Di-jets production in quark gluon plasmas

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Abstract

In azimuthal di-hadron correlation two broad and narrow structures are observed, which is called "away-side jet" and "near-side jet" respectively. We can describe them as perturbations around the equilibrium baryon density by linearization of the hydrodynamic equations. It is found that the localized perturbations are able to propagate in quark gluon plasma (QGP) for long distances.

The RHIC experiments indicate the existence of a hot and dense fireball of matter which behaves like a perfect fluid of quarks and gluons. Relativistic hydrodynamics is applied for describing the evolution of this fluid. Interaction between the localized perturbations on the background baryon density is able to create back-to-back di-jets structures as shown in the figure 1[1-2].

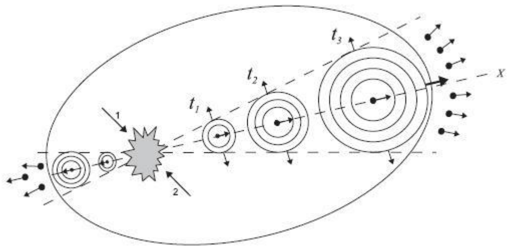

Figure 1 : the di-jets productions in a hot QGP

The total energy-momentum tensor reads,

$$T_{\mu\nu} = (\in + p)u_\mu u_\nu - p g_{\mu\nu} \tag{1}$$

Where $\in$ and p are the energy density and pressure respectively. The four-vector velocity u^ν is considered by $u^0 = \gamma$, $\vec{u} = \gamma\vec{v}$ and $u^\nu u_\nu = 1$ which γ is the Lorentz factor given by $\gamma = (1 - v^2)^{-1/2}$; so $\vec{v} = \vec{v}(x, y, z, t)$ is the matter velocity.

Energy-momentum is conserved and we have

$$\partial_\nu T^\nu_\mu = 0 \tag{2}$$

The relativistic version of the Euler equation is resulted by projecting (2) onto the direction perpendicular to u^μ [3-4]

$$\frac{\partial\vec{v}}{\partial t} + (\vec{v}.\vec{\nabla})\vec{v} = -\frac{1}{\gamma^2(\in + p)}\left(\vec{\nabla}P + \vec{v}\frac{\partial P}{\partial t}\right) \tag{3}$$

The relativistic version of the continuity equation for the baryon density is

$$\partial_\nu j^\nu_B = 0 \tag{4}$$

Since $j^\nu_B = u^\nu \rho_B$, the above equation can be rewritten as

$$\frac{\partial\rho_B}{\partial t} + \gamma^2\vec{v}\rho_B\left(\frac{\partial\vec{v}}{\partial t} + (\vec{v}.\nabla)\vec{v}\right) + \vec{\nabla}.(\rho_B\vec{v}) = 0 \tag{5}$$

Where ρ_B is the baryon density which is

$$\rho_B = \frac{1}{3}\frac{\gamma_Q}{(2\pi)^3}\int d^3k\left[n_{\vec{k}} - \bar{n}_{\vec{k}}\right] \tag{6}$$

with

$$n_{\vec{k}} \equiv n_{\vec{k}}(T) = \frac{1}{1+e^{(k-\frac{1}{3}\mu)/T}} \qquad ,\bar{n}_{\vec{k}} \equiv \bar{n}_{\vec{k}}(T) = \frac{1}{1+e^{(k+\frac{1}{3}\mu)/T}} \tag{7}$$

where μ is the baryon chemical potential.
The energy density and the pressure are

$$\epsilon = \mathcal{B} + \frac{\gamma_G}{(2\pi)^3}\int d^3k\, k\left(e^{k\backslash T} - 1\right)^{-1} + \frac{\gamma_Q}{(2\pi)^3}\int d^3k\, k\left[n_{\vec{k}} + \bar{n}_{\vec{k}}\right] \tag{8}$$

and

$$p = -\mathcal{B} + \frac{1}{3}\left\{\frac{\gamma_G}{(2\pi)^3}\int d^3k\, k\left(e^{k\backslash T} - 1\right)^{-1} + \frac{\gamma_Q}{(2\pi)^3}\int d^3k\, k\left[n_{\vec{k}} + \bar{n}_{\vec{k}}\right]\right\} \tag{9}$$

in which expressions $\gamma_G = 2(polarizations) \times 8(colors) = 16$ and $\gamma_Q = 2(spins) \times 2(flavors) \times 3(colors) = 12$ are the statistical factor for gluons and quarks respectively. Also $\mathcal{B}$ is the bag energy which can be calculated using the MIT bag model.
The sound velocity is

$$c_s^2 = \frac{\partial p}{\partial \epsilon} = \frac{1}{3} \tag{10}$$

The relativistic version of Euler equation for the QGP at $T = 0$ is achieved, [5]

$$\rho_B\left(\frac{\partial\vec{v}}{\partial t} + (\vec{v}.\vec{\nabla})\vec{v}\right) = \frac{v^2-1}{3}\left(\vec{\nabla}\rho_B + \vec{v}\frac{\partial\rho_B}{\partial t}\right) \tag{11}$$

