Doppler Boosting and cosmological redshift on relativistic jets

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Abstract: In this study our goal was to identify the possible effects that influence with the Spectral Energy Distribution of a blazar, which we deducted that are Doppler Boosting effect and cosmological redshift. Then we investigated how the spectral energy distribution varies by changing intrinsic parameters of the jet like its Lorentz factor, the angle of the line of sight respect to the jet orientation or the blazar redshift. The obtained results showed a strong enhancing of the Spectral Energy Distribution for nearly 0º angles and high Lorentz factors, while the increase in redshift produced the inverse effect, reducing the normalization of the distribution and moving the peak to lower energies. These two effects compete in the observations of all known blazars and our simple model confirmed the experimental results, that only those blazars with optimal characteristics, if at very high redshift, are suitable to be measured by the actual instruments, making the study of blazars with a high redshift an issue that needs very deep observations at different wavelengths to collect enough data to properly characterize the source population.

I. INTRODUCTION

We know that active galactic nuclei or AGN are galaxies with an accreting supermassive blackhole in the centre. The blackhole attracts matter by its enormous gravitational force and an accretion disk may be formed. Some of the matter in this disk is expelled by the strong magnetic fields creating two jets. More specifically, in this study we are going to work with blazars, a well-known type of AGN which have one of its jets pointing directly or nearly towards the Earth. Blazars have normally a large radiation power and the small jet-line of sight angles make them the best candidates to be measured even if they have considerable redshift. Each blazar Spectral Energy Distribution or SED generally has its maximum in the range between X-rays and γ-rays (MeV-GeV) with two main contributions. The synchrotron radiation component peaks in the hard X-rays and the Inverse Compton (IC) effect in the 100 GeV γ-rays but there are some evidences in [1] that reveal that this measured values can be wrong as there is what it is called "blazar sequence".

According to this effect, the more powerful blazars shift their SED to lower energies while the weaker ones do not. For synchrotron, the peak shifts to ultraviolet (UV) while the IC's peak falls below the GeV range. Moreover, powerful blazars' SED are dominated by the IC effect. This is theoretically an intrinsic effect of the radiation source and that reduction makes them more easily to detect on the X-rays range of the spectrum if they redshift is not great enough. This blazar sequence phenomena added to the strong redshift effect for z>6, results in a situation where only extremely powerful blazars with small angles can be measured from the Earth. Being able to study other types of blazars requires instruments with a better sensitivity in the MeV and hard X-rays range of the spectrum, which is not achievable at present.

As an academic study we wanted to explore the combined effect produced by the Doppler Boosting effect and the cosmological redshift. We started by obtaining our model emitter source, the relativistic jets created in blazars. These jets that point at us are constituted by ionized matter and we focused our study in charged particles like electrons and positrons and their high energy spectrum emission. Inside the jet those particles are moving at relativistic speeds, producing high energy interactions in the process. This scenario produces a wide spectrum of radiation that mainly comes, as we can see in more detail in [2], from Inverse Compton scattering. Low energy photons inside the jet are scattered by relativistic electrons, which leads to an energy transfer, obtaining high energy photons between the MeV and GeV range. There is a second important component of the spectrum, at lower frequencies, that comes from synchrotron radiation. It is related to the radiation emitted by all these charged particles which are accelerated by the magnetic fields present inside the jet. Other radiation contributions are neglected in this study due to their minimal relevance in the studied spectrum range.

We modelled these two processes phenomenologically to contribute to the spectral energy distribution, from now on SED, as follows:

$$\varepsilon' \times L'(\varepsilon')_1 = \frac{N_1 \varepsilon'^{\alpha}}{\gamma^2} exp\left(-\frac{\varepsilon'}{\varepsilon_1}\right)$$
$$\varepsilon' \times L'(\varepsilon')_2 = \frac{N_2 \varepsilon'^{\alpha}}{\gamma^2} exp\left(-\frac{\varepsilon'}{\varepsilon_2}\right) \quad (1)$$

