The effect of wave-particle interactions and turbulence on solar flare electron transport and X-ray spectrum

Iain G. Hannah, Eduard Kontar & Hamish Reid
Department of Physics & Astronomy, University of Glasgow

Abstract

RHESSI solar flare hard X-ray (HXR) observations sometimes cannot be adequately interpreted in terms of purely collisional electron transport. We instead present numerical simulations where we consider Langmuir waves generated by the energetic electron-beam. We demonstrate how the wave-particle interactions in the presence of turbulent density perturbations affect the high frequency Langmuir waves and in turn, the flare accelerated electron distribution. The consequences of this self-consistent treatment are discussed for the observable X-ray spectrum.

Electron Transport

We consider the self-consistent 1D ($v_\parallel > v_\perp$) transport of a power law of accelerated electrons $f(v,x,t)$ from the corona to chromosphere using the equations of quasi-linear relaxation[1,2,3,4,5,6]. This allows us include the response of the background plasma in the form of Langmuir waves of spectral energy density $W(v,x,t)$. We numerically solve the following equations on a grid of v, x evolving the system forward in time t:

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} = \frac{4\pi^2 e^2}{m^2}\frac{\partial}{\partial v}\left(\frac{W}{v}\frac{\partial f}{\partial v}\right) + \gamma_{C_F}\frac{\partial}{\partial v}\left(\frac{f}{v^2}\right)$$

$$\frac{\partial W}{\partial t} + \frac{3v_T^2}{v}\frac{\partial W}{\partial x} + \frac{v^2}{L}\frac{\partial W}{\partial v} = \left(\frac{\pi\omega_p}{n}v^2\frac{\partial f}{\partial v} - \gamma_{C_W} - 2\gamma_L\right)W + Sf$$

The 1st two terms on the LHS describe the resonant wave-particle interaction $\omega_p = kv$. We also include coulomb collisions γ_C, Landau damping γ_L, spontaneous emission S, the effect of the background density gradient $\partial W/\partial v$, where $L^{-1} = \omega_p/(\partial\omega_p/\partial v)$. See[6] or Hamish Reid's talk. We start with a velocity power-law ($\alpha=8$) of electrons flat below $E_B = 7\,\mathrm{keV}$, Gaussian spatial distribution and $n_B = 10^7\,\mathrm{cm}^{-3}$. Initial wave distribution is $W \approx 0$.

$$f(v,x,t=0) \propto n_B v^{-\alpha}\exp\left(-\frac{x^2}{d^2}\right) \quad if\, v \geq v_B$$

Turbulent background density

The background plasma changes with position and is a combination of two density profiles (see Figure 1)

1. $n_0(x)$: Constant coronal density increasing sharply at the transition region and through the chromosphere
2. $\Delta n(x)$: Perturbations ($N=10^3$) of the background density profile randomly drawn from a $\beta=5/3$ Kolmogorov-type power density spectrum with $\Delta n/n \approx 1\%$ and wavelengths $10^4 < \lambda < 10^7$ cm

$$n(x) = n_0(x)\left[1 + C\sum_{n=1}^{N}{\lambda_n}^{\beta/2}\sin\left(2\pi x/\lambda_n + \phi_n\right)\right]$$

