University of Glasgow

Flare energy transport by Alfvenic waves

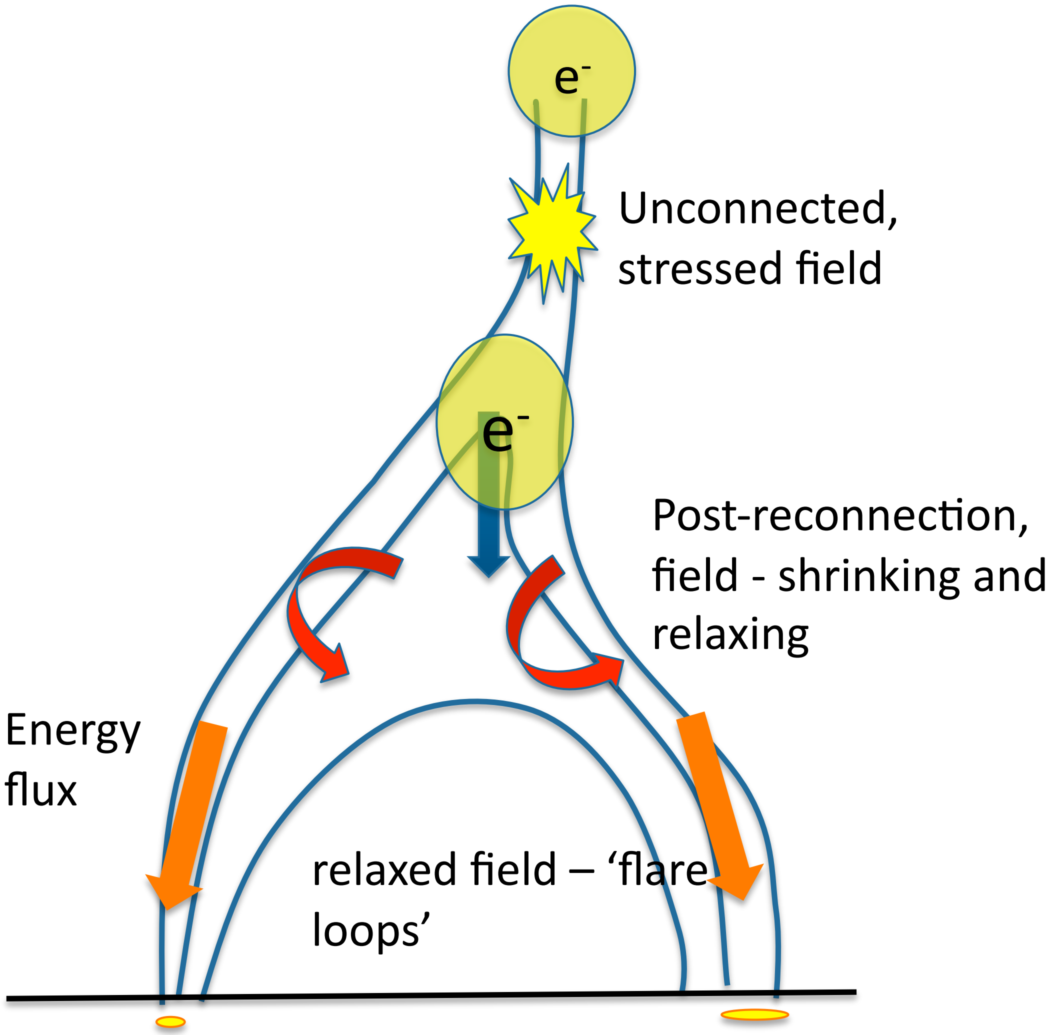
Lyndsay Fletcher

University of Glasgow

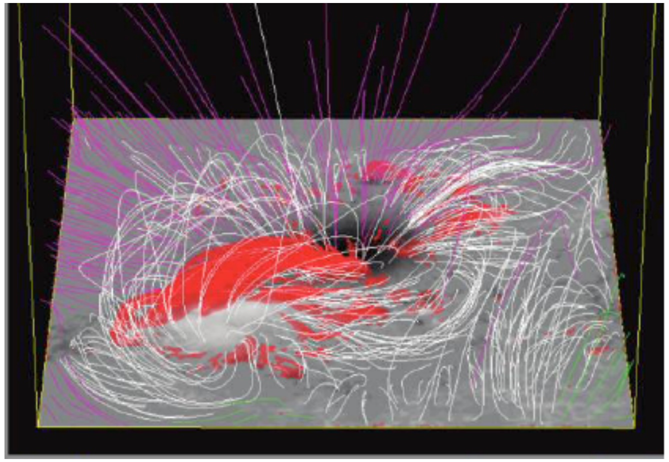
Overview:

- Flare cartoons
- Flare energy/flux/number requirements
- Production of MHD waves at reconnection regions
- Wave requirements
- Can wave reach chromosphere without damping?