We used index '1' for synchrotron's contribution and index '2' for the Inverse Compton's one. We divided by γ^2, where γ is the jet Lorentz factor, which is related to special relativity and depends on the relative velocity, and to impose that the luminosity remains equal in the laboratory frame (to be distinguished from the observer 'apparent' emission). Letter ε is used for the energy, and α and exponent that we define phenomenologically to have a value of 0.5 from its measured range that goes from 0.5-1. The variables N_1, N_2, ε_1 and ε_2 in the expressions work as parameters to normalize our model and we have been modifying their value during this study in order to make sure that our spectrum peaks where similar in intensity, being the IC peak slightly dominant to match the experimental data. We used $N_1=10^5$, $N_2=1$, $\varepsilon_1=10^5$ and $\varepsilon_2=10^{11}$. The primes indicate that these quantities are measured in the fluid's reference frame while the quantities without them are measured directly by the observer.

With the expressions in equation 1, we computed the flux's SED measured from the observer's reference frame at a redshift equal to zero (ε x $F(\varepsilon)_o$). Cosmological redshift, z, is related to the measured lengthened wavelength from a distant object due to the expansion of the Universe. It can be calculated comparing the relative change between the observed and the emitted wavelength of a well-known source. Then, we compared this ε x $F(\varepsilon)_o$ with the same quantity from the laboratory's reference frame situated in the Earth, ε x $F(\varepsilon)^z_o$, which has an attenuation due to the cosmological redshift effect. For all the descripted processes we assumed that the particle and photon emission in the jet reference frame was isotropic, to simplify our flux's SEDs calculus.

We used a simple model which showed that the Doppler Boosting effect compete with the cosmological redshift, getting different peak positions from varying the value of parameters like the redshift (z), the angle of the line of sight with respect to the jet (θ) and the jet Lorentz factor (γ).

II. DOPPLER BOOSTING

As the emitting flow of the jet travels at relativistic speed, we can account for changes in the intrinsic jet flux's SED. This variation on the SED is caused by the Doppler Boosting effect, which can be also called Doppler de-Boosting effect when there is a reduction in value. This effect has three contributions, first of all it reflects the impact of the Doppler effect (known as a modifier of the frequency of radiation, making it more reddish or bluer depending on the velocity and direction of motion of the emitter). It also considers the light retardation effect, which reduces the time in which a relativistic source is apparently emitting. Finally, there is the contribution of the relativistic aberration, which causes an increase of the apparent energy distribution by concentrating towards the observer all the radiation emitted with a distortion of the angle in which the source emits.

In our simple model we gathered all these phenomena and computed the result. We got that the Doppler Boosting effect can be summarized as a factor δ seen in detail in [3]:

$$\delta = \frac{1}{\gamma(1-\beta\cos\theta)} \quad (2)$$

This δ, known as Doppler factor, depends on the relativistic velocity of the source, included in the jet's Lorentz factor, and on the angle measured by the observer. The Doppler Boosting transformation affects the energy as well as the SED by following a simple relation:

$$\varepsilon = \delta\,\varepsilon'$$
$$\varepsilon \times L(\varepsilon)_i = \varepsilon' \times L'(\varepsilon')_i \cdot \delta^p \quad (3)$$

The value of the exponent p goes, as we can see in [4], from p=4 for a spherical isotropic source or so called 'blob' to p=3 for a straight conventional jet. For clarity and simplicity, we will not study blobs further, so all the work from now on will be focused on the emitted SED from a straight jet.

III. COSMOLOGICAL REDSHIFT

Although we compute a certain Doppler redshift or blueshift as a result from the velocity of the ionized matter in the jet and jet-line of sight angle we cannot neglect that our Universe is in expansion. Hence, we need to consider a cosmological redshift which increases the radiation's wavelength by a factor (1+z) that reduces the total energy observed:

$$\varepsilon = \varepsilon' / (1+z) \quad (4)$$

This parameter z is called redshift factor and it is related with the luminosity distance:

$$d_L = d_M\,(1+z) \quad (5)$$

where d_M is the comoving distance. Moreover, we calculated this comoving distance, using a flat (K=0) universe model described in [5], for different values of z and then we used its value to calculate the relation between the measured flux's SED viewed from the observer (ε x $F(\varepsilon)^z_o$) at the given redshift and the flux's SED (ε x $F(\varepsilon)_o$) of the studied object but neglecting the cosmological redshift:

$$\varepsilon \times F(\varepsilon)^z_o = \frac{\varepsilon \times F(\varepsilon)_o}{(1+z)^4} = \frac{\varepsilon \times L(\varepsilon)}{(1+z)^4\, 4\pi {d_M}^2} = \frac{\varepsilon \times L(\varepsilon)}{(1+z)^2\, 4\pi {d_L}^2} \quad (6)$$

where the 'z' index indicates that these quantities have been transformed by the cosmological redshift and the 'o' index indicates a Doppler Boosting transformation.

In our model we have not considered any contribution to the redshift due to gravitational effects. If some super massive objects are along the path from our blazar to the observer, we neglected all interaction between the SED and them.

IV. RESULTS

After working with our simplified model, we obtained a better vision on how the observed flux's SED was affected by the selected parameters. All the resultant plots show the different flux's SEDs versus the energy, ε, in log-log scale. The ε x $F(\varepsilon)$ is measured in three different reference frames. We used the index 'o' to describe the SED after using the Doppler Boosting transform, which correspond to what an observer will see for and object at a determined comoving distance, but neglecting the cosmological redshift (after determining the d_M, we did not divide by $(1+z)^4$. The 'z' index indicates that the SED is transformed by Doppler Boosting and then redshifted due to the expansion of the Universe. This apparent flux reflects what a real observer would measure in the Earth from an emitter with a certain redshift z. Finally, we computed the flow frame flux's SED, which is measured in the rest frame of the jet and has not been transformed by Doppler Boosting, neither by the cosmological redshift effect.

We structured this section in three main parts, each one focused in one of the intrinsic parameters that control our model. To study effect of the angle of the line of sight with respect to the jet, we are going to study values of θ from 0 to 90º. The studied jet Lorentz factors will be γ=2,5 and 10, to typify the low, moderate, and high relativistic regimes of the jet. The last parameter that we will use is the redshift, we will use z=0.01 (to avoid an indetermination in the mathematic model for really close objects), 1, 5, and 10 which will provide a wide perspective on objects located at different distances.

A. Flux's SED dependence on θ

As the Doppler factor δ depends on the angle θ we started to compare the results for a given value of the redshift, and the jet Lorentz factor, z=1 and γ=2 while changing the angle of sight respect to the jet from 0º, 30º and 90º . We grouped the two components of the flux's SED, showing the hard X-rays and soft γ-rays coming from the synchrotron radiation (ranged between 100 eV to 10^7 eV) and the higher energetic ones coming from the Inverse Compton in the $10^6 - 10^{13}$ eV range.

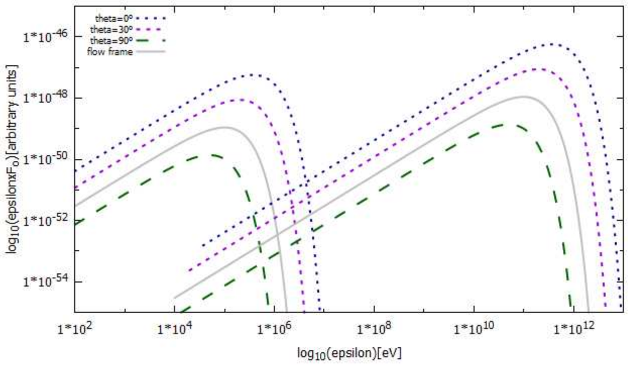

FIG.1: Flux's SED transformed with the Doppler Boosting equation. We used as parameters z=1 and γ=2 and we varied θ between 0º, 30º and 90º. We compare the ε x $F(\varepsilon)_o$ of a jet for each angle with the flux's SED measured at the flow reference frame. The synchrotron and the IC components are plotted in the same line style for an easy recognition.

