Instability models for ELMAG

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1 Introduction

As high energy photons emitted from blazars propagate through space, it interacts with the background photon fields of the universe, which by inverse Compton scattering causes a cascading process. It has been proposed that plasma instabilities may lead to energy loss during the cascade, such that electrons/positrons could be cooled down before inverse Compton scattering could occur.[1] As such, the observed spectra would be altered from what one may expect to see if no such energy loss had occurred, and so taking these losses into account may provide further understanding of the cascade process. The goal of this project has been to implement various plasma instability models suggested in the literature into the Fortran program ELMAG.[2] Essentially, this has involved reproducing the results of Batista et al., where different models were gathered and implemented in their own program.[3]

2 Project work

The first step of the project was getting familiar with the background material (the article by Batista et al.) and the ELMAG source code, in addition to learning the programming language Fortran 90. Next was implementing the models presented by Batista et al. in Fortran, and to verify that the results in figure 1 matched the results found by Batista et al. After getting the code for the different models to work, it was implemented into the ELMAG source code, updating the energy loss function `eloss()` and adding a new module and input file for the plasma instability parameters. Finally, the program was run several times while varying the parameters, producing different output spectra.

3 Results

3.1 Comparison of the energy loss

The energy dependence of the instability losses for the different models varies greatly, as can be seen in figure 1. The similarities in models A and D are apparent, seeing as they are mathematically alike except for some numerical differences.[3] A particular detail of interest is the discontinuity in model C, which had not been mentioned in the literature. Furthermore, the energy loss from model B is seen to be much lower than the other models, and in fact significantly lower than the interaction rate of the inverse Compton scattering itself. For this reason, apart from a comparison of all models in figures 1 and 2, model B has been dropped in later simulations.

The output spectra of the different models are shown in figure 2. Note in particular the behaviour of model C at the lower end of the spectrum. Also as previously stated, model B gives no apparent deviation from the case without any instability losses.

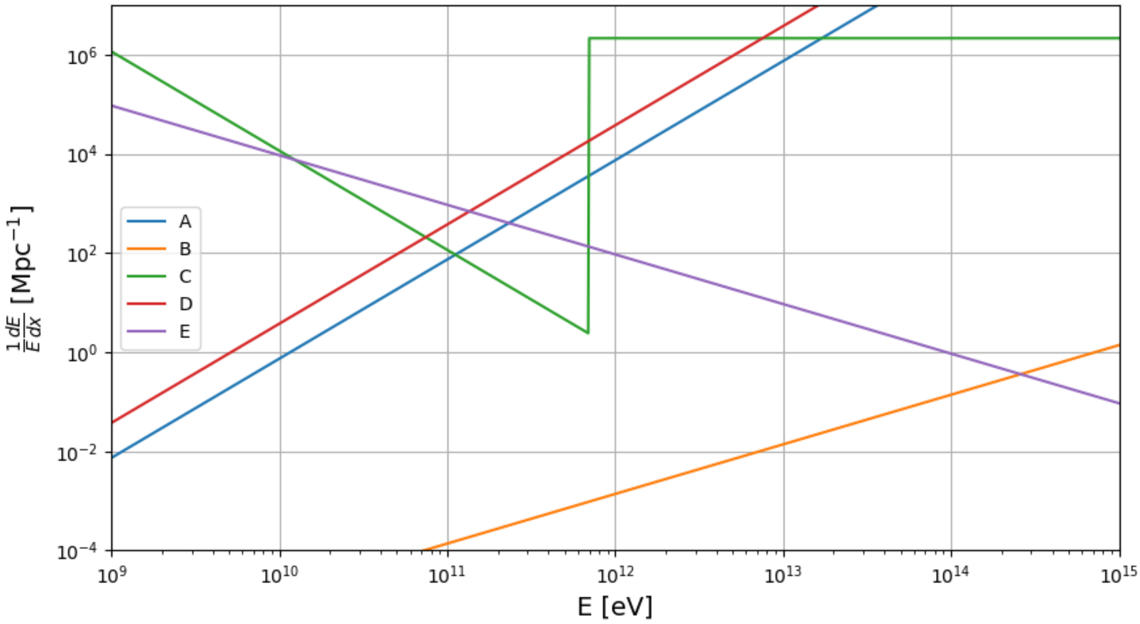

Figure 1: Comparison of energy losses for the different models using the spectral parameters $T_{\rm IGM} = 10^4$ K, $n_{\rm IGM} = 10^{-7}$ cm-3 and $\mathcal{L}_{\rm beam} = 10^{45}$ erg/s with no redshift. In model B, $10^{-0.05}$ Mpc is chosen as the co-moving distance to the source.

