Momentum Conservation in Flares

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History of flare momentum studies

- "The importance of particle beam momentum in beam-heated models of solar flares," Brown & Craig 1984 (14 citations)
- "The unimportance of beam momentum in electronheated models of solar flares," McClymont & Canfield, 1984 (12 citations)
- "Momentum balance in four solar flares," Canfield et al., 1990 (49 citations)

Four Impulses

- Primary energy release in the corona (CME?)
- Chromospheric heating: evaporation and downward shock (Kostiuk & Pikel'ner 1974)
- Interruption of evaporative flow (new idea 1997)
- "Coronal rain" from cooling loops

Seismic Waves ("sunquakes")





Seismic wave:

- example of 28-Oct-03
- multiple radiant points
- HXR association
- now many examples
 (Kosovichev 2007)

Acoustic source:

- holographic imaging
- WLF (left) matches source
- "egression power" (right) easier to see in umbra (Source Lindsey & Donea 2008)

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Representative Parameters

Table 1. Representative parameters for an X-class flare with CME and quake

Property	Value
Total energy of flare	$10^{32} { m erg}$
Flare loop height	$1 \times 10^9 { m cm}$
Coronal density (preflare)	$1 \times 10^9 \ {\rm cm}^3$
Coronal field	$1 \times 10^3 {\rm G}$
Impulsive sub-burst duration	10 s
Impulsive phase duration	100 s
Number of sub-bursts	10
Impulsive sub-burst footpoint area	$3 \times 10^{17} \ \mathrm{cm}^2$
Evaporation speed	$5 \times 10^7 \mathrm{~cm~s^{-1}}$
Evaporated mass	$1 \times 10^{14} \mathrm{~g}$
Draining time	1000 s
CME mass	$1 \times 10^{15} \mathrm{~g}$
CME speed	$2 \times 10^8 \mathrm{~cm~s^{-1}}$
Seismic wave energy	$4 \times 10^{27} \text{ erg}$

Momentum conservation in primary energy release



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Momentum cartoon¹



¹Simplified view of vertical component

Momentum estimates¹

Label (Fig. 1)	Phenomenon	Mass g	Velocity km/s	$\Delta t \ s$	$\begin{array}{c} \text{Momentum}^i \\ \text{g cm s}^{-1} \end{array}$	Δp dyne/cm ²
$egin{array}{c} a \\ a \\ b \\ b' \end{array}$	Primary $(e^-)^{\alpha}$ Primary (waves) Evaporation flow Radiation ^{β}	3×10^{11} 10^{14}	c/3 c/3 500 c	10 10 30 10	3×10^{21} 1×10^{20} 5×10^{21} 1×10^{19}	$\begin{array}{c} 1\times10^{3}\\ 1\times10^{2}\\ 6\times10^{2}\\ 3\end{array}$
c d	CME Draining	10 ¹⁵ 10 ¹⁵	2000 10	$\begin{array}{c} 100 \\ {\sim} 10^4 \end{array}$	$\begin{array}{c} 2 \times 10^{23} \\ 2 \times 10^{21} \end{array}$	$\begin{array}{c} 7\times10^2\\ 0.07\end{array}$
	Seismic wave		6	20-50	1×10^{21}	

 Table 2. Vertical momentum components, model X-class flare with CME

 $^{\alpha}$ 20 keV

 $^{\beta}$ White-light flare

¹Scaled to X1

Inferences about momentum

- There is sufficient momentum in the coronal energy flux to explain the seismic wave
- CME acceleration predicts one photospheric impulse; evaporation two of opposite signs
- We don't know which particular mechanism couples best into the sunquake yet



Speculations

- Analysis of momentum transfer should help in understanding sunquakes (Shock? Backwarming? Lorentz force?)
- The initial flare energy release and coupling into CME flows, if any, require wave concepts (ExB/v_A)
- There are several immediate problems worth analysis (imho)

http://sprg.ssl.berkeley.edu/~hhudson/presentations/warwick.101119

Backup slides

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Flare energy

Short-lived

Small-scale¹



Woods et al 2004



Hudson et al 2006 ¹TRACE 0.5" pixels

The Lorentz force in context

"...an enormous amount of magnetic energy...seems to be annihilated during the flare. This should cause a subsequent relaxation of the entire field structure...moving large masses..." - Wolff 1972

"The magnetic force applied to the photosphere...1.2 x 10²² dyne..." - Anwar et al. 1993 (McClymont)

"Magnetic forces should be of particular significance... where the magnetic field is significantly inclined from vertical." - Donea & Lindsey 2005

"Our estimates suggest that the work done by Lorentz forces in this back reaction could supply enough energy to explain observations of flare-driven seismic waves."

- Hudson et al. 2008 ("Jerk")

Magnetic changes during flares

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-	Time																			

"Confusogram" legend: 10x10 2.5" pixels 240 minutes time base 500 G magnetic range

(Sudol & Harvey 2005)

Significance of low β

• In the active-region corona, except possibly for small inclusions, β is low. Thus gas pressure is explicitly unimportant.

• At low β all visible structures are mere tracers and can't be dynamically important.

• This also applies to the sunspot regions where seismic waves are launched.