variety of criteria.



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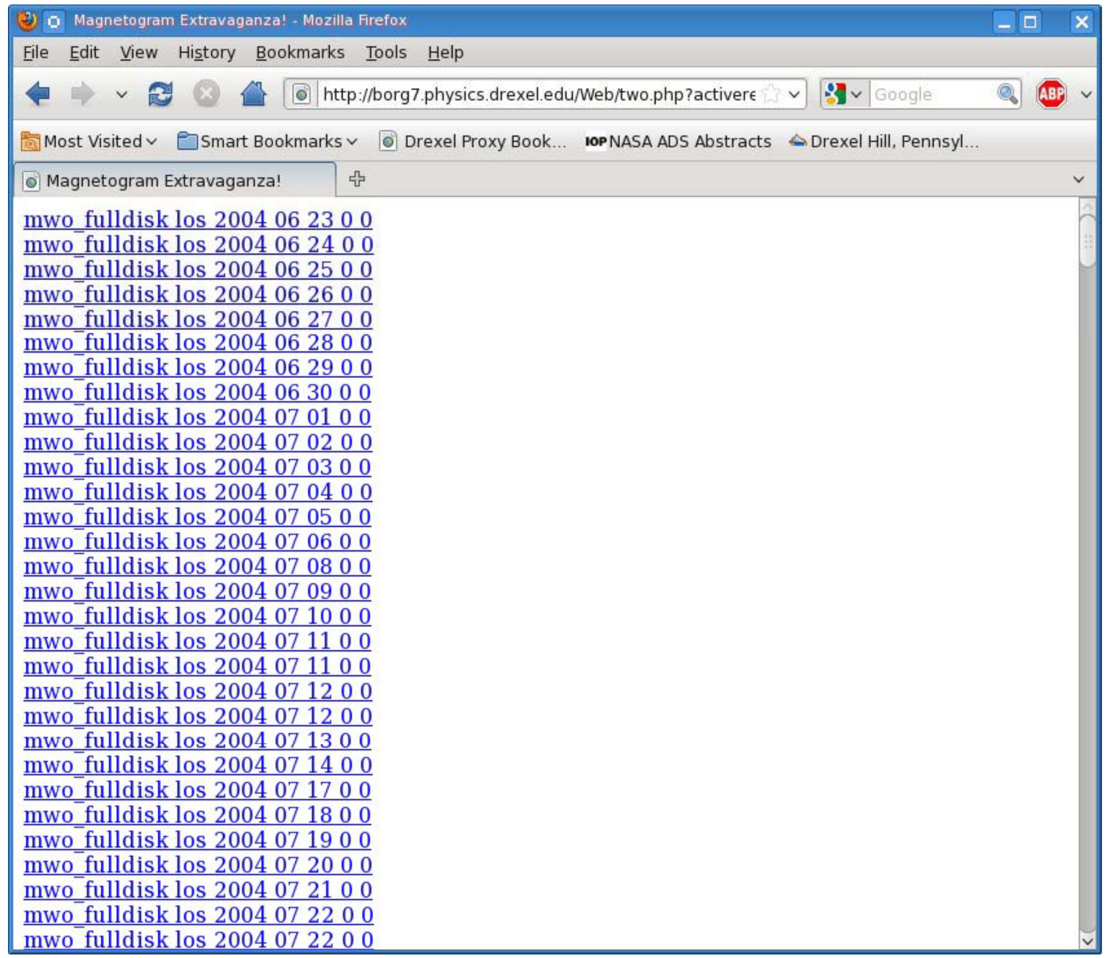
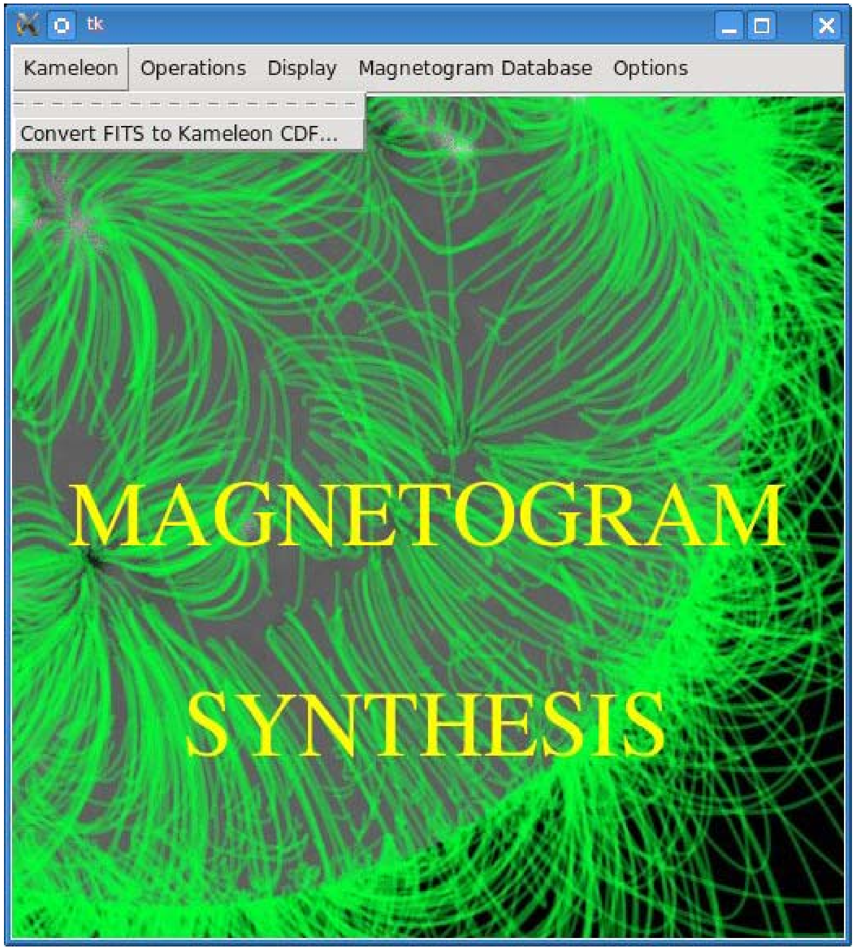


