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Tomography in the Ecliptic using HI-1

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Overview

- Theory of tomographic inversion applied to electron densities in the heliosphere
- Using HI data to formulate an inverse equation based on Thomson scattering by electrons
- Solution to the inverse equation using iterative estimation
- Separating the F- and K-corona in HI data
- Regularisation of the inverse equation (eg. positive densities, smooth gradient)
- Example of the method applied to Earth directed CMEs

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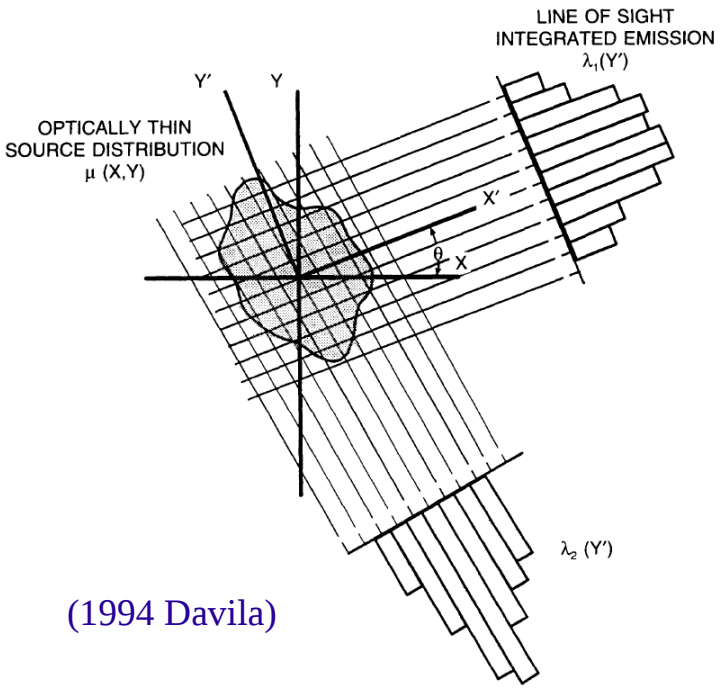
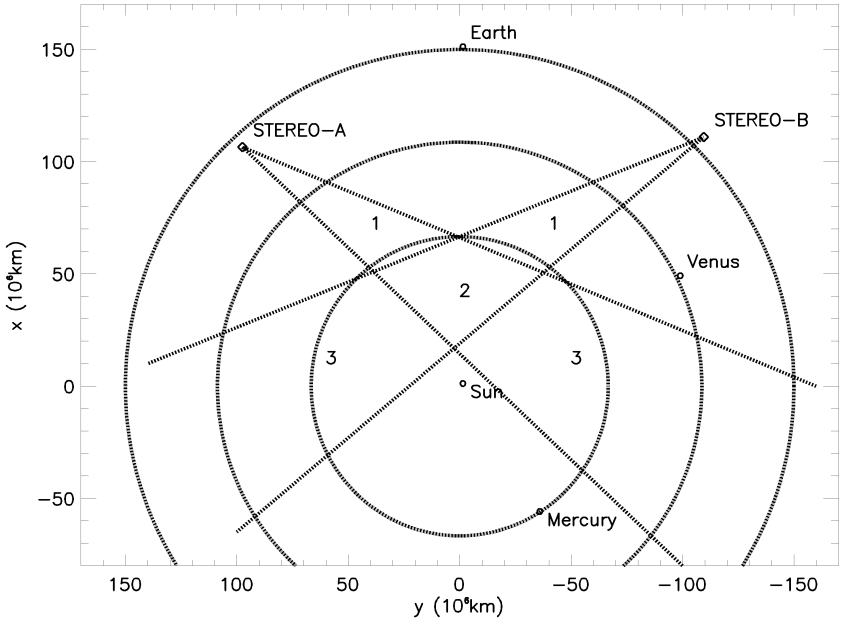
Tomography: Theory



(1994 Davila)



- Single observing position produces line-of-sight ambiguities
- These may be avoided using multiple points of view
- Tomography may be performed in the region common to FOV of STEREO A and B

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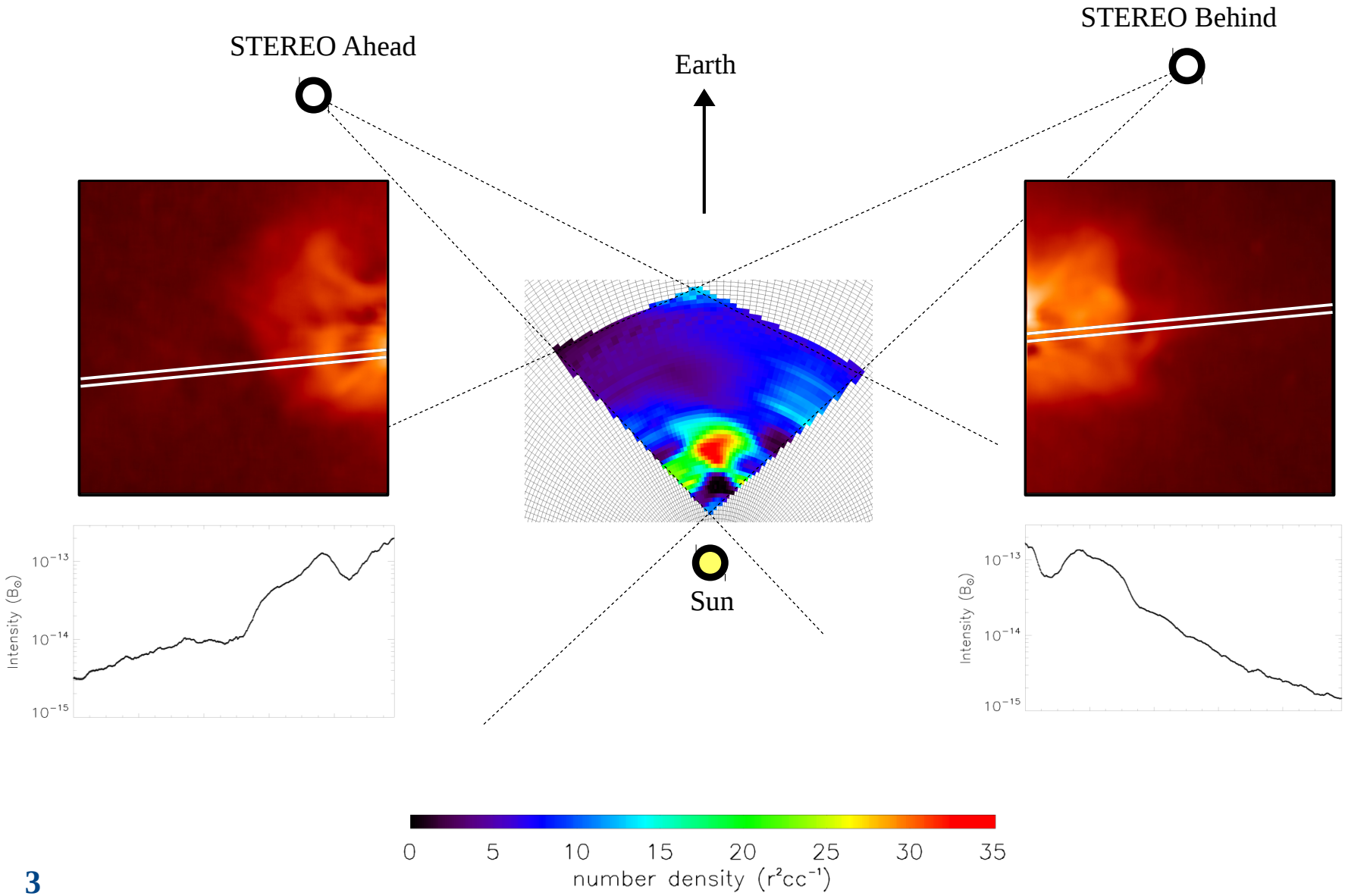
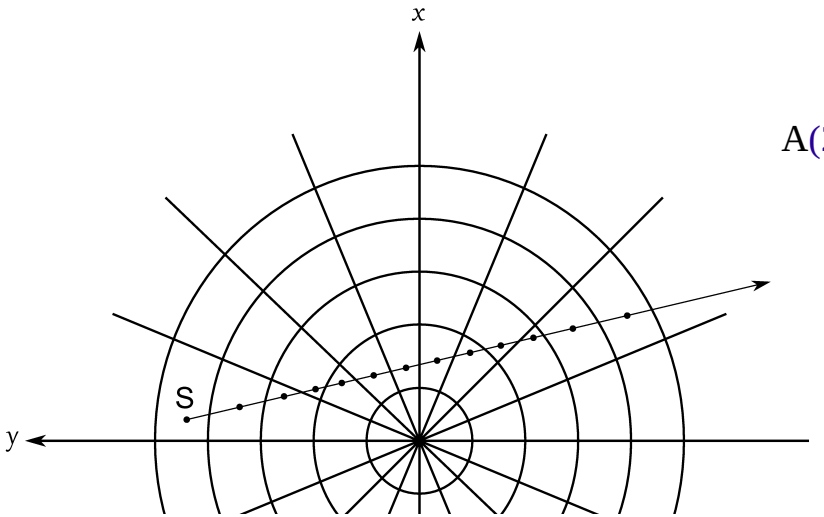
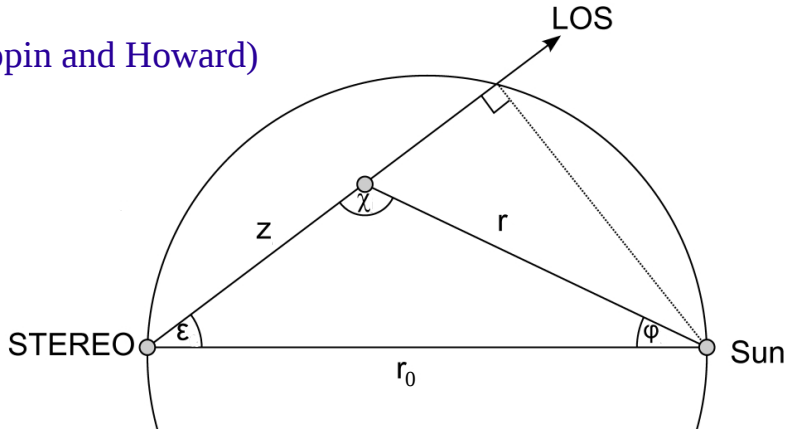
Tomography with STEREO HI



The Inverse Equation



A(2009 Tappin and Howard)



- The equation ***y*** = ***Hx*** may be formulated by applying a grid to the heliosphere, with a resolution is *1.5*^{o} longitudinally by *1/160 AU* radially
- ***y*** = data array, ***H*** = physical operator, ***x*** = density array
- ***H****(r, χ)* is based on Thomson scattering
- ***H*** and ***y*** are known, which means we can find ***x***

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Solving the Inverse Problem

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x}$$

$\boldsymbol{y}$: M ~ 2000 elements

$\boldsymbol{x}$: N ~ 5000 elements

$\boldsymbol{H}$: NxM elements... > 10^7

$\therefore$ Too big to solve Analytically

- Instead we solve it using an iterative estimation method: the *Conjugate gradient algorithm*

  - make initial guess at density array: $\boldsymbol{x}_o = 8r^{-2}$ electrons cc $^{-1}$
  - Find residual $\boldsymbol{r}_o = \boldsymbol{y} - \boldsymbol{H}\boldsymbol{x}_o$
  - update value of $\boldsymbol{x}_i$ such that the value of $\boldsymbol{r}_i$ is reduced
  - repeat until $\boldsymbol{r}_i$ is sufficiently small

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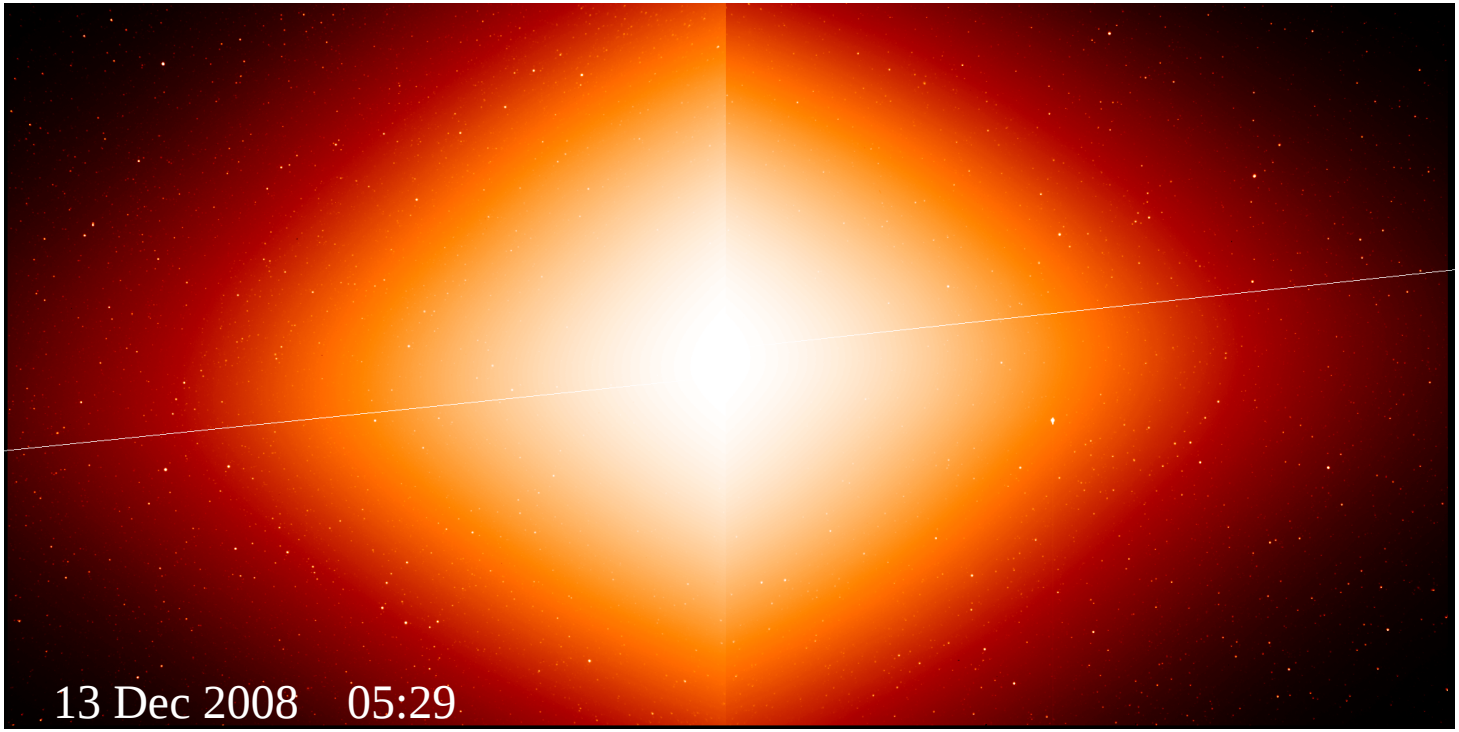
Background Subtraction

STEREO A STEREO B



- HI-1 data dominated by F-corona (dust)

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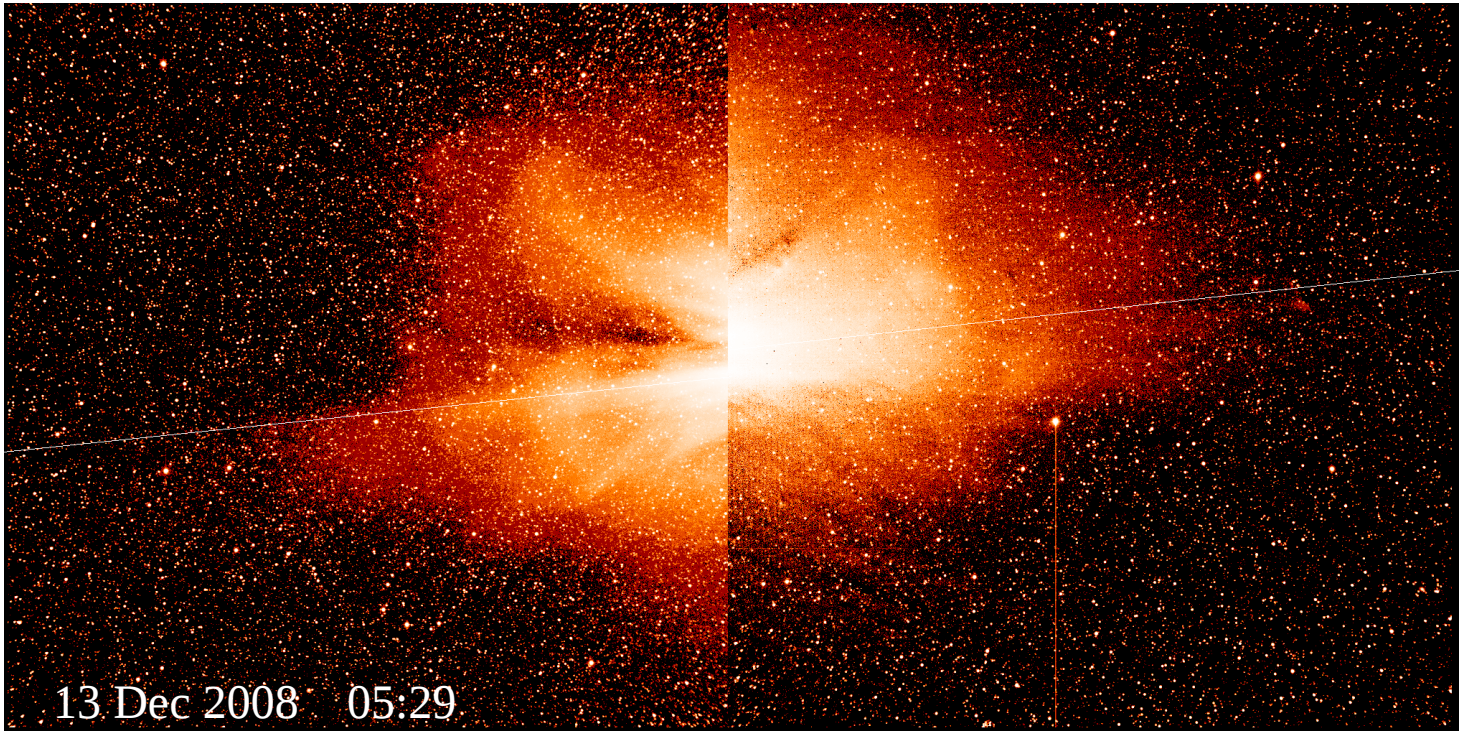
Background Subtraction

STEREO A STEREO B



- HI-1 data dominated by F-corona (dust)
- One-day minimum subtracted from each pixel

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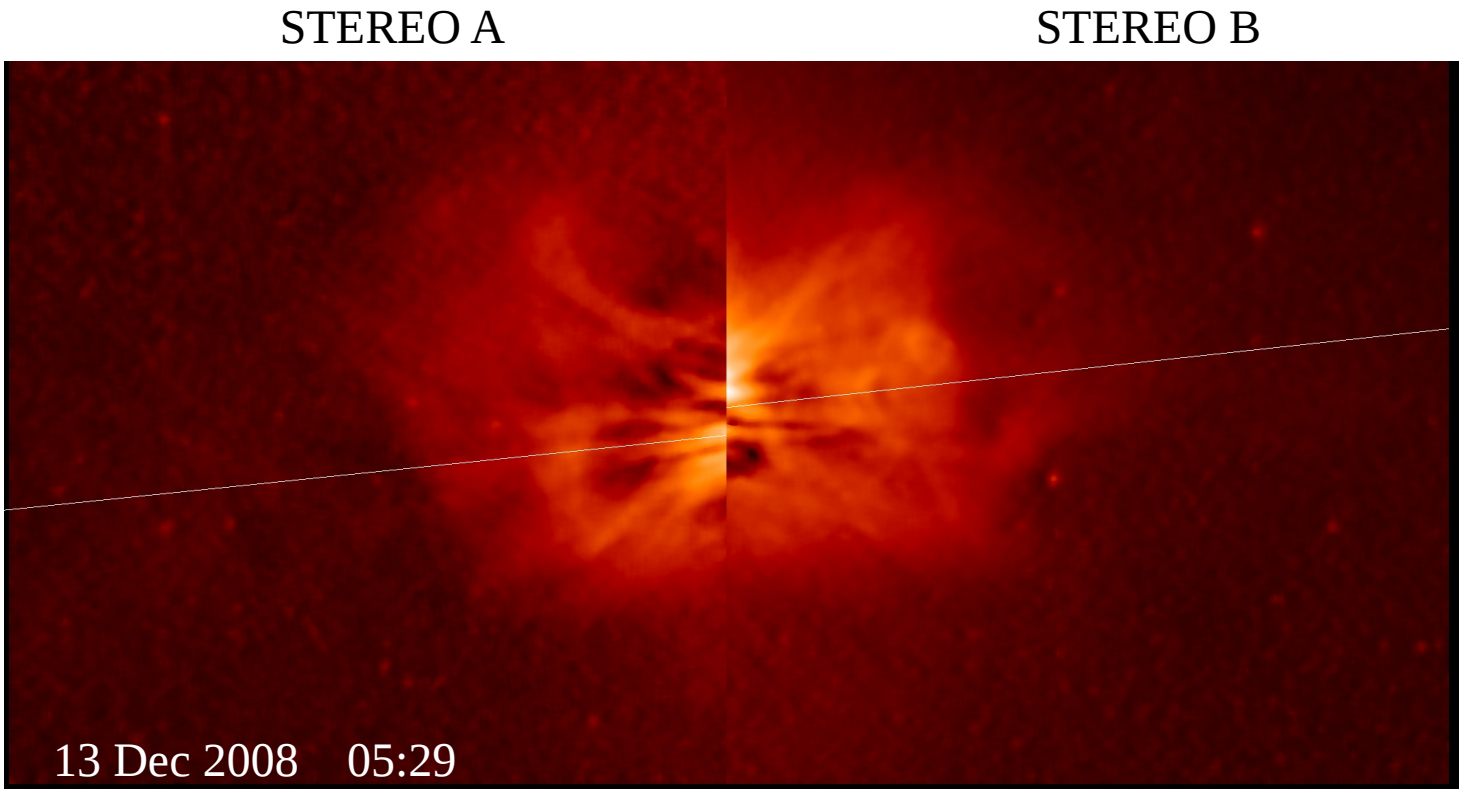
Background Subtraction



- HI-1 data dominated by F-corona (dust)
- One-day minimum subtracted from each pixel
- Apply median filter over nearby pixels

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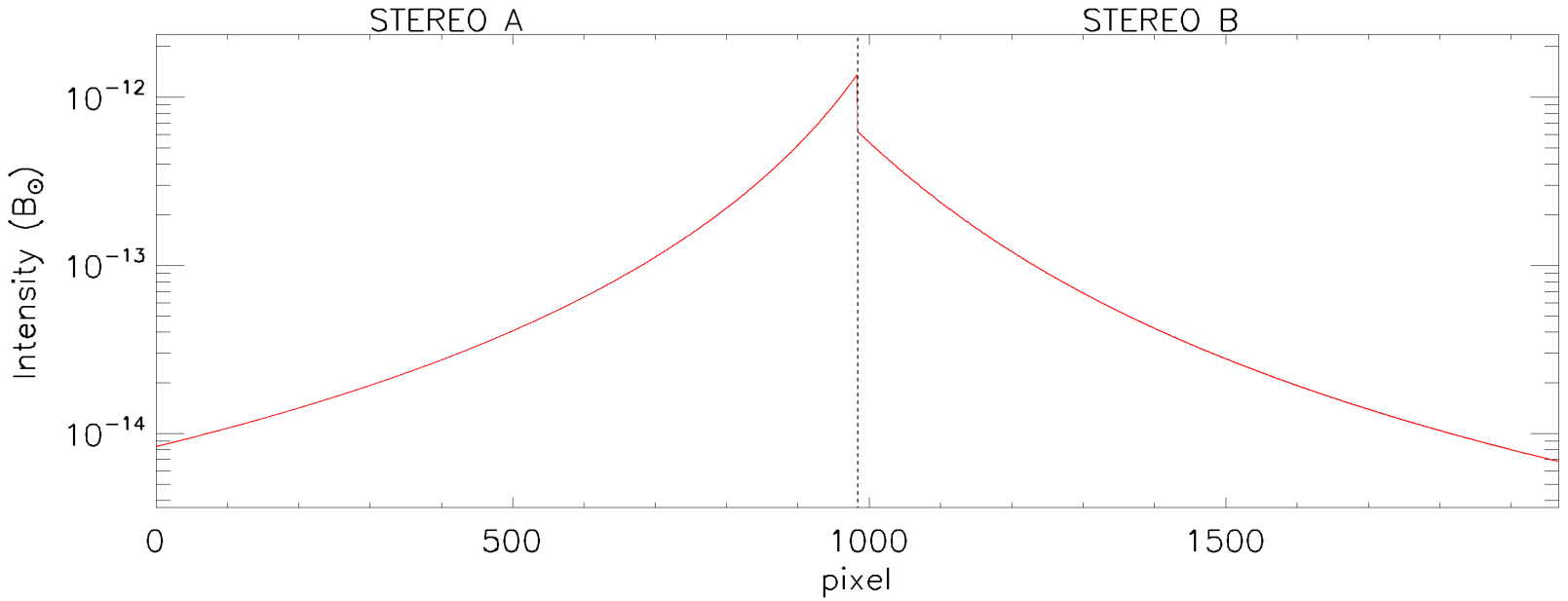
K-Corona Intensity Correction



