data and methods in hard X-ray solar flares physics

michele piana

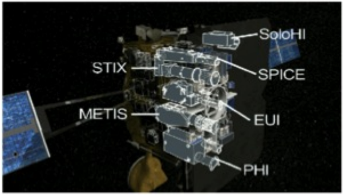
dipartimento di matematica, università di genova and cnr - spin, genova

2013 meeting of the italian community in solar and heliospheric physics
catania, september 4-6 2013

hard X-ray telescopes

rhessi (2002)

stix (2017)

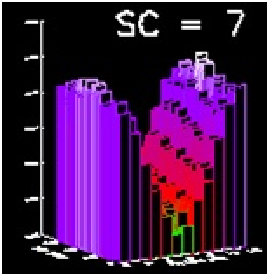


hard x-ray telescopes

- do not focus radiation
- modulate radiation
- record very indirect information on the observed physics
- need math to work

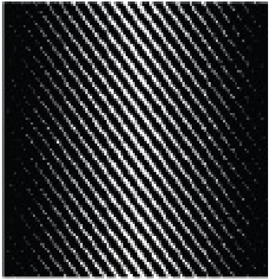
modulation

rhessi (2002)



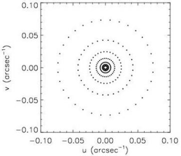
- rotation: yes
- hardware: grids (uniform)
- processing: data stacking

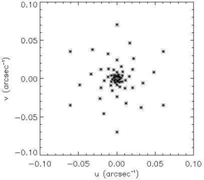
stix (2017)

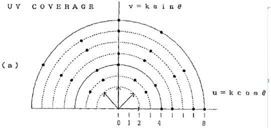


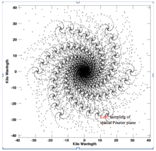
- rotation: no
- hardware: grids (moire patterns)
- processing: numerical integration

visibilities









visibilities:

$$V(u_j, v_j; \epsilon) = \int\int I(x, y; \epsilon) e^{2\pi i(u_j x + v_j y)} dxdy \quad j = 1, \ldots, M$$

imaging from visibilities

difficult issues:

- visibility generation from measured counts (as a function of time and energy)
- image reconstruction
- image interpretation: electron maps

HESPE

FP7 cooperation project 'high energy solar physics data in europe (HESPE)'

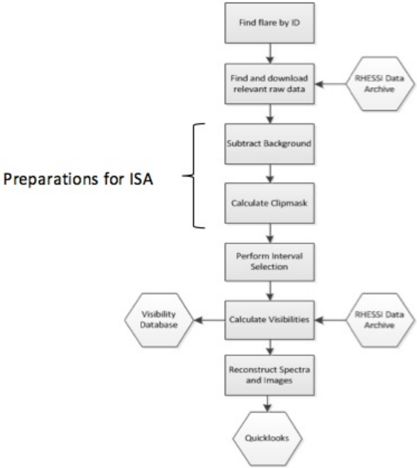
HESPE crew:

- DIMA-UNIGE (coordinator)
- fachhochschule nordwestschweiz
- university of glasgow
- universitaet graz
- observatoire de paris
- SSL berkeley
- NASA GSFC
- CNR - SPIN

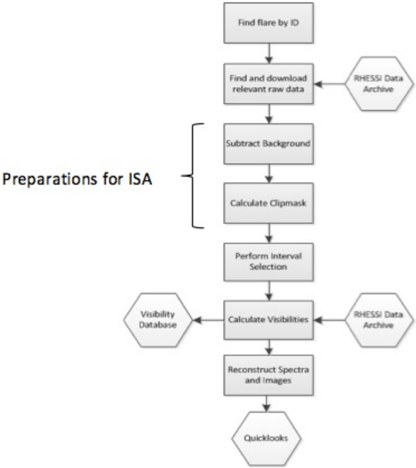
HESPE goals:

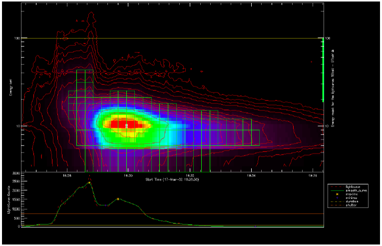
- automatic generation of optimized visibilities
- computational corpus of spectroscopy, imaging and imaging spectroscopy methods
- interpretation in the framework of advanced flare models

interval selection algorithm



interval selection algorithm





imaging methods

- uv_smooth: interpolation in the frequency plane + extrapolation based on soft-thresholding and positivity (massone a m, emslie a g, hurford g j, prato m, kontar e p and piana m, *astrophysical journal*, 2009)
- back projection (non-uniform weights, tapering) (giordano s, massone a m and emslie a g, *astronomy and astrophysics*, in preparation)
- visibility-based CLEAN: standard CLEAN + polar/tapered back-projection (giordano s, massone a m and emslie a g, *astronomy and astrophysics*, in preparation)
- bayesian filtering of visibilities: particle filter with smoothing along the time/energy direction (sorrentino a, massone a m and schwartz r, *astronomy and astrophysics*, in preparation)
- sequential monte carlo algorithm: regularized convergence to the posterior distribution at a fixed time/energy interval (sorrentino a, massone a m and schwartz r, *astronomy and astrophysics*, in preparation)

electron maps - 1

(piana m, massone a m, hurford g j, prato m, emslie a g, kontar e p and schwartz r a *astrophysical journal*, 2007)

two nested inverse problems:

1. instrumental: from visibilities to photon flux (fourier inversion problem from limited data)
2. physical: from local photon flux to electron flux (solution of the bremsstrahlung equation)

electron maps - 1

(piana m, massone a m, hurford g j, prato m, emslie a g, kontar e p and schwartz r a *astrophysical journal*, 2007)

two nested inverse problems:

1. instrumental: from visibilities to photon flux (fourier inversion problem from limited data)
2. physical: from local photon flux to electron flux (solution of the bremsstrahlung equation)

$$F(x, y; E) \to \mathcal{A}(F(x, y; E)) = I(x, y; \epsilon) \to \mathcal{B}(I(x, y; \epsilon)) = V(u, v; \epsilon)$$

$$V(u, v; \epsilon) = \mathcal{B}(\mathcal{A}(F(x, y; E)))$$

electron maps - 1

(piana m, massone a m, hurford g j, prato m, emslie a g, kontar e p and schwartz r a *astrophysical journal*, 2007)

two nested inverse problems:

1. instrumental: from visibilities to photon flux (fourier inversion problem from limited data)
2. physical: from local photon flux to electron flux (solution of the bremsstrahlung equation)

$$F(x, y; E) \to \mathcal{A}(F(x, y; E)) = I(x, y; \epsilon) \to \mathcal{B}(I(x, y; \epsilon)) = V(u, v; \epsilon)$$

$$V(u, v; \epsilon) = \mathcal{B}(\mathcal{A}(F(x, y; E)))$$

theorem:

$$[\mathcal{B}, \mathcal{A}] = 0$$

proof (hint): apply fubini's theorem

electron maps -2

(piana and massone, *solar physics*, 2013)

reconstruction algorithm for electron maps

part 1:

1. fix a (u, v) point
2. construct the photon visibility spectrum $V(u, v; \epsilon)$
3. define the electron visibility spectrum $W(u, v; E) = \int \int F(x, y; E) e^{2\pi i(ux+vy)} dxdy$
4. solve the spectral problem $V = \mathcal{A} W$
5. back to 1.

electron maps -2

(piana and massone, *solar physics*, 2013)

reconstruction algorithm for electron maps

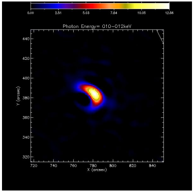
part 1:

1. fix a (u, v) point
2. construct the photon visibility spectrum $V(u, v; \epsilon)$
3. define the electron visibility spectrum $W(u, v; E) = \int \int F(x, y; E) e^{2\pi i(ux+vy)} dxdy$
4. solve the spectral problem $V = \mathcal{A}W$
5. back to 1.

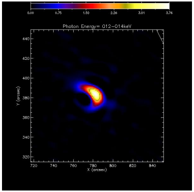
part 2:

1. fix an electron energy E
2. construct the set $W(u, v; E)$ for all (u, v) points
3. solve the image reconstruction problem $W = \mathcal{B}F$
4. back to 1.