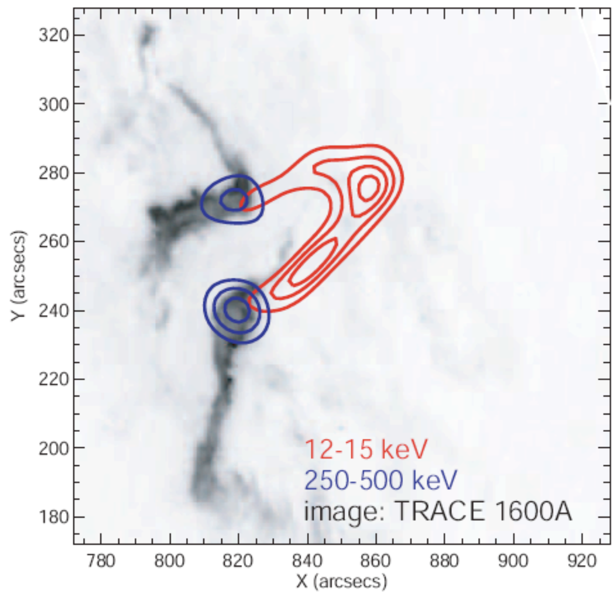
Flare basics



Footpoint emission (optical, UV, EUV, SXR, HXR)
Fast electrons/ions



Schrijver et al.

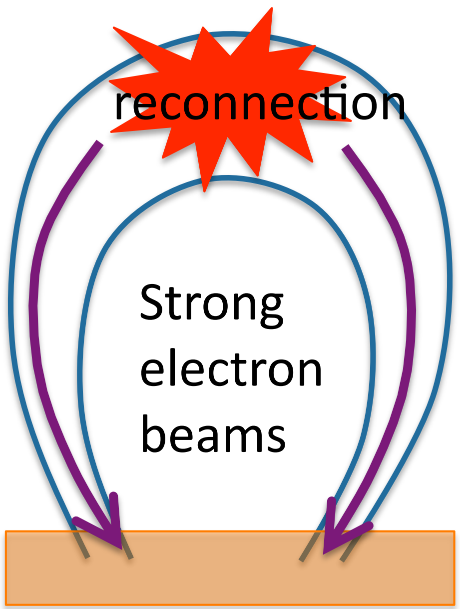


Krucker et al.

Energy transport and acceleration

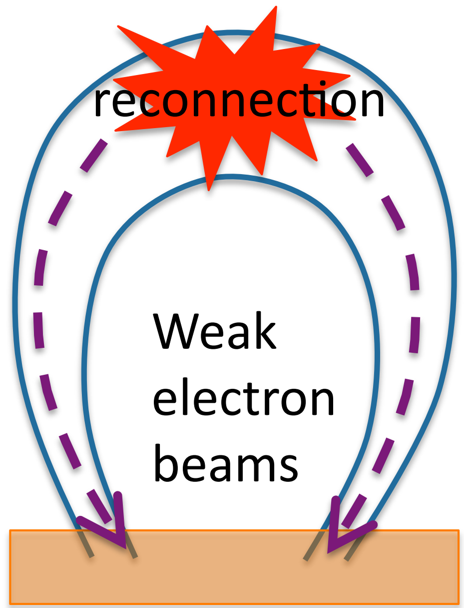
- **How does energy reach chromosphere**
- **Where are particles accelerated?**

Coronal electron acceleration (Standard model)