- Use ***y*** = ***Hx*** to determine theoretical values of intensity
  - Theoretical Intensity, $x = 8.0r^2$ electrons cc^{-1}

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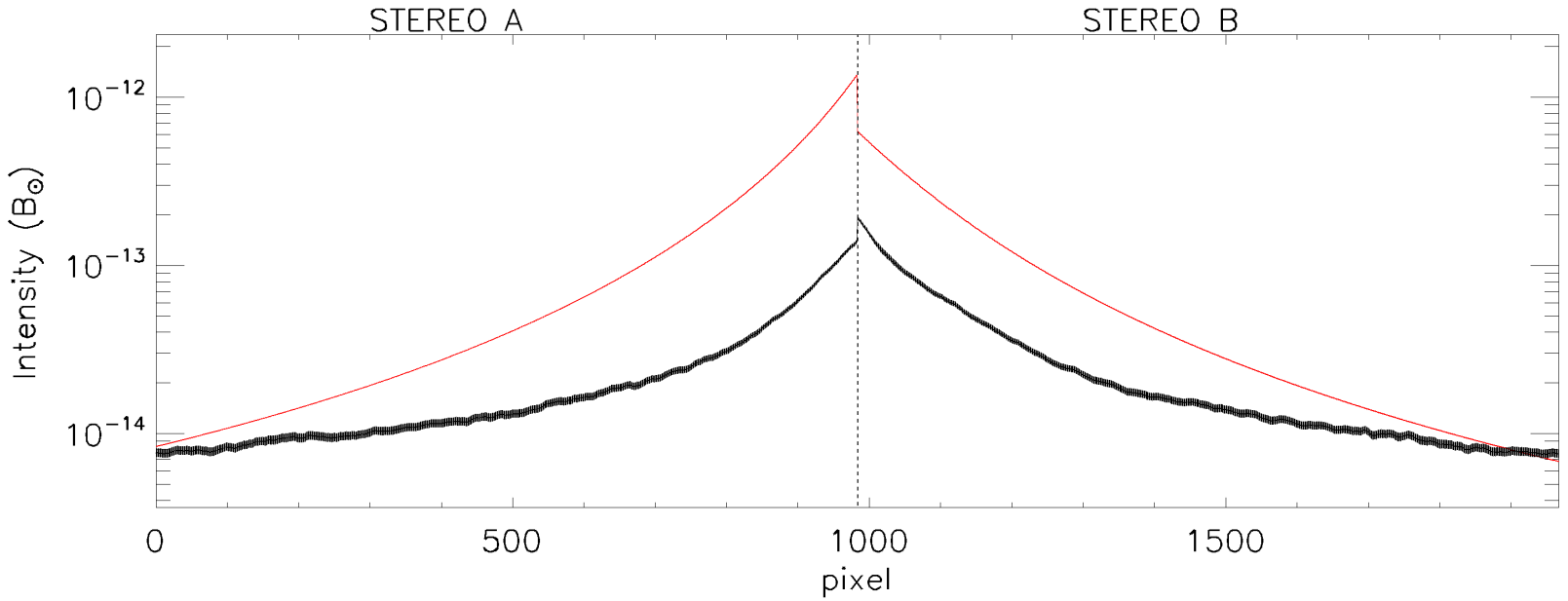
K-Corona Intensity Correction



- Use ***y*** = ***Hx*** to determine theoretical values of intensity
- Ratio of *theoretical* to *observed* provides a correction factor

– Theoretical Intensity, $x = 8.0r^2$ electrons cc^{-1}

– Observed Intensity, two-week average (28 Nov – 11 Dec 2008)

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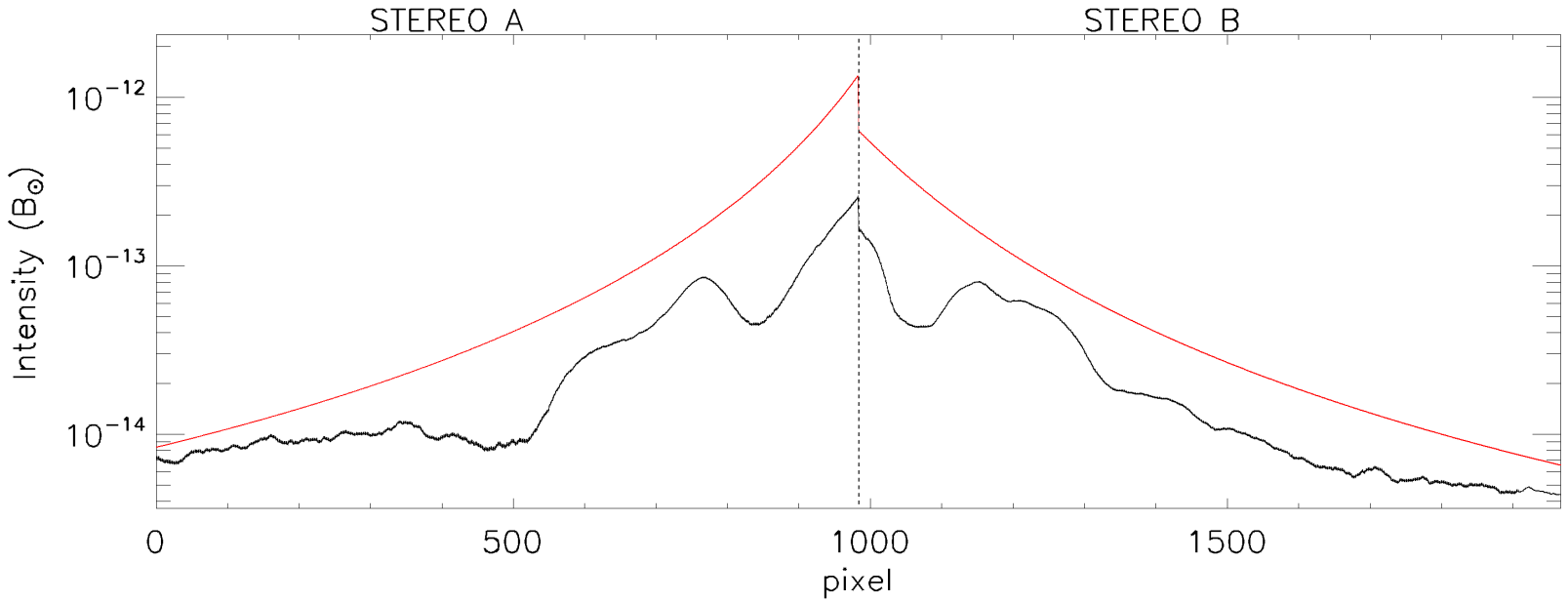
K-Corona Intensity Correction



- Use ***y*** = ***Hx*** to determine theoretical values of intensity
- Ratio *theoretical* to *observed* provides a correction factor
- This may be applied to individual HI images

– Theoretical Intensity, $x = 8.0r^2$ electrons cc^{-1}

– Observed Intensity, 13 Dec 2008 05:29

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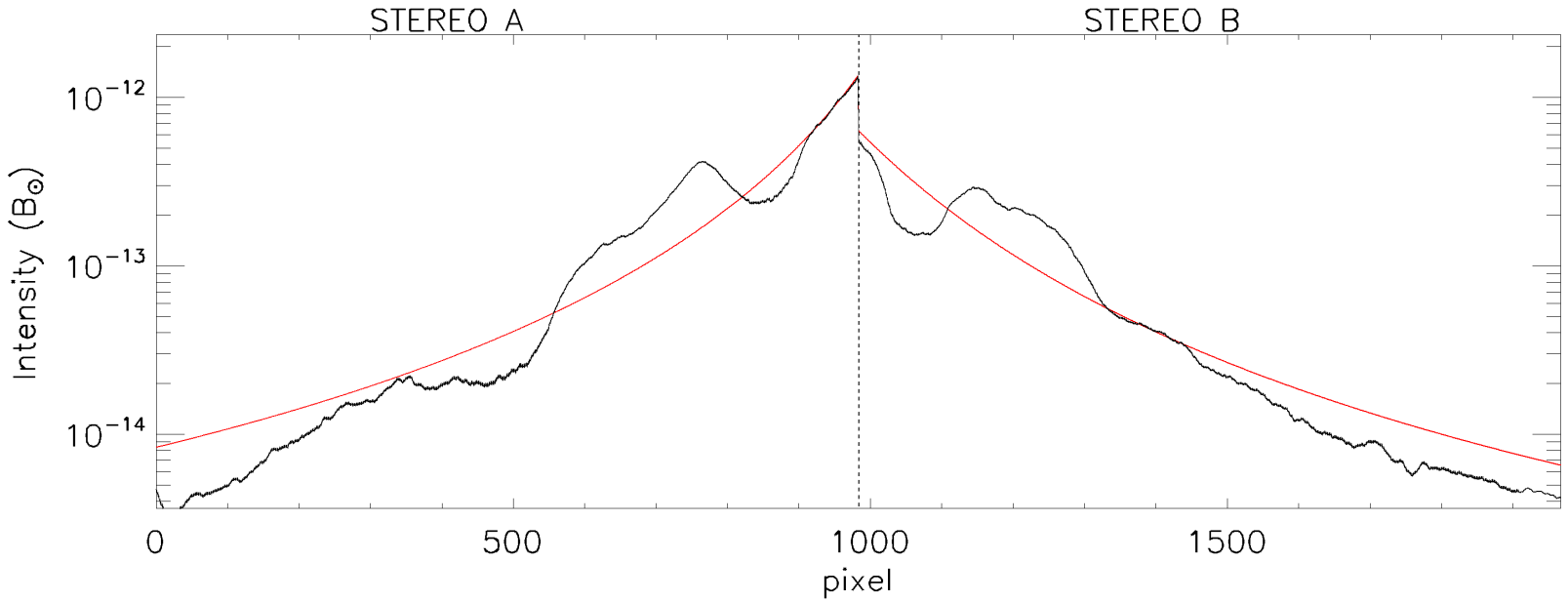
K-Corona Intensity Correction



- Use ***y*** = ***Hx*** to determine theoretical values of intensity
- Ratio *theoretical* to *observed* provides a correction factor
- This may be applied to individual HI images

– Theoretical Intensity, $x = 8.0r^2$ electrons cc^{-1}

– Corrected Intensity, 13 Dec 2008 05:29

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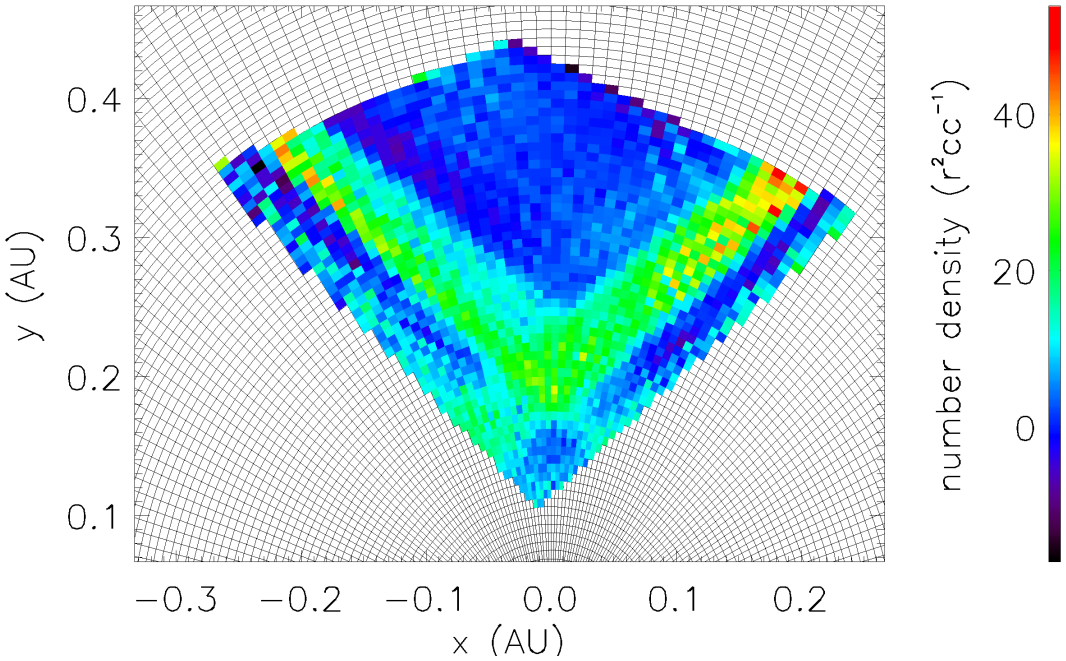
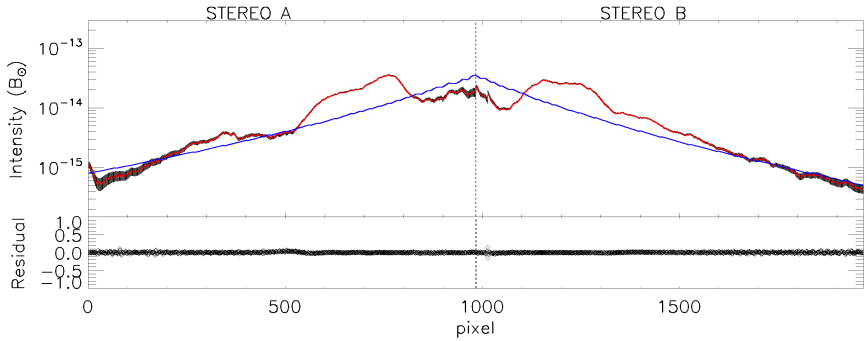
Regularisation



- *'Map'* represents density array, ***x***



- Data
- Initial guess $x = 8.0r^{2}$
- Solution

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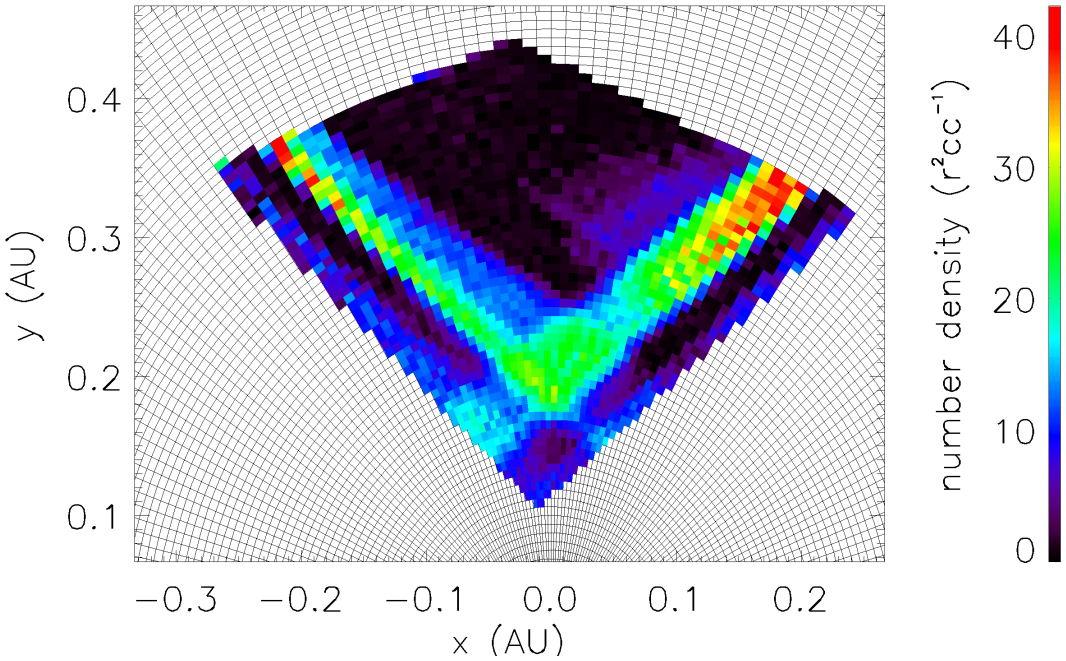
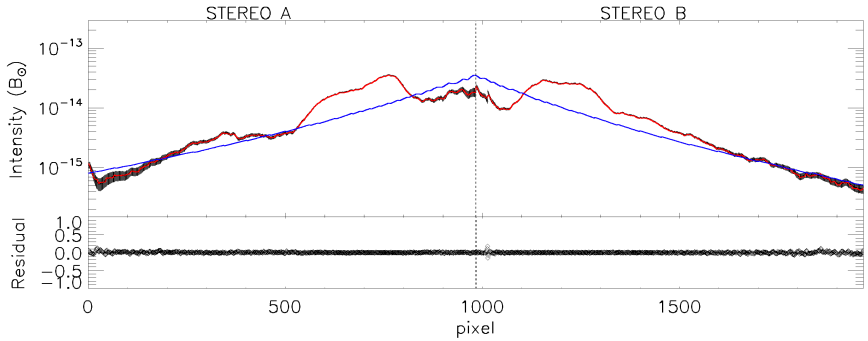
Regularisation



- *'Map'* represents density array, $\boldsymbol{x}$
- Reset negative values to $\boldsymbol{x}_o$ after each iteration



– Data
– Initial guess $x = 8.0r^{2}$
– Solution

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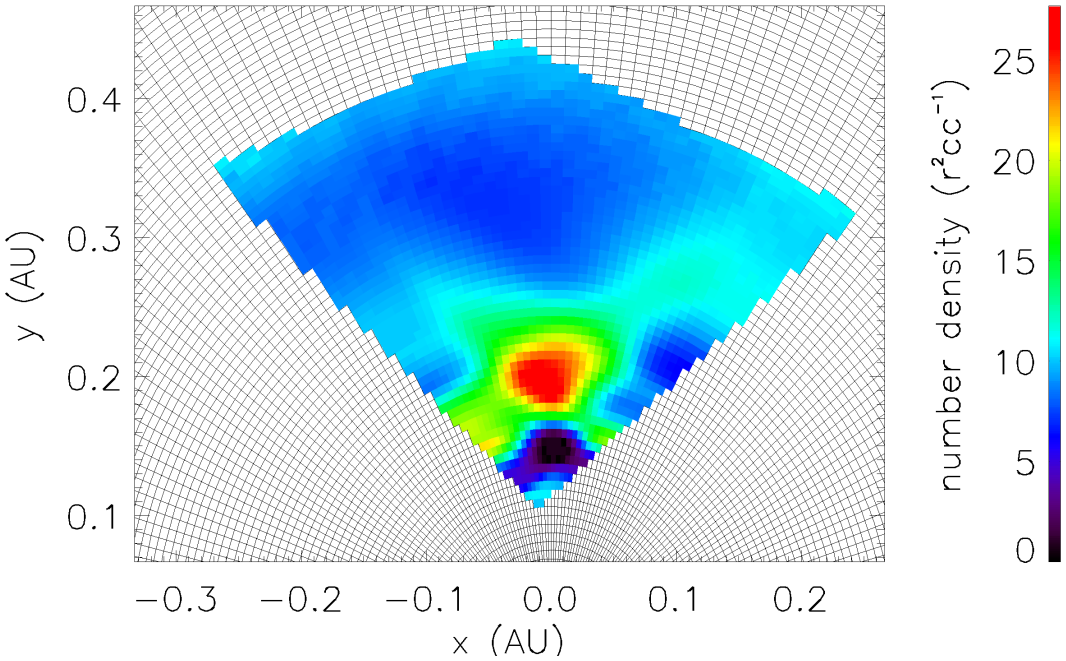
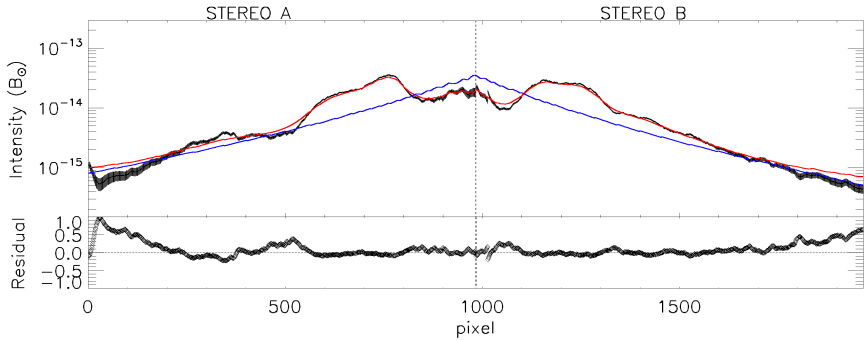
Regularisation



- *'Map'* represents density array, $\boldsymbol{x}$
- Reset negative values to $\boldsymbol{x}_o$ after each iteration
- Include *'regularisation'* matrices, $\boldsymbol{D\varphi}$ and $\boldsymbol{D^2r}$



– Data
– Initial guess $x = 8.0r^{2}$
– Solution

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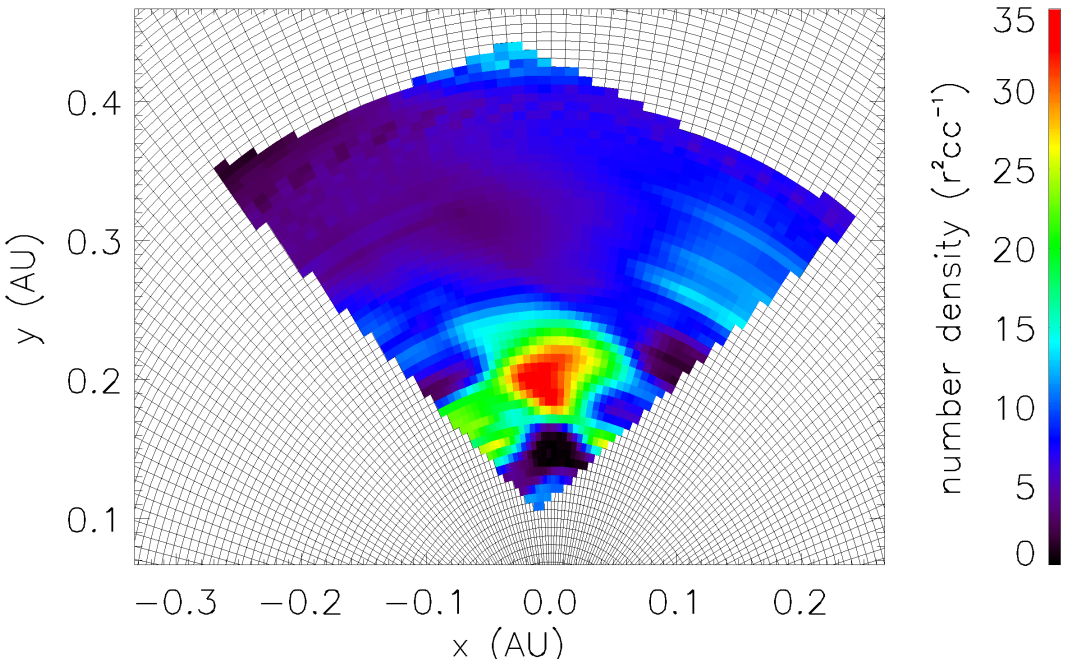
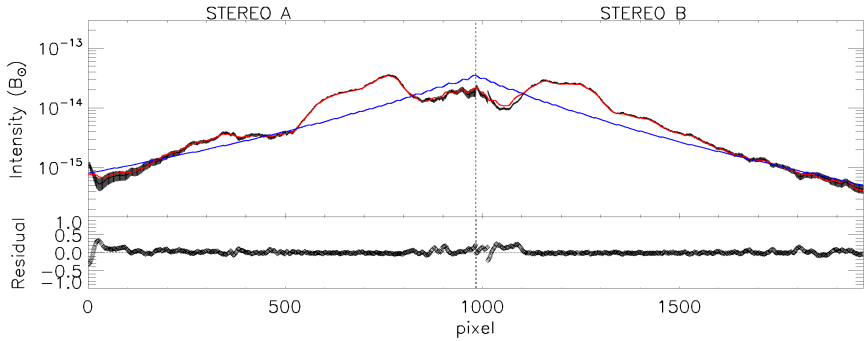
Regularisation





