# Conical Flow induced by Quenched QCD Jets

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We suggest that the energy/momentum loss by quenched QCD jets created in heavy ion collisions at RHIC propagates as a collective excitation or "conical flow" of the produced matter. We solve the linearized relativistic hydrodynamic equations to detail the flow picture. We argue that for RHIC collisions the direction of this flow should form a cone at a specific large angle with the jet of about $70^o$, and thus lead to peaks in particle correlations at the angle $\Delta\phi = \pi \pm 1.2$ rad relative to the large-$p_t$ trigger.

## 1. Introduction

**Jet quenching** is an important phenomenon, predicted and observed at RHIC ( see [1] for a review). Although the main research so far has been related to the calculation of the energy loss $dE/dx$ of the fastest parton, we focus [2] on the fate of this lost energy. We point out that as hydrodynamics describes well sQGP excitations, it should be used to predict the collective flow developed after a local deposition of energy/momentum.

We will concentrate on jets transversing the whole medium and being maximally quenched. This is what occurs in the two particle correlation experiments ([3], [4]), where the strong quenching biases the trigger jet to be produced close to the surface of the colliding region and to move outwards, forcing its companion to move inwards through matter. As it propagates at the speed of light, it deposits its energy along its trajectory. As is well known, the interference of perturbations from a supersonically moving body creates a conical flow behind the shock waves. Similar ideas were also discussed in [5].

## 2. Linearized Hydrodynamics

We assume that the energy-momentum density deposited by the jets is small compared to the total energy of the medium, which allows us to linearize the problem. The approximation breaks down close to the jet, where the thermalization of the lost energy takes place. We will assume that this process happens at distances of the order of the "sound attenuation length" $\Gamma_s = (4/3)\eta/(\epsilon + p)$, with $\eta$ being the shear viscosity.

In this approximation, all the components of the perturbed stress energy tensor induced by the jet can be expressed in terms of the momentum densities $\delta T^{0\mu}$. The linearized hydro equations for these variable in a static medium can be splitted in two modes [2]:

i) Sound waves, which are propagating modes. The coherent superposition of this modes leads to a Mach cone.

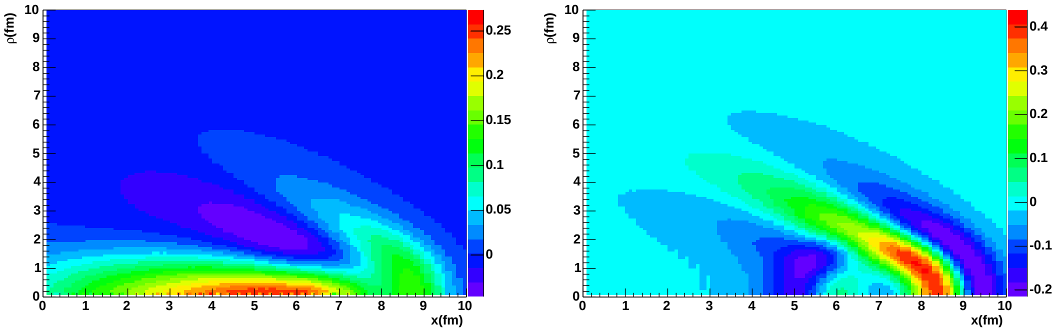


Figure 1. Velocity field $v_x$ created by a jet moving along the $\hat{x}$ direction ($c_s^2 = 1/3$, $\Gamma_s = 1/(4\pi T)$, $\sigma = \Gamma_s$). The jet is assumed to disappear at $t = 7$ fm while the spectrum calculated at $t = 10$ fm. The two figures (a) and (b) are for scenarios 1 and 2, respectively. The values of the parameters are arbitrary. Note that in (a) matter moves preferentially along the $\hat{x}$ direction, while in (b) it is in the Mach direction.

ii) Diffusion mode, or diffusion, which is not propagating.