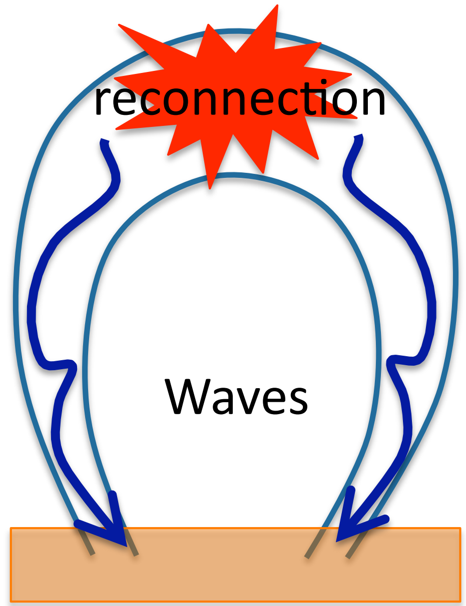
No chromospheric acceleration

Chromospheric re-acceleration (Brown et al. 2009)



Beam electrons re-accelerated in chromosphere

Chromospheric acceleration (Fletcher & Hudson 2008)



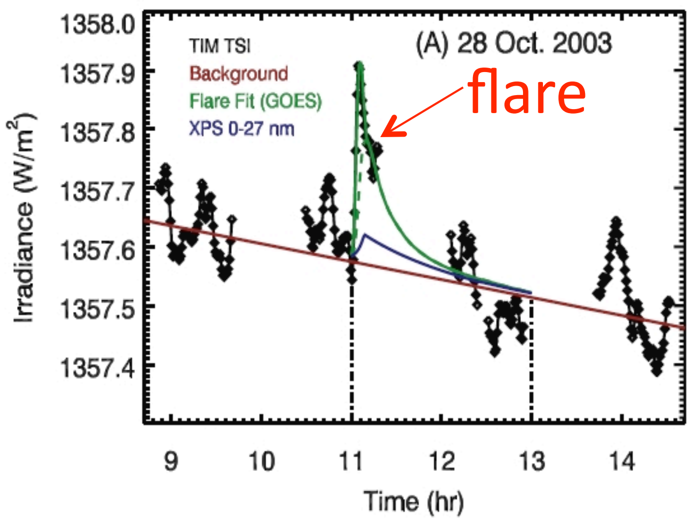
Chromospheric electrons locally accelerated

Flare energy requirements

Power directly measured in the optical can be up to 10^{29} erg s^{-1}

Power in fast electrons inferred from hard X-rays is around the same.

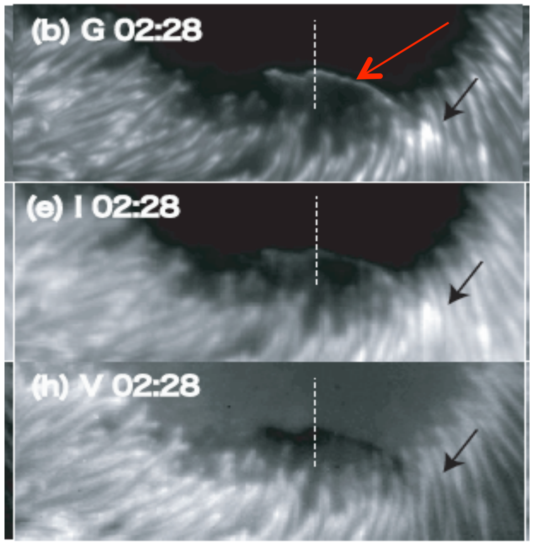
Flare total irradiance



Woods et al 2005

Flare energy = 6 x 10^{32} ergs over ~ 1000 sec.

Isobe et al 2007



G-band (CH molecule)

Fe (stokes I)

Fe (Stokes V)

