Blazar Heating –
The Rosetta Stone for Structure Formation?

Christoph Pfrommer

in collaboration with

Avery E. Broderick, Phil Chang, Ewald Puchwein, Volker Springel

1 Heidelberg Institute for Theoretical Studies, Germany
2 Canadian Institute for Theoretical Astrophysics, Canada

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1. Physics of blazar heating
   - TeV emission from blazars
   - Propagation of TeV photons
   - Plasma instabilities

2. The intergalactic medium
   - Properties of blazar heating
   - Thermal history of the IGM
   - The Lyman-\(\alpha\) forest

3. Structure formation
   - Entropy evolution
   - Bimodality of galaxy clusters
   - Formation of dwarf galaxies
Outline

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TeV gamma-ray astronomy

H.E.S.S.  
MAGIC I  
VERITAS  
MAGIC II
The TeV gamma-ray sky

There are several classes of TeV sources:

- **Galactic** - pulsars, BH binaries, supernova remnants
- **Extragalactic** - mostly blazars, two starburst galaxies

**VHE γ-ray Sky Map**

(E > 100 GeV)

VHE γ-ray sources:
- Blazer (HBL)
- Blazer (LBL)
- Flat Spectrum Radio Quasar
- Radio Galaxy
- Starburst galaxy
- Pulsar Wind Nebula
- Supernova Remnant
- Binary System
- Wolf-Rayet Star
- Open Cluster
- Unknown
Unified model of active galactic nuclei
The blazar sequence
1 TeV photons can pair produce with 1 eV photons:

\[ \gamma + \gamma \rightarrow e^+ + e^- \]

mean free path for this depends on the density of 1 eV photons:
→ typically \( \sim 100 \) Mpc
→ pairs produced with energy of 0.5 TeV \((\gamma = 10^6)\)

these pairs inverse Compton scatter off the CMB photons
→ mean free path is \( \sim 30 \) kpc
→ producing gamma-rays of \( \sim 1 \) GeV

\[ E \sim \gamma^2 E_{\text{CMB}} \sim 1 \text{ GeV} \]

each TeV point source is also a GeV point source
What about the cascade emission?

Every TeV source should be associated with a 1-100 GeV gamma-ray halo – not seen!

Neronov & Vovk (2010)
Missing plasma physics?

How do beams of $e^+/e^-$ propagate through the IGM?

- Plasma processes are important
- Interpenetrating beams of charged particles are unstable
- Consider the two-stream instability for two beams:

  \[ \omega_p \gamma = \sqrt{\frac{4\pi e^2 n_e}{\gamma^2 m_e}} \]

  \[ \lambda_p = \frac{\gamma c}{\omega_p} \]

- One frequency (timescale) and one length in the problem:
Two-stream instability: mechanism

wave-like perturbation with $k \parallel \mathbf{v}_{\text{beam}}$, longitudinal charge oscillations in background plasma (Langmuir wave):

- initially homogeneous beam-$e^-$:
  - attractive (repulsive) force by potential maxima (minima)
- $e^-$ attain lowest velocity in potential minima $\rightarrow$ bunching up
- $e^+$ attain lowest velocity in potential maxima $\rightarrow$ bunching up
Two-stream instability: mechanism

Wave-like perturbation with $k \parallel \mathbf{v}_{\text{beam}}$, longitudinal charge oscillations in background plasma (Langmuir wave):

- Beam-$e^+/e^-$ couple in phase with the background perturbation: enhances background potential
- Stronger forces on beam-$e^+/e^-$ $\rightarrow$ positive feedback
- Exponential wave-growth $\rightarrow$ instability
Oblique instability

\( \mathbf{k} \) oblique to \( \mathbf{v}_{\text{beam}} \): real word perturbations don’t choose “easy” alignment = \( \sum \) all orientations

Bret (2009), Bret+ (2010)
consider a light beam penetrating into relatively dense plasma

maximum growth rate

\[
\sim 0.4 \gamma \frac{n_{\text{beam}}}{n_{\text{IGM}}} \omega_p
\]

oblique instability beats IC by two orders of magnitude
Beam physics – growth rates

- non-linear evolution of these instabilities at these density contrasts is not known
- expectation from PIC simulations suggest substantial isotropization of the beam
- plasma instabilities cool the beam, no energy left over for IC off the CMB
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TeV blazar luminosity density

- collect luminosity of all 23 TeV blazars with good spectral measurements
- account for the selection effects
- TeV blazar luminosity density is a scaled version ($\sim 0.2\%$) of that of quasars!
- assume that they trace each other for all $z$