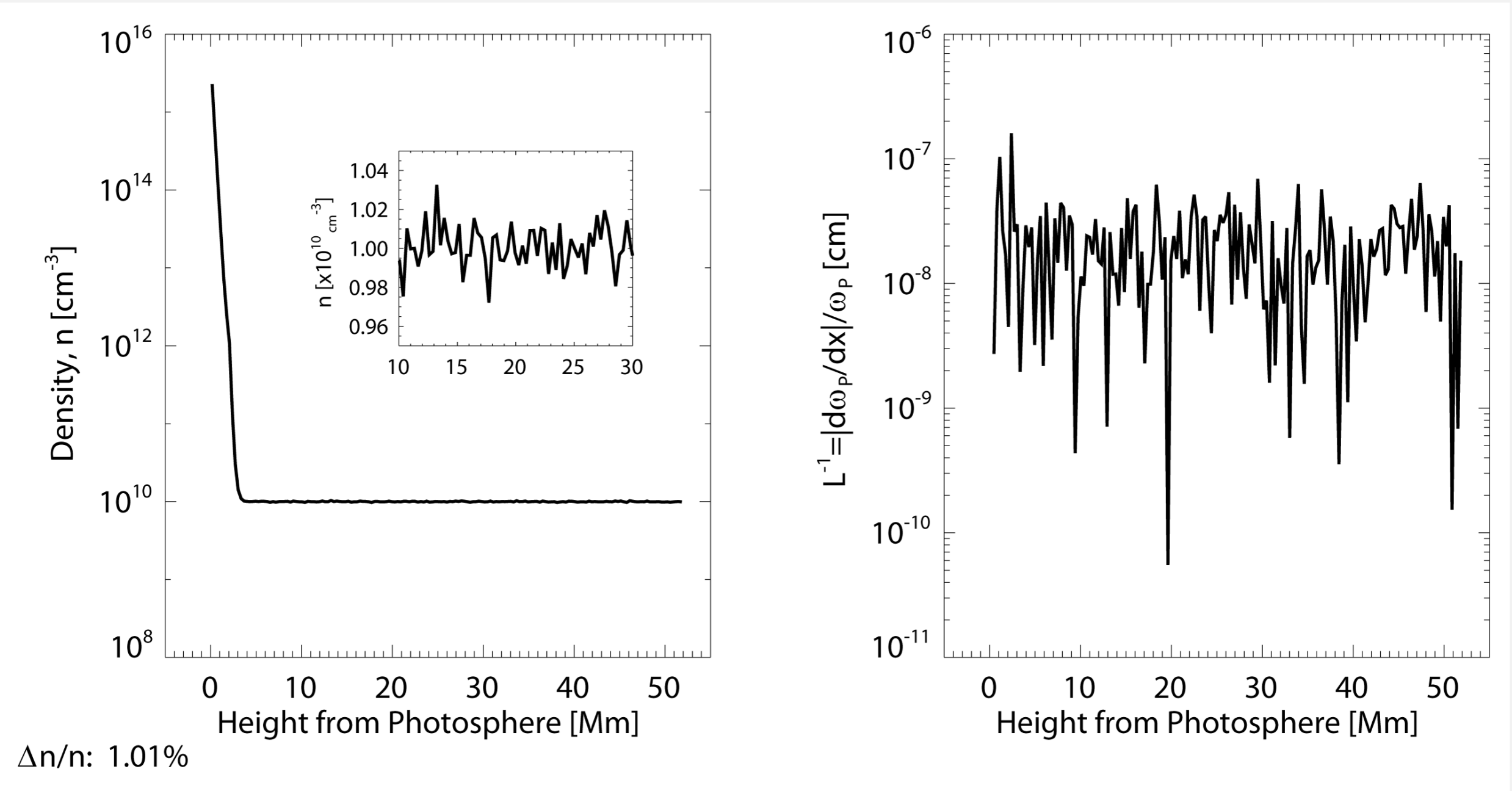

Figure 1: *Background density profile* ***n(x)*** *(left) and measure of the changing density gradient* ***L^{-1}(x)*** *(right),*

References
[1] Vedenov, A. A., & Velikhov, E. P. 1963, Sov. J. Exp. Th Phys., 16, 682
[2] Drummond, W. E., & Pines, D. 1964, Ann. Phys., 28, 478
[3] Ryutov, D. D. 1969, Sov. J. Exp. Theor. Phys.,
[4] Hamilton, R. J., & Petrosian, V. 1987, ApJ, 321, 721
[5] Kontar, E. P. 2001a, Sol. Phys., 202, 131
[6] Hannah, I.G., Kontar, E. P. & Sirenko, O. K., 2009, ApJ, 707, L45-L50
[7] Koch, H. W. & Motz, J. W. 1959, Reviews of Modern Physics, 31, 920
[8] Haug, E. 1997, A&A, 326, 417

Simulation Results

With the same initial conditions we run three simulations:

1. **No waves (e⁻ and Coulomb collisions)**
2. **No dW/dv (dn/dx there but no effect)**
3. **All terms**

Ran until simulated time is 1 sec and all the electrons / waves have velocities below our lower limit (LHS of grid), see Figure 2.