Source FWHM = 5 x 10^7 cm

Flare energy radiated from a small area: HXR footpoints $\approx 10^{17}$ cm^2,

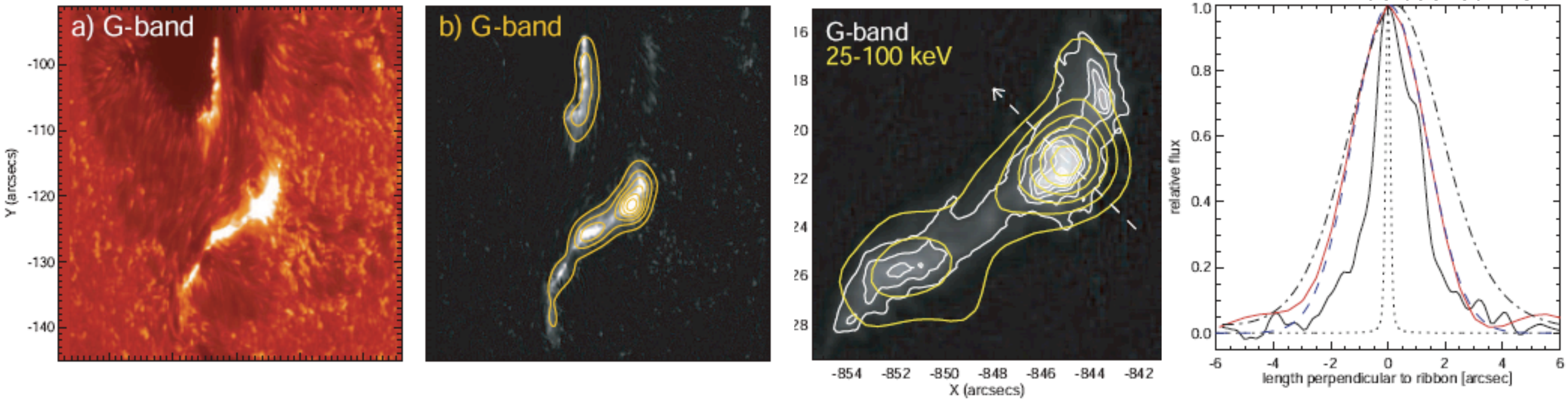
(WL footpoints can be smaller.)

Power per unit area ≈ 10^{11-12} erg cm^{-2}

Flare HXR footpoint sizes and beam stability

Recent analysis of a Hinode/RHESSI flare (Krucker et al 2010)

Red = source profile
Blue dashed = G1 PSF



RHESSI source FWHM is < 0.”2 larger than RHESSI G1 PSF.

$$\sigma_{FP}^2 = \sigma_{image}^2 - \sigma_{psf}^2 \quad \text{giving } \sigma_{FP} < 1.1''$$

- collisional thick target beam electron flux = 5×10^{19} el cm^{-2}s^{-1}
- collisional thick target beam energy flux = 3×10^{12} ergs cm^{-2} s^{-1}

Beam density is so high, that beam/return current system should be unstable to Bunemann instability

(Hoyng et al. 1974, Brown & Melrose, 1977; Vlahos & Papadopoulos 1979)

Flare energy transport by waves

A wave-based view:

Following coronal reconnection, field reorganises, generating MHD disturbances (fast, slow, Alfvén).

Alfvén wave pulse travels rapidly along B, carrying a Poynting flux. It is the agent for flare energy transport to the chromosphere.

So, need to have enough energy in the wave, traveling fast enough to explain footpoint simultaneity to ~0.1s, and undamped in corona

Wave energy transfer in flares has been proposed by several authors (e.g. Emslie & Sturrock 1982, Melrose 1993, Haerendel 2006, Fletcher & Hudson 2008, Haerendel 2009)