Figure 1 shows how the doppler boosted transformed flux's SED, with the 'o' index, has a variation of around 2 orders of magnitude in value between the two extreme cases. We can deduce from the plot that for small angles we get a boosting effect, the curves are over the flow frame SED, while for bigger angles (around 60º), the δ falls below 1, and we observe a de-boosting effect. It is also remarkable to observe the energy shift in the peaks, being shifted to higher frequencies by the doppler boost or to lower ones due to the 90º angle. The energy shifts are within a range of a few MeV in the synchrotron component to hundreds of GeV in the Inverse Compton which follow the ratio $\delta_{0º}/ \delta_{90º}$ =7.47.

If we repeat the same graphic with a higher relativistic jet, γ=10, we expect to get similar results but magnified by the increase in the Doppler factor.

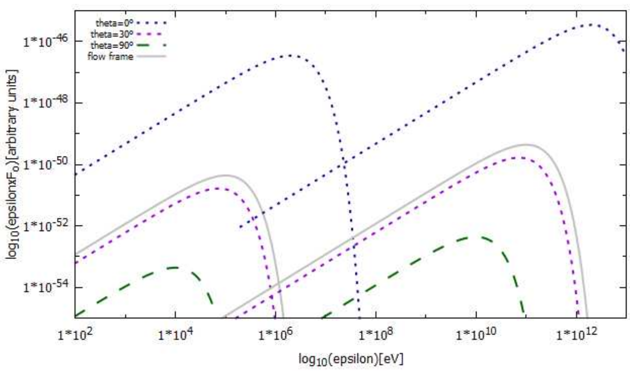

FIG.2: Flux's SED transformed with the Doppler Boosting equation. We used as parameters z=1 and changed γ=10 and we varied θ between 0º, 30º and 90º. We compare the ε x $F(\varepsilon)_o$ of a jet for each angle with the flux's SED measured at the rest source's reference frame.

Figure 2 shows what we were expecting, the higher γ separates the curves, increasing the angle effect on the ε x $F(\varepsilon)_o$. For the 0º angle we observe a similar Doppler Boosting effect than in the previous case. The main difference is visible in the 30º angle. While it was boosted for slight relativistic regimes, it becomes de-boosted for high values of γ. The shift on the peaks is increased by a factor 10. We can deduce that outside the low angles with respect to the jet, the cosmological redshift will reduce even more the observed SED, making them considerably more difficult to measure for the actual instruments.

B. Flux's SED dependence on γ

As the jet is relativistic, we proposed three scenarios with values of the jet Lorentz factor going from a low relativistic effect with γ=2 to a moderate γ=5 and then a high relativistic regime for γ=10. To have a reference point to compare the different figures we fixed three different angles, θ=0º, 5º and 60º. However, for all the cases we have chosen a z=5, a typical value for high redshift observable blazars as seen in [6].

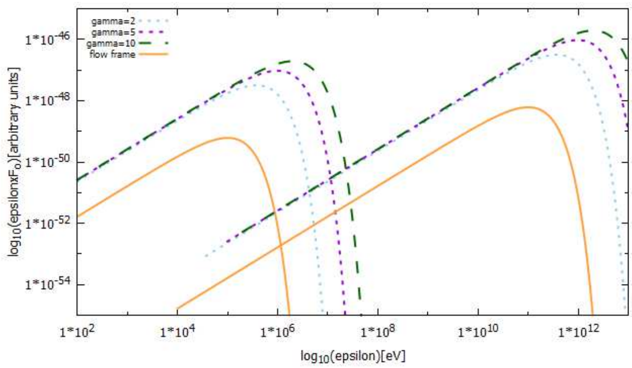

FIG.3: Flux's SED transformed with the Doppler Boosting equation. We used as parameters z=5 and θ=0º and we varied γ between 2, 5 and 10. We compare the ε x $F(\varepsilon)_o$ of a jet for the three Lorentz factors with the flux's SED measured at the flow frame.