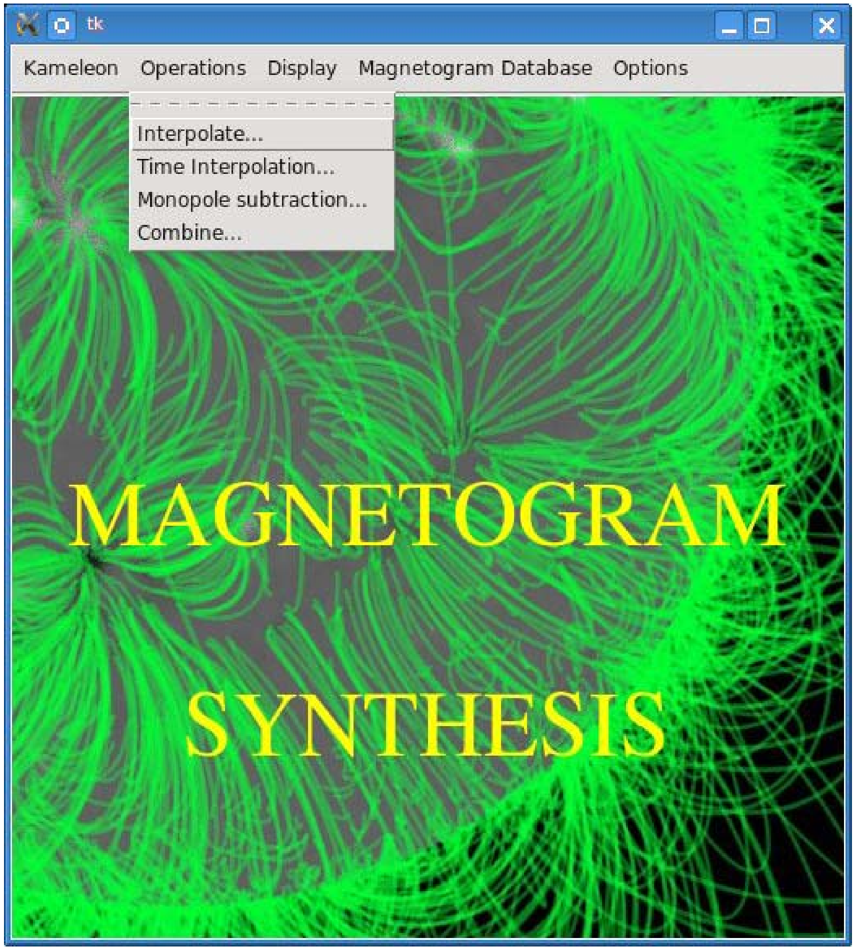
Importing and Converting

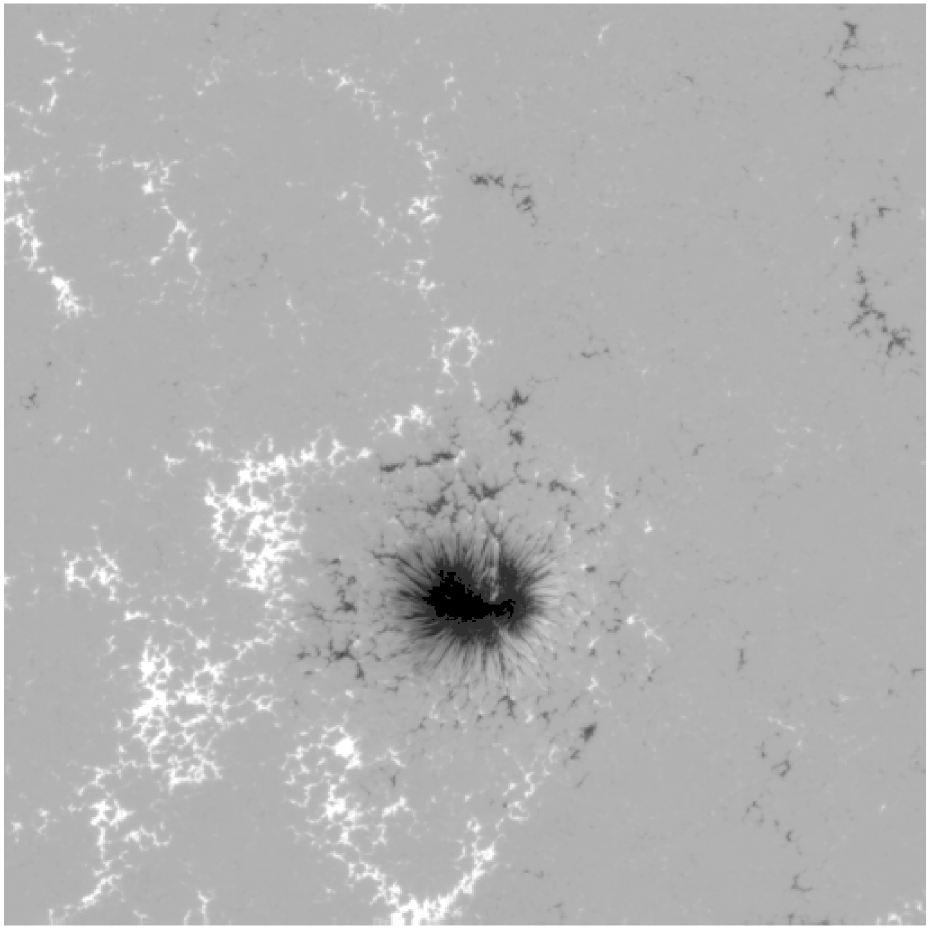
- Can import and convert magnetograms into Kameleon format from the following sources:
  - Kitt Peak VT / SOLIS-VSM (full disk and synoptic)
  - GONG Network (full disk and synoptic)
  - SOHO MDI (full disk and synoptic)
  - Mees IVM (AR)
  - Mt. Wilson (full disk and synoptic)
  - Wilcox (full disk and synoptic)
  - MSFC-TVM (AR)
  - Hinode SOT-SP (AR)
- To be added:
  - SDO
  - Hinode SOT-NFI