- *'Map'* represents density array, $\boldsymbol{x}$
- Reset negative values to $\boldsymbol{x}_o$ after each iteration
- Include *'regularisation'* matrices, $\boldsymbol{D\varphi}$ and $\boldsymbol{D^2r}$
- Add weighting each pixel to account for range of intensities (factor ~10^2)

– Data
– Initial guess $x = 8.0r^2$
– Solution

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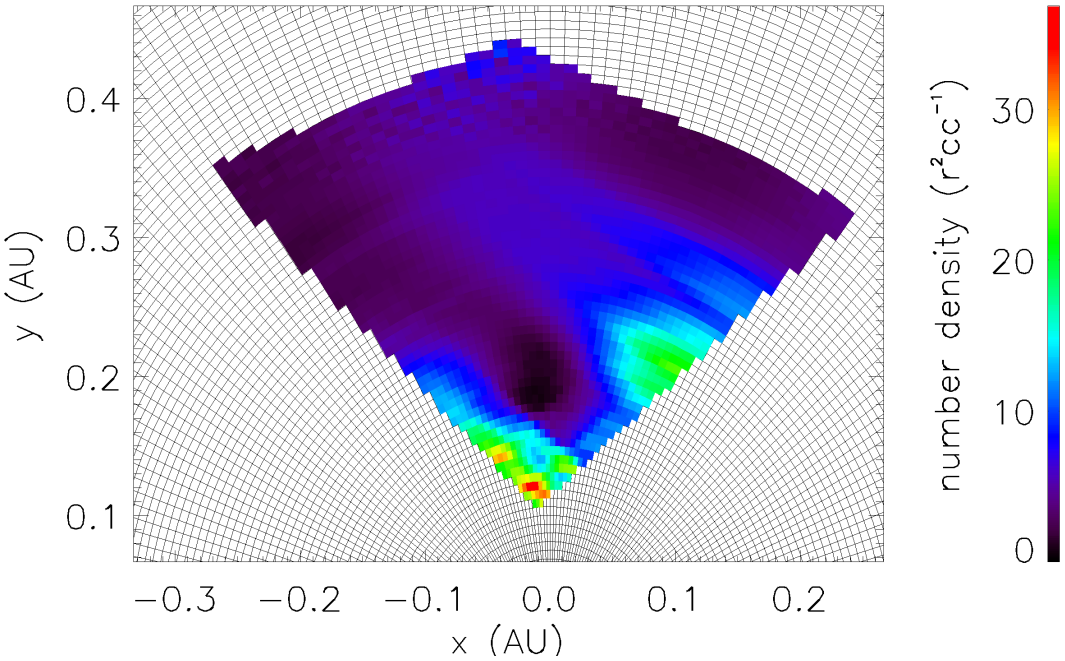
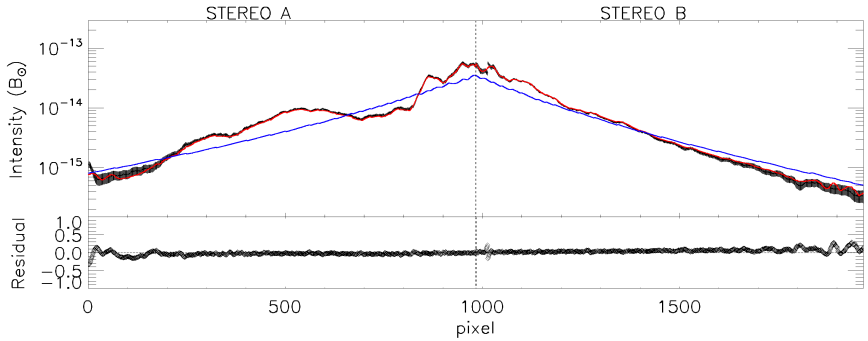
Density Results – Dec 2008 CME



12 Dec 2008 19:29

Density (peak) = 35.8 $e^- r^2 cc^{-1}$

Distance = 18 $*10^6$ km



- Data
- Initial guess
- Solution

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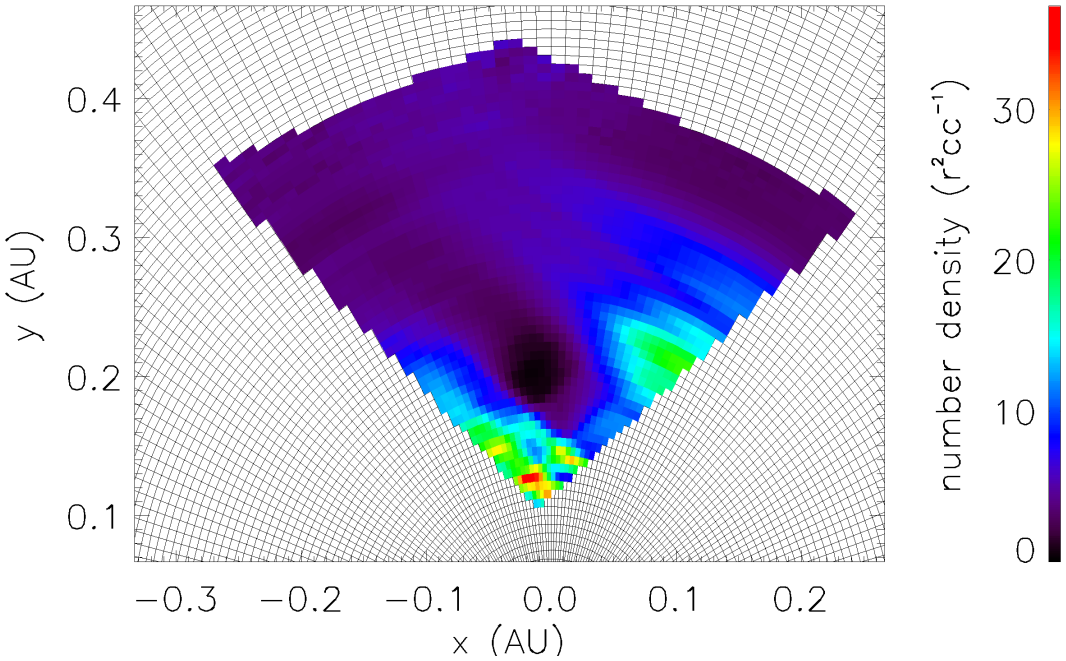
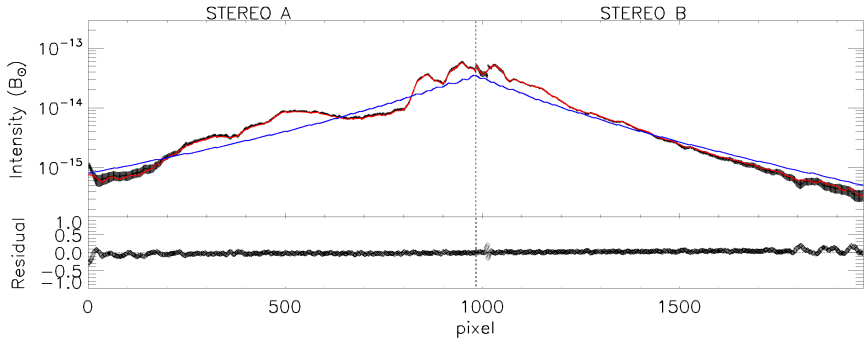
Density Results – Dec 2008 CME



12 Dec 2008 20:09

Density (peak) = 35.7 $e^- r^2 cc^{-1}$

Distance = 19 $*10^6$ km



- Data
- Initial guess
- Solution

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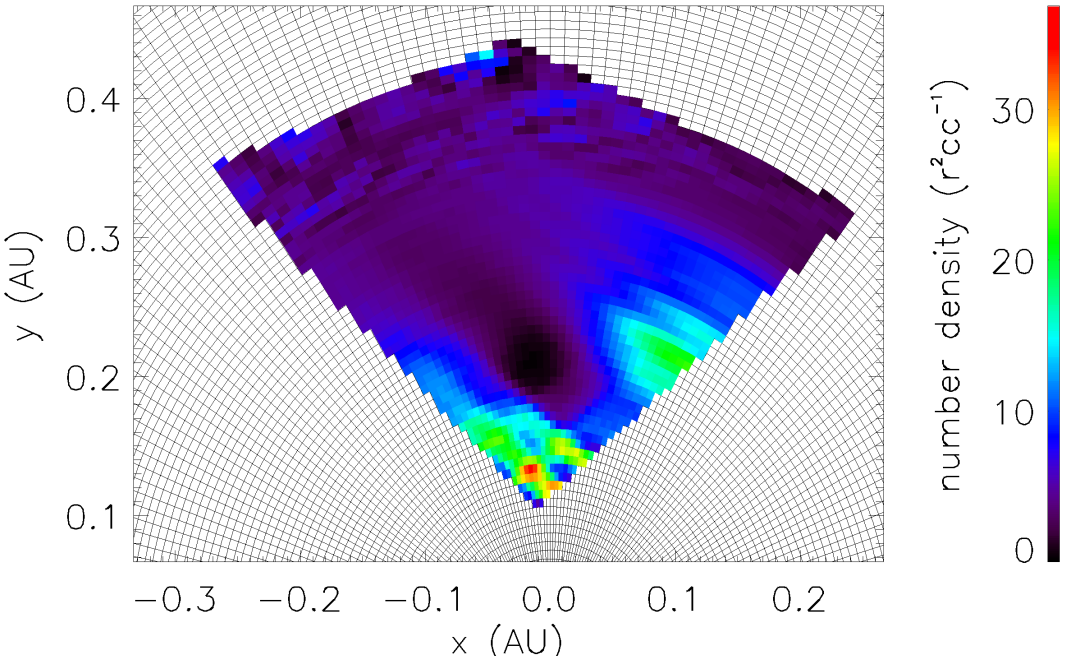
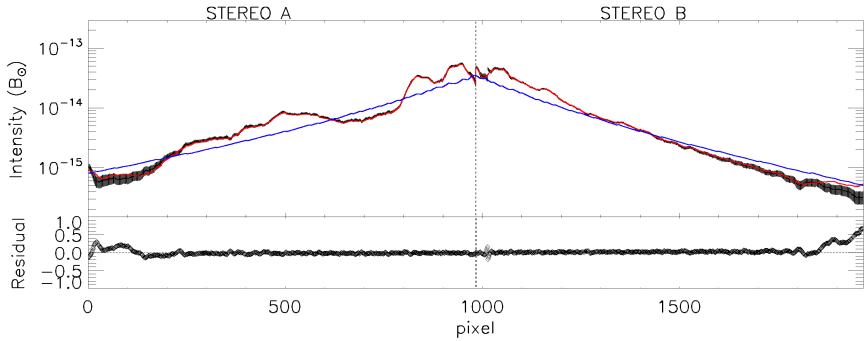
Density Results – Dec 2008 CME



12 Dec 2008 20:49

Density (peak) = 34.8 $e^- r^2 cc^{-1}$

Distance = 20 $*10^6$ km



- Data
- Initial guess
- Solution

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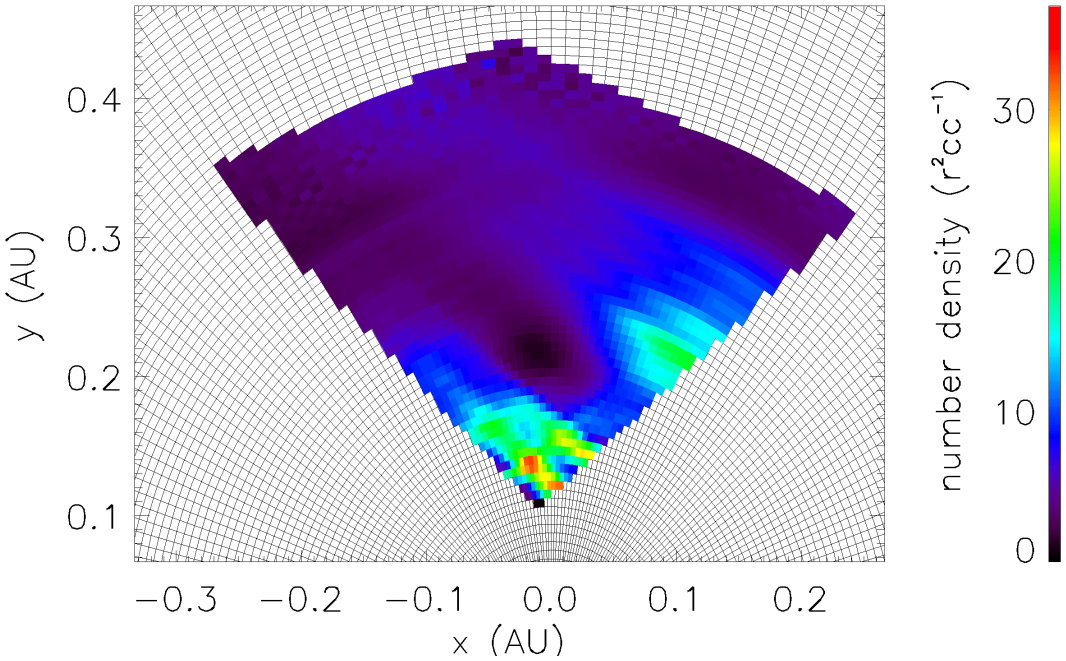
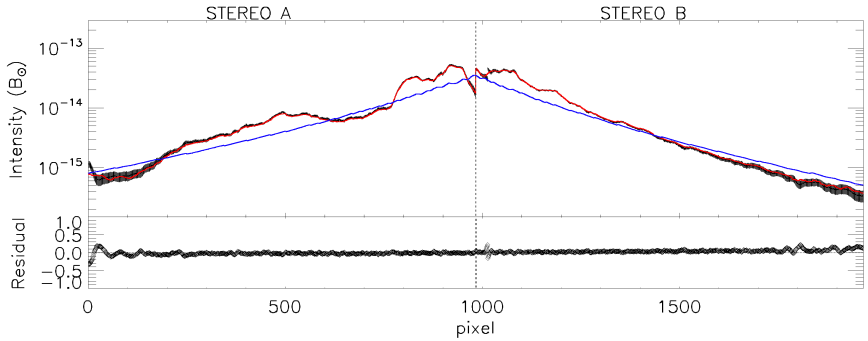
Density Results – Dec 2008 CME



12 Dec 2008 21:29

Density (peak) = 34.8 $e^- r^2 cc^{-1}$

Distance = 20 $*10^6$ km



- Data
- Initial guess
- Solution

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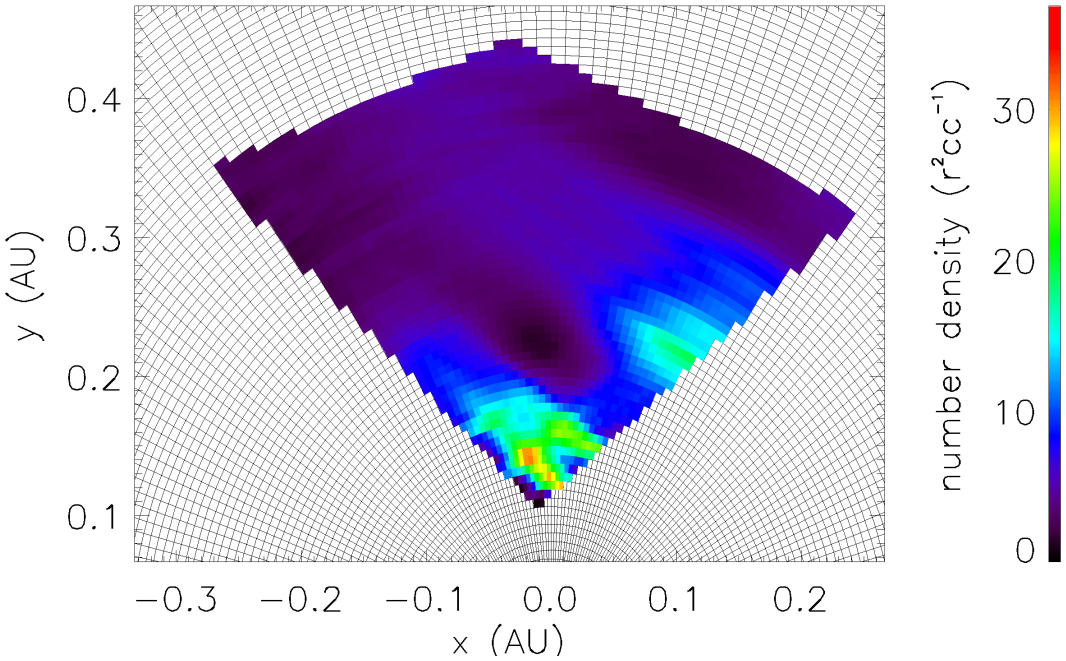
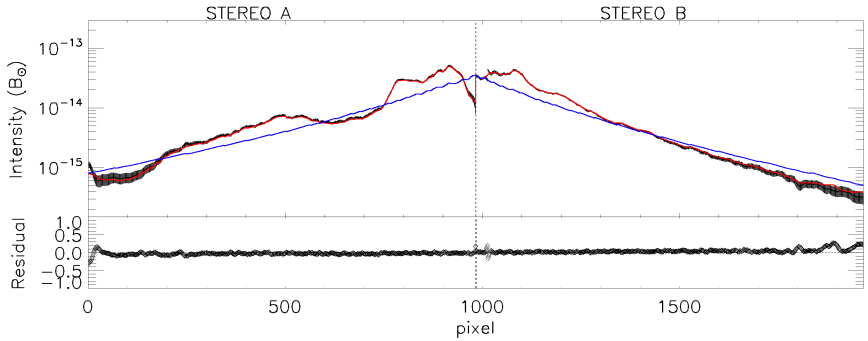
Density Results – Dec 2008 CME



12 Dec 2008 22:09

Density (peak) = 32.9 $e^- r^2 cc^{-1}$

Distance = 21 $*10^6$ km



- Data
- Initial guess
- Solution

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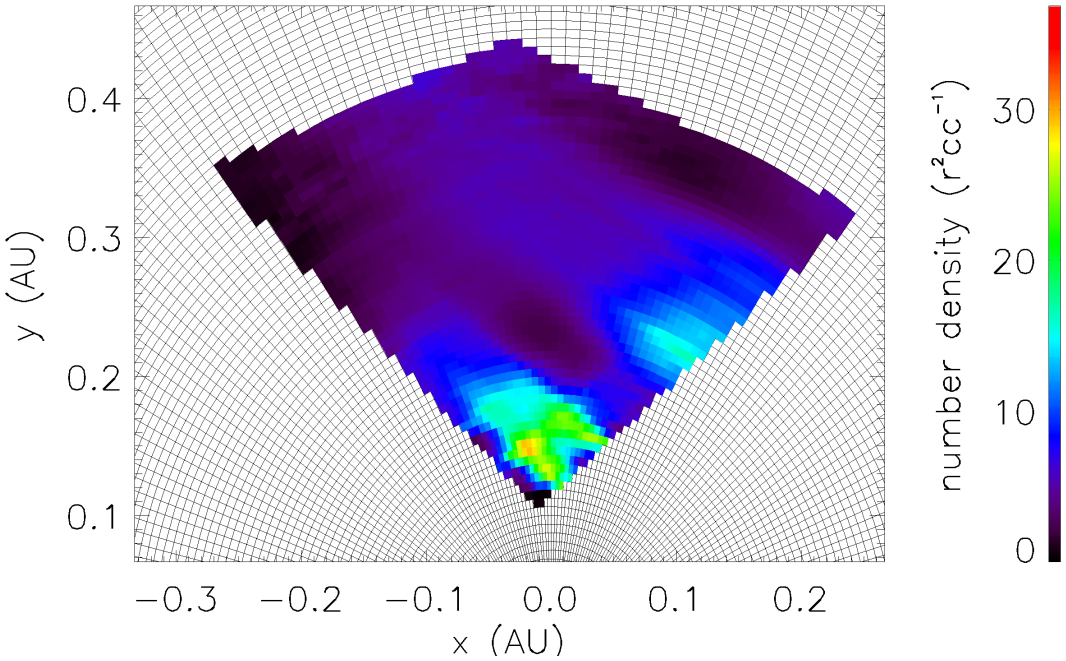
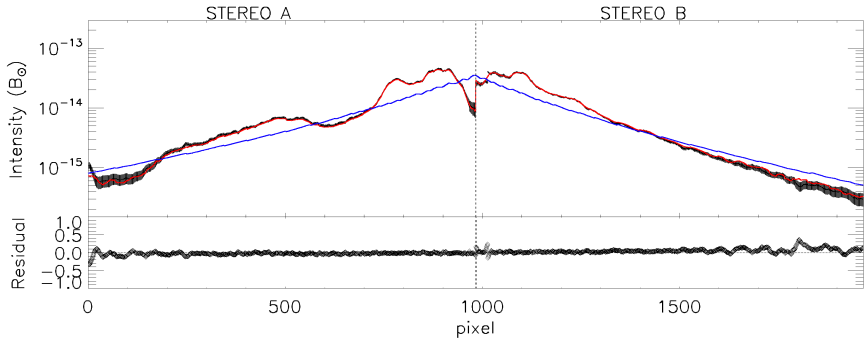
Density Results – Dec 2008 CME



12 Dec 2008 22:49

Density (peak) = 31.1 $e^- r^2 cc^{-1}$

Distance = 21 $*10^6$ km



- Data
- Initial guess
- Solution

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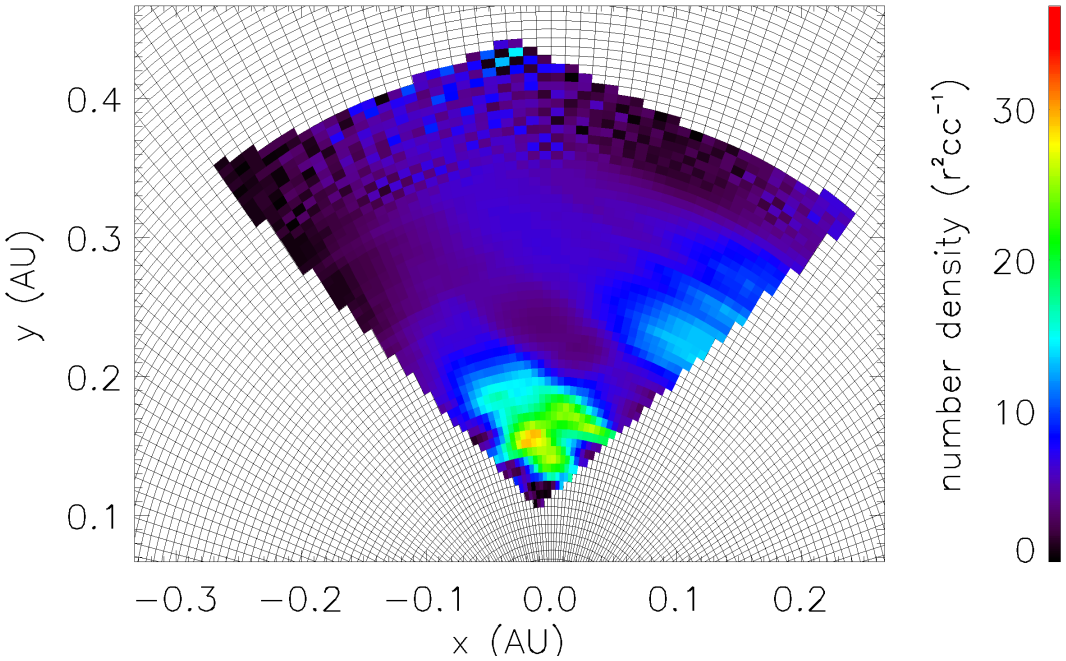
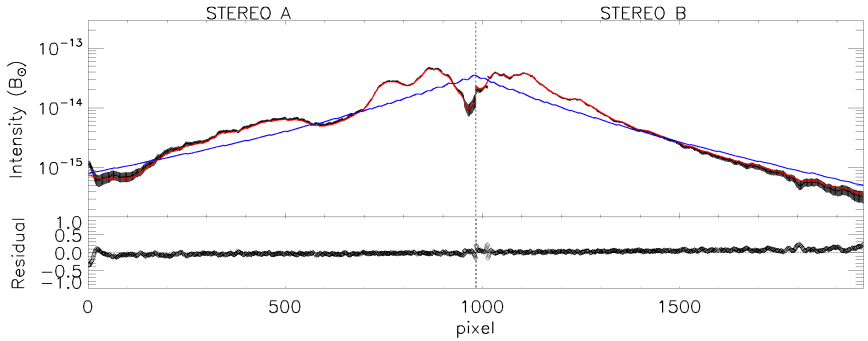
Density Results – Dec 2008 CME