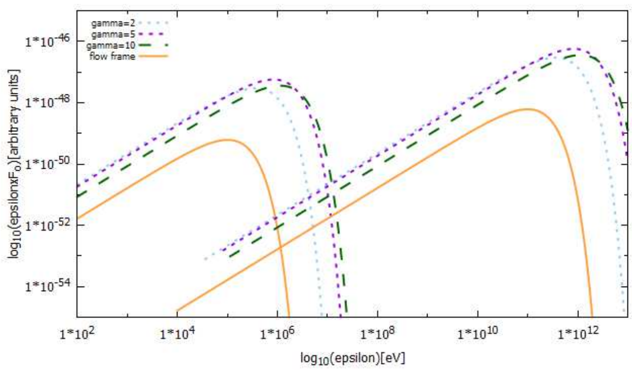

FIG.4: Flux's SED transformed with the Doppler Boosting equation. We used as parameters z=5 and θ=5º and we varied γ between 2, 5 and 10. We compare the ε x $F(\varepsilon)_o$ of a jet for the three Lorentz factors with the flux's SED measured at the flow frame.

Figures 3 and 4 show that for small angles the jet Lorentz factor enhance the flux's SED measured in the flow's frame by 2 orders of magnitude in both components in figure 3 and slightly 1 order in figure 4. The more relativistic the jet becomes, the strongest the Doppler Boosting effect is, and the ε x $F(\varepsilon)_o$ peak shifts to higher energies, but in figure 4 we start to appreciate a change in that behaviour. We expect for the 60º angle plot a smaller boost or even a de-boost effect.

Figure 5 supports this:

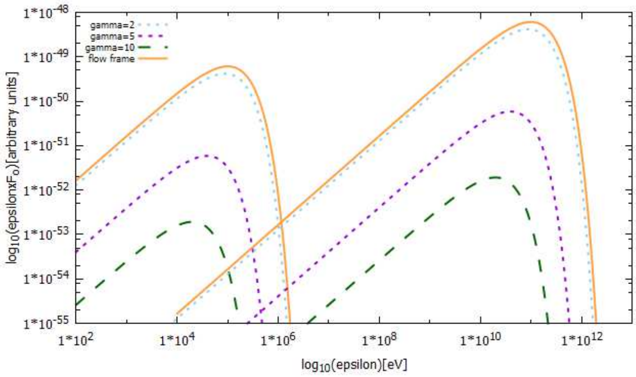

FIG.5: Flux's SED transformed with the Doppler Boosting equation. We used as parameters z=5 and θ=60º and we varied γ between 2, 5 and 10. We compare the ε x $F(\varepsilon)_o$ of a jet for the three Lorentz factors with the flux's SED measured at the flow frame.

The Doppler Boosting effect in fact de-boosts the ε x $F(\varepsilon)_o$ and shifts the peaks to lower energies. In fact, the increasing Lorentz factor helps to amplify this de-boosting effect.

The global results show that for a small given angle the γ factor increases the observed flux's SED. However, this increment depended heavily on the studied angle, so as we encountered in figure 5, bigger angles like θ=60º, showed results of a de-boosting effect despite the increase of γ. We could conclude that in a general situation, the behaviour of the Doppler Boosting effect depends on both the angle of the line of sight with respect to the jet and the jet Lorentz factor, as we demonstrated in this two firsts sections, and their contributions share relevance in the increase or decrease of the observed flux's SED.

This give credit to the studies that classify blazars as one of the higher redshift objects detectable of the Universe. One of the major reasons for this is having their jets aligned with our sight, which optimize the Doppler Boosting effect that allow us to detect theirs SEDs in the X-ray and γ-ray spectrum.

C. Flux's SED dependence on z

To finish our study, we wanted to compare how the increase in cosmological redshift competed against the Doppler Boosting effect for a blazar whose jet has an angle of θ=0º and a high relativistic Lorentz factor γ=10. We selected four values for z, being z=0.01 our nearest source example and then we increased the redshift to z=2, z=5 and z=10 as the furthest emitter in our model. By applying the Doppler Boosting effect and afterwards computing the cosmological redshift associated with each z, we are going to compare the ε x $F(\varepsilon)^z_o$ with the flux's SED of the jet in its rest frame.

