THE PHYSICS AND COSMOLOGY OF TEV BLAZARS IN A NUTSHELL

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The extragalactic gamma-ray sky at TeV energies is dominated by blazars, a subclass of accreting super-massive black holes with powerful relativistic outflows directed at us. Only constituting a small fraction of the total power output of black holes, blazars were thought to have a minor impact on the universe at best. As we argue here, the opposite is true and the gamma-ray emission from TeV blazars can be thermalized via beam-plasma instabilities on cosmological scales with order unity efficiency, resulting in a potentially dramatic heating of the low-density intergalactic medium. Here, we review this novel heating mechanism and explore the consequences for the formation of structure in the universe. In particular, we show how it produces an inverted temperature-density relation of the intergalactic medium that is in agreement with observations of the Lyman-\(\alpha\) forest. This suggests that blazar heating can potentially explain the paucity of dwarf galaxies in galactic halos and voids, and the bimodality of galaxy clusters. This also transforms our understanding of the evolution of blazars, their contribution to the extra-galactic gamma-ray background, and how their individual spectra can be used in constraining intergalactic magnetic fields.

1 Introduction

The extragalactic gamma-ray sky is dominated by “blazars”. These are a subclass of super-massive black holes, situated at the center of every galaxy, which drive powerful relativistic jets and electromagnetic radiation out to cosmological distances. An important subset of blazars exhibit hard power-law spectra that extend to TeV photon energies (high-energy-peaked BL Lacs). The Universe is opaque to the emitted TeV gamma rays because they annihilate and pair produce on the extragalactic background light which is emitted by galaxies and quasars through the history of the universe. The mean free path for this reaction is \(\lambda_{\gamma\gamma} \sim (700 \ldots 35) \left( E/\text{TeV} \right)^{-1} \text{Mpc} \) for redshifts \(z = 0 \ldots 1\), respectively, and is approximately constant at \(\lambda_{\gamma\gamma} \sim 35 \left( E/\text{TeV} \right)^{-1} \text{Mpc} \) for higher redshifts. The resulting ultra-relativistic pairs of electrons and positrons are commonly assumed to lose energy primarily through inverse Compton scattering with photons of the cosmic microwave background, cascading the original TeV emission a factor of \(\sim 10^3\) down to GeV energies.

However, there are two serious problems with this picture: the expected cascaded GeV emission is not seen in the individual spectra of those blazars (Neronov & Vovk 2010) and the emission of all unresolved blazars would overproduce the observed extragalactic gamma-ray background (EGRB) at GeV energies if these objects share a similar cosmological evolution as
Figure 1: Initial pair beam cooling rates due to the kinetic oblique instability (thick solid) and inverse Compton scattering (dotted) as a function of gamma-ray energy ($E$) at a number of redshifts ($z$). In all cases, we consider a mean-density region, and the isotropic-equivalent luminosity of the source at energy $E$, $E_{LE}$, is $10^{45}$ erg s$^{-1}$, similar to the brightest TeV blazars seen from Earth. We list the initial pair Lorentz factor, $\gamma$, and cooling lengthscale along the top and right axes, respectively (from Broderick et al. 2012).

2 Beam-plasma instabilities

Recently, we have shown that there is an even more efficient mechanism that competes with this cascading process. Plasma instabilities driven by the highly anisotropic nature of the ultra-relativistic pair distribution provide a plausible way to dissipate the kinetic energy of the TeV pairs locally, heating the intergalactic medium (Broderick et al. 2012). We can understand the two-stream instability intuitively by considering a longitudinal wave-like perturbation of the charge of the background plasma along the beam direction (i.e., a Langmuir wave). The initially homogeneous beam electrons feel repulsive (attractive) forces by the potential minima (maxima) of the electrostatic wave in the background plasma. As a result, electrons (positrons) attain their lowest velocity in the potential minima (maxima), which causes them to bunch up. Hence, the bunching within the beam is simply an excitation of a beam Langmuir wave that couples in phase with the background perturbation. This enhances the background potential and implies stronger forces on the beam pairs. This positive feedback loop causes exponential wave-growth, i.e. the onset of an instability. In practice, oscillatory modes that propagate in an oblique direction to the beam grow substantially faster than the two-stream instability just discussed. The reason is that electric fields can more easily deflect ultra-relativistic particles than change their parallel velocities (see Broderick et al. 2012, for details).