12 Dec 2008 23:29

Density (peak) = 29.6 $e^- r^2 cc^{-1}$

Distance = 22 $*10^6$ km



- Data
- Initial guess
- Solution

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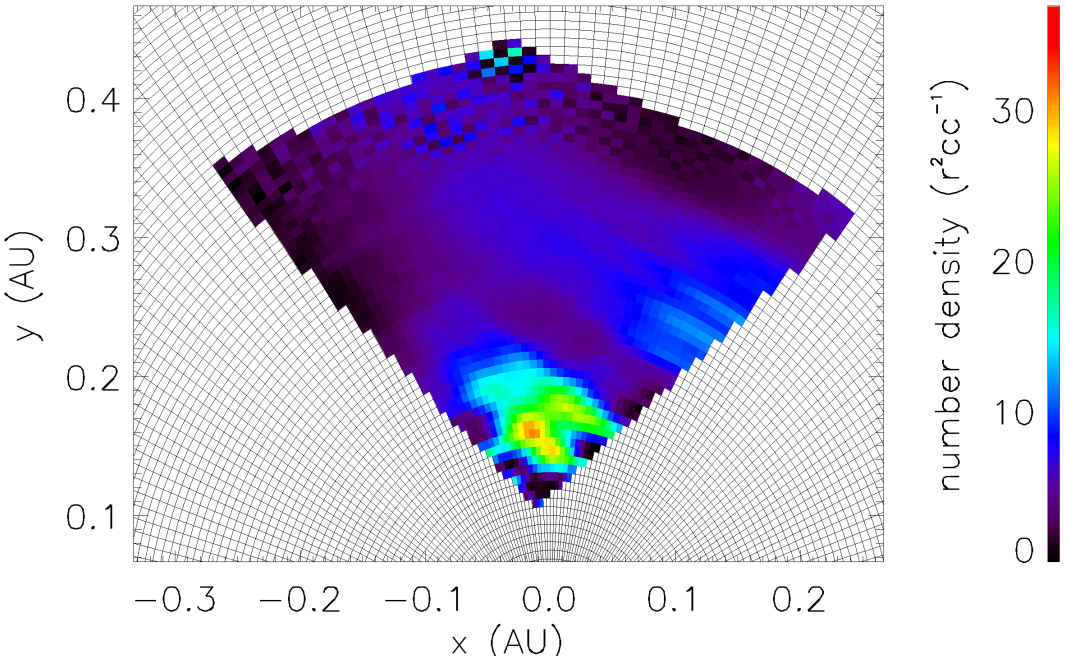
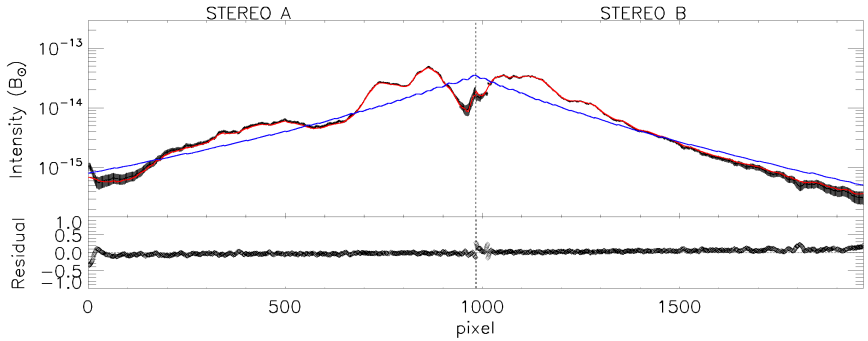
Density Results – Dec 2008 CME



13 Dec 2008 00:09

Density (peak) = 29.6 $e^- r^2 cc^{-1}$

Distance = 23 $*10^6$ km



- Data
- Initial guess
- Solution

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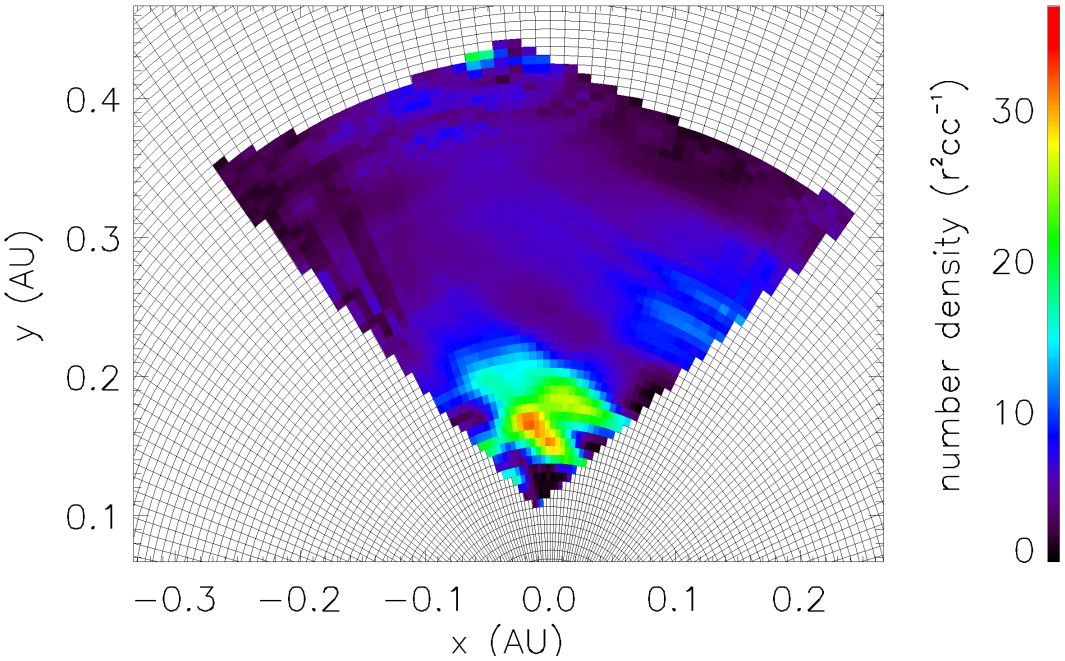
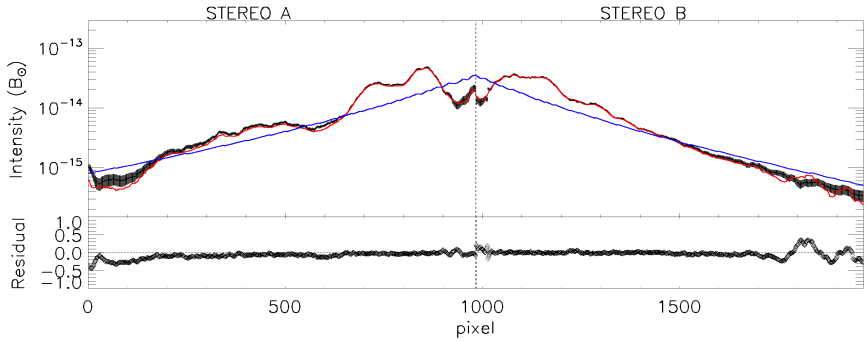
Density Results – Dec 2008 CME



13 Dec 2008 00:49

Density (peak) = 31.1 $e^- r^2 cc^{-1}$

Distance = 23 $*10^6$ km



- Data
- Initial guess
- Solution

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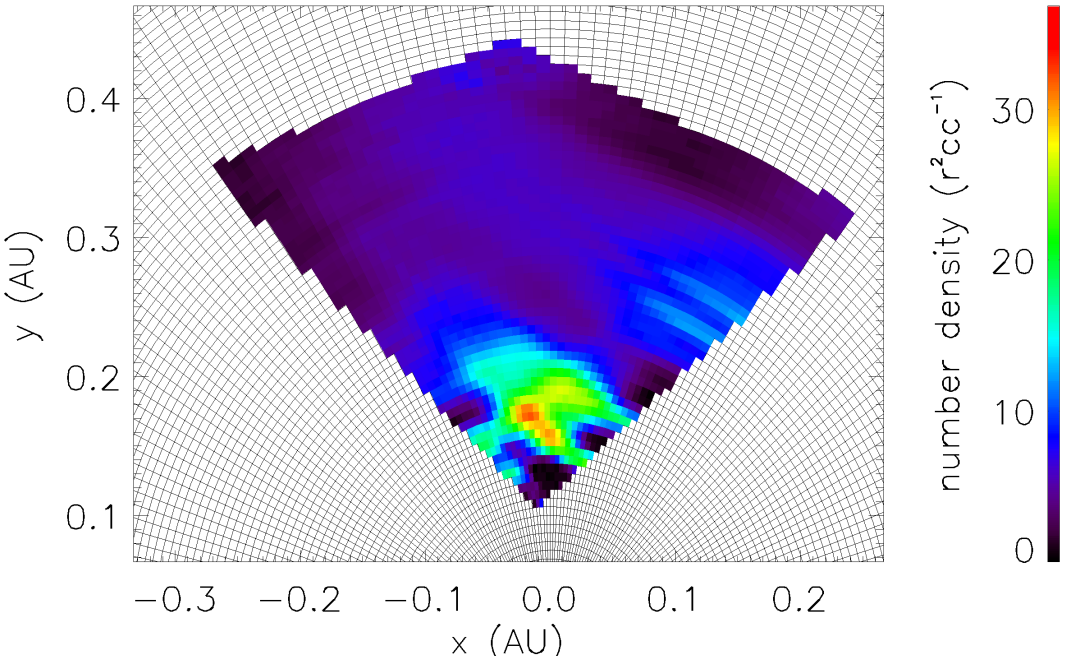
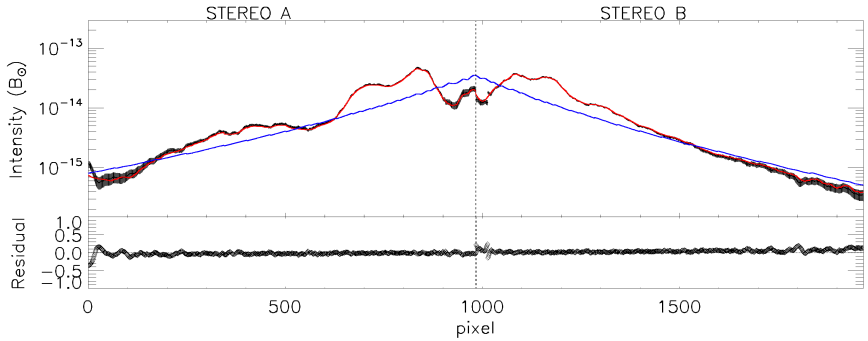
Density Results – Dec 2008 CME



13 Dec 2008 01:29

Density (peak) = 32.2 $e^- r^2 cc^{-1}$

Distance = 24 $*10^6$ km



- Data
- Initial guess
- Solution

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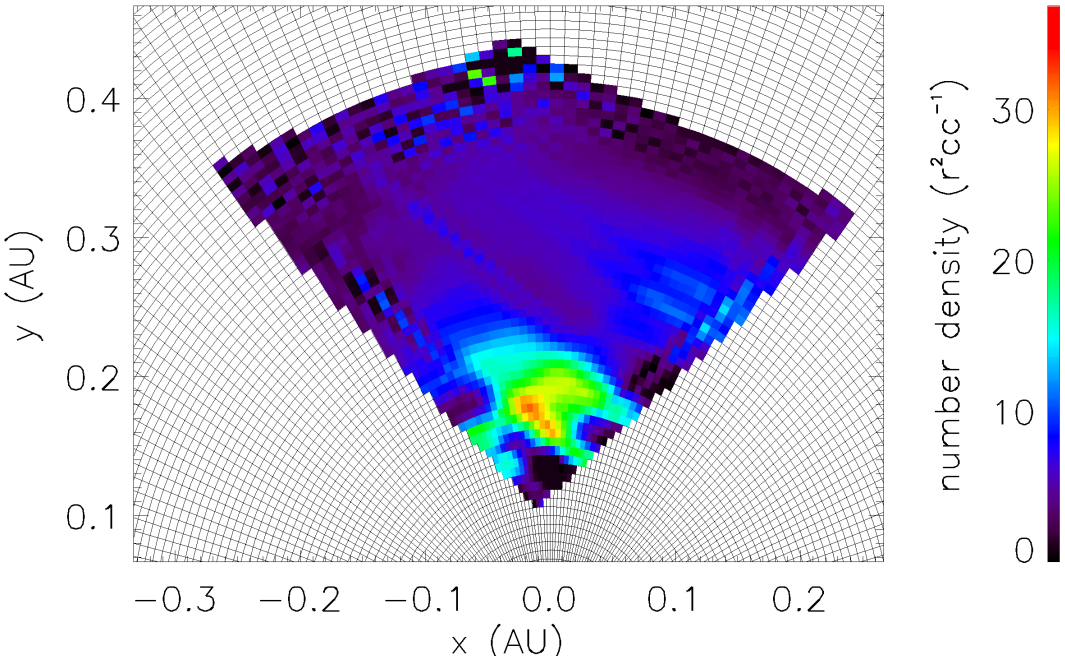
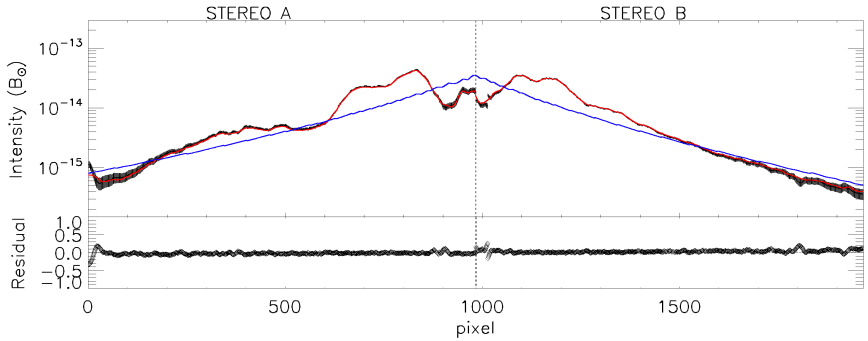
Density Results – Dec 2008 CME



13 Dec 2008 02:09

Density (peak) = 32.4 $e^- r^2 cc^{-1}$

Distance = 25 $*10^6$ km



- Data
- Initial guess
- Solution

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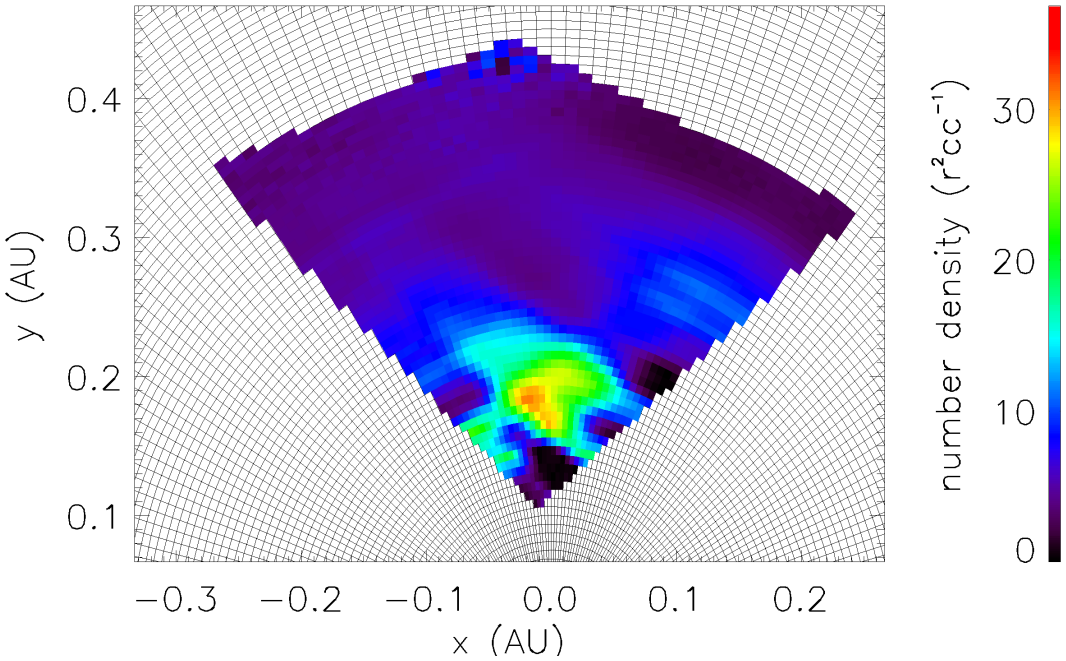
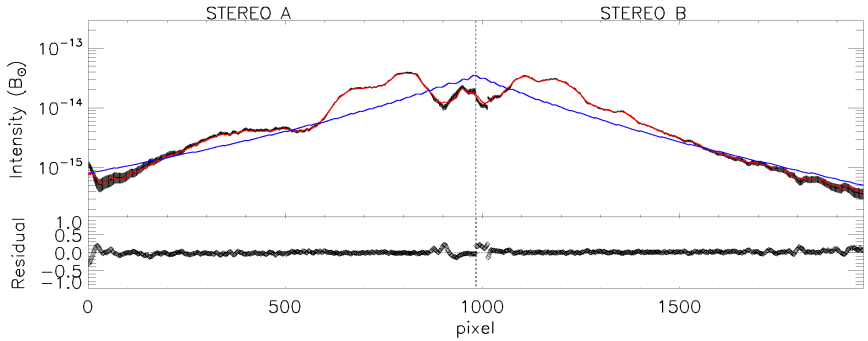
Density Results – Dec 2008 CME



13 Dec 2008 02:49

Density (peak) = 32.0 $e^- r^2 cc^{-1}$

Distance = 26 $*10^6$ km



- Data
- Initial guess
- Solution

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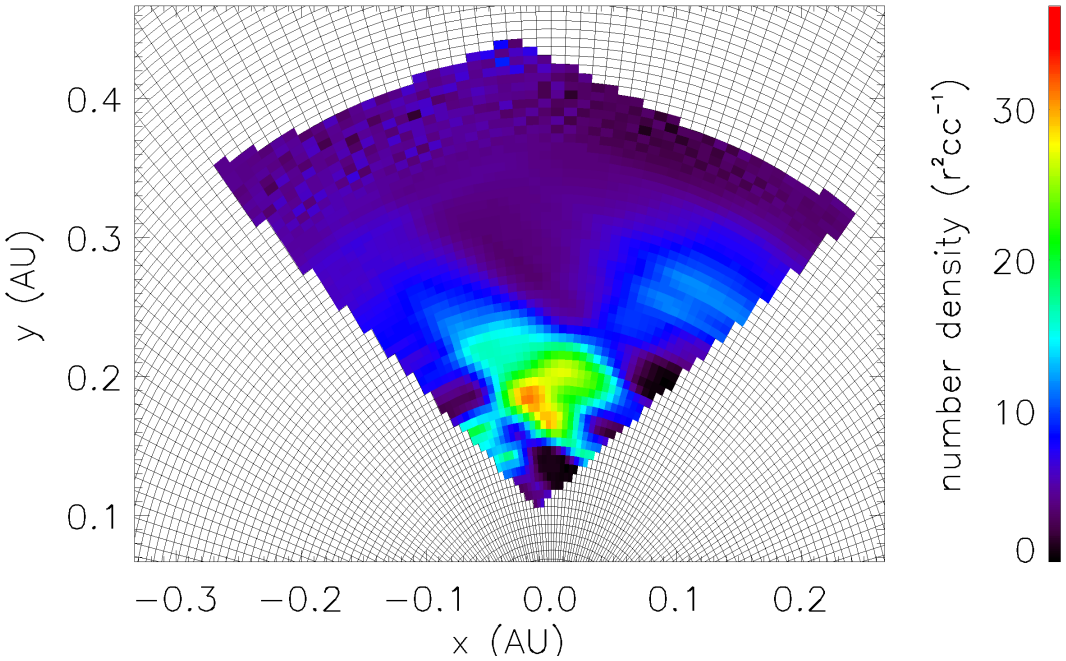
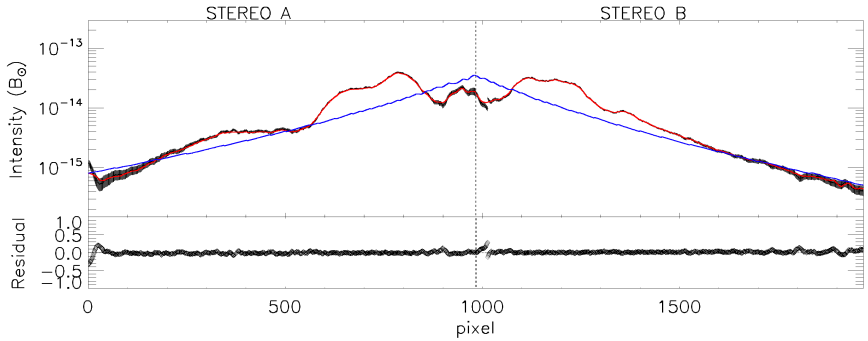
Density Results – Dec 2008 CME



13 Dec 2008 03:29

Density (peak) = 31.1 $e^- r^2 cc^{-1}$

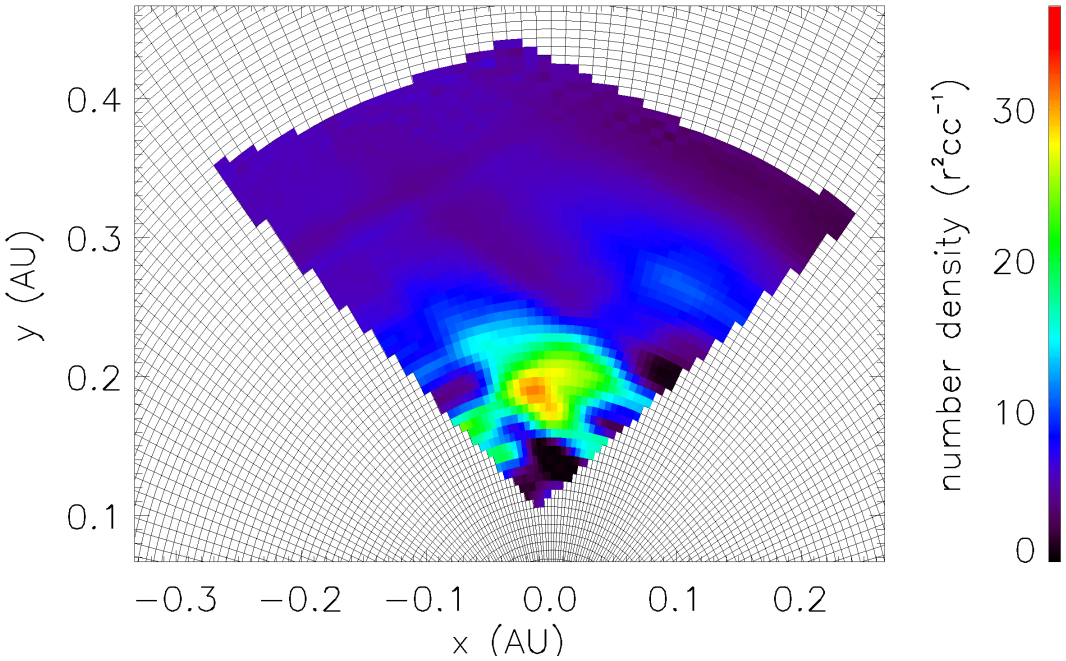
Distance = 27 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