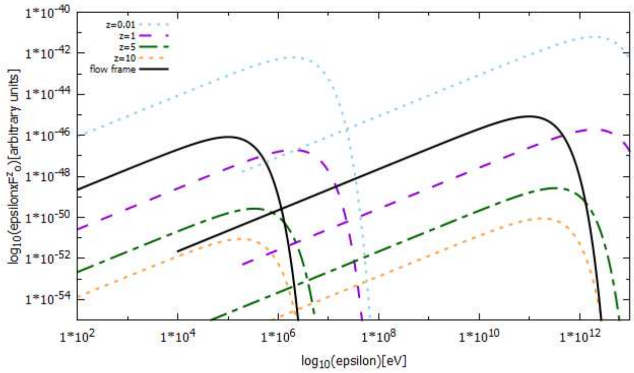

FIG.6: Observed flux's SED transformed with the Doppler Boosting equation and then applying the cosmological redshift. We used as parameters γ=10 and θ=0º and we varied z between 0.01, 1, 5 and 10. We compare the four different ε x $F(\varepsilon)^z_o$ obtained with the flux's SED measured at the flow frame with z=0.01.

Figure 6 shows in colours the different observed flux's SEDs for the selected range of redshifts. Grey and black curves represent the flux's SED in the jet rest frame to easy compare with the observed flux's SED. Due to the almost 0 redshift, the first violet curve appears as the Doppler Boosted. The next higher z curves show a non-lineal attenuation of the SED's peak. We can observe that for the z=0.01 (showed in the plot) and for all the others z values, the observed flux's SED never appear below the source one. Increasing the angle in the next figure, we expect to reduce the observed SED significantly and check if it falls enough to justify why it is hard to detect active galactic nuclei at high redshifts.

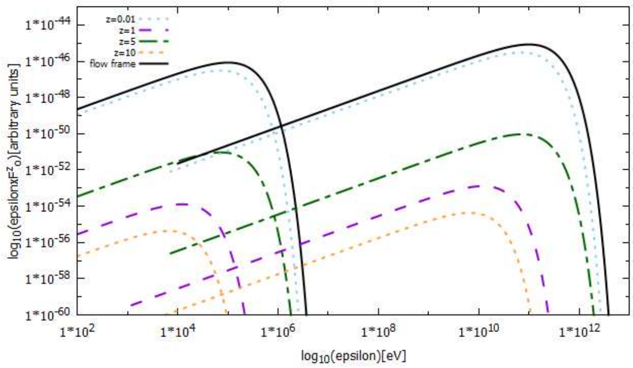

FIG.7: Observed flux's SED transformed with the Doppler Boosting equation and then applying the cosmological redshift. We used as parameters γ=10 and θ=30º and we varied z between 0.01, 1, 5 and 10. We compare the four different ε x $F(\varepsilon)^z_o$ obtained with the flux's SED measured at the flow frame with z=0.01.

As the angle is increased to 30º, we notice a drastic reduction on ε x $F(\varepsilon)^z_o$ in figure 7, falling below the flux's SED measured from the rest reference frame of the jet. This proves again that the Doppler Boosting is sensitive to small changes in the angle but does not reveal if redshift alone can revert the boosted SED from a direct pointing to us jet.

To better understand how the competition between the cosmological redshift and the Doppler Boosting occurs, we plotted for two significant z values (z=1 and z=10), both the ε x $F(\varepsilon)_o$ and ε x $F(\varepsilon)^z_o$ comparing them with the flux's SED in the jet's rest frame.