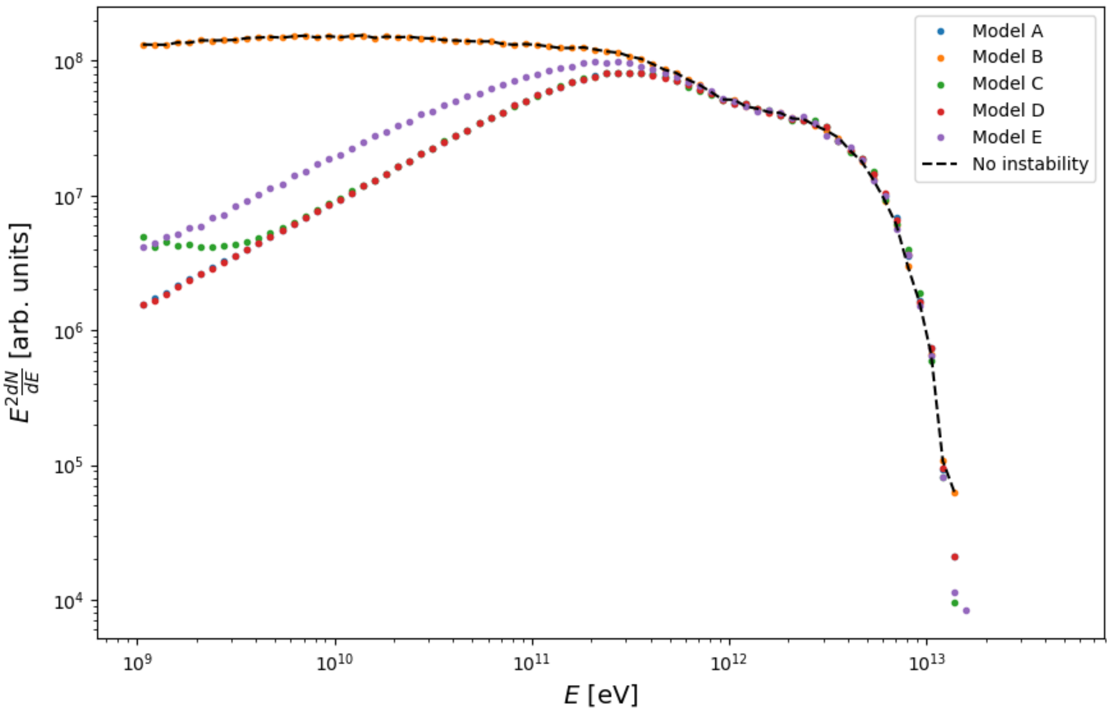

Figure 2: Comparison of the the different spectra resulting from the various energy loss models. Again, spectral parameters are $T_{\rm IGM} = 10^4$ K, $n_{\rm IGM} = 10^{-7}$ cm-3 and $\mathcal{L}_{\rm beam} = 10^{45}$ erg/s

3.2 Variation of IGM temperature

The differnet models responses to variation in the IGM temperature are shown in figure 3. Models A and D do not show any significant dependence on temperature, whereas model E has a weakening of the spectrum for greater temperatures. Model C also varies with the temperature, most apparent at lower energies.

3.3 Variation in IGM density

Responses to variation in IGM density is shown in figure 4. Again, models A and D show no variation. Model E shows some dependence on the density, while we see a peak at the low end of the spectrum for model C as density increases.

3.4 Variation in luminosity

Responses to variation in luminosity are shown in figure 5. Models A and D still show no significant variation, although for model A there can be seen a small change in behaviour at the very lowest energies. Model E shows a small dependence on the luminosity, and again there are peaks at the low end of the spectrum for model C.

