Evidence for magnetic loop asymmetry from HXR footpoint areas

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SUMMARY

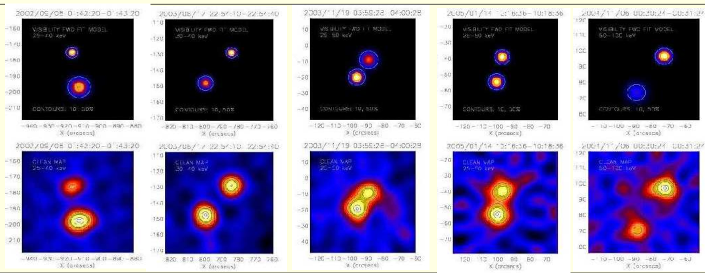
- Flare footpoint asymmetries are common
- Are seen by RHESSI both in size (new) and flux
- Previously HXR[1,2,3] and radio[4] showed only flux asymmetries
- The usual interpretation is in terms of magnetic asymmetry
- Convergent magnetic fields
  - cause trapping
  - localize the precipitation of electrons

Our new measurements of footpoint areas
- **show that footpoint area correlates with footpoint flux;**
- **models without pitch angle diffusion are ruled out;**
- **pitch angle diffusion is a significant factor in traps.**

[1] Sakao 1995, Ph.D. Thesis, Tokyo Univ.
[2] Aschwanden et al 1999
[3] Alexander & Metcalf, 2002
[4] Wang et al 1995, Kundu et al, 1995

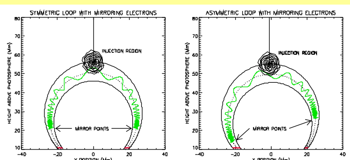
EXAMPLES OF DOUBLE-SOURCE FLARES MAPPED FROM VISIBILITIES

THE SAME FLARES MAPPED WITH RHESSI CLEAN



INTERPRETATION: MAGNETIC ASYMMETRY AND MIRRORING

In asymmetric loops, the footpoint is larger where the mirror point is lower, where precipitation is enhanced, hence X-ray flux should correlate with area or width (Melrose and White, 1979).

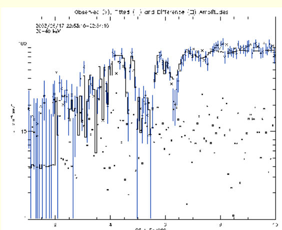


HOW THE NEW METHOD WORKS

RHESSI is a modulation collimator, i.e., a Fourier imager
Its modulation profiles yield flare visibilities
Image model using 8-12 parameters
Compute visibilities from the model (i.e. Fourier transform)
Vary the parameters until model and flare visibilities agree

The next figure shows some observed amplitudes for RHESSI visibilities

EXAMPLE OF AMPLITUDE PROFILE



A Double-component RHESSI flare

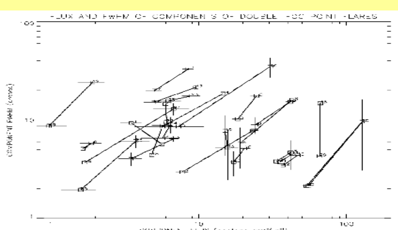
- Bumps and wiggles are caused by the sources “beating” against each other.
- Curve was fit by a set of 8 parameters describing two circular Gaussians

$\chi^2 \sim 1$ from count statistics

Validation of fit:
Agreement with bumps/wiggles
Cross sections thru χ^2 space
Residual max as fraction of bmap max
Sensitivity to increasing # of parameters
Similarity to imaging by other means

SOME OBSERVED WIDTHS AND FLUXES

- A sample of 26 double-component events
- FWHM plotted against flux
- The brighter component is also wider (as predicted by Melrose & White, 1979)
- The slope of the lines between faint & bright components is almost always positive.
- Error bars measure confidence in result



COMPARISON OF RHESSI OBSERVATIONS OF AREA AND FLUX ASYMMETRY WITH MODELS

- APPLICATION OF OUR NEW RESULTS TO THE PHYSICS OF FOOTPOINT ASYMMETRY

Assume:
- - electron's mirror invariants hold
  - footpoint fill factors = 1
  -
- Two extremes for pitch angle scattering:
  - t(scattering) >> t(mirroring) (Aschwanden et al)
  - t(scattering) << t(mirroring) (new)
- Compare asymmetries with predictions

CYCLE #1
- Symmetric injection
- loss cone 1 < loss cone 2
- LEG 1: N p_1 electrons mirror, $N(1-p_1)$ precipitate
- LEG 2: N $(1-p_2)$ precipitate directly
  N $(1-p_2)-(1-p_1)$ precipitate indirectly