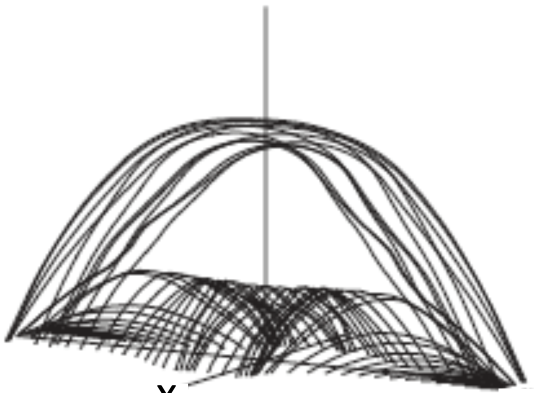
Birn et al. 3D simulations

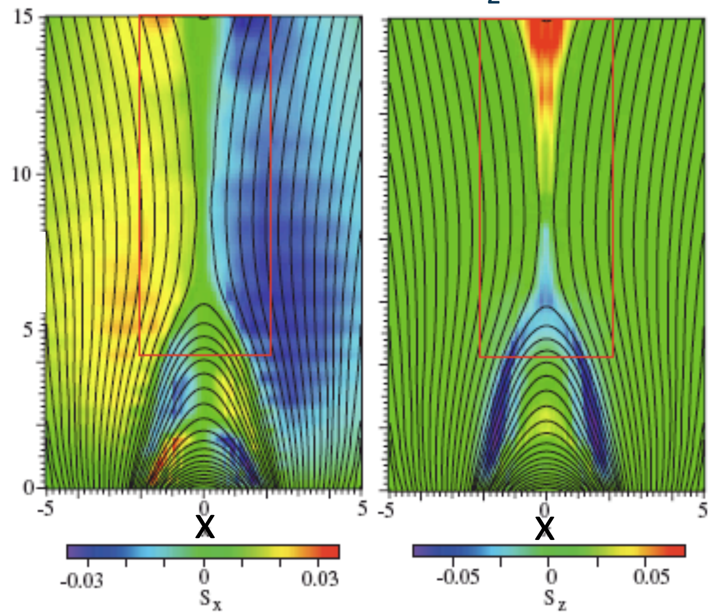
Birn et al. (2009) - 3D MHD simulations to study energy transport away from reconnection regions: Poynting flux, enthalpy flux, KE flux.

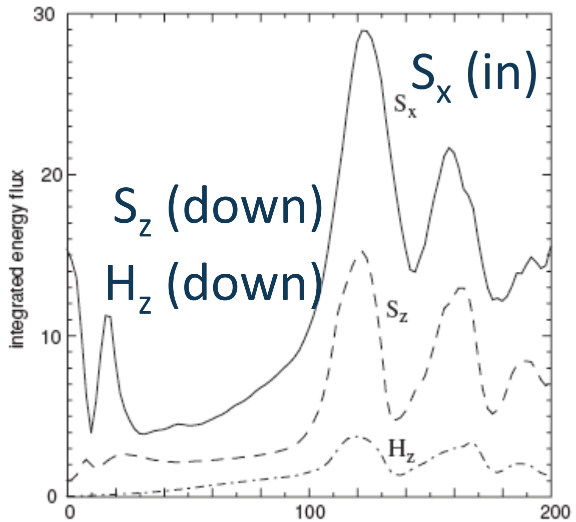
Initial condition; 3D sheared arcade model of Birn et al (2003), localised finite η, low β plasma ($\beta \sim 0.01$)

<u>Conclusion</u>: Dominant energy transfer at reconnection region is redirection of Poynting Flux mostly into downwards Poynting flux.