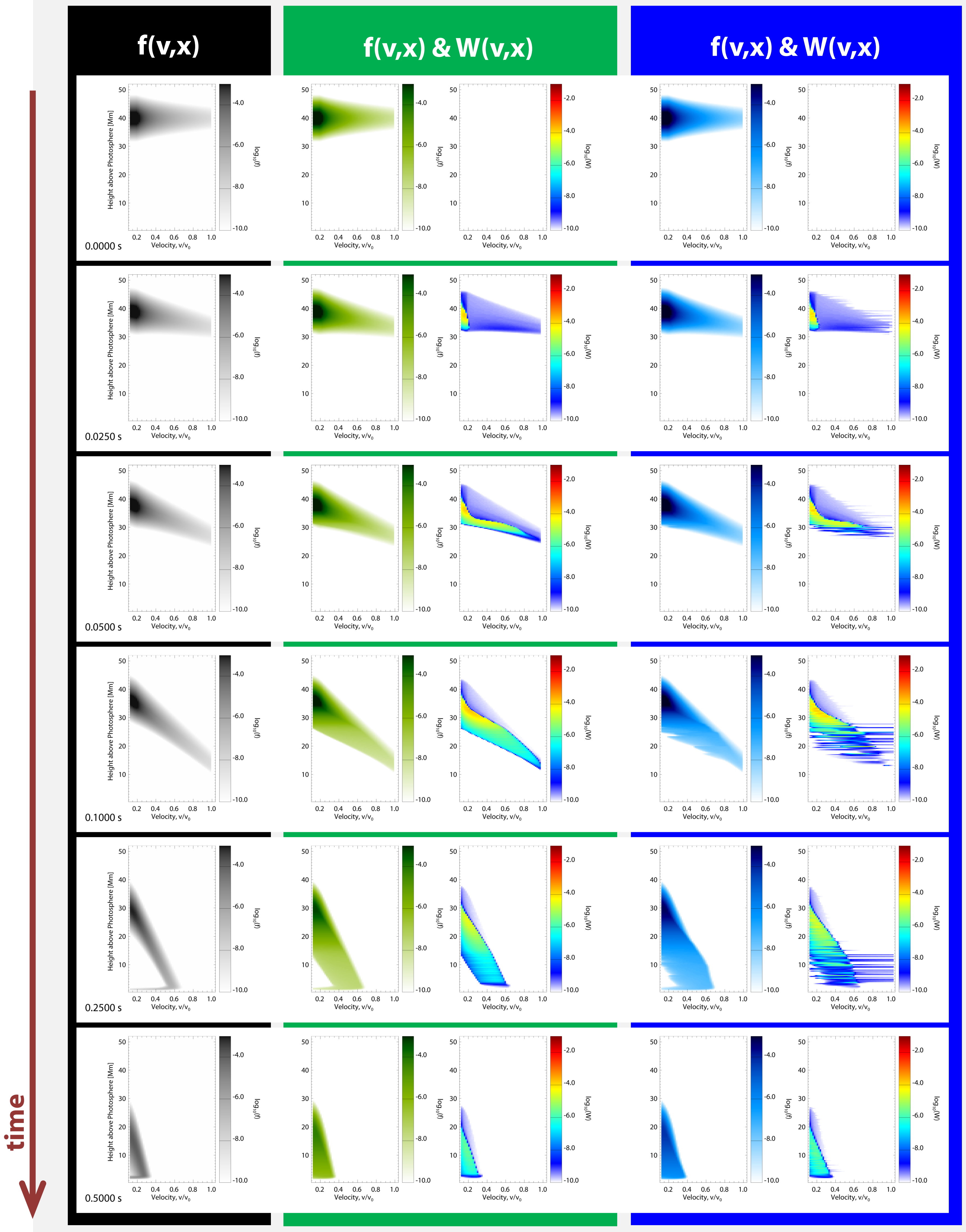

Figure 2: *The electron distribution f(v,x) and spectral energy density W(v,x) as a function of time (increasing top to bottom) for the 3 simulations.*

The time & spatially integrated X-ray spectra for each simulation (Figure 3) is calculated from $f(v,x,t)$ using the bremsstrahlung cross-section[7,8] $Q(\epsilon,E)$ and estimate of beam area A

$$I(\epsilon) = \frac{A}{4\pi R^2}\sum_{x=x_1}^{x_2}\sum_{t=0}^{t_f}\left[n(x)\frac{f(v,x,t)}{m_e}Q(\epsilon,E)\right]dE\,dx\,dt$$

Conclusions

The background density perturbations do have a visible effect on the X-ray spectrum. There are several aspects that we still need to investigate:

- A more "realistic" coronal turbulence: $\Delta n, \lambda$?
- Different e⁻ distribution: n_B, α, $f(t)$?
- X-ray spectra of footpoints vs coronal source?
- Structure of background density $n_0(x)$?