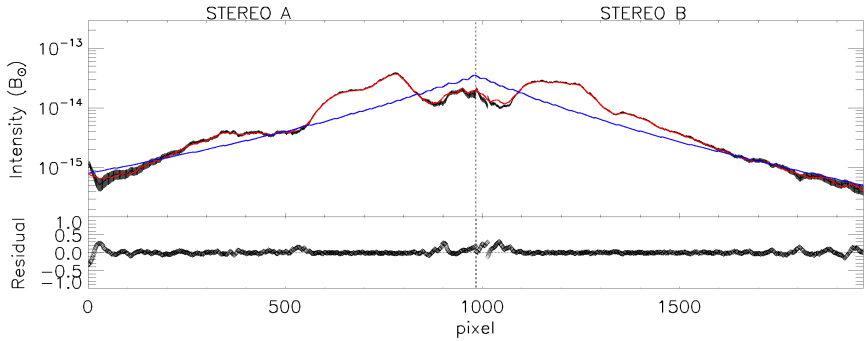
Density Results – Dec 2008 CME



13 Dec 2008 04:09

Density (peak) = 31.1 $e^- r^2 cc^{-1}$

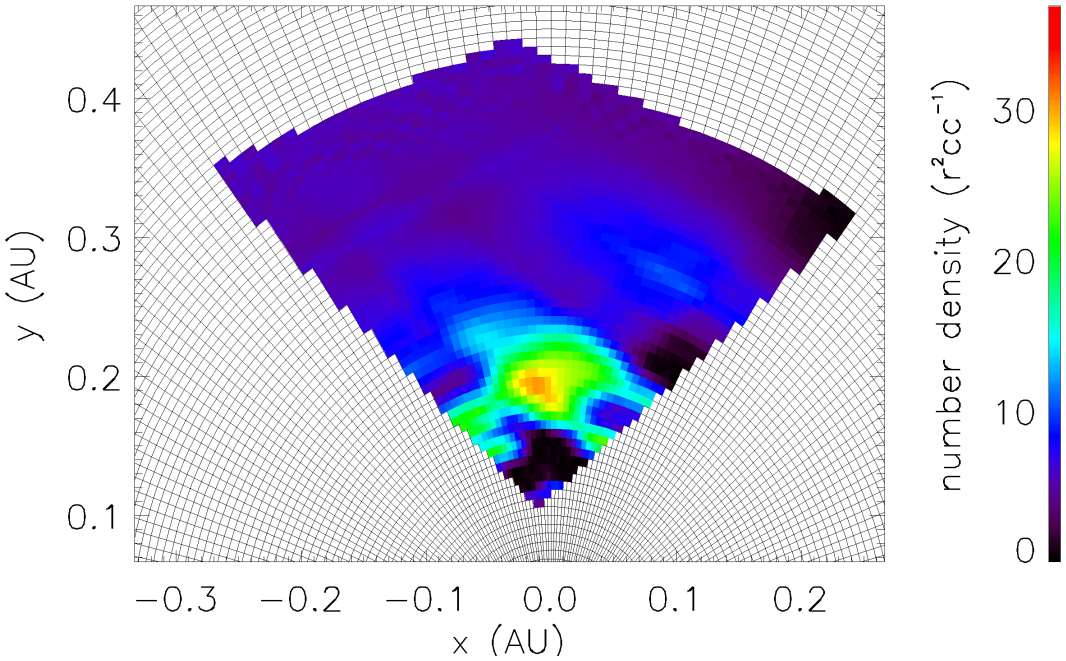
Distance = 28 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

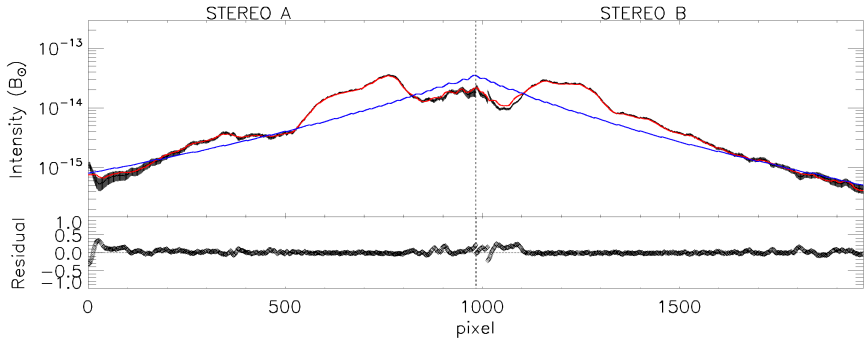
Density Results – Dec 2008 CME



13 Dec 2008 04:49

Density (peak) = 30.5 $e^- r^2 cc^{-1}$

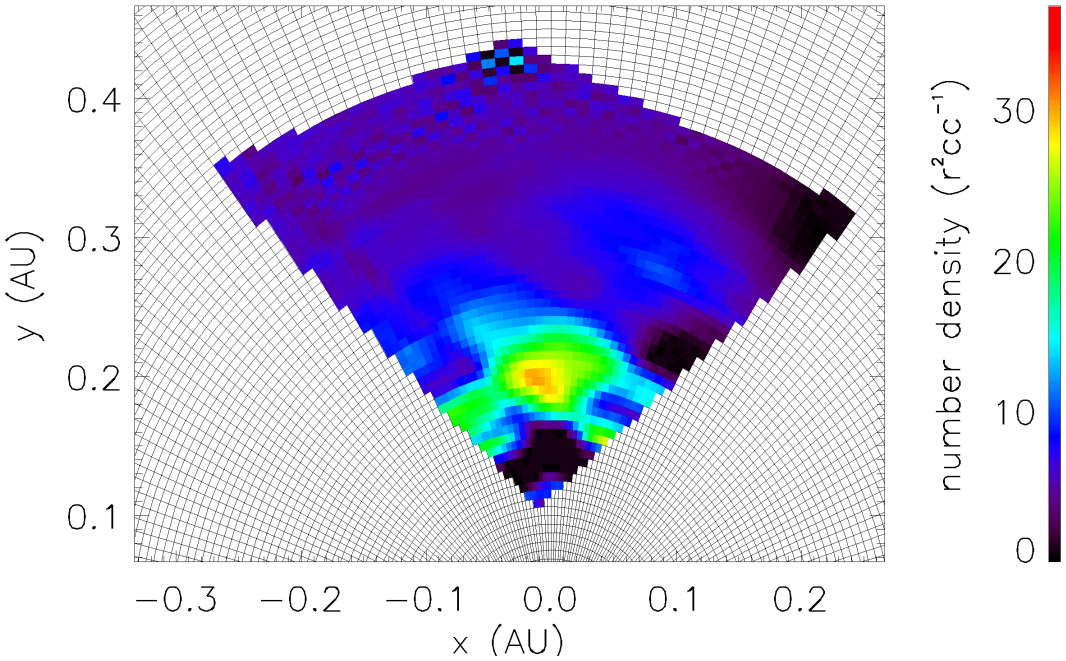
Distance = 28 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

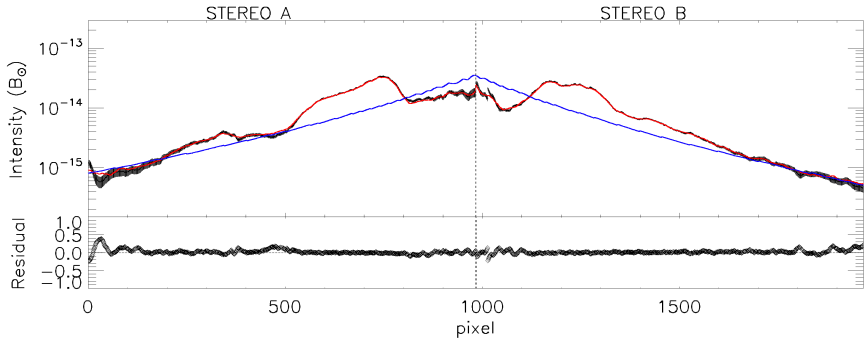
Density Results – Dec 2008 CME



13 Dec 2008 05:29

Density (peak) = 30.4 $e^- r^2 cc^{-1}$

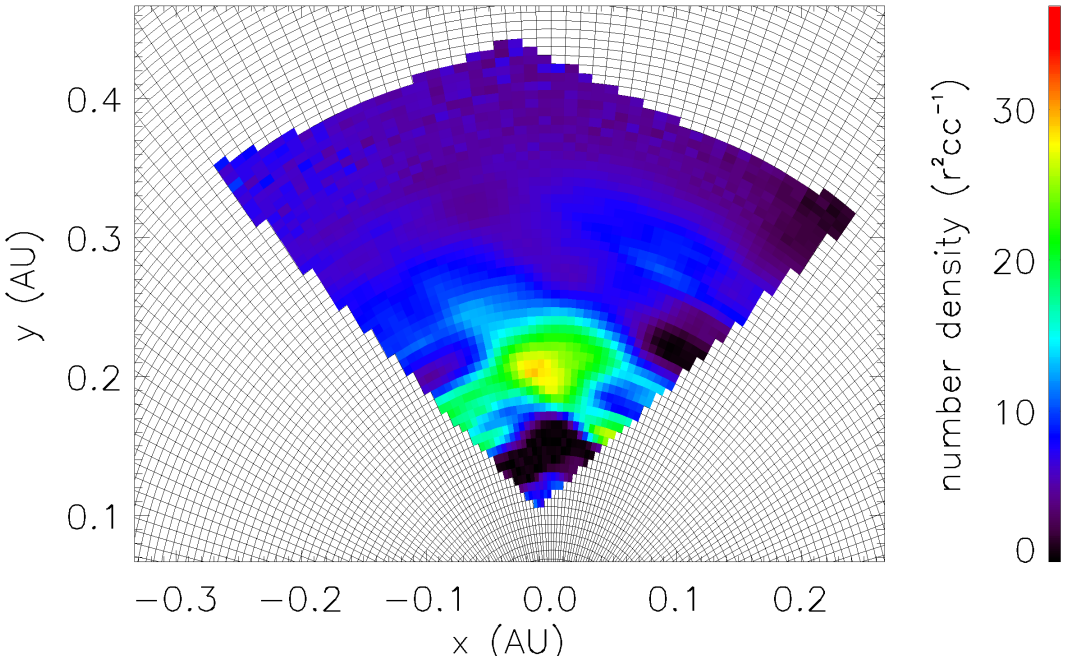
Distance = 29 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

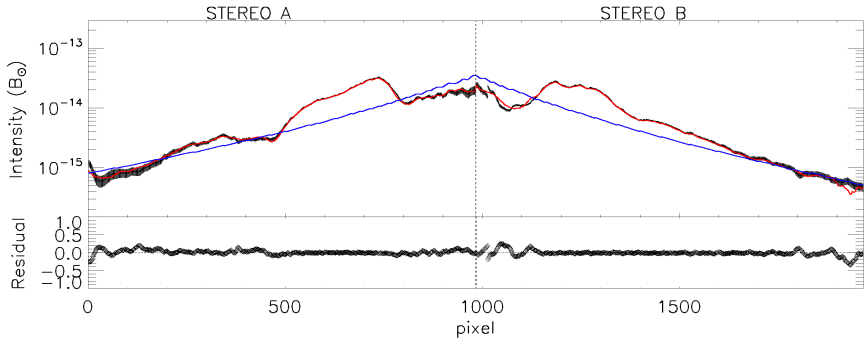
Density Results – Dec 2008 CME



13 Dec 2008 06:09

Density (peak) = 29.3 $e^- r^2 cc^{-1}$

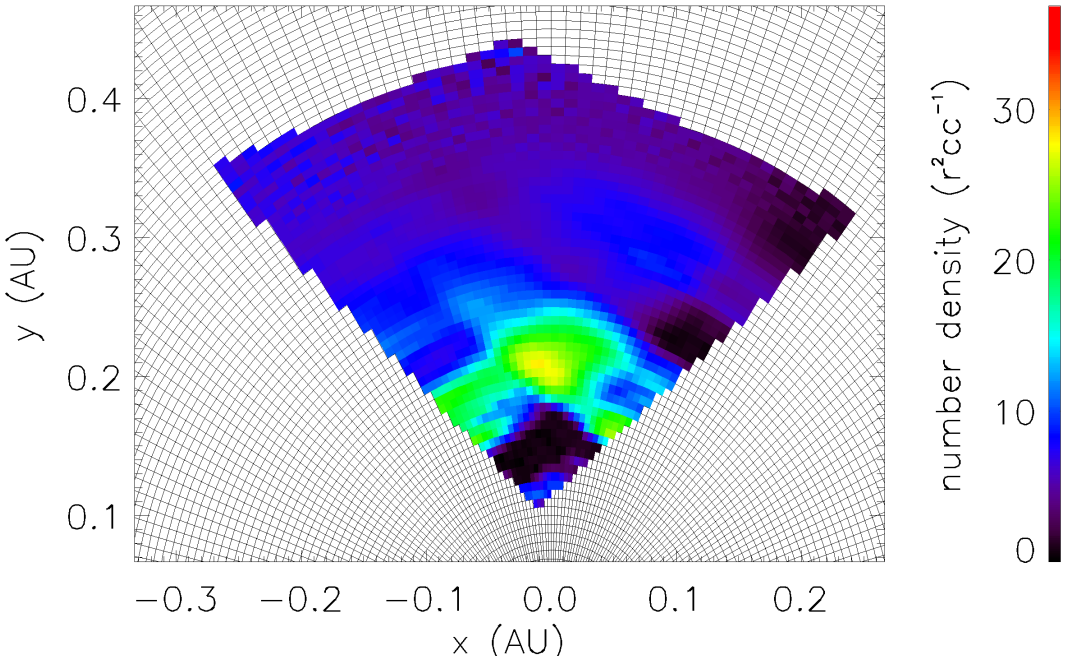
Distance = 30 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

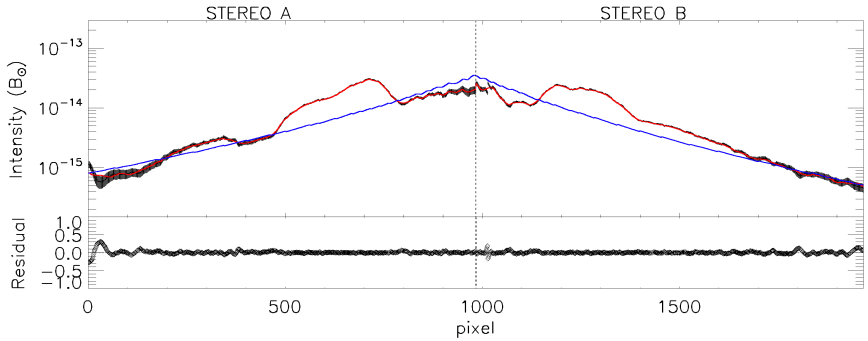
Density Results – Dec 2008 CME



13 Dec 2008 06:49

Density (peak) = 28.3 $e^- r^2 cc^{-1}$

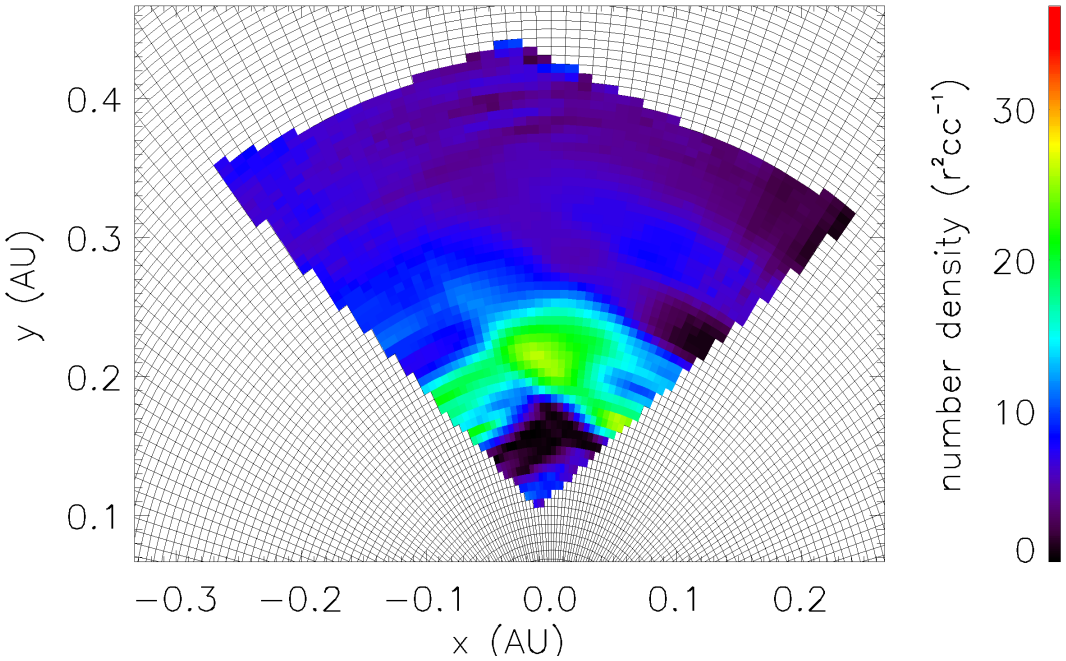
Distance = 31 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

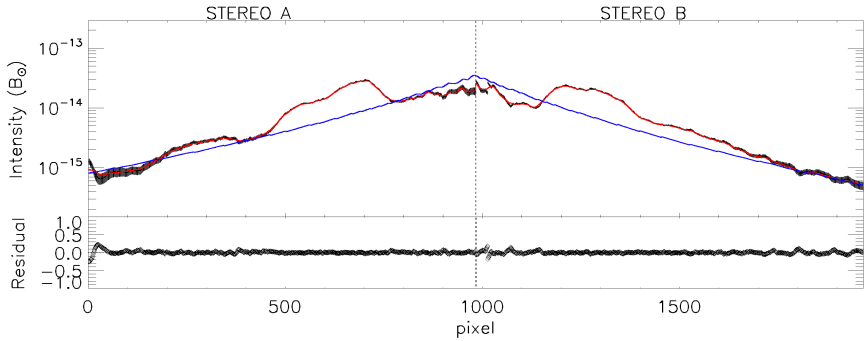
Density Results – Dec 2008 CME



13 Dec 2008 07:29

Density (peak) = 26.1 $e^- r^2 cc^{-1}$

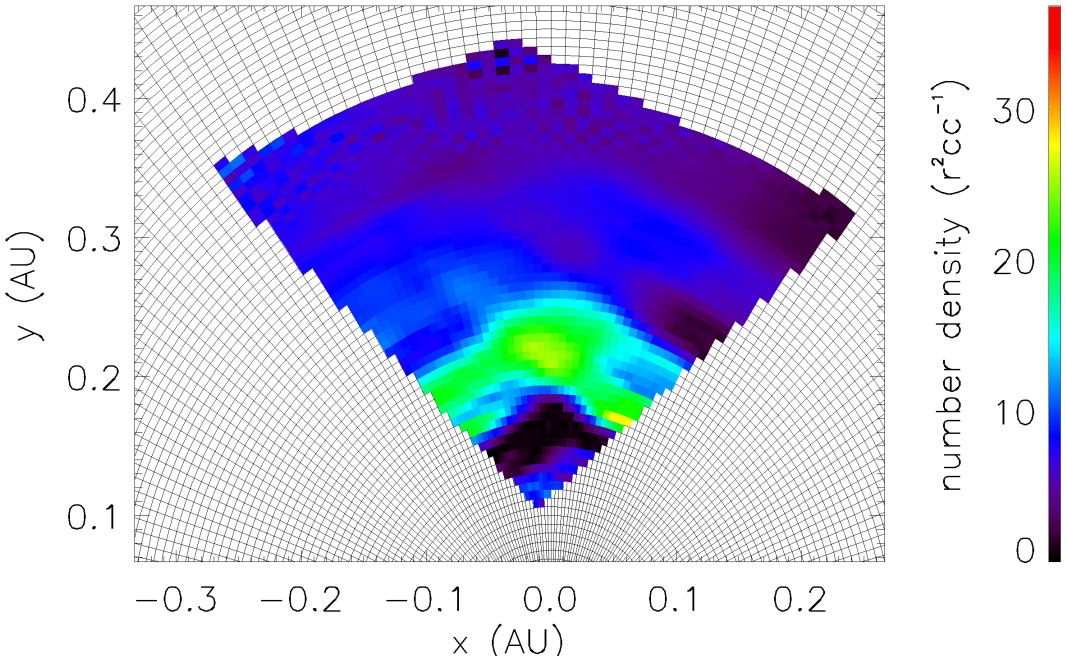
Distance = 32 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

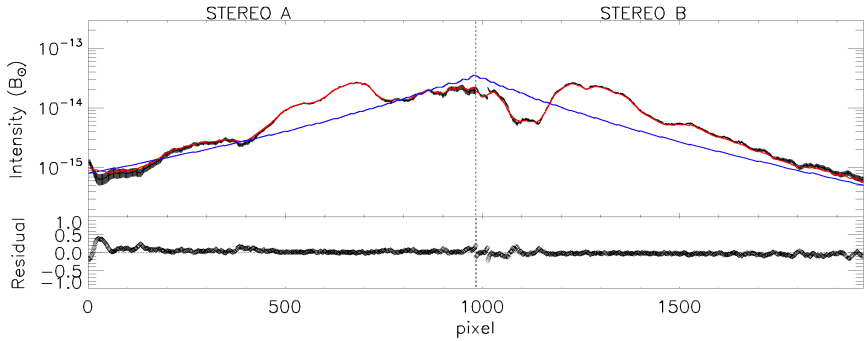
Density Results – Dec 2008 CME



13 Dec 2008 08:09

Density (peak) = 26.0 $e^- r^2 cc^{-1}$

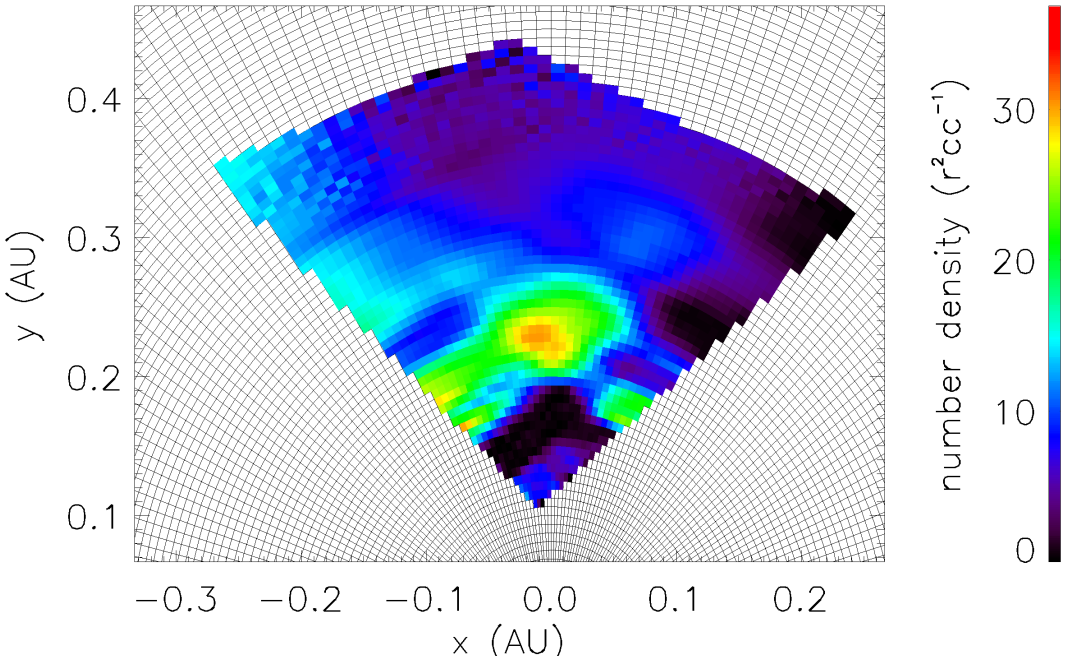
Distance = 33 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