In order to determine the initial conditions, we consider an infinitesimal displacement $dt_0$ of the jet (moving at the speed of light) in the $x$ direction at time $t_0$. The final fields are the superposition of the disturbances from all the infinitesimal displacements. The most general expression for the jet induced variation of the fields $\delta T^{0\mu}_{dt_0}(t = t_0, \vec{x})$ is:

$$\delta T^{00}_{dt_0}(t = t0, \vec{x}) = e_0(x, r) \quad , \quad \delta T^{0i}_{dt_0}(t = t0, \vec{x}) = g_0(x, r)\delta^{ix} + \vec{\partial} g_1(x, r) \ , \tag{1}$$

with $e_0$, $g_0$ and $g_1$ functions with typical scale $\sigma \sim \Gamma_s$. As these functions depend on the unknown details of the thermalization process we consider two different scenarios:

*Scenario 1*, the excitation is due to $e_0$ and $g_0$. In this scenario the diffuson mode is excited, and matter flows preferentially along the jet direction (Fig.1a).

*Scenario 2*, in which the excitation is due to $g_1$. In this case only sound modes are excited and matter moves in the Mach direction ($cos\Theta_M = c_s/cs$) (Fig.1b).

## 3. Spectrum

We use the Cooper-Fry prescription with the perturbed fields to calculate the spectrum induced by the companion jet. As our medium is static, we use fixed time freeze-out with temperature $T_{frzt}$ and volume of the fireball V:

$$\frac{dN}{d^3p} = \int_V d^3V e^{-\frac{E}{T_{frzt}} + \delta} \quad , \quad \delta = \frac{E}{T_{frzt}} \frac{\delta T}{T_{frzt}} + \frac{\vec{p}\vec{v}}{T_{frzt}} \ , \tag{2}$$

We distinguish two opposite regimes in the spectrum:

**Low energy particles** $E \sim T_{frzt}$. Expanding the exponential in (2) we can express the spectrum in terms of the deposited energy-momentum. One finds that soft particles are insensitive to the shape of the flow field and their angular dependence is just a cosine between the observed particle and the jet directions.

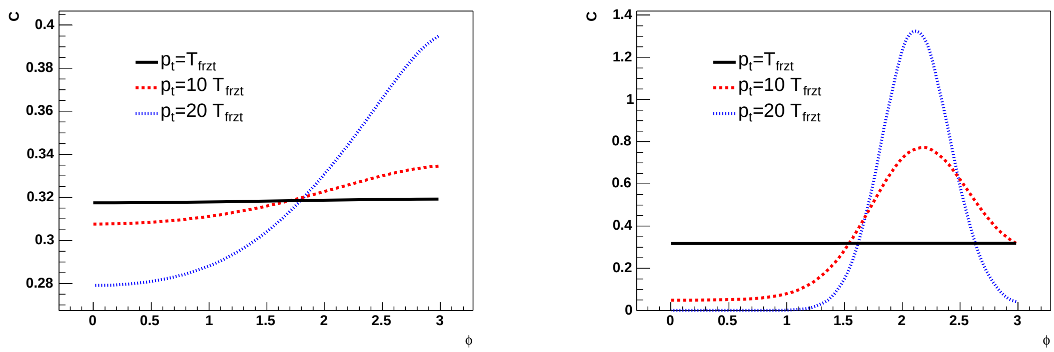


Figure 2. The normalized spectrum of associated secondaries versus the azimuthal angle $\phi$. The three curves are for different $p_t$ at $y = 0$ for $c_s^2 = 1/3$, $\Gamma_s = 1/(4\pi T)$, $\sigma = \Gamma_s$. Note the different scales. The jet disappears completely at $t = 7$ fm while the spectrum is calculated at $t = 10$ fm. The two figures are for scenarios 1 and 2, respectively.

**High energy particles** $E >> T_{frzt}$ The integral is dominated by the points of maximum modification of hydrodynamic fields and, thus, is sensitive to the flow pattern.

In Fig.2 we show the normalized spectrum of particle production at fixed $p_t$

$$C = \frac{1}{Q}\frac{dN}{dyd^2p_t}(y=0,p_t,\phi) \quad , \quad Q = \int_0^{2\pi} d\phi \frac{dN}{dyd^2p_t}(y=0,p_t,\phi) \ , \qquad (3)$$

induced by a jet moving at $y = 0$ and $\phi = \pi$ for the two scenarios of matter excitation. The diffusion mode hides the Mach cone in the final spectrum, and we do not observe such a structure in Fig.2a; we do observe it, however, in Fig.2b, where only sound is excited. The parameters in Fig.2 are arbitrary (apart from $\Gamma_s$, set to its minimal bound). These spectra are very sensitive to $\Gamma_s$, which could provide a experimental constraint on its value potentially more restrictive than elliptic flow, as the gradients are stronger.