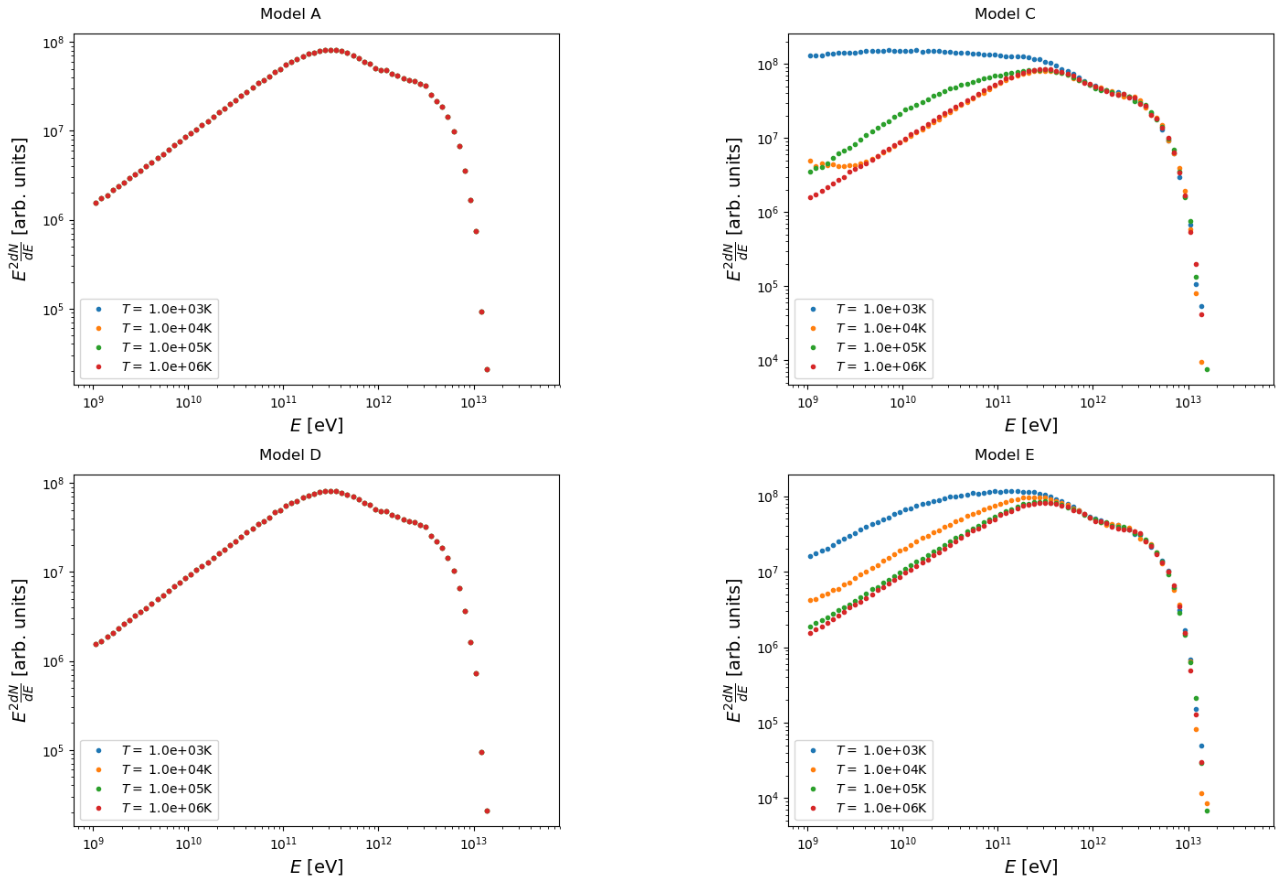

Figure 3: Variations in the parameter for the IGM temperature for models A, C, D and E. The other parameters are kept at $n_{\rm IGM} = 10^{-7}$ cm^{-3} and $\mathcal{L}_{\rm beam} = 10^{45}$ erg/s