Unstable electromagnetic waves grow fastest when the velocity dispersions are smallest across their wave fronts. As these velocity dispersions get larger and larger, i.e., for increasing temperature, the growth rate of the unstable oblique mode moves into the finite temperature or kinetic regime, where the exponential growth rate is reduced due to the effects of phase mixing and decoherence. In Fig. 1, we show the pair beam cooling rates due to the kinetic oblique instability in the linear regime, $\Gamma_{M,K}$ (Bret et al. 2010a) for a beam density that obeys the

the underlying black hole or parent galaxy population (Venters 2010). As a putative solution to the first problem, comparably large magnetic fields have been hypothesized which would deflect the pairs out of our line-of-sight to these blazars (Neronov & Vovk 2010), diluting the point-source flux into a lower surface brightness “pair halo”. However, magnetic deflection of pairs (and hence their inverse Compton emission) out of our line-of-sight is on average balanced by deflecting other pairs into our line-of-sight, so that the resulting isotropic EGRB remains invariant. This represents a substantial problem to unifying the hard gamma-ray blazar population with that of other active galactic nuclei (AGN), is at odds with the underlying physical picture of accreting black hole systems, and suggests an unlikely conspiracy between accretion physics and the formation of structure.
steady-state Boltzmann equation, i.e., we account for production and various loss processes of the pairs. Most importantly, we find that $\Gamma_{\text{M,k}}$ dominates over the inverse Compton cooling rate $\Gamma_{\text{IC}}$ by more than an order of magnitude for the parameters of luminous TeV blazars.

Analytical quasi-linear calculations of the cold regime (Schlickeiser et al. 2012) and numerical work of the oblique instability in the kinetic regime (Bret et al. 2010b) with smaller density contrasts than considered here suggest that the dominance of the oblique instability carries over in the regime of non-linear saturation, although there is currently a debate about the role of induced scattering by thermal ions on this non-linear saturation (Miniati & Elyiv 2013, Schlickeiser et al. 2013, Chang et al. in prep.). In the following, we assume that a large fraction of the free kinetic energy of the pairs is transferred to the electromagnetic modes in the background plasma, which should eventually be dissipated, heating the intergalactic medium (IGM).

3 Implications for the blazar luminosity function and the gamma-ray sky

To assess implications for the gamma-ray sky and the thermal evolution of the IGM, we construct a blazar luminosity function (BLF). In Broderick et al. (2012), we collect the luminosity of all 23 TeV blazars with good spectral measurements and account for selection effects (sky coverage, duty cycle, galactic occultation, TeV flux limit). The resulting BLF is shown in Fig. 2.

Most notably, the TeV blazar luminosity density is a scaled version of that of quasars. This implies that quasars and TeV blazars appear to be regulated by the same mechanism and are contemporaneous elements of a single AGN population, i.e., the TeV-blazar activity does not lag quasar activity. Hence we adopt the plausible assumption that both distributions trace each other for all redshifts and work out the implications of this assertion.
Introduction to the Fermi EGRB and Blazar Population Evolution

To quantify the impact on the gamma-ray sky, we need to expand the BLF to include the intrinsic energy spectra, $dN/dE$, of blazars and adopt a typical broken power-law spectrum

$$ \frac{dN}{dE} = f \hat{F}_E = f \left[ \left( \frac{E}{E_b} \right)^{\Gamma_l} + \left( \frac{E}{E_b} \right)^{\Gamma_h} \right]^{-1}, $$

where $E_b \simeq 1$ TeV is the break energy, $\Gamma_h \simeq 3$ is the high-energy spectral index, and the intrinsic low-energy slope $\Gamma_l$ is softened with increasing propagation length due to the higher probability of high-energy photons to annihilate on the extragalactic background light. This yields a steeper (larger) observed $\Gamma_F$, which we draw from the distribution of local blazars as observed by the Fermi gamma-ray telescope (that are not affected by spectral softening due to pair production effects). We arrive at the BLF, $d^3N/(d\log L_{\text{TeV}} dz dE d\Gamma_l)$, i.e., the distribution of blazars with TeV luminosity $L_{\text{TeV}}$, redshift $z$, gamma-ray energy $E$, and $\Gamma_l$.