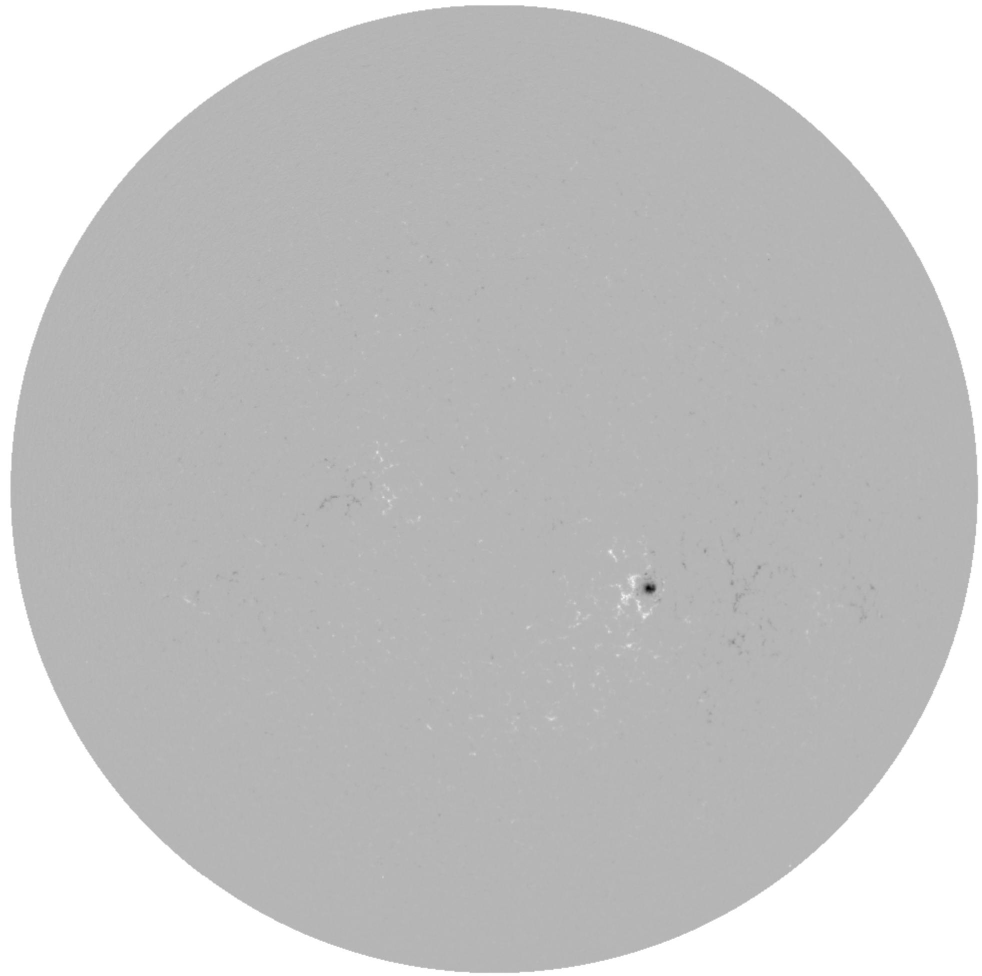
Lightweight Processing Example

- Interpolate Hinode/SOT-SP onto MDI full disk grid
- Combine the two using a direct overwrite.