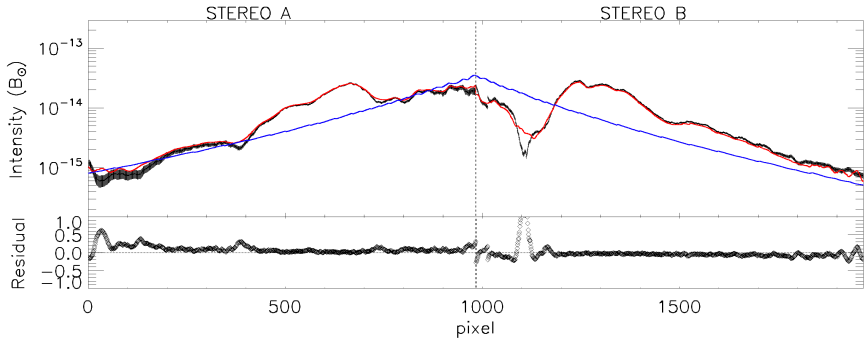
Density Results – Dec 2008 CME



13 Dec 2008 08:49

Density (peak) = 30.6 $e^- r^2 cc^{-1}$

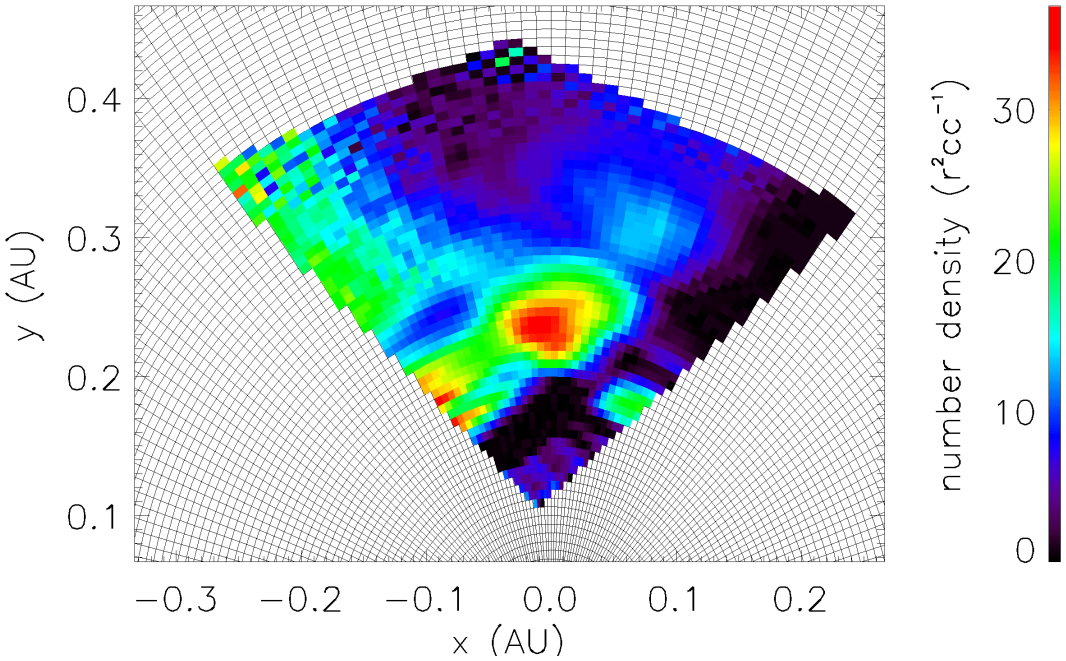
Distance = 34 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

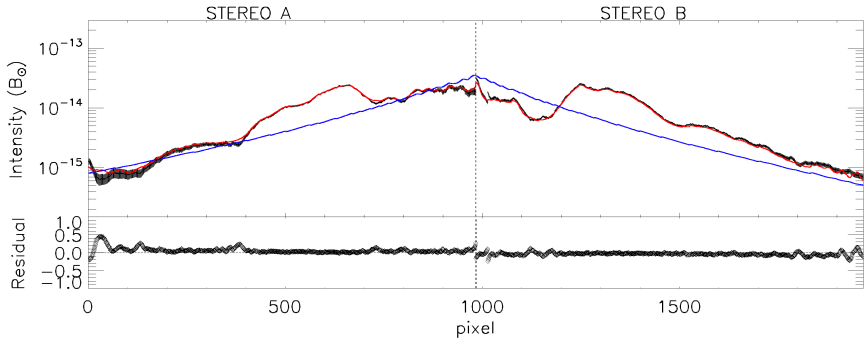
Density Results – Dec 2008 CME



13 Dec 2008 09:29

Density (peak) = 35.9 $e^- r^2 cc^{-1}$

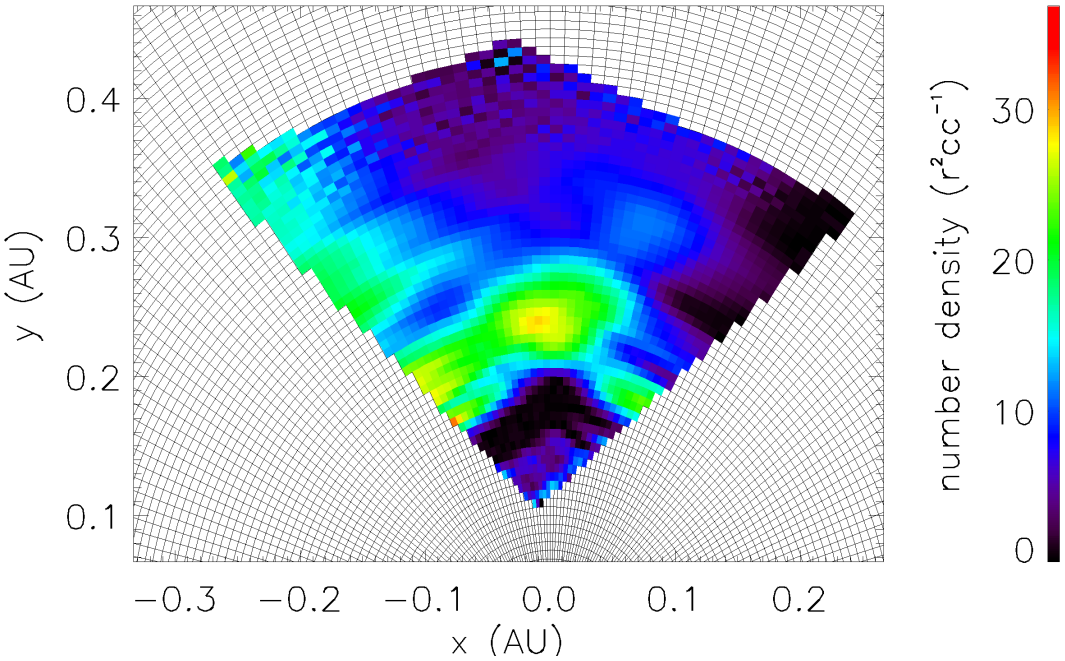
Distance = 35 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

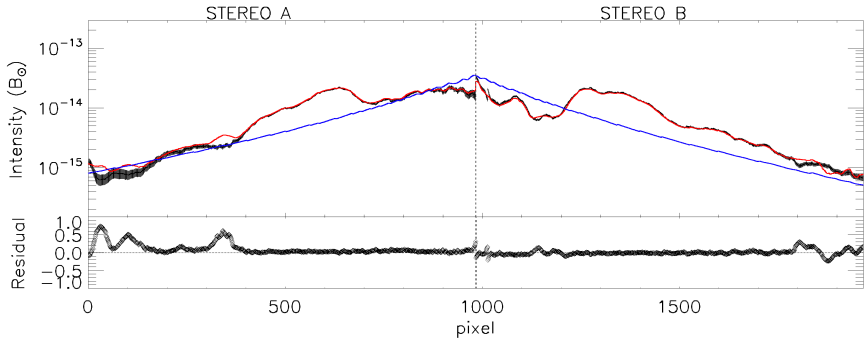
Density Results – Dec 2008 CME



13 Dec 2008 10:09

Density (peak) = 29.0 $e^- r^2 cc^{-1}$

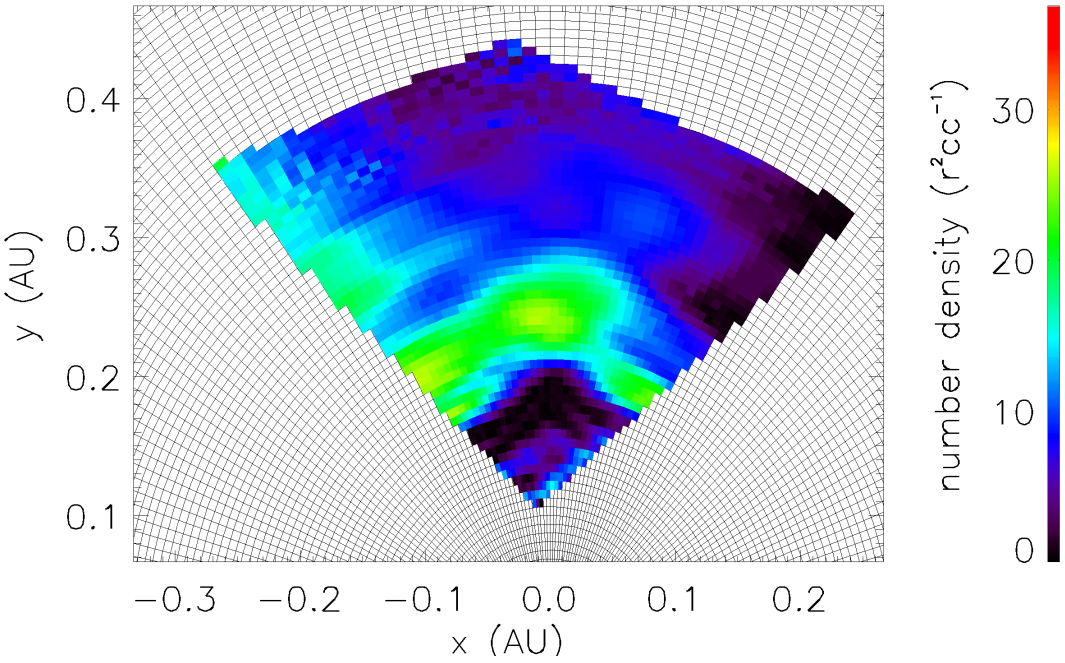
Distance = 36 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

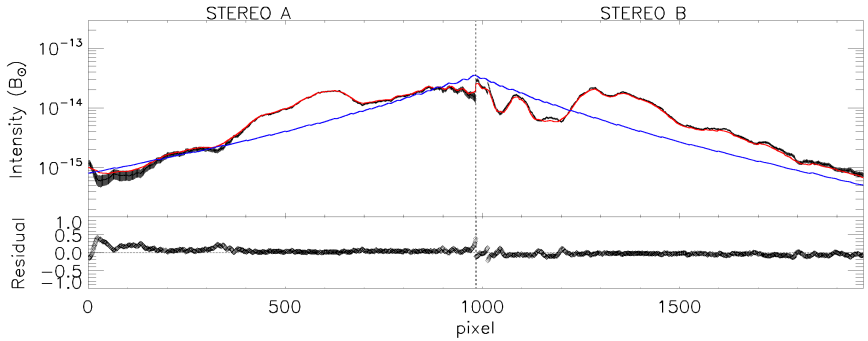
Density Results – Dec 2008 CME



13 Dec 2008 10:49

Density (peak) = 25.9 $e^- r^2 cc^{-1}$

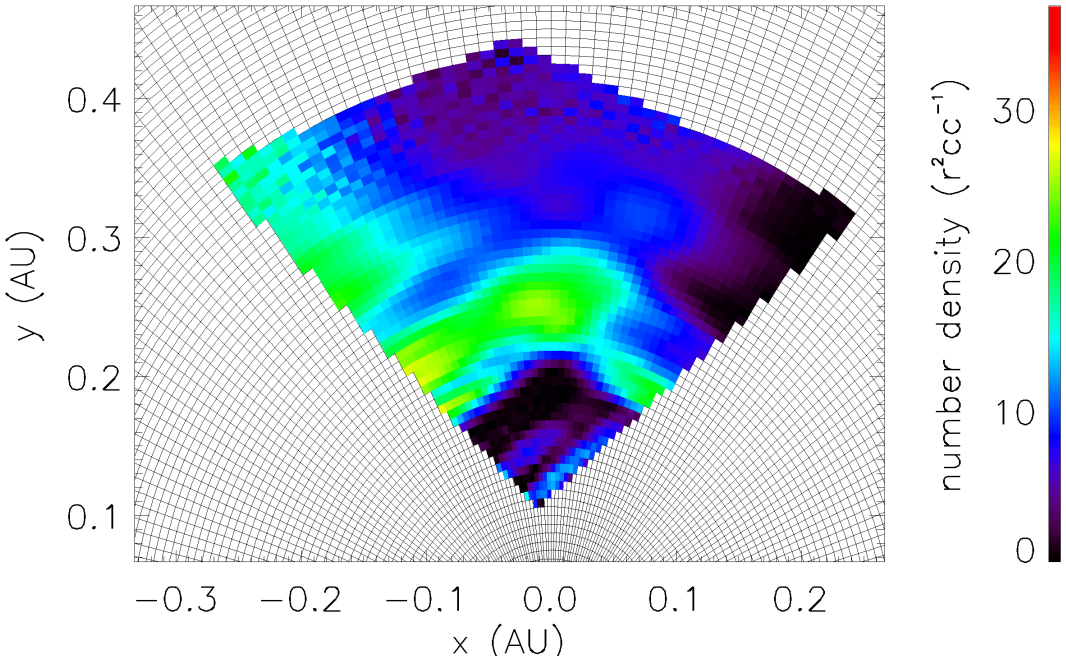
Distance = 36 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

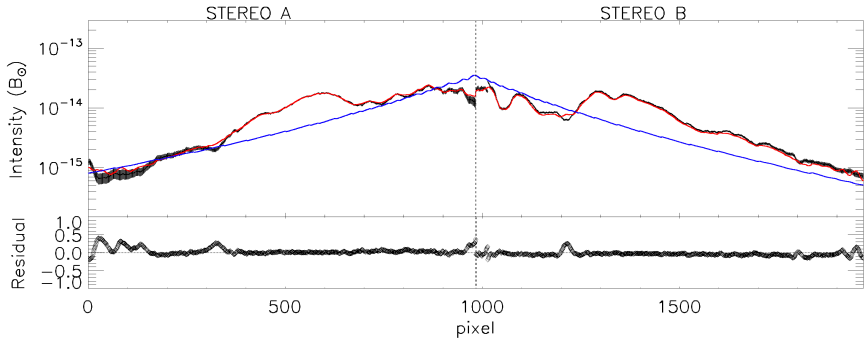
Density Results – Dec 2008 CME



13 Dec 2008 11:29

Density (peak) = 25.6 $e^- r^2 cc^{-1}$

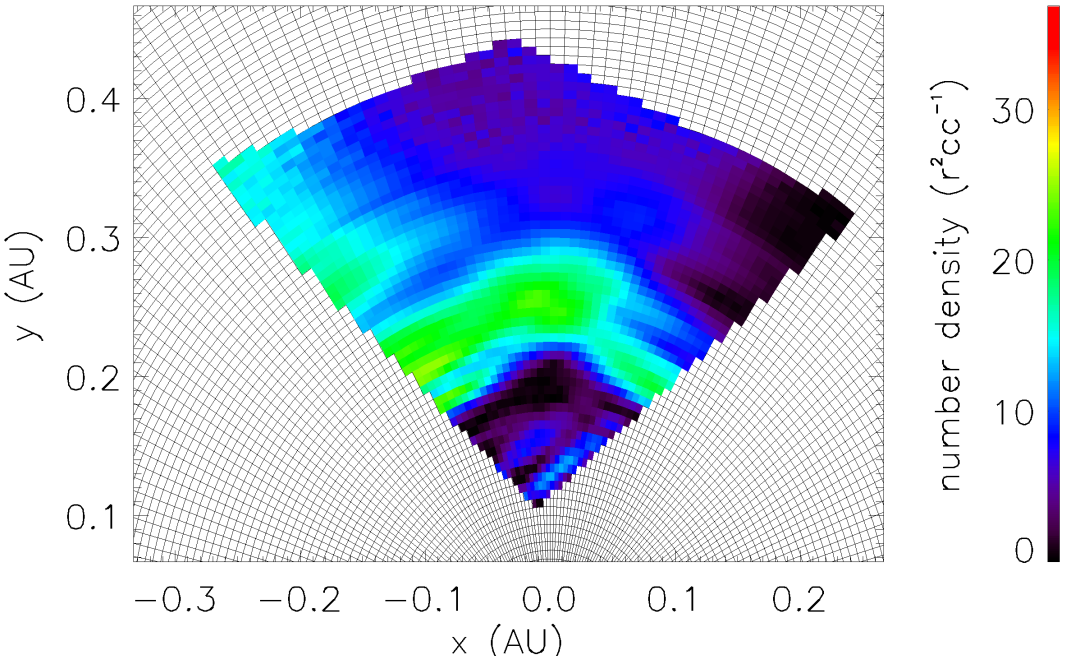
Distance = 38 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

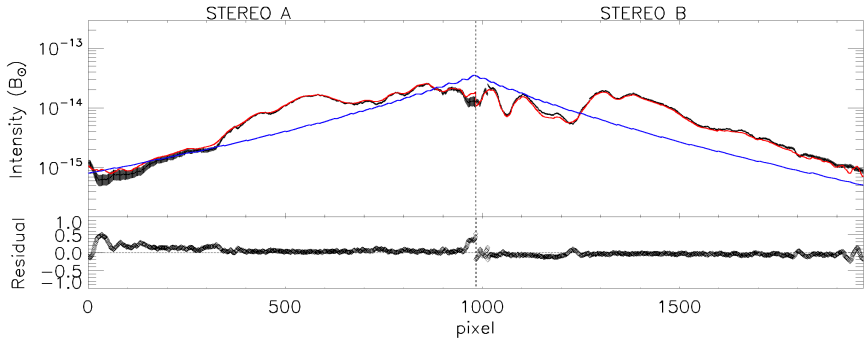
Density Results – Dec 2008 CME



13 Dec 2008 12:09

Density (peak) = 23.4 $e^- r^2 cc^{-1}$

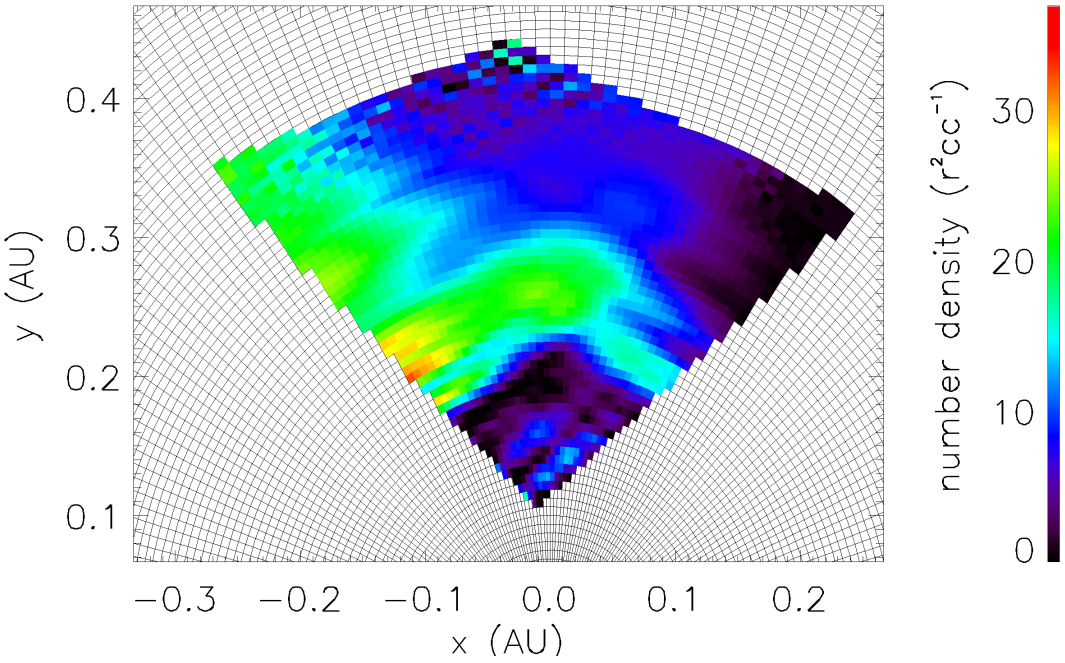
Distance = 38 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

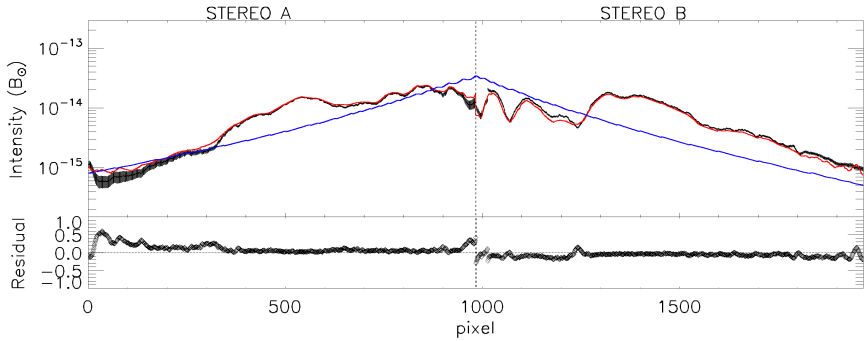
Density Results – Dec 2008 CME



13 Dec 2008 12:49

Density (peak) = 24.5 $e^- r^2 cc^{-1}$

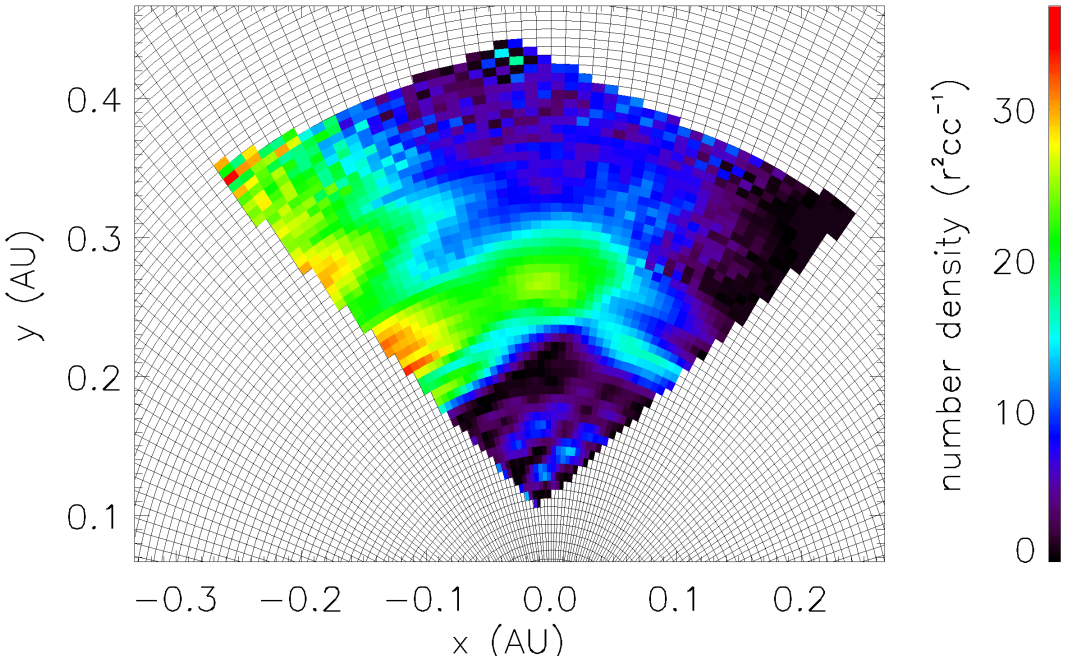
Distance = 38 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