Initial stage of plasmoid ejection

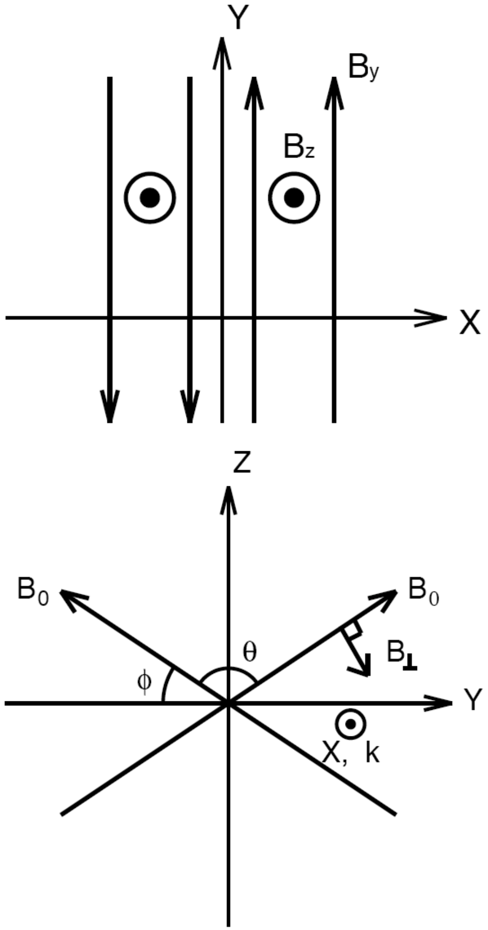




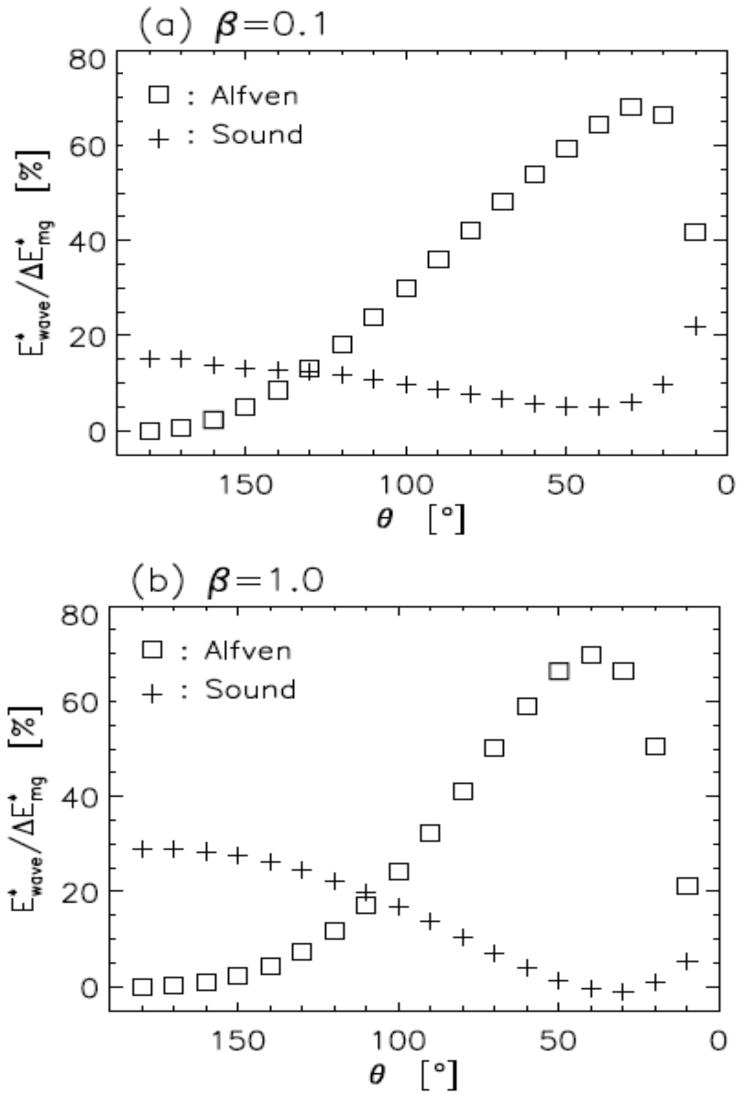


Kigure et al., 2.5 D simulations

2.5 D MHD simulations, localised resistivity, periodic boundaries



Initial configuration



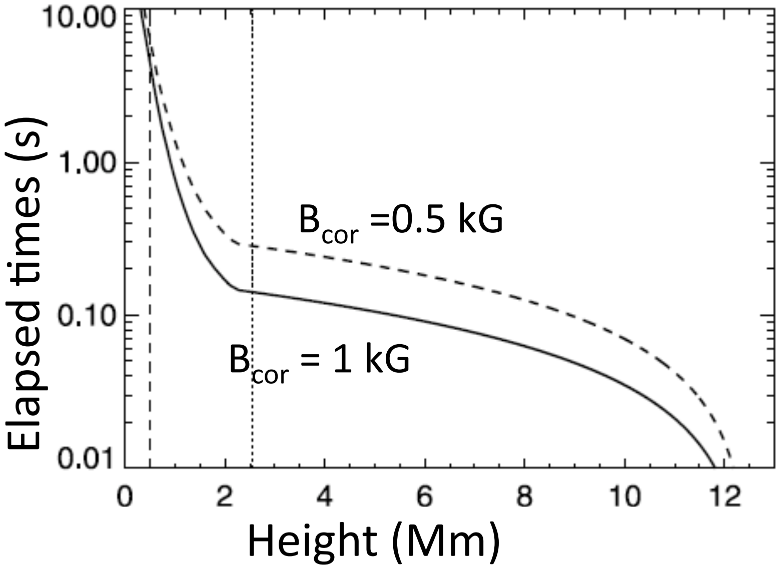
Percentage of magnetic energy released as by reconnection as Alfven/sound waves, as function of crossing angle

θ= 180 corresponds to no B_z, so no Alfven mode

Kigure et al. (2010)

Requirements for flare wave energy

Wave Poynting Flux $S = v_a \, \delta B^2 / 4\pi$



Observational requirements:

S up to 3 x 10^{12} erg cm^{-2} s^{-1}

Travel time ~ 0.1s to chrom. (Sakao 94)

Implications for field & perturbation:

e.g. dB/B ~ 5%, B_{cor} ~ 1kG, n_{cor} ~ 10^9 cm^{-3}
or B_{cor} ~ 700G, n_{cor} ~ 5.10^8 cm^{-3}

A coronal B of 700-1000 G?