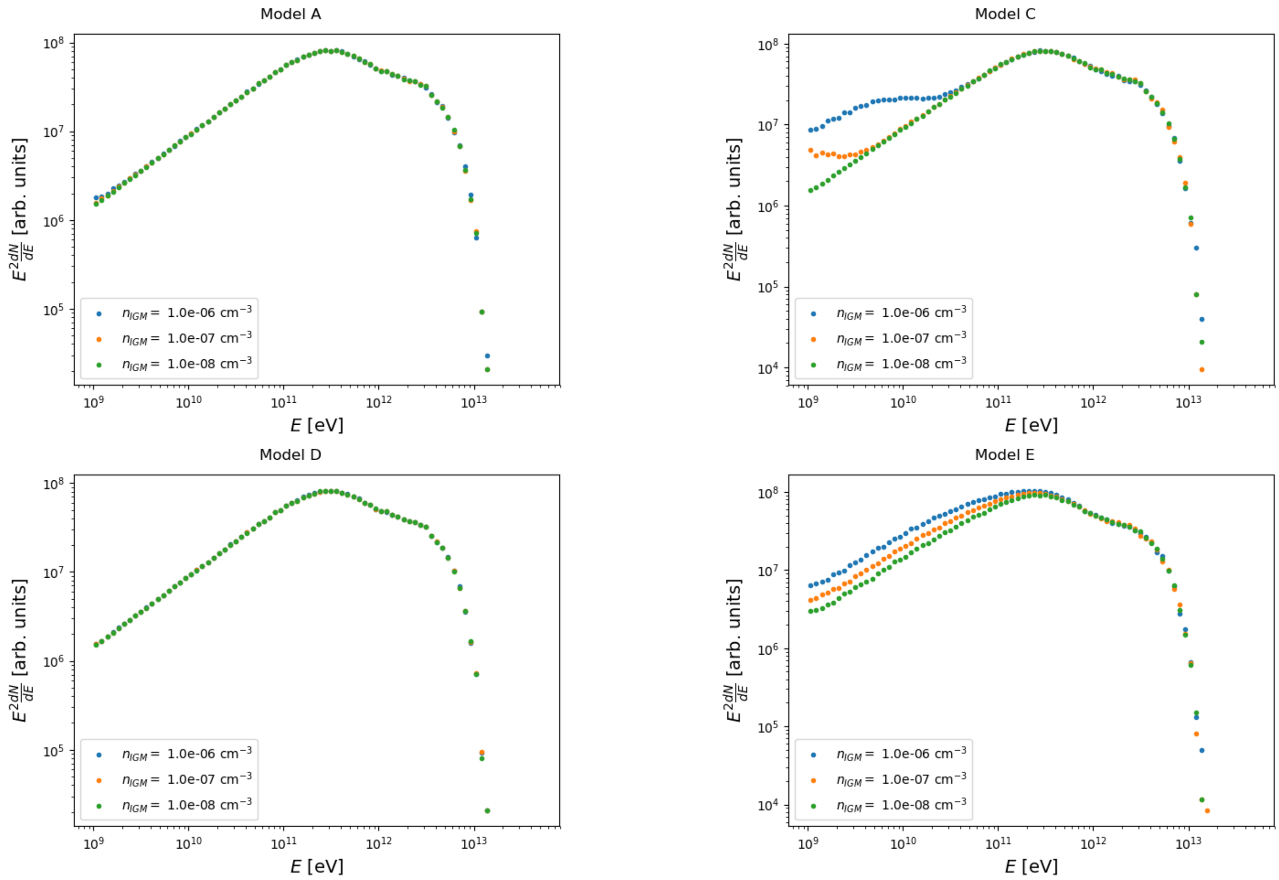

Figure 4: Variations in the parameter for the IGM number density for models A, C, D and E. The other parameters are kept at $T_{\rm IGM} = 10^4$ K and $\mathcal{L}_{\rm beam} = 10^{45}$ erg/s