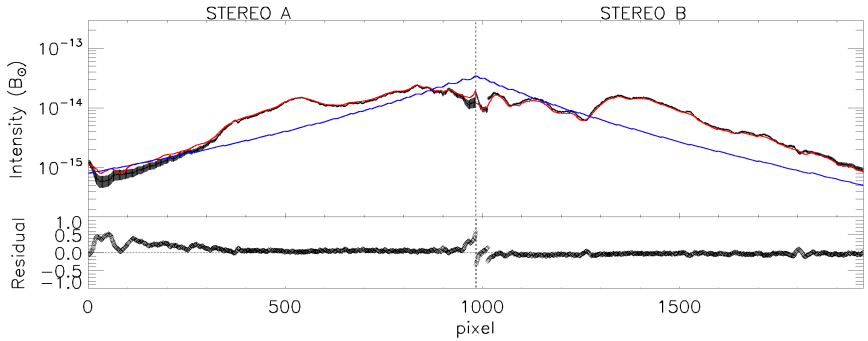
Density Results – Dec 2008 CME



13 Dec 2008 13:29

Density (peak) = 25.9 $e^- r^2 cc^{-1}$

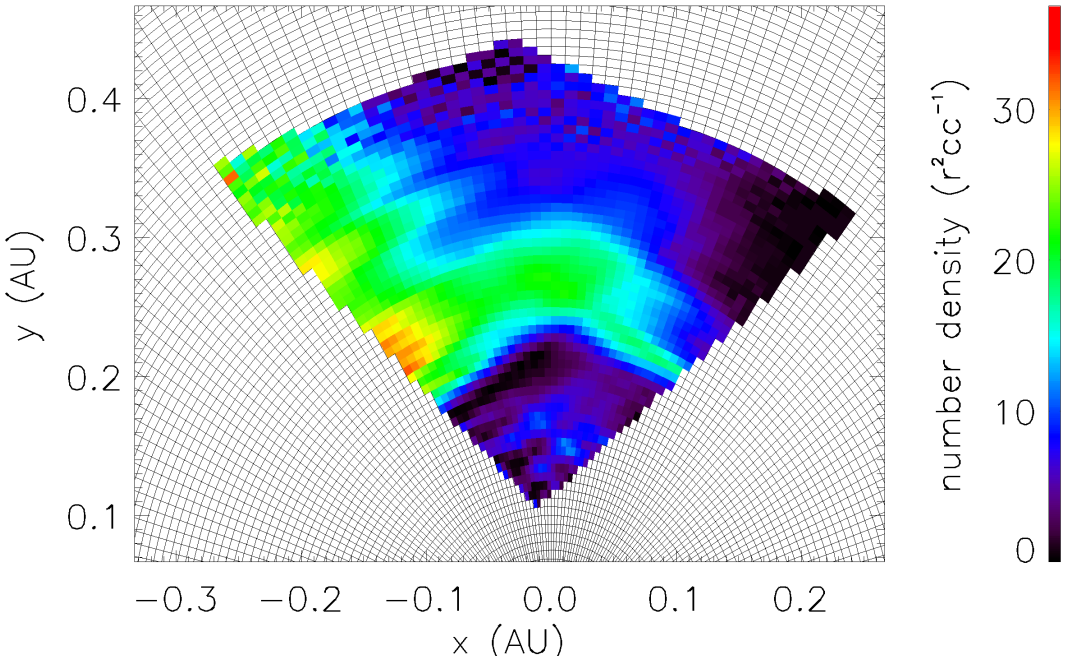
Distance = 39 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

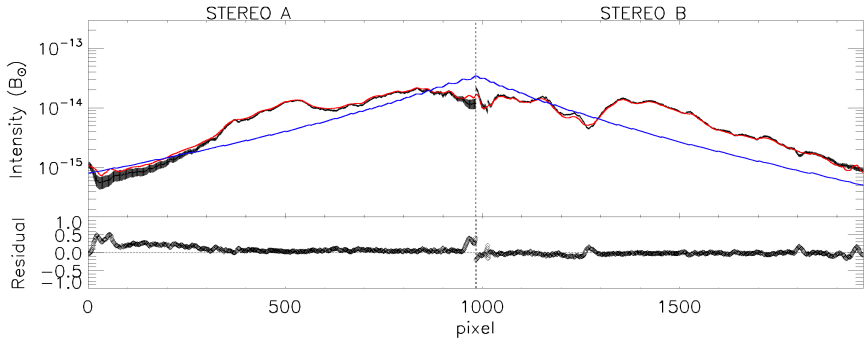
Density Results – Dec 2008 CME



13 Dec 2008 14:09

Density (peak) = 22.1 $e^- r^2 cc^{-1}$

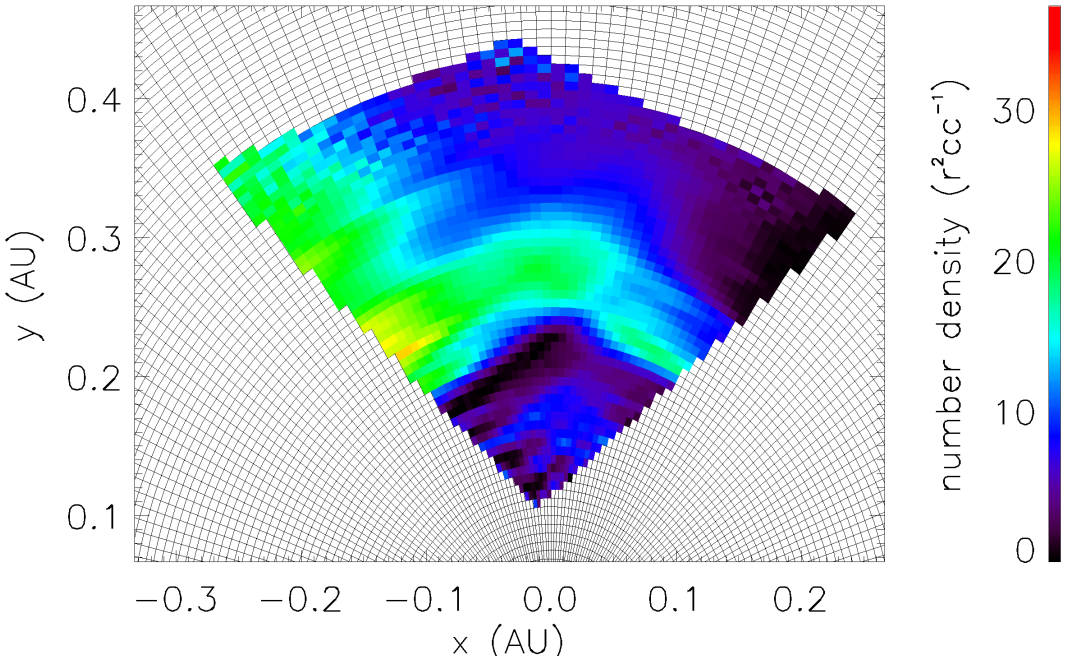
Distance = 40 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

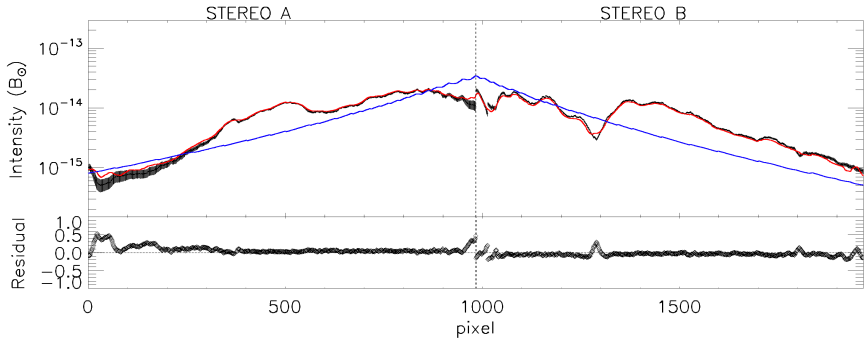
Density Results – Dec 2008 CME



13 Dec 2008 14:49

Density (peak) = 20.3 $e^- r^2 cc^{-1}$

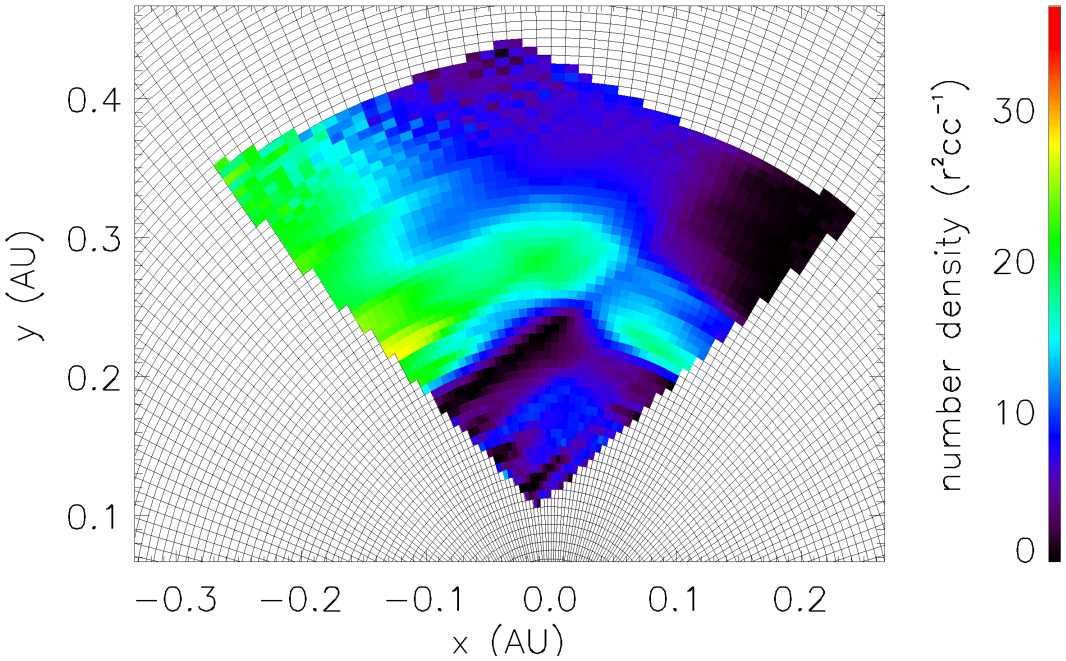
Distance = 41 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

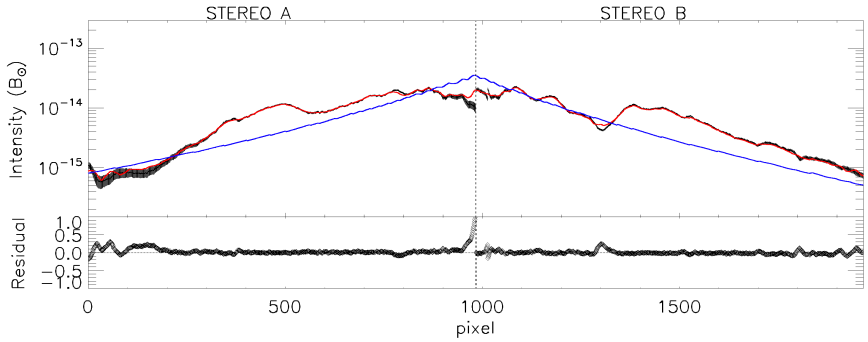
Density Results – Dec 2008 CME



13 Dec 2008 15:29

Density (peak) = 20.4 $e^- r^2 cc^{-1}$

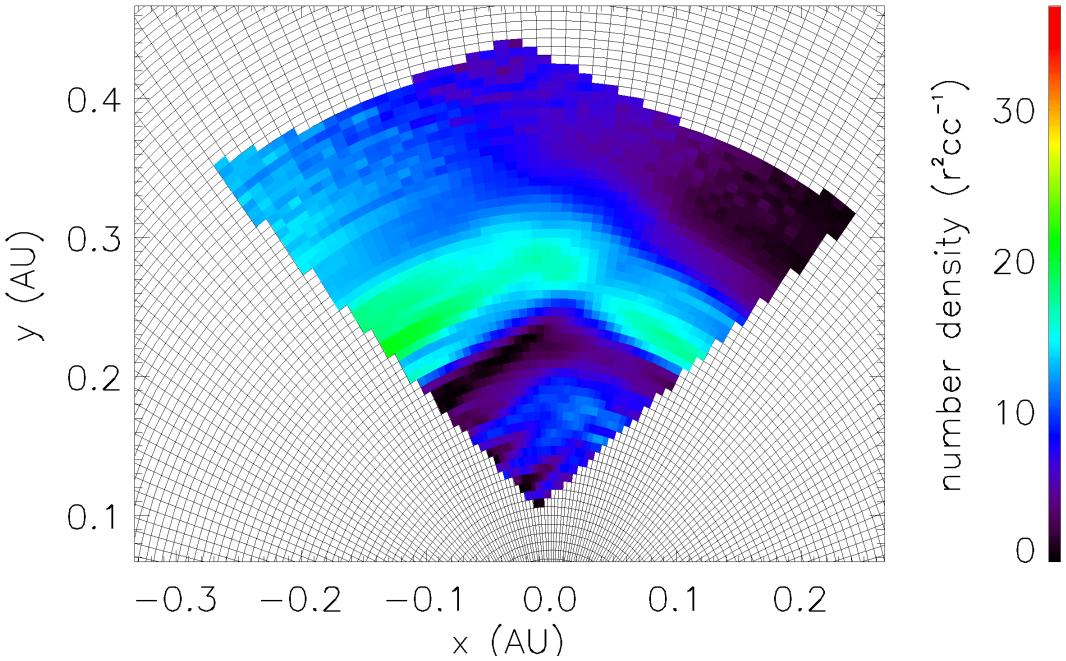
Distance = 42 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

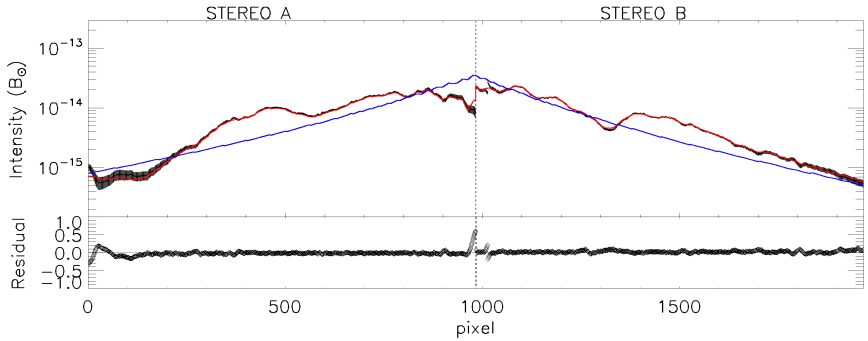
Density Results – Dec 2008 CME



13 Dec 2008 16:09

Density (peak) = 17.1 $e^- r^2 cc^{-1}$

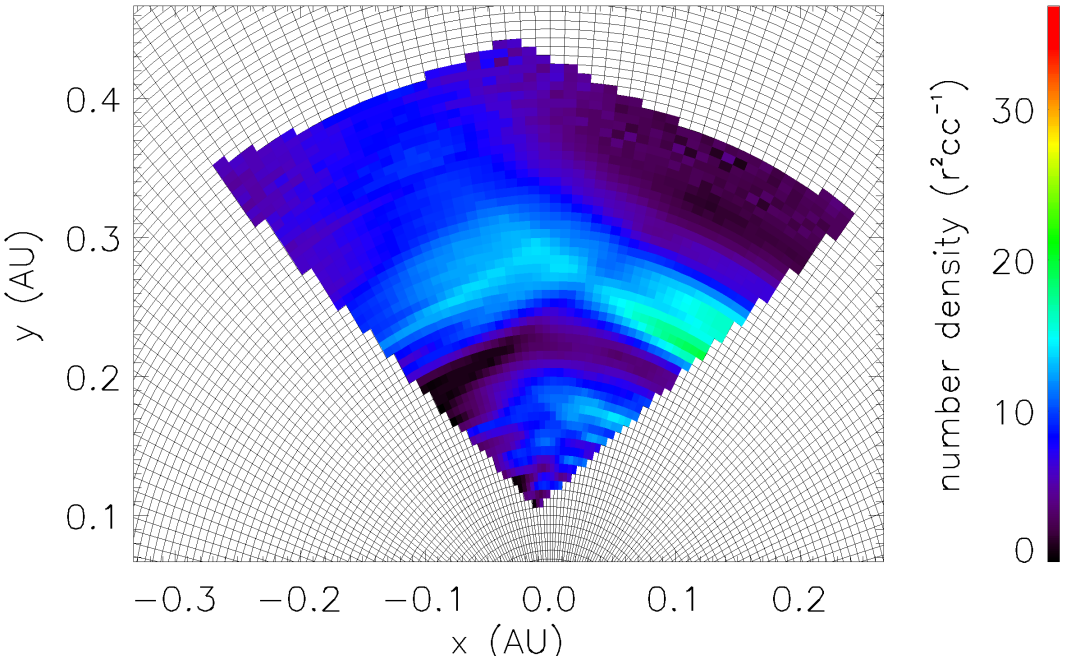
Distance = 42 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

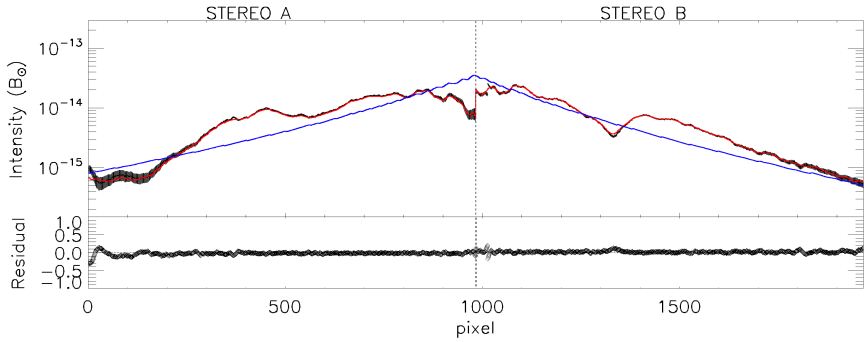
Density Results – Dec 2008 CME



13 Dec 2008 16:49

Density (peak) = 14.1 $e^- r^2 cc^{-1}$

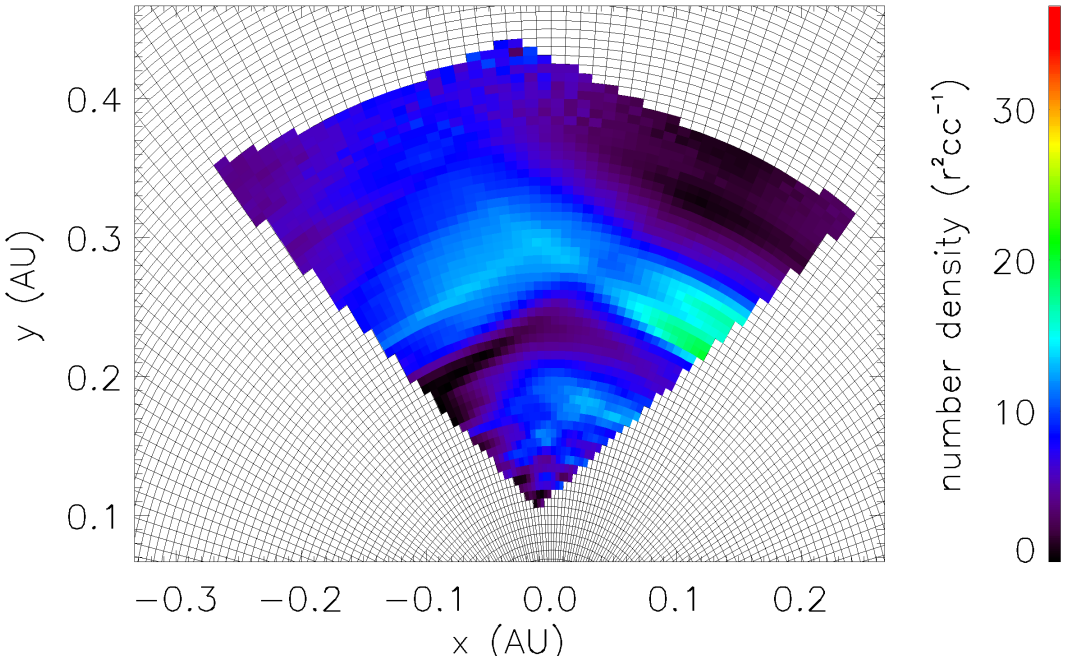
Distance = 41 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

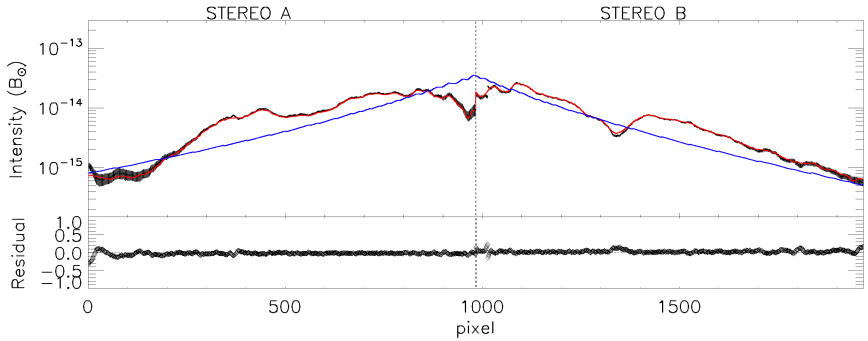
Density Results – Dec 2008 CME



13 Dec 2008 17:29

Density (peak) = 13.6 $e^- r^2 cc^{-1}$

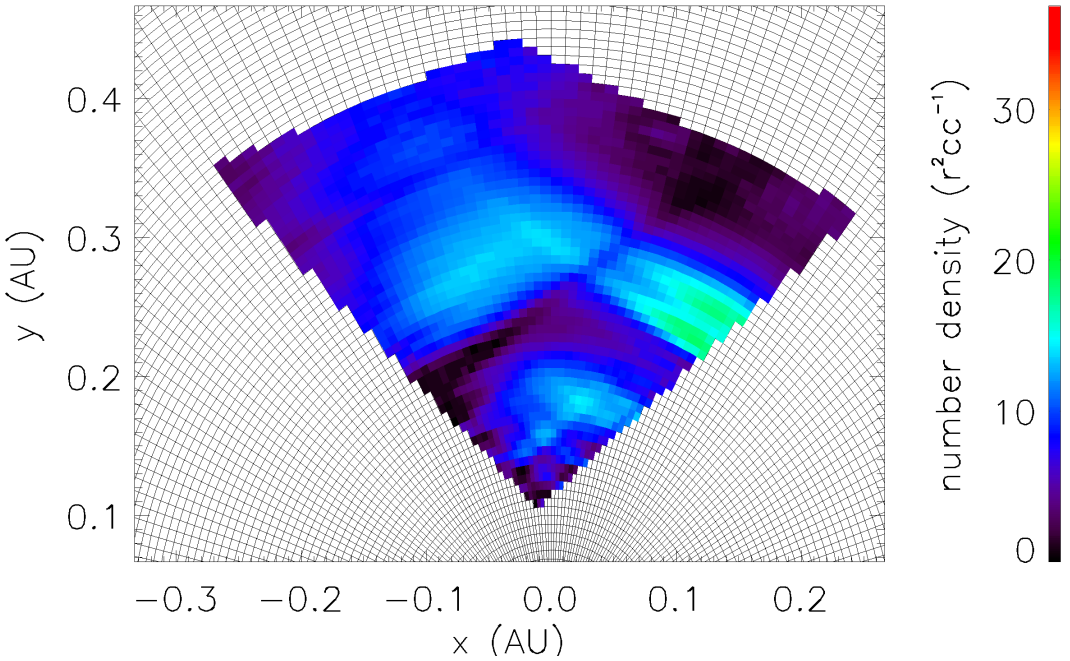
Distance = 44 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