A stretched coordinates system can be employed for studying the small amplitude nonlinear waves in the medium as [6]

$$\begin{cases} \xi = \varepsilon(x - c_1t) + \varepsilon^2 P_0(\eta,\tau) + \varepsilon^3 P_1(\eta,\xi,\tau) + \cdots \\ \eta = \varepsilon(x + c_2t) + \varepsilon^2 Q_0(\xi,\tau) + \varepsilon^3 Q_1(\eta,\xi,\tau) + \cdots \\ \tau = \varepsilon^3 t \end{cases} \tag{12}$$

where ξ and η denote the trajectories of the two traveling breaking waves toward the right and left directions, respectively and ε is the small expansion parameter. The variables c_1 , c_2 are the unknown phase velocity. The equations (3)and (5) can be rewritten by the dimensionless variables:

$$\rho = \frac{\rho_B}{\rho_0}\,, \qquad v = \frac{v}{c_s} \tag{13}$$

which ρ_0 is equilibrium baryon density, against which perturbations may be happened.
Now we consider the series expansions of the dependent variables as

$$\rho = 1 + \epsilon^2\rho_1 + \epsilon^3\rho_2 + \epsilon^4\rho_3 + \cdots \tag{14}$$

$$v = \epsilon^2 v_1 + \epsilon^3 v_2 + \epsilon^4 v_4 + \cdots \tag{15}$$

considering ρ_1 as, $\rho_1 = \rho_1^1(\xi,\tau) + \rho_1^2(\eta,\tau)$, the first nonzero terms of equations (3) and (5) lead to

$$v_1 = c_1\rho_1^1(\xi,\tau) - c_2\rho_1^2(\eta,\tau), \qquad c_1 = c_2 = \frac{1}{\sqrt{3}} \tag{16}$$

Substituting (16) in higher order terms respect to ε one can fins the typical breaking wave equations as

$$\frac{\partial \rho_1^1}{\partial \tau}+\frac{2\sqrt{3}}{9}\rho_1^1\frac{\partial \rho_1^1}{\partial \xi}=0 \tag{17}$$

$$\frac{\partial \rho_1^2}{\partial \tau}+\frac{2\sqrt{3}}{9}\rho_1^2\frac{\partial \rho_1^2}{\partial \eta}+\frac{2\sqrt{3}}{3}\rho_1^2\frac{\partial \rho_1^1}{\partial \xi}=0 \tag{18}$$

By transferring to (x,t) space the breaking waves become

$$\frac{\partial \hat{\rho}_1^1}{\partial t}+\frac{1}{\sqrt{3}}\frac{\partial \hat{\rho}_1^1}{\partial x}+\frac{2\sqrt{3}}{9}\hat{\rho}_1^1\frac{\partial \hat{\rho}_1^1}{\partial x}+\frac{1}{3}\hat{\rho}_1^2\left[\frac{\partial \hat{\rho}_1^1}{\partial t}-\frac{1}{\sqrt{3}}\frac{\partial \hat{\rho}_1^1}{\partial x}\right]=0 \tag{19}$$

$$\frac{\partial \hat{\rho}_1^2}{\partial t}-\frac{1}{\sqrt{3}}\frac{\partial \hat{\rho}_1^2}{\partial x}-\frac{2\sqrt{3}}{9}\hat{\rho}_1^2\frac{\partial \hat{\rho}_1^2}{\partial x}+\frac{2\sqrt{3}}{3}\hat{\rho}_1^2\frac{\partial \hat{\rho}_1^1}{\partial x}+\frac{1}{3}\hat{\rho}_1^1\left[\frac{\partial \hat{\rho}_1^2}{\partial t}+\frac{1}{\sqrt{3}}\frac{\partial \hat{\rho}_1^2}{\partial x}+\frac{2\sqrt{3}}{9}\hat{\rho}_1^2\frac{\partial \hat{\rho}_1^1}{\partial x}\right]-\frac{2\sqrt{3}}{27}{\hat{\rho}_1^2}^2\frac{\partial \hat{\rho}_1^1}{\partial x}=0 \tag{20}$$

Considering $\hat{\rho}_1^1(x,t_0)=\hat{\rho}_1^2(x,t_0)=\mathrm{sech}^2\,x$ as the initial condition, the evolution of the breaking backward and forward waves can be simulated numerically. Simulations indicate that the localized breaking waves are enough stable to reach the borders of the QGP region and change the hadronization pattern during the QGP freezing out. Figure 2 shows the time evolution of the baryon density pulses at zero temperature.

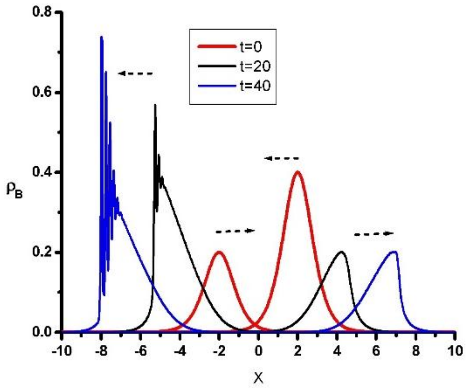

Figure 2 : Time evolution of the baryon density pulses at zero temperature, x and t are in fm.

Conclusion

Formation of near-side and far-side jets in the heavy ion collisions has been explained using the interaction of localized perturbations in the baryon density of QGP. It is shown that the established breaking waves are enough stable to reach the borders of QGP.

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