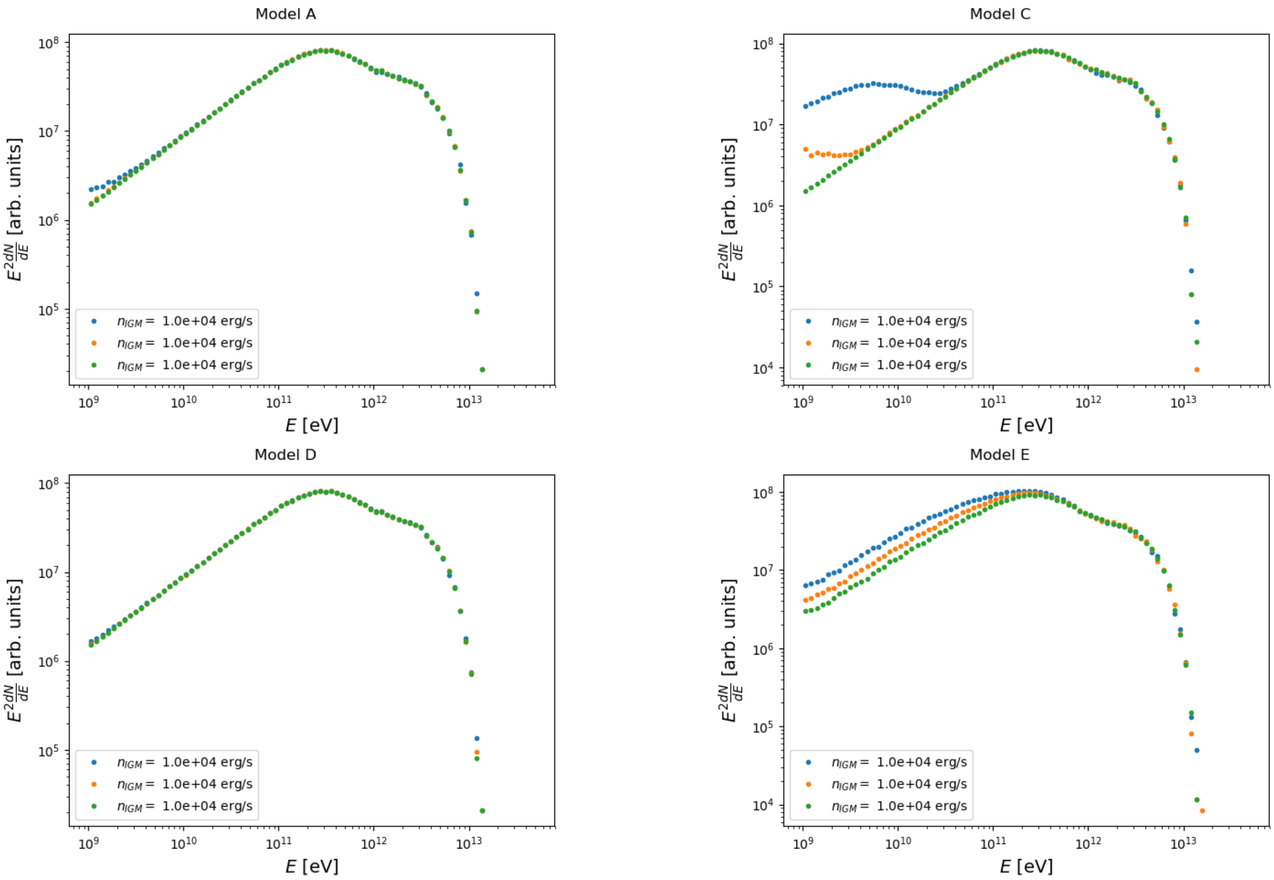

Figure 5: Variations in the parameter for the luminosity for models A, C, D and E. The other parameters are kept at $T_{\mathrm{IGM}} = 10^4$ K and $n_{\mathrm{IGM}} = 10^{-7}$ cm-3

4 Discussion

4.1 Discontinuity in model C

The discontinuity in model C shown in figure 1 is obviously of a nonphysical nature. As it has not been addressed in the literature, the discontinuity has been left this way for the simulations, and assuming there are no mistakes in the implementation here, it should probably be corrected.

4.2 Variation of parameters

The results when varying the parameters for temperature, density and luminosity are mostly similar to the findings of Batista et al. except for two notable differences. Firstly, it is found here that model E is generally more dependent on variation of all parameters compared to the results of Batista et al. Secondly, the specific case of $T_{\mathrm{IGM}} = 100\,\mathrm{K}$ when varying the temperature yields strange behaviour for model C, in particular the apparent randomness at high energies. On the other hand, notice in particular the similar behaviour for model C at low energies as found by Batista et al. and also the detail at the very lowest end of the spectrum for model A when varying the luminosity.

5 Learning outcome

Throughout the project I have been introduced to the physics behind propagation of high energy light through space. I have learned about the concept of light interacting with background photon fields producing a cascade process which may be simulated by programs like ELMAG and compared to observed spectra in order to gain further understanding of the process. Furthermore, I have learned how to use the programming language Fortran 90, and how it may be used to build modular code. Lastly, I have gained further experience in working with scientific literature, and collaborating with an instructor for a project.

References

[1] Broderick, Avery E., Philip Chang, and Christoph Pfrommer: *The cosmological impact of luminous TeV blazars. Implications of plasma instabilities for the intergalactic magnetic field and extragalactic gamma-ray background.* The Astrophysical Journal, 752(1):22, 2012. https://doi.org/10.1088%2F0004-637x%2F752%2F1%2F22.

[2] Blytt, M., M. Kachelriess, and S. Ostapchenko: *ELMAG 3.01: A three-dimensional Monte Carlo simulation of electromagnetic cascades on the extragalactic background light and in magnetic fields.* 2019. https://arxiv.org/abs/1909.09210.

[3] Alves Batista, Rafael, Andrey Saveliev, and Elisabete M. de Gouveia Dal Pino: *The Impact of Plasma Instabilities on the Spectra of TeV Blazars.* Mon. Not. Roy. Astron. Soc., 489(3):3836–3849, 2019. https://arxiv.org/abs/1904.13345.