Broderick, Chang, C.P. (2011)
Evolution of the heating rates

Chang, Broderick, C.P. (2011)
Blazar heating vs. photoheating

- total power from AGN/stars vastly exceeds the TeV power of blazars
- \( T_{\text{IGM}} \sim 10^4 \text{ K} \) (1 eV) at mean density \((z \sim 2)\)
  \[
  \varepsilon_{\text{th}} = \frac{kT}{m_p c^2} \sim 10^{-9}
  \]
- radiative energy ratio emitted by BHs in the Universe (Fukugita & Peebles 2004)
  \[
  \varepsilon_{\text{rad}} = \eta \Omega_{\text{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}
  \]
- fraction of the energy energetic enough to ionize H I is \( \sim 0.1\):
  \[
  \varepsilon_{\text{UV}} \sim 0.1 \varepsilon_{\text{rad}} \sim 10^{-6} \rightarrow kT \sim \text{keV}
  \]
- photoheating efficiency \( \eta_{\text{ph}} \sim 10^{-3} \rightarrow kT \sim \eta_{\text{ph}} \varepsilon_{\text{UV}} m_p c^2 \sim \text{eV} \)
  (limited by the abundance of H I/He II due to the small recombination rate)
- blazar heating efficiency \( \eta_{\text{bh}} \sim 10^{-3} \rightarrow kT \sim \eta_{\text{bh}} \varepsilon_{\text{rad}} m_p c^2 \sim 10 \text{ eV} \)
  (limited by the total power of TeV sources)
Thermal history of the IGM

Chang, Broderick, C.P. (2011)
Evolution of the equation of state

- Blazars and extragalactic background light are uniform
  → Blazar heating independent of density
  → Causes inverted equation of state, $T \propto 1/\delta$

- Blazars completely change the thermal history of the diffuse IGM and late-time structure formation

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Chang, Broderick, C.P. (2011)
Equation of state

Puchwein, C.P., Springel, Broderick, Chang (2011)
Ly-\(\alpha\) spectra

![Graph showing Ly-\(\alpha\) spectra with transmitted flux fraction \(e^{-\tau}\) as a function of velocity [km s\(^{-1}\)]. The graph includes two curves: one for 'no blazar heating' and another for 'intermediate b. h.' The plot also shows the transmitted flux fraction \(e^{-\tau}\) and the change in transmitted flux \(\Delta e^{-\tau}\) as a function of velocity.

Puchwein+ (2011)
Ly-α flux PDFs and power spectra

Puchwein+ (2011)
Voigt profile fitting – line width distribution

PDF of $b$ [skm$^{-1}$] for $N_{HI} > 10^{13}$ cm$^{-2}$ in the range $2.75 < z < 3.05$. The graph shows distributions for different levels of blazar heating:
- Dashed line: no blazar heating
- Blue dashed line: weak blazar heating
- Green line: intermediate blazar heating
- Red dashed line: strong blazar heating

Kirkman & Tytler '97 and Puchwein+ (2011) noted different heating effects based on the line width distribution.
impressive improvement in modelling the Lyman-α forest is a direct consequence of the peculiar properties of blazar heating:

- heating rate independent of IGM density → naturally produces the inverted EOS that Lyman-α forest data demand
- recent and continuous nature of the heating needed to match the redshift evolutions of all Lyman-α forest statistics
- magnitude of the heating rate required by Lyman-α forest data ∼ the total energy output of TeV blazars (or equivalently ∼ 0.2% of that of quasars)
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Physics of blazar heating  
The intergalactic medium  
Structure formation

Entropy evolution  
Bimodality of galaxy clusters  
Formation of dwarf galaxies

Entropy evolution

- temperature evolution
- entropy evolution

C.P., Chang, Broderick (2011)

- evolution of the entropy, $K_e = kTn_e^{-2/3}$, at mean density
- blazar heating substantially increases the entropy floor ($z \lesssim 2$)
Evolution of the entropy equation of state

- blazar heating substantially increases the entropy in voids
- scatter is also increased → larger stochasticity of structure formation
Blazar heating is an amalgam of pre-heating and AGN feedback:

- **blazar heating is not localized** ($\neq$ AGN feedback)
  - changes initial conditions for forming groups (but provides no stability for cool cores, CCs)

- **blazar heating generates time-dependent entropy floor** ($\neq$ pre-heating)
  - solves the classical problems of pre-heating ($z \sim 3$):
    - provides a physical mechanism
    - does not starve galaxy formation for $z \lesssim 3$
    - early forming groups can cool and develop observed low-$K_e$ cores
How efficient is heating by AGN feedback?

- **cavity enthalpy**
  \[ E_{\text{cav}} = 4 P V_{\text{tot}} \]

- in some cases
  \[ E_{\text{cav}} \gtrsim E_{\text{bind}}(R_{2500}) \]

- **cavity energy only couples weakly into ICM, but prevents cooling catastrophe**

- on a buoyancy timescale, no AGN outburst transforms a CC to a non-cool core (NCC) cluster!

C.P., Chang, Broderick (2011)
Mass accretion history of groups/clusters

- Peak entropy injection from blazar heating ($z \sim 1$) matches formation time of groups.
- Early forming groups are unaffected and develop cool cores.
- Late forming groups have an elevated entropy core.