Different projections of this BLF onto its independent variables allow comparison to Fermi data. Integrating this distribution over $L_{\text{TeV}}$, $E$ and $\Gamma_l$ and adopting integration limits that account for the Fermi flux limit $S_{\text{min}}$ yields the redshift distribution of Fermi blazars (left panel of Fig. 3). Interestingly, an evolving (increasing) blazar population is consistent with the observed declining number evolution of blazars due to the Fermi flux limit and the low intrinsic luminosity of the hard blazars. Masking these resolved blazars and integrating the blazar distribution over $L_{\text{TeV}}$, $z$, and $\Gamma_l$ yields the contribution of blazars to the isotropic EGRB (right panel of Fig. 3). This demonstrates that an evolving population of hard blazars matches the latest data of the EGRB by the Fermi Collaboration at energies $\gtrsim 3$ GeV extremely well. Moreover, the modeled log $N$-log $S$ distribution and the anisotropic EGRB, which mainly probes nearby objects below the detectability limit, provide an excellent match to the Fermi data (Broderick et al. 2013). Hence, this naturally solves the two mysteries introduced in Sect. 1 in a unified model of blazars and their underlying black hole population without the need to invoke large magnetic fields. Critical to this success is the absence of inverse Compton cascades that would otherwise redistribute energy between the unabsorbed and the absorbed spectrum into the energy range around 10 GeV, thus vastly overproducing the tight limits provided by Fermi.
4 Rewriting the thermal history of the IGM and the Lyman-α forest

We find that for our BLF, every region in the universe is heated by at least one TeV blazar back to $z \sim 5$, providing a novel heating mechanism of the gas at mean density that is ten times larger at the present time than what has been previously considered (Chang et al. 2012). This can be interpreted as a gradually rising (and density dependent) entropy enhancement after $z = 3$ (left panels of Fig. 4). Unlike photoheating, the blazar heating rate per unit volume does not depend on density since (1) the distributions of TeV blazars and the extragalactic background light are uniform on the cosmological scales of the mean free path of pair production, $\lambda_{\gamma\gamma}$, and (2) it is nearly independent of the IGM density. Hence this particular heating process deposits more energy per baryon in low-density regions and naturally produces an inverted temperature-density relation in voids that reaches asymptotically $T \propto 1/\rho$ (right panels of Fig. 4). This unique property in combination with the recent and continuous nature of blazar heating is needed to solve many problems present in previous calculations of Lyman-α forest spectra.

Detailed cosmological simulations that include blazar heating show superb agreement with all statistics used to characterize Lyman-α forest spectra (Puchwein et al. 2012). In particular, our simulations with blazar heating simultaneously reproduce the observed effective optical depth and temperature as a function of redshift, the observed probability distribution functions...
Figure 5: Comparing the Lyman-α forest in hydrodynamical cosmological simulations with and without blazar heating. Left. Probability distribution functions of the transmitted flux fraction for simulations with and without blazar heating for two different normalisations of the blazar heating rate are compared to observational constraints from Kim et al. 2007. Right. The normalised distribution function of Lyman-α line widths, $b$, for simulations with and without blazar heating at redshift $z = 3$ are compared to observational constraints by Kirkman et al. (1997). Both panels show simulation results for a UV background that was matched to the observed mean transmission (from Puchwein et al. 2012).

of the transmitted flux (Fig. 5), and the observed flux power spectra, over the full redshift range $2 < z < 3$. Additionally, by deblending the absorption features of Lyman-α spectra into a sum of thermally broadened individual lines, we find superb agreement with the observed lower cutoff of the line-width distribution (Fig. 5) and abundances of neutral hydrogen column densities per unit redshift. This concordance between Lyman-α data and simulation results, which are based on the most recent cosmological parameters, also suggests that the inclusion of blazar heating alleviates previous tensions on constraints of the normalization of the density power spectrum, $\sigma_8$, derived from Lyman-α measurements and other cosmological data.