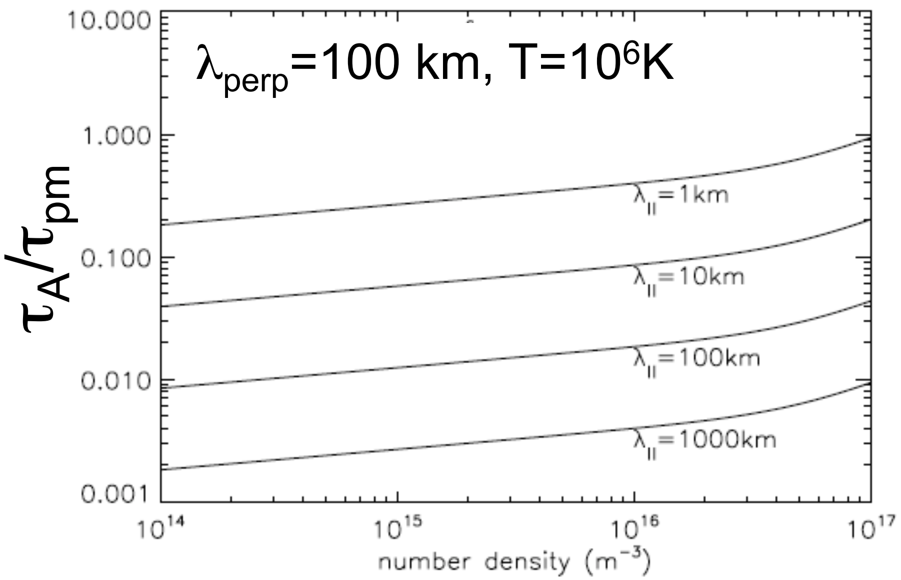
-characteristic of values determined from gyrosynchrotron emission at ~10,000km above the photosphere in active regions.
-Also found in extrapolations (Regnier et al)

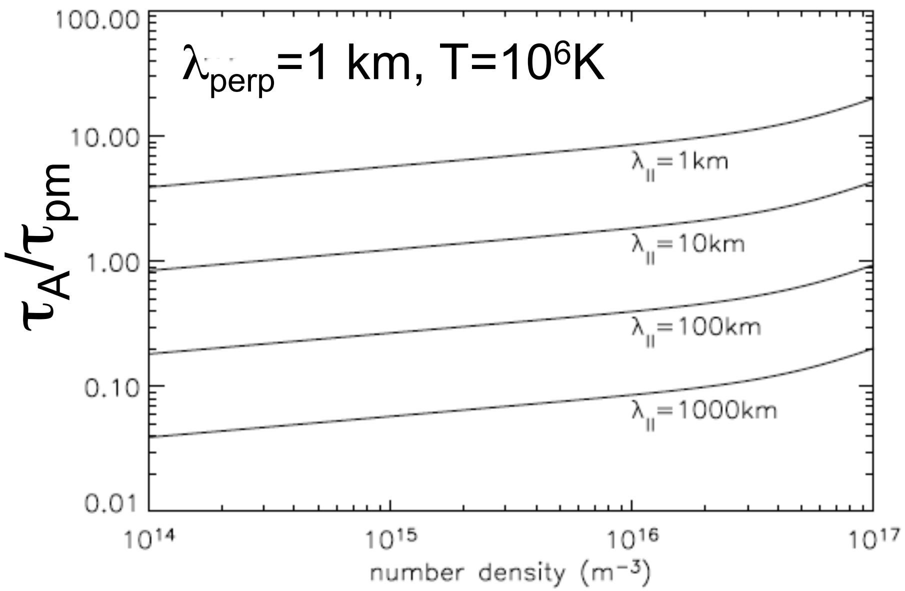
Alfven Wave (non-)Damping

Can the wave energy reach the chromosphere to make footpoints?
i.e., is it damped in the corona or not?