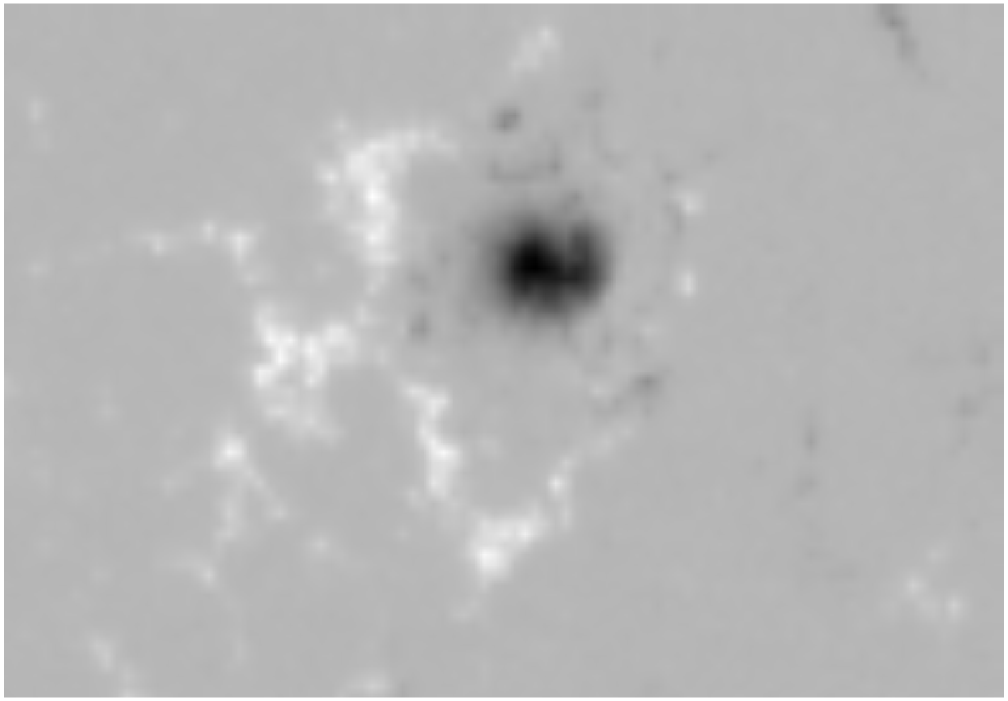




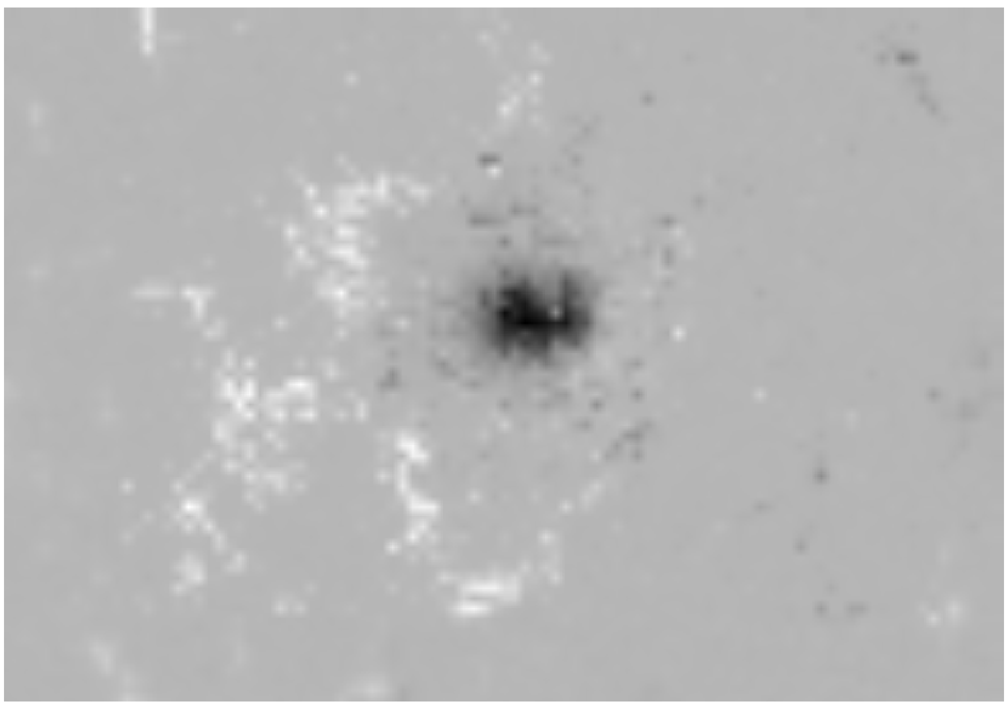
Hinode /SOT



SOHO/MDI



SOHO/MDI original



Combined

Heavyweight Processing Example

Surface velocity estimation using the Differential Affine Velocity Estimator (DAVE) (Shuck 2006):

MHD Magnetic Induction Equation (MIE):

$$\partial_t B_z + \boldsymbol{\nabla}_h \cdot (B_z\, \boldsymbol{v}_h - v_z\, \boldsymbol{B}_h) = 0, \tag{1}$$

Flux Transport Velocities:

$$\mathbf{F} = B_z\, \boldsymbol{u}_{\mathrm{F}} = B_z\, \boldsymbol{v}_h - v_z\, \boldsymbol{B}_h, \tag{2}$$

Transformed MIE for Line-of-Sight Magnetograms

$$\partial_t B_z + \boldsymbol{\nabla}_h \cdot (B_z\, \boldsymbol{u}_{\mathrm{F}}) = 0. \tag{3}$$

Affine Velocity Profile:

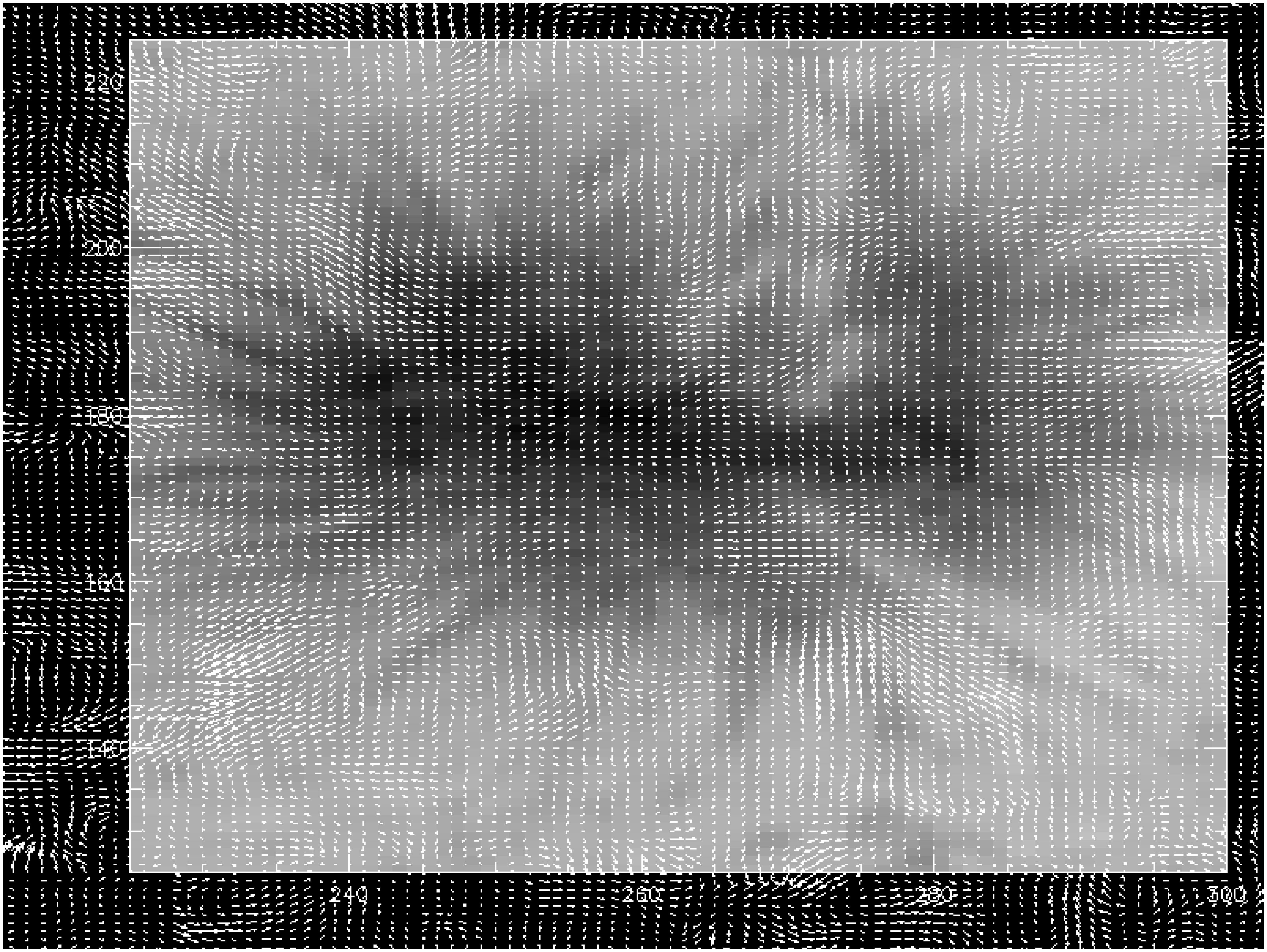
$$\boldsymbol{v}\,(\boldsymbol{P}; \boldsymbol{x}) = \begin{pmatrix} \widehat{u}_0 \\ \widehat{v}_0 \\ \widehat{w}_0 \end{pmatrix} + \begin{pmatrix} \widehat{u}_x & \widehat{u}_y \\ \widehat{v}_x & \widehat{v}_y \\ \widehat{w}_x & \widehat{w}_y \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}, \tag{4}$$

Solution: least squares minimization of (1) or (3)

DAVE

- Using DAVE and the vector magnetogram version DAVE4VM combined with the doppler velocities we can extract the 3D vector velocity in the photosphere.
- This will be used as a boundary condition to global 3D MHD models.

DAVE



Summary

- We are developing a tool to combine magnetograms.
  - using KAMELEON as the low-level manager of the data structures, I/O interfaces and basic interpolation layer
- Upon this foundation we add two processing layers (lightweight and heavyweight)
- Have added ability to ingest and interpolate most current magnetogram files
- GUI and lightweight processing layer nearly complete
- Heavyweight layer is well underway.