5 Implications for the formation of dwarf galaxies and galaxy clusters

We have seen that blazar heating dramatically changes the thermal history of the diffuse IGM, which necessarily implies a number of important implications for late-time structure formation (Pfrommer et al. 2012). Unlike photoionization models, which typically invoke the heating at reionization, blazar heating provides a well defined, time-dependent entropy enhancement that rises dramatically after $z \sim 2$, suppressing the formation of late forming dwarf galaxies. On small scales, thermal pressure opposes gravitational collapse. This introduces a characteristic length and mass scale below which galaxies do not form. A hotter intergalactic medium implies a higher thermal pressure and a higher Jeans mass $M_J$ at redshift $z$,

$$M_J \propto \frac{c_s^3(z)}{\sqrt{G^3 \rho(z)}} \propto \left( \frac{T_{\text{IGM}}(z)}{G^3 \rho(z)} \right)^{1/2} \rightarrow M_{J,\text{blazar}} / M_{J,\text{photo}} \approx \left( \frac{T_{\text{blazar}}}{T_{\text{photo}}} \right)^{3/2} \gtrsim 30,$$

where $c_s$, $\rho$, and $T_{\text{IGM}}$ are the sound speed, density, and temperature of the IGM, respectively, and $G$ is Newton’s gravitational constant. That is, blazar heating increases $M_J$ by 30 over pure photoheating models.

However, there are complications due to non-linear collapse and a delayed pressure response in an expanding universe. This causes a slight reduction of the suppression factor (Fig. 6). Hence, our redshift-dependent entropy enhancement due to blazar heating increases the characteristic
halo mass below which dwarf galaxies cannot form by a factor of approximately 10 (50) at mean density (in voids) over that found in the standard model, preventing the formation of late-forming dwarf galaxies. This may help resolve the “missing satellites problem” in the Milky Way of the low observed abundances of dwarf satellites compared to cold dark matter simulations and may bring the observed early star formation histories into agreement with galaxy formation models. At the same time, it is a very plausible explanation of the “void phenomenon” (Peebles & Nusser 2010) by suppressing the formation of galaxies within existing dwarf halos, thus reconciling the number of dwarfs in low-density regions in simulations and the paucity of those in observations.

Finally, this suggests a scenario for the origin of the cool core/non-cool core bimodality in galaxy clusters and groups, which are separated into different classes depending on their core temperatures. Early forming galaxy groups are unaffected because they can efficiently radiate the additional entropy, developing a cool core. However, late-forming groups do not have sufficient time to cool before the elevated entropy enhancement is gravitationally reprocessed through successive mergers—counteracting cooling and potentially raising the core entropy further to potentially form a non-cool core cluster.

6 Conclusions and Outlook

In a series of papers, we have proposed a novel plasma-astrophysical mechanism that promises transformative and potentially radical changes of our understanding of gamma-ray astrophysics and the physics of the intergalactic medium. This can also alter our picture of the formation of dwarf galaxies and galaxy cluster thermodynamics. Detailed comparisons of predictions of blazar heating with Lyman-α forest data and Fermi observation of blazar statistics as well as the isotropic and anisotropy gamma-ray backgrounds have been very successful and encouraging.

Nevertheless, we are clearly only beginning to explore the process and implications of plasma-instability driven blazar heating. Many aspects are only poorly understood and are now starting to be investigated, including the physics of the instability in the regime of non-linear saturation. Detailed cosmological simulations of blazar heating are critical in understanding its impact on non-linear structure formation. We hope that this work motivates fruitful observational and theoretical efforts toward consolidating the presented picture or to modify parts of it.
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