## 4. Varying the speed of sound

At RHIC jets do not propagate in a static medium, but in a expanding one, which evolves though three different phases :(i) QGP ($c_s \approx 1/\sqrt{3}$), (ii) mixed phase ($c_s \approx 0$) and (iii) "resonance gas", ($c_s \approx \sqrt{.2}$). We study two consequences of the changing $c_s$:

1. Modification of the effective distance traveled by sound, which reflects in a change of Mach angle. Performing a time weighted average through the previous stages:

$$cos\theta_M = \bar{c}_s/c = \frac{1}{c\tau}\int_0^{\tau} c_s dt \ . \Longrightarrow \quad \theta_{emission} = \pi \pm arccos(\bar{c}_s/c) \approx 1.9, 4.3. \qquad (4)$$

This emission angle matches the position of the maximum in the angular distribution of secondaries associated with a jet trigger [3], [4].

2. Appearance of reflected waves. We studied the spherical sound wave produced by an infinitesimal displacement of the jet for different functions $c_s(t)$ (interpolating between the three stages) with different minima (Fig.3a) . If the speed of sound goes to zero in

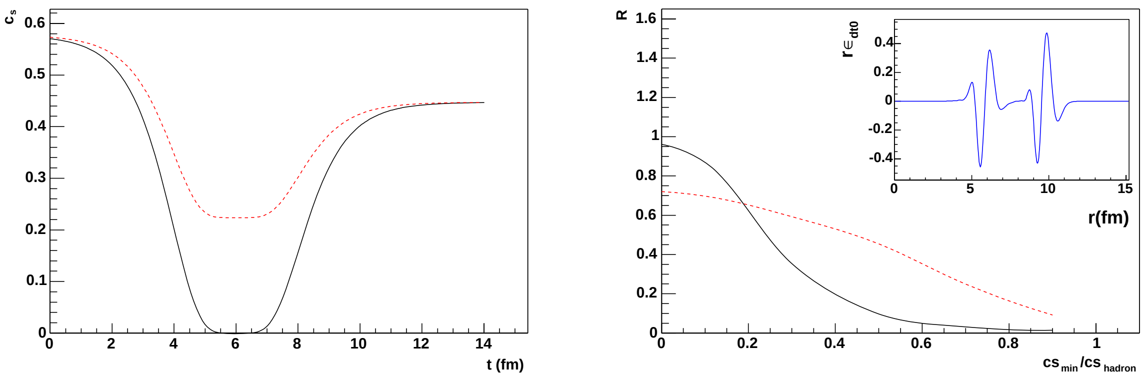


Figure 3. (a) $c_s$ as a function of t. The two curves are different interpolations with different minima at the mixed phase (0 (solid) and $1/2\sqrt{2}$ (dashed)) (b) Ratio of amplitudes of the reflected and transmitted waves as a function of the minimal $c_s$ in units of $c_s$ of the hadron gas for $\Gamma_s = 0$ (solid) and $\Gamma_s = 0.1$ (dashed). The inset shows the double pulsed structure of the perturbed energy density (arbitrary units) for $c_{min} = 0$ and $\Gamma_s = 0$.

the mixed phase (first order phase transition), this spherical wave splits into forward and backward moving waves. The amplitude of the reflected wave decreases as the minimum of $c_s$ increases (Fig.3b). The backward moving wave eventually bounces back at the origin, leading to a double pulsed spherical disturbance. The interference of those waves should lead to a double cone in the flow pattern at sufficiently late times. The amplitude of the second cone depends on how close to zero $c_s$ is in the mixed phase. The effect of this double cone in the particle spectra remains to be studied and we will be done elsewhere.

## 5. Conclusions

We suggest that the energy lost by jets is not just absorbed by the medium, but appears as hydrodynamical collective motion similar to "sonic booms". This happens because the QGP seems to be a near-perfect liquid, with remarkably small viscosity As a result, a cone of particles moving in the Mach direction appears. Data on the particle distribution associated with the quenched jet (the away side from high energy hadron trigger) indeed show two peaks, with cone angles which agree well with our prediction.

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