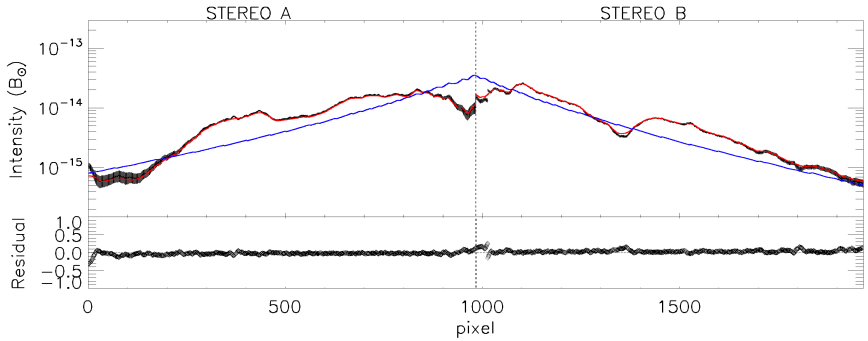
Density Results – Dec 2008 CME



13 Dec 2008 18:09

Density (peak) = 14.1 $e^- r^2 cc^{-1}$

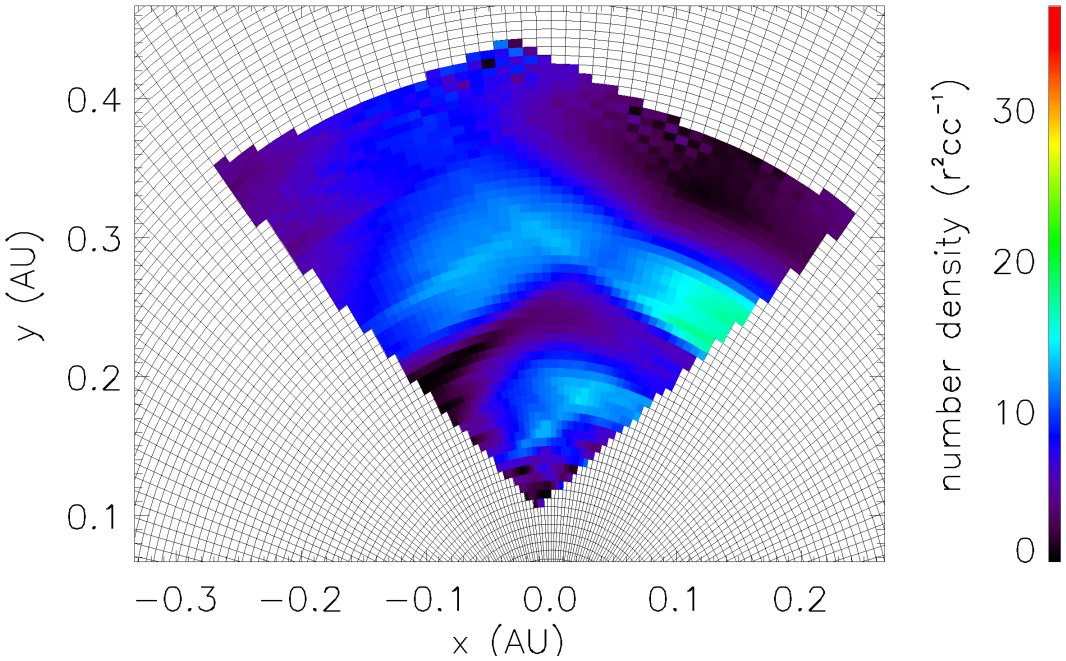
Distance = 45 $*10^6$ km



- Data
- Initial guess
- Solution

Science & Technology Facilities Council

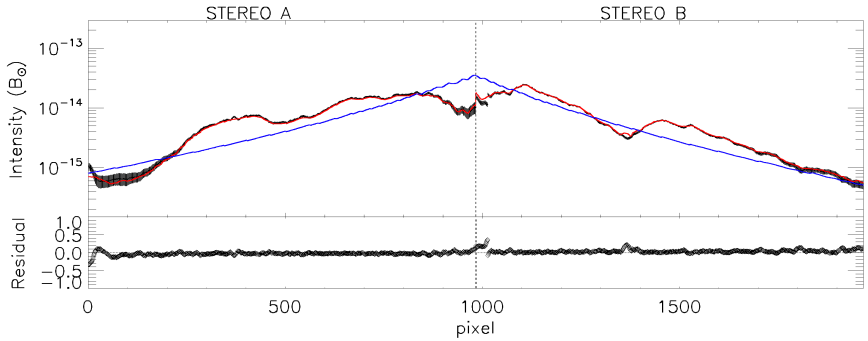
Density Results – Dec 2008 CME



13 Dec 2008 18:49

Density (peak) = 13.1 $e^- r^2 cc^{-1}$

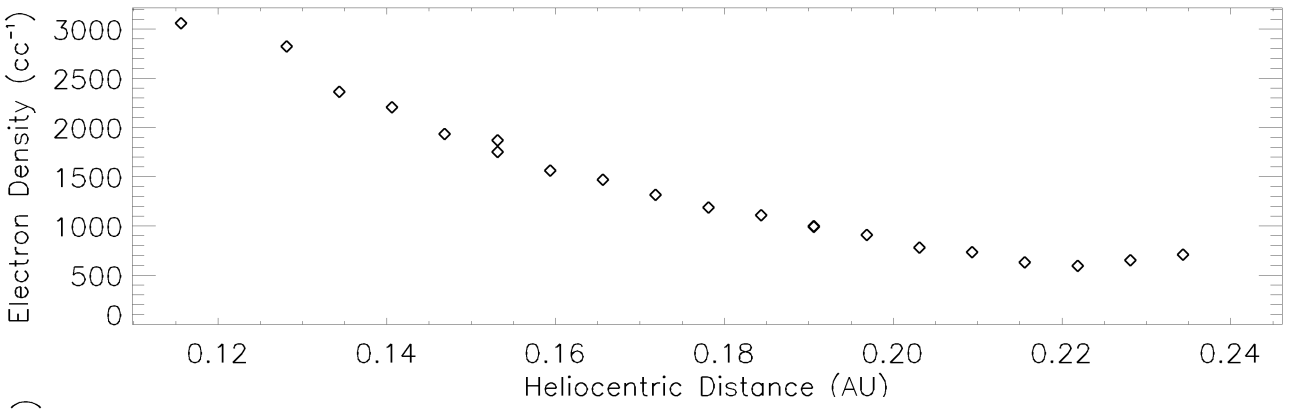
Distance = 44 $*10^6$ km

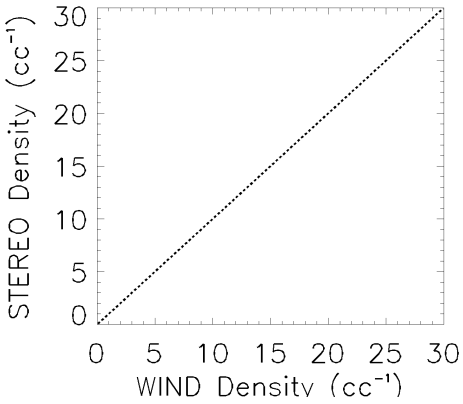


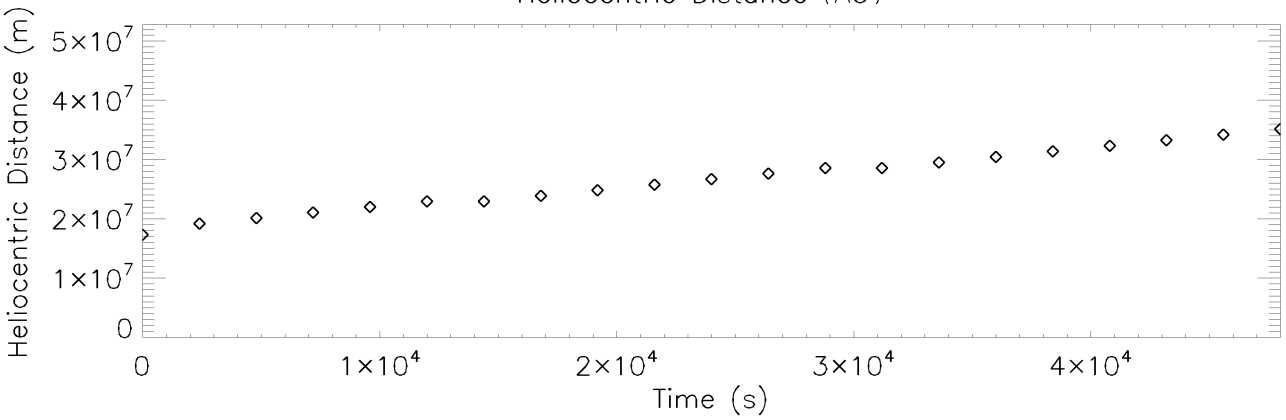
- Data
- Initial guess
- Solution

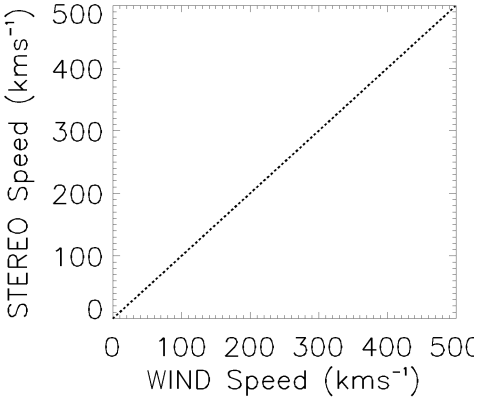
Science & Technology Facilities Council

Dec 2008 CME Speed and Density









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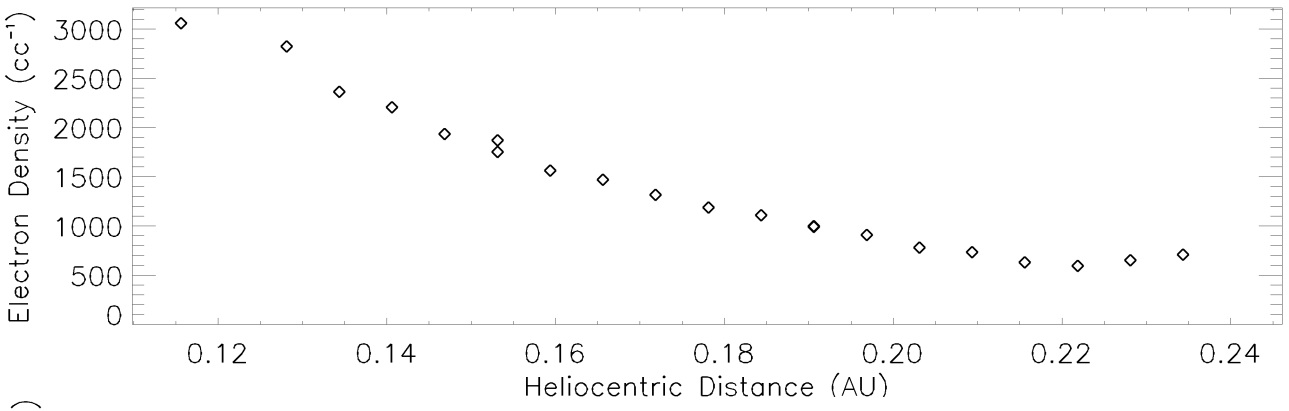
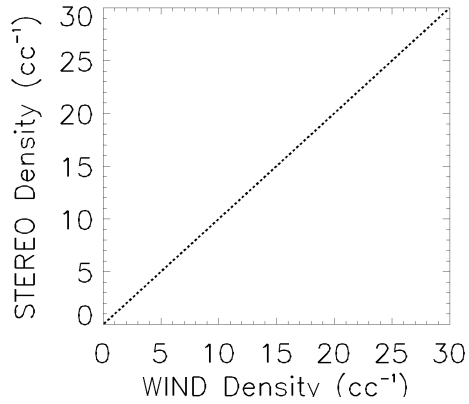
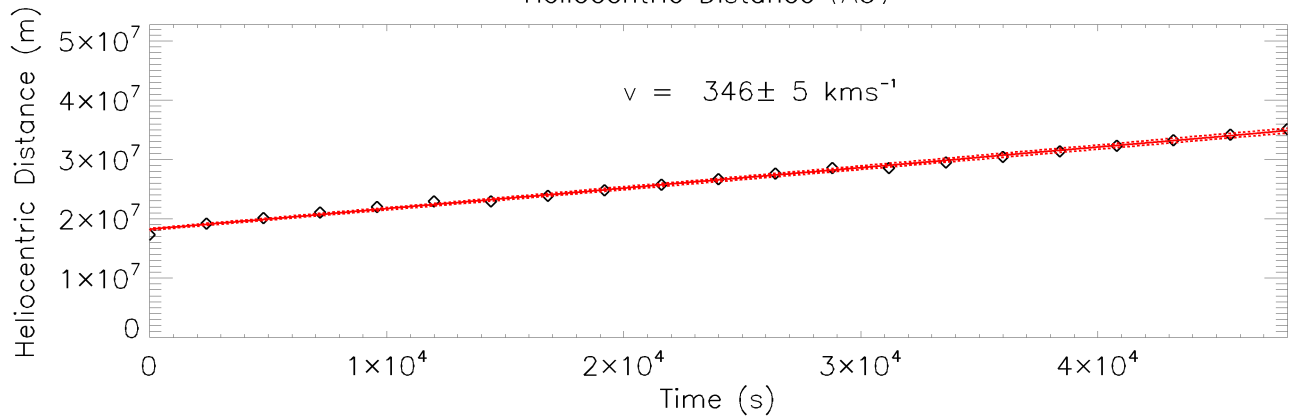
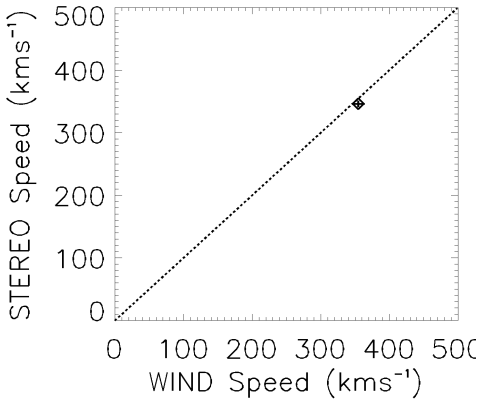
Dec 2008 CME Speed and Density









- Assume constant velocity

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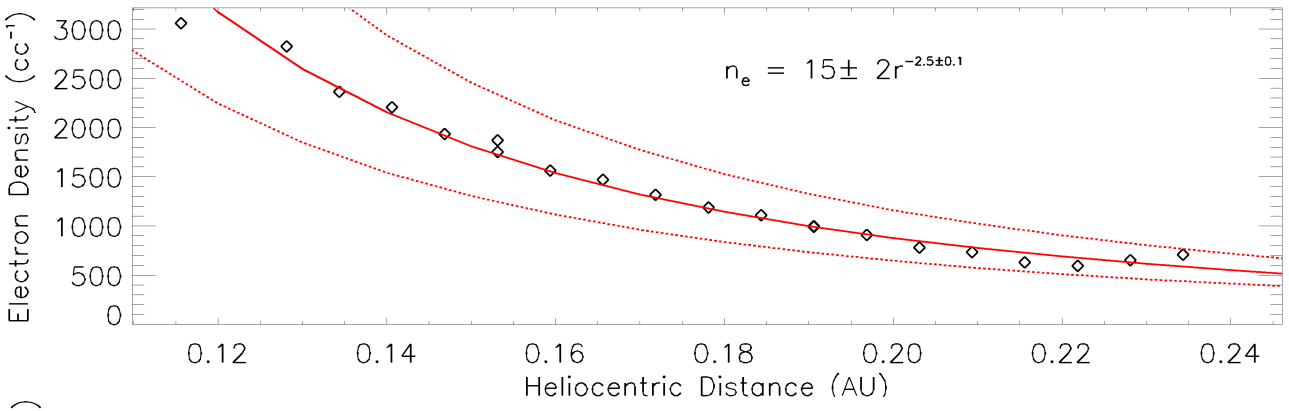
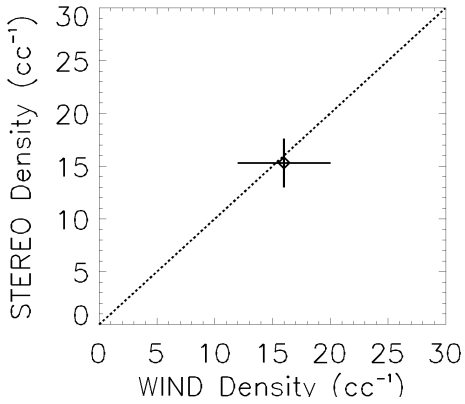
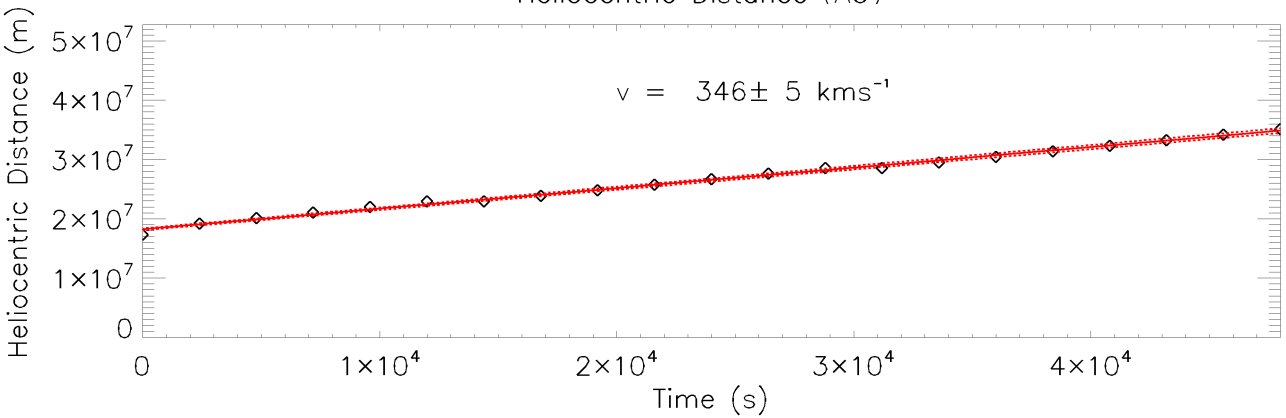
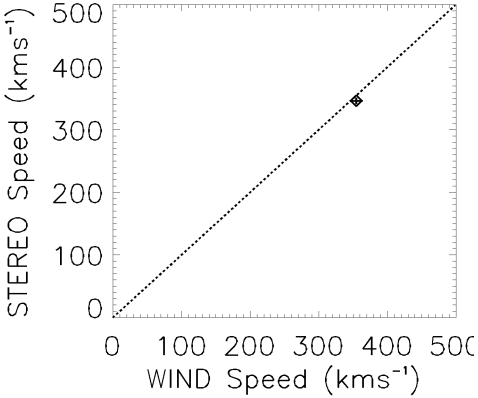
Dec 2008 CME Speed and Density









- Assume constant velocity
- Assume density and radius follow power law
- Regularisation terms can be tuned to give more accurate value for density

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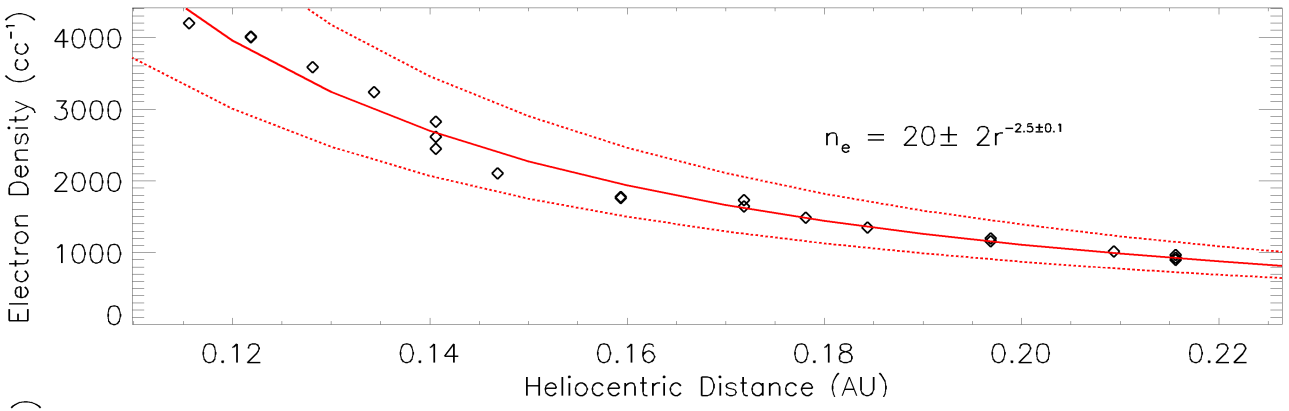
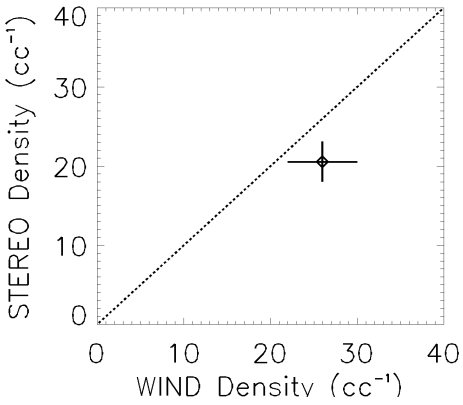
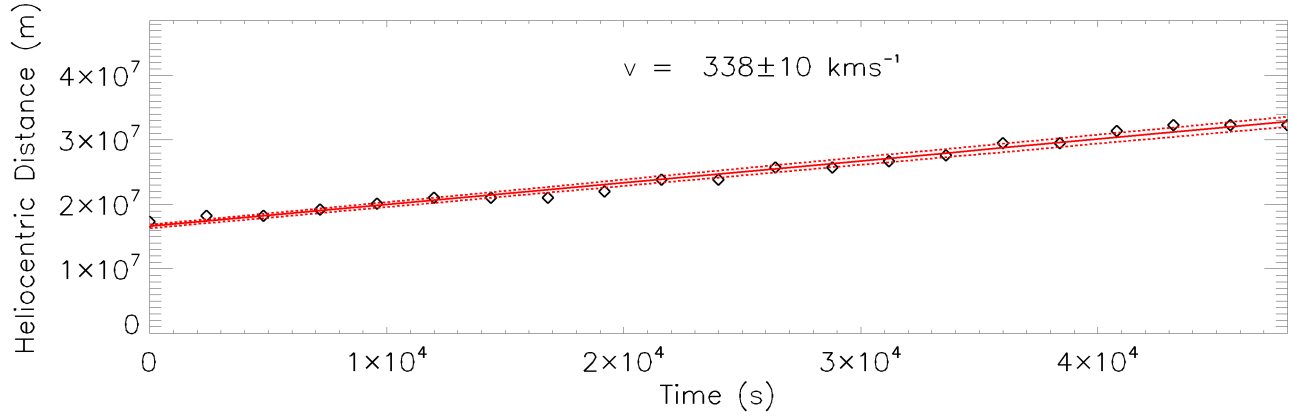
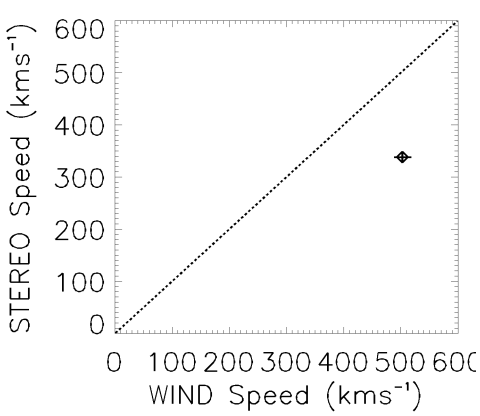
Oct 2011 CME Speed and Density









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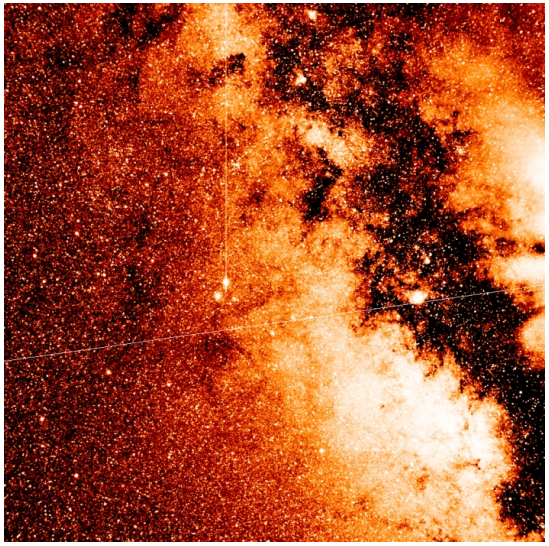
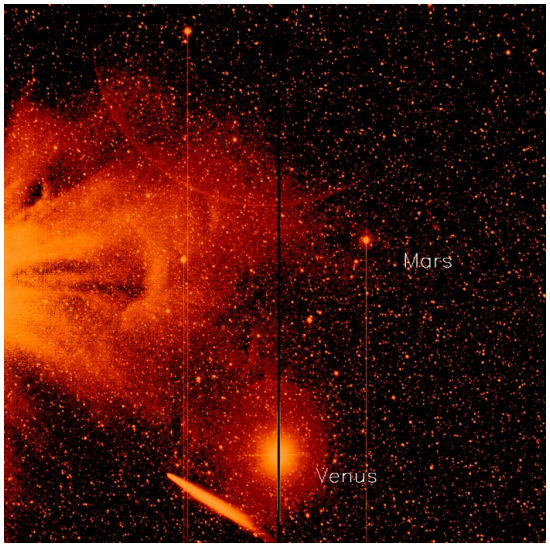
Limitations





- The galactic plane passes through the FOV of each spacecraft ~2 times per year
- Planets and comets frequently obscure images
- Relative position of the two spacecraft causes line-of-sight problems
- CME must be Earth-directed

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Summary

- Electron density distribution in the ecliptic has been measured using combined HI data from both STEREO spacecraft
- The technique may be used if corrections are applied to produce a physically consistent K-corona intensity
- Iterative algorithm typically produces a density distribution with a mean residual of less than 5% of observations
- May be used to estimate CME speeds and densities
- Only two CMEs to which this technique has been applied