TRAP-PRECIPITATION MODELS

- Electrons in a magnetic loop are trapped or precipitate depending on their pitch angle (α).
- The dependence of trapping and precipitation on pitch angles follows from the approximations:

$$\mu = \tfrac{1}{2} mv^2 \sin^2\alpha / B = \text{constant} \quad (1)$$
$$\tfrac{1}{2} mv^2 = \text{constant} \quad (2)$$

- The flux of the magnetic field (B) over any cross section (S) is independent of position, so

$$B(x) \cdot S(x) = B_1 \cdot S_1 = B_2 \cdot S_2 = \text{constant} \quad \text{(1,2 refer to footpoints.)}$$

- Define α_1 and α_2 to be the critical pitch angles (loss-cone angles) at the loop apex.
- Then taking ratios gives an expression relating footpoint areas and loss cone angles:

$$\sin^2\alpha_1 / \sin^2\alpha_2 = S_1 / S_2 \quad (3)$$

Electron trap “cycle”:
- electrons flow down loop leg from apex
- partial mirroring
- back flow over apex
- partial second mirroring

TWO LIMITING CASES

MODEL 1: NO PITCH ANGLE SCATTERING

(Aschwanden et al, 1995, Alexander & Metcalf 2002)

CYCLE #1
- N electrons injected into each leg
- LEG 1: N p_1 electrons mirror, N $(1-p_1)$ precipitate
- LEG 2: N p_2 electrons mirror, N $(1-p_2)$ precipitate
- All pitch angles become isotropic
- LEG 1: Fraction $(1-p_1)$ from leg 2 precipitate
- LEG 2: Fraction $(1-p_2)$ from leg 1 precipitate
- All pitch angles become isotropic

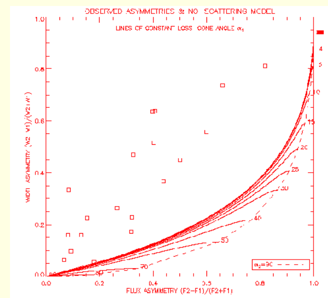
CYCLE #2,3,...
- Trapped electrons continue to bounce
- No more electrons can precipitate

Fluence ratio: $q_1/q_2 = (1-p_1) / \{1-p_2+p_1-p_2\}$
$= (1-\mu_1)/(1-\mu_2+\mu_1-\mu_2)$

MODEL 1: NO PITCH ANGLE SCATTERING

The colored curves show model flux and width asymmetries for given loss-cone angles. The curves within the crescent region cover the entire space of loss cone angles α_1=0-90° and α_2=0-90°.

However, the observed asymmetries (squares) lie entirely outside the space given by possible loss cone angles. The observed flux asymmetries would have to be higher and/or the width asymmetries much lower to agree with the model.



MODEL 2: RAPID PITCH ANGLE SCATTERING

CYCLE #1: Similar to above, but pitch angles isotropize.

CYCLE #2,3,...
- Each cycle has electron total reduced by a factor p_1*p_2
- So the fluence is also reduced by p_1*p_2 from the preceding cycle
- Thus the fluence into each leg is a geometric series:

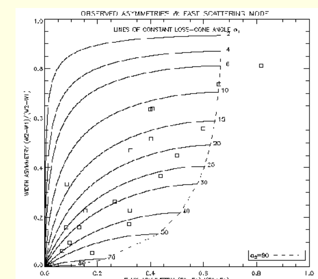
$q_1 = N (1-p_1)(1+p_2) \{1+(p_1p_2)+(p_1p_2)^2+(p_1p_2)^3 +...\}$
$q_2 = N (1-p_2)(1+p_1) \{1+(p_1p_2)+(p_1p_2)^2+(p_1p_2)^3 +...\}$

Fluence ratio: $q_1/q_2 = (1-p_1)(1+p_2) / (1-p_2)(1+p_1)$
$= (1-\mu_1)(3+\mu_2) / (1-\mu_2)(3+\mu_1)$

MODEL 2: RAPID PITCH ANGLE SCATTERING

The blue curves show flux and width asymmetries for given loss-cone angles α_1=0-90° and α_2=0-90° for the case of rapid isotropization of pitch angles

Now there are loss-cone angle contours that bracket the observations.



CONCLUSIONS

Observed footpoint area and flux asymmetries disagree with a model without pitch angle scattering.
A model with pitch angle scattering is consistent with the observations.
This suggests that pitch angle diffusion is important in flare loops.
Systematics in the determination of areas must be carefully considered.
Comparisons with magnetograms can check the sign of the width asymmetry.
Microwave observations can aid is estimating the degree of trapping, to check the consistency of our results.