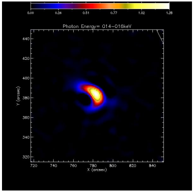
photon maps



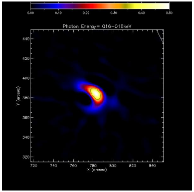
10-12 keV



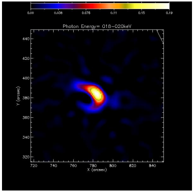
12-14 keV



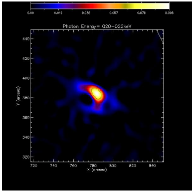
14-16 keV



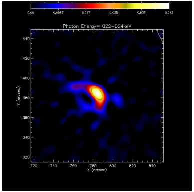
16-18 keV



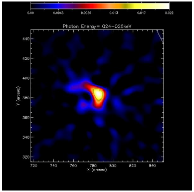
18-20 keV



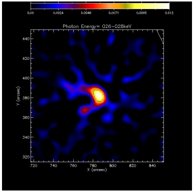
20-22 keV



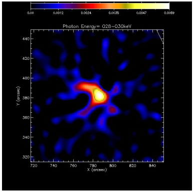
22-24 keV



24-26 keV

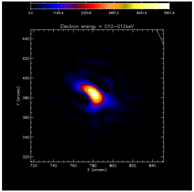


26-28 keV

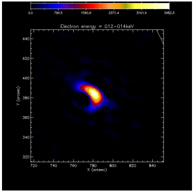


28-30 keV

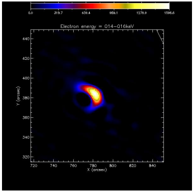
electron maps



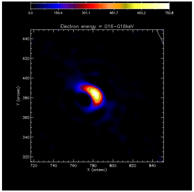
10-12 keV



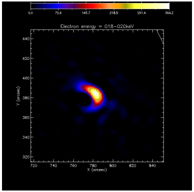
12-14 keV



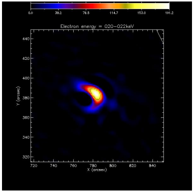
14-16 keV



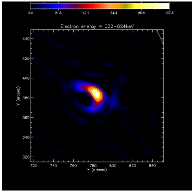
16-18 keV



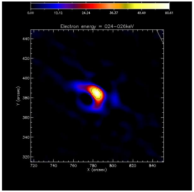
18-20 keV



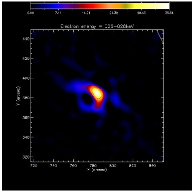
20-22 keV



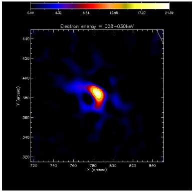
22-24 keV



24-26 keV

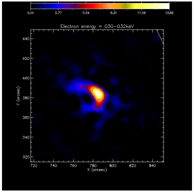


26-28 keV

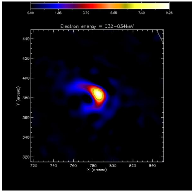


28-30 keV

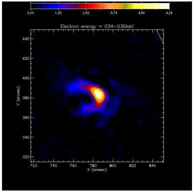
electron maps (continued)



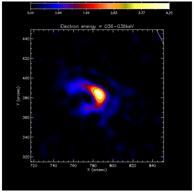
30-32 keV



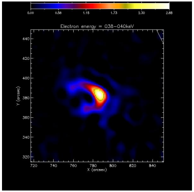
32-34 keV



34-36 keV

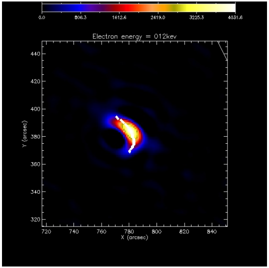


36-38 keV



38-40 keV

continuity equation - 1



$$F(s,E) = F_+(s,E) + F_-(s,E)$$

$$\pm\frac{\partial}{\partial s}F_\pm(s,E) - \frac{\partial}{\partial E}\left(-\frac{dE}{ds}F_\pm(s,E)\right) = S(s,E)$$

the physics is in:

- the energy loss rate $\frac{dE}{ds}(n,T)$
- the injection term $S(s,E)$

continuity equation - 2

the electron continuity equation hides a hyperbolic nature: (pinamonti, torre, codispoti, massone and piana, *astrophysical journal*, in preparation)

some definitions:

$$\Phi_{\pm}(s,E) := -\frac{dE}{ds}F_{\pm}(s,E) \qquad A(s,E) := -\frac{dE}{ds}\frac{S(s,E)}{\sqrt{2mE}}$$

$$x(E) := x_0 - \int_{E_0}^{E} \frac{1}{\frac{dE}{ds}}dE' \qquad \Phi(s,E) = \Phi_{+}(s,E) + \Phi_{-}(s,E)$$

wave equation for the electron maps:

$$-\frac{\partial^2}{\partial x^2}\Phi(s,E(x)) + \frac{\partial^2}{\partial s^2}\Phi(s,E(x)) = 2\frac{\partial}{\partial x}A(s,(E(x))$$

initial conditions:

$$\lim_{x\to\infty}\Phi(x,s\pm x) = 0 \qquad \lim_{x\to\infty}\partial_x\Phi(x,s\pm x) = 0 \qquad \forall s$$

green function

$$\Box G(s, s'; x, x') = -\partial_x \delta(s, s'; x, x')$$

two solutions:

$$G(s, s'; x, x') = \delta_{\pm}(x - x' \mp |s - s'|)$$

but just one (δ_-) is coherent with the initial conditions. therefore:

$$\Phi(s, E(x)) = (\delta_- * 2A)(x, s)$$

$$F(s, E(x)) = \sqrt{\frac{2}{m}} \frac{1}{\frac{dE}{ds}} \int \delta(x - x' + |s - s'|) \frac{dE}{ds} \frac{S(s', E(x'))}{\sqrt{E(x')}} dx' ds'$$

lhs: measurements

rhs: models (for the energy loss rate and for the injection term)

model selection

example 1 (torre, pinamonti, emslie, guo, massone and piana, *astrophysical journal*, 2012): how hot and dense is the flaring target?

- spitzer's model for the energy loss term
- box function for the injection term

- density: $n = (2.0 \pm 0.1) \times 10^{11}$ cm^{-3}
- temperature: $T = (1.61 \pm 0.05)$ keV

model selection

example 1 (torre, pinamonti, emslie, guo, massone and piana, *astrophysical journal*, 2012): how hot and dense is the flaring target?

- spitzer's model for the energy loss term
- box function for the injection term

- density: $n = (2.0 \pm 0.1) \times 10^{11}$ cm^{-3}
- temperature: $T = (1.61 \pm 0.05)$ keV

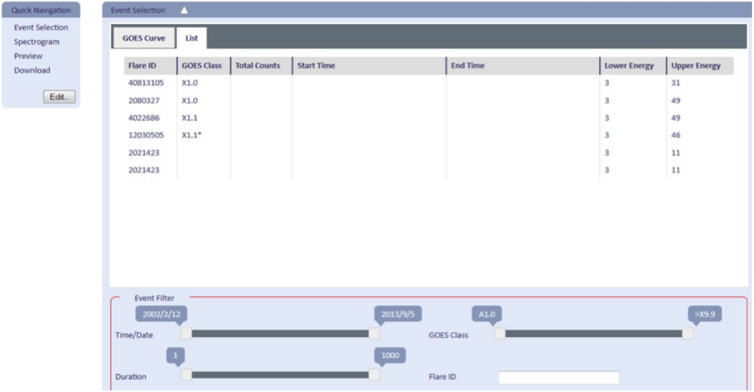
example 2 (codispoti, torre, piana and pinamonti, *astrophysical journal*, 2013): are there return currents balancing the charge equilibrium violation?

- the energy loss rate accounts for return currents
- box function for the injection term