In MHD, to damp Alfven waves by phase mixing before wave reaches chromosphere need small scales of non-uniformity of field.

e.g., wave damps only if λ_{perp}=100 km and $\lambda_{||}$ < 1 km, or if λ_{perp}=1 km and $\lambda_{||}$ < 10 km. So if scales are larger, wave can reach chrom.

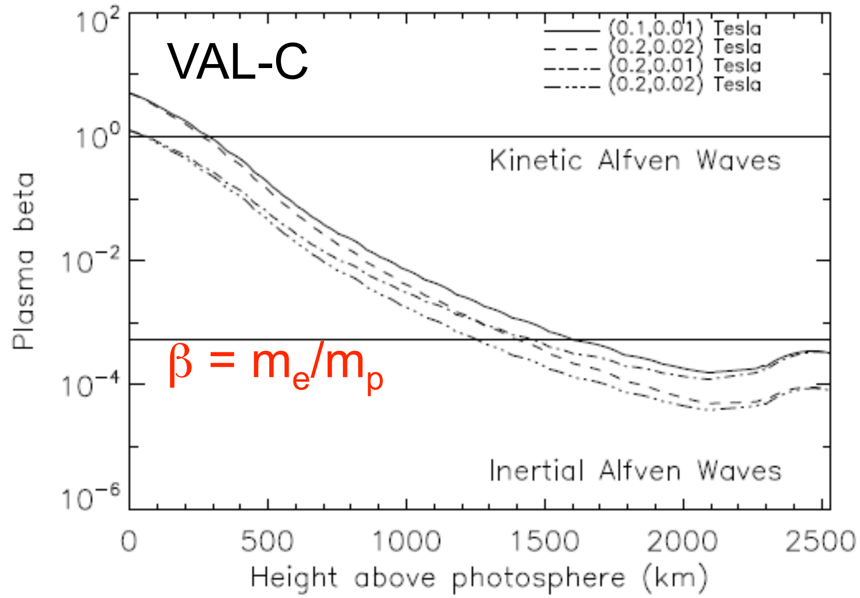




Wave (non-)damping in 'inertial' regime

In corona & upper chromosphere, $v_A \approx v_{th,e}$ i.e., $\beta \approx m_e/m_p$

The wave has an $E_{||}$ and can damp by electron acceleration (c.f. magnetospheric systems)



Case of $\beta << m_e/m_p$ ('inertial' regime)

$$E_{\|} = \left(\frac{k_{\|} k_{\perp} \lambda_e^2}{1 + k_{\perp}^2 \lambda_e^2} \right) E_{\perp}$$

if $k_{\perp}$ large - i.e. $\lambda_{\perp} \approx 3$m can damp by accelerating electrons to 10s of keV. But if scales are large, wave can reach chromosphere.

(McClements & Fletcher 2009)

Wave (non-)damping in kinetic regime

Case of $1 > \beta \geq m_e/m_p$ (kinetic regime):
Wave can damp for larger transverse scales – order of $\rho_s = c/\omega_{pi}$

Damping by Landau resonance (electron acceleration, Bian & Kontar 2010) – damping rate (s^{-1}) is:

$$\gamma = \frac{\sqrt{\pi}}{2}\frac{v_A^2}{v_{te}}k_{||}k_\perp^2\rho_s^2$$

(Bian & Kontar)

Sample values, assuming $\lambda_{||}$ = 100km

	T	n_e	B	τ_{cross}	Req'd $\lambda_\perp$
Corona	10^6 K	10^9 cm^{-3}	500 G	0.1s	$\lambda_\perp$ = 0.3 km
Chrom.	10^4 K	10^{11} cm^{-3}	1 kG	1s	$\lambda_\perp$ = 0.7 km

Damping by Landau resonance requires perpendicular scales of 100s of metres. But if scales are larger waves can reach chrom.

University of Glasgow

Conclusions

- With tightening observational constraints the coronal electron beam/ collisional thick target model is increasingly challenged

- Fletcher & Hudson (2008) propose to transport energy to chromosphere with Alfvenic perturbations, and accelerate electrons in the Alfvenic turbulence generate there.

- MHD simulations suggest that magnetic energy released as field reconfigures emerges in wave modes, primarily Alfven modes in an initially sheared field.

- Waves can reach chromosphere without significant damping, unless perpendicular scales of magnetic field are order of metres.

- Can wave energy arriving at chromosphere lead to heating and acceleration of electrons? – another question.