C.P., Chang, Broderick (2011)
Entropy profiles: effect of blazar heating

varying formation time

\[ K_e \text{ [keV cm}^{-2}\text{]} \]

\[ r / R_{200} \]

\[ z = 0 \]
\[ M_{200} = 3 \times 10^{13} M_{\odot} \]

\[ z = 0.5 \]

\[ z = 1 \]

\[ z = 2 \]

optimistic blazar

varying cluster mass

\[ K_e \text{ [keV cm}^{-2}\text{]} \]

\[ r / R_{200} \]

\[ M_{200} = 1 \times 10^{14} M_{\odot}, \quad z = 0.5 \]

\[ M_{200} = 3 \times 10^{13} M_{\odot}, \quad z = 0.5 \]

\[ M_{200} = 1 \times 10^{13} M_{\odot}, \quad z = 0.5 \]

optimistic blazar

C.P., Chang, Broderick (2011)

- cluster entropy profile immediately after formation (no cooling)
- largest effect for late forming, small objects
Scenario for the bimodality of cluster core entropies?

- entropy core, $K_{e,0}$, immediately after formation is set by the $z$-dependent blazar heating

- only late forming groups ($z \lesssim 1$) are directly affected by blazar (pre-)heating

- if the cooling time, $t_{\text{cool}}$, is shorter than the time period to the successive merger, $t_{\text{merger}}$, the group will radiate away the elevated core entropy and evolve into a CC

- if $t_{\text{cool}} > t_{\text{merger}}$, merger shocks can gravitationally reprocess the entropy cores and amplify them → potentially those forming clusters evolve into non-cool core (NCC) systems
**Gravitational reprocessing of entropy floors**

- Larger $K_{e,0}$ of a merging cluster facilitates shock heating → increase of $K_{e,0}$ over entropy floor
- Entropy floor of 100 keV cm$^2$ at $z = 3$ in non-radiative simulation:
  - net entropy amplification factor $\sim 3–5$ for clusters and groups (Borgani+ 2005)
- Expect median of $K_{e,0} \sim 150$ keV cm$^2$; maximum $K_{e,0} \sim 600$ keV cm$^2$
**Bimodality of cluster core entropies**

- *Chandra* observations match blazar heating expectations!
- Need hydrodynamic simulations to confirm this scenario

Cavagnolo+ (2009)
on small enough scales, the thermal pressure can oppose gravitational collapse of the gas

characteristic length scale below which objects will not form

Jeans wavenumber and mass is obtained by balancing the sound crossing and free-fall timescales

$$k_J(a) \equiv \frac{a}{c_s(a)} \sqrt{4\pi G \bar{\rho}(a)}$$

$$M_J(a) \equiv \frac{4\pi}{3} \bar{\rho}(a) \left( \frac{2\pi a}{k_J(a)} \right)^3 = \frac{4\pi^{5/2}}{3} \frac{c_s^3(a)}{G^{3/2} \bar{\rho}^{1/2}(a)}$$

blazar heating increases the IGM temperature by $\sim 10$:

$$\frac{M_{J,\text{blazar}}}{M_{J,\text{photo}}} = \left( \frac{c_{s,\text{blazar}}}{c_{s,\text{photo}}} \right)^3 = \left( \frac{T_{\text{blazar}}}{T_{\text{photo}}} \right)^{3/2} \gtrsim 30$$
Filtering mass – dwarf formation

\[ M_F = \left( \frac{h}{10^10\ M_\odot} \right) \]

linear theory

non-linear theory

blazar heating

only photoheating

\[ 1 + \delta = 1, \quad z_{\text{reion}} = 10 \]

C.P., Chang, Broderick (2011)
C.P., Chang, Broderick (2011)

- Blazar heating efficiently suppresses the formation of void dwarfs within existing DM halos of masses $< 3 \times 10^{11} \, M_\odot$ ($z = 0$)
- Reconciling the number of void dwarfs in simulations and the paucity of those in observations
“Missing satellite” problem in the Milky Way

- late forming satellites (< 10 Gyr) not observed!

- blazar heating suppresses late satellite formation, reconciling low observed dwarf abundances with CDM simulations

Maccio & Fontanot (2010)
Maccio+ (2010)
Conclusions on blazar heating

- novel mechanism; dramatically alters thermal history of the IGM:
  - uniform and $z$-dependent preheating
  - rate independent of density $\rightarrow$ inverted EOS
  - consistent picture of Lyman-$\alpha$ forest

- significantly modifies late-time structure formation:
  - group/cluster bimodality of core entropy values
  - may suppress Sunyaev-Zel’dovich power spectrum
  - dwarf formation: “missing satellite” problem, void phenomenon

- explains puzzles in high-energy astrophysics:
  - TeV blazars can evolve like quasars
  - extragalactic gamma-ray background at $E \gtrsim 10$ GeV
  - invalidates intergalactic $B$-constraints from blazar spectra