15–Apr–2002

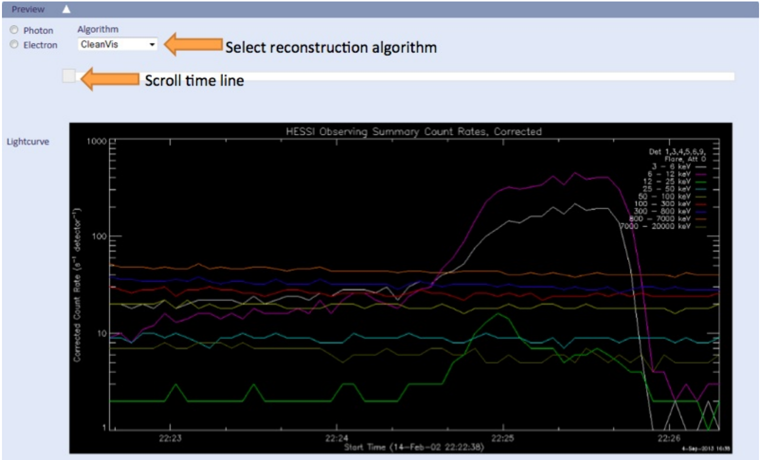
Time[UT]	Mod	$E_0[keV]$	$n[cm^{-3}]$	$h_s[cm^{-5}keV^{-1}s^{-1}]$	χ^2
00:03:00-00:06:00	Mod 1	7.7 ± 0.2	$(8.0 \pm 0.8) \times 10^{10}$	$(1.6 \pm 0.3) \times 10^{30}$	0.80
	Mod 2	2.5 ± 0.1	$(1.81 \pm 0.16) \times 10^{11}$	$(4.7 \pm 0.8) \times 10^{30}$	1.04
	Mod 3	7.9 ± 1.9	$(7.86 \pm 0.12) \times 10^{9}$	$(4.2 \pm 0.5) \times 10^{30}$	0.82
	Mod 4	0	$(3.4 \pm 0.3) \times 10^{10}$	$(9.52 \pm 1.19) \times 10^{30}$	3.58
00:06:00-00:09:00	Mod 1	8.2 ± 0.3	$(6.3 \pm 0.6) \times 10^{10}$	$(1.04 \pm 0.21) \times 10^{30}$	0.33
	Mod 2	3.2 ± 0.1	$(1.42 \pm 0.11) \times 10^{11}$	$(3.3 \pm 0.5) \times 10^{30}$	0.55
	Mod 3	3.5 ± 0.8	$(6.99 \pm 0.12) \times 10^{9}$	$(3.5 \pm 0.4) \times 10^{30}$	0.43
	Mod 4	0	$(2.30 \pm 0.19) \times 10^{10}$	$(7.2 \pm 0.8) \times 10^{30}$	2.45
00:09:00-00:12:00	Mod 1	4.9 ± 1.2	$(1.6 \pm 0.3) \times 10^{10}$	$(5.1 \pm 2.3) \times 10^{28}$	0.65
	Mod 2	3.2 ± 0.6	$(4.5 \pm 0.7) \times 10^{10}$	$(3.45 \pm 1.11) \times 10^{29}$	0.70
	Mod 3	0.2 ± 0.1	$(4.47 \pm 0.11) \times 10^{9}$	$(1.00 \pm 0.24) \times 10^{30}$	0.79
	Mod 4	0	$(6.2 \pm 0.5) \times 10^{9}$	$(1.4 \pm 0.3) \times 10^{30}$	1.21

HESPE database - 1

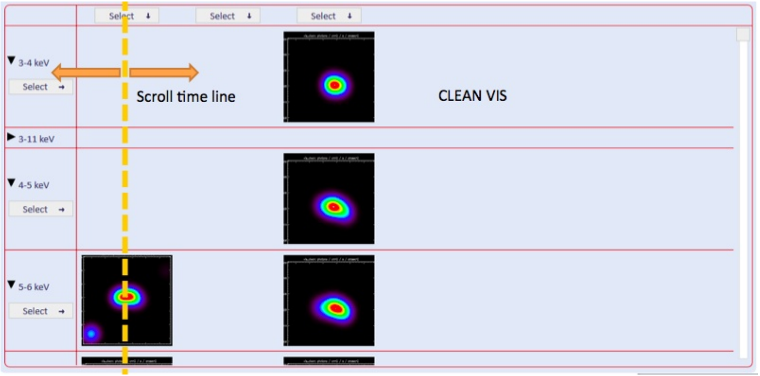


Flare ID	GOES Class	Total Counts	Start Time	End Time	Lower Energy	Upper Energy
40813105	X1.0				3	31
2080327	X1.0				3	49
4022686	X1.1				3	49
12030505	X1.1*				3	46
2021423					3	11
2021423					3	11

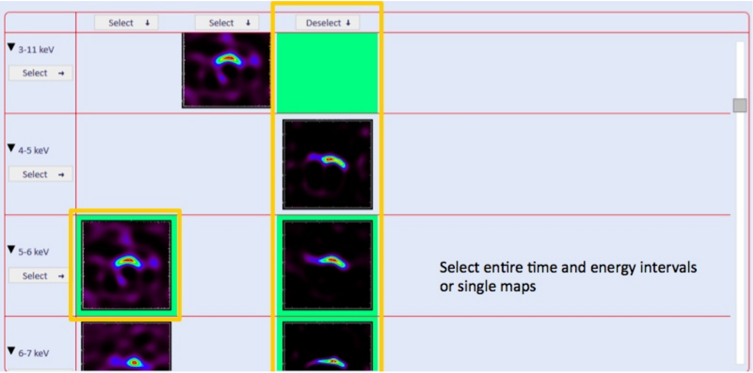
HESPE database - 2



HESPE database - 3



HESPE database - 4



HESPE database - 5