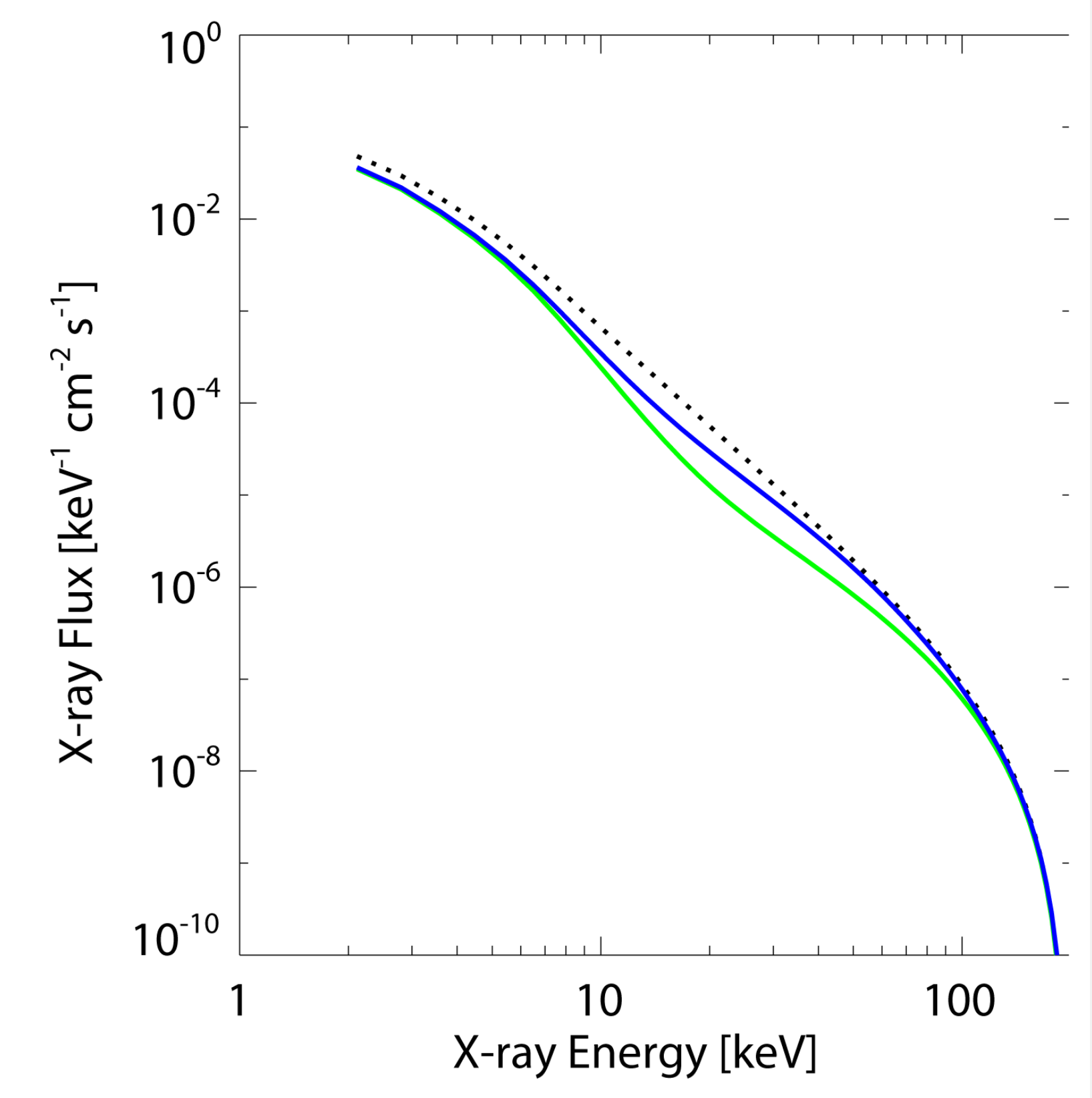

Figure 3 *Time and spatially integrated X-ray spectrum for the 3 simulations, shown in Figure 2.*

contact info: iain@astro.gla.ac.uk