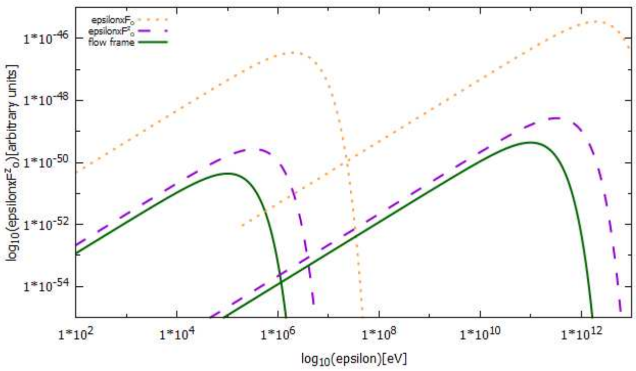

FIG.8: Comparison of the ε x $F(\varepsilon)_o$ and ε x $F(\varepsilon)^z_o$ with the flux's SED measured in the flow frame. We use z=1, γ=10 and θ=0º as they are the typical measured blazar parameters.

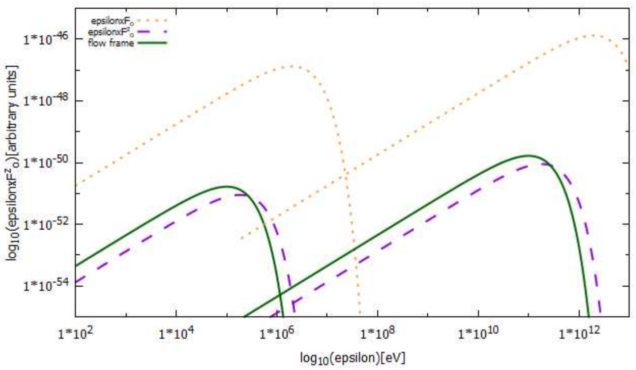

FIG.9: Comparison of the ε x $F(\varepsilon)_o$ and ε x $F(\varepsilon)^z_o$ with the flux's SED measured in the flow frame. We use z=10, γ=10 and θ=0º which simulates a hypothetic high redshift blazar.

In figures 8 and 9 we can observe as a summary all the processes used in this study. The flux measured in the jet's rest frame is Doppler Boosted initially due to the relativistic relative velocity of the fluid inside the jet, shifting the SED peak to higher frequencies and enhancing the flux value. Due to the Universe expansion, this SED is attenuated before arriving to us, which make that the observed flux's SED appears shifted to lower energies.

Our model inspection ends here and despite going up to z=10, a higher redshift than any measured blazar right now, the Doppler Boosting effect dominates over the cosmological redshift. That dominance should reflect in the experimental data by being able to observe high redshift blazars with redshifts up to 10. Nevertheless, as we early have seen in [6], the higher redshift blazar measured was about z=6, and most of blazar's known population is between z=1 and z=3.

V. CONCLUSIONS

The dependence on the jet Lorentz factor is highly correlated with the angle. For smaller angles (0º-10º) enhances the ε x $F(\varepsilon)_o$ while increasing the γ. Out of this limits the nature of the effect changes, seeing higher de-boosting effects while increasing the γ.

As we just said, the angle of the observer line of sight with respect to the jet plays a major role in this model. A change in the angle can suppose up to a 100% variation in the flux's SED at even small relativistic regimes. Furthermore, blazars are one of the brightest measured objects in the sky because they generally have a near 0º value of θ and are always in a high relativistic regime with typical values of γ around 10. Following the same argument, the strong angle dependence could make a powerful and distant blazar that is slightly out of sight to became impossible to measure due to de-boosting effects provided by that angle.

Finally, we studied the effect of cosmological redshift on top of the Doppler Boosting effect. As we worked with a fixed θ and γ, we noticed a remarkable attenuation, but it was never enough (inside our defined bounds for parameters) to completely revert the boosting effect, although there was an important shift of the flux's SED. This result drives us to the conclusion that Doppler Boosting effect would allow us to measure blazars with relatively high values of z but the mechanism known as blazar sequence, which intrinsically lower the most powerful blazars, added to the strong shift of the SED's peak due to the cosmological redshift, are the main reasons that restrict their study nowadays. By exploring the lower energy spectrum (hard X-rays and MeV range) provided with new instruments that could achieve a good sensitivity we will be able to observe the flux's SED peaks of even further blazars